WASHINGTON STATE AQUATIC HABITAT GUIDELINES PROGRAM

Stream Habitat Restoration Guidelines

2012

CHAPTER 1

STREAM HABITAT RESTORATION GUIDLINES

Chapter 1. Stream Habitat Restoration Guidelines

Few endeavors in resource and environmental management in the Pacific Northwest are more compelling than rapidly expanding efforts to restore the region’s streams and rivers. The region’s history and strongly held values are inseparably intertwined with our streams and rivers. In coastal and inland settings, historic and current settlement and development patterns have centered on streams for transportation, residential, municipal, agricultural, and industrial water supply, power generation, and crop irrigation. Pacific Northwest streams and rivers, and their floodplains provide; food, construction aggregates, and recreational opportunities. Their floodplains provide relatively flat, fertile agricultural land and their forested riparian zones historically supplied timber. However, competing uses of stream corridors in modern society, combined with large-scale alteration of watersheds, have directly and indirectly impacted the abundance, quality, and stability of stream and riparian habitats. Streams, with their associated floodplain and riparian ecosystems compose the sole habitat, or critical habitat elements for a majority of the region’s native fish and wildlife. Approximately 85% of Washington’s terrestrial vertebrate wildlife species depend on riparian habitats for all or critical portions of their life histories. This rich floral and faunal biodiversity is the basis for much of the state’s cultural heritage, economy, and famous quality of life.

After more than a century of adverse impacts from a multitude of economic activities following Euro-American settlement, recognition of the need to restore streams has spread throughout the Puget Sound region, coastal watersheds draining directly to the Pacific Ocean, and the entire Columbia River watershed. Much of this awareness and activity is driven by the serious decline of the region’s once robust anadromous runs of wild salmon, cutthroat, bull trout, smelt, and sturgeon. The accelerating interest in stream restoration also stems from a desire to restore wild populations of native resident salmonid fish species, including redband, cutthroat and bull trout, and other aquatic and riparian species, many of which have been listed as threatened or endangered under the federal Endangered Species Act and the Washington Wildlife Code.

Securing supplies of clean, cool water for a host of human and wildlife needs also depends on healthy stream systems in functionally intact watersheds. A majority of the state’s major rivers and hundreds of tributary streams fail to attain federal and state water quality standards for a host of pollutants including heavy metals and toxic compounds and nutrients, and for temperature, turbidity, dissolved oxygen and biological oxygen demand parameters. Great progress has been achieved in reducing industrial and municipal point sources of water pollution, yet a large challenge remains to achieve and maintain reductions of urban, rural and wildland sources of non-point water pollution. The purpose of the *Stream Habitat Restoration Guidelines* (SHRG) is to promote process based natural stream restoration, rehabilitating aquatic and riparian ecosystems. These guidelines advance a watershed scale assessment of the stream system, establishing goals, objectives and design for restoring optimum sustainable native biodiversity, using principles of landscape ecology and integrated aquatic ecosystem restoration.

While a number of specific watershed assessment, characterization, project design and construction approaches are presented in this volume, these guidelines do not offer a “cookbook” approach that provides every step and equation along the way. Rather, the intent is to provide readers with a comprehensive list of factors and criteria to consider, which are essential to make informed decisions when planning and designing stream restoration and rehabilitation work. **Readers are strongly cautioned not to pluck and apply individual techniques from these guidelines without first conducting the necessary watershed and reach based assessments and analysis.** The techniques presented in these guidelines are not meant to limit the designer. Other innovative stream restoration techniques may exist and are sure to be developed and included in future editions of this document.

Topics addressed in the SHRG include site, reach, and watershed assessment, problem identification, general approaches to restoring stream and riparian habitat, factors to consider in identifying and selecting an approach, approaches to solving common restoration objectives, and stream and riparian habitat restoration techniques. Watershed processes and conditions that shape stream channels, stream ecology, geomorphology, hydrology, hydraulics, planting considerations and erosion control, and construction considerations are also presented in the main text and appendices.

1.1 Historic Impacts to Streams and Watersheds

Degraded stream systems reflect degraded conditions in their contributing watersheds. Degraded or altered conditions in all watersheds in the working landscape reflect similar patterns, from forested or shrub-steppe wildlands managed for grazing and timber production, to agricultural lands, to intensively urbanized watersheds. These patterns of watershed “hardening” tend to increase the magnitude and frequency of high flows after precipitation events, and increase sediment and pollutant inputs into stream systems. The annual hydrograph, as differentiated from the storm event flow response described above, is also changed. High spring runoff flows often increase, while seasonal low flows (base flows) decline or cease. Direct alterations include channel straightening, dredging, widening, narrowing, levee construction, floodplain fill, and riparian zone modification. Indirect activities include those that alter the principal processes that create and maintain stream channel conditions. Timber harvest and forest management, road building, grazing, agriculture and urbanization all influence the supply and transport of water, sediment, energy (light and heat), nutrients, solutes, and organic matter (ranging from woody material to leaf litter).

Watershed hardening is obvious and intuitively understood in urbanized watersheds, and erosion associated with agriculture is well recognized by the public. Gains have been realized in broadening public awareness of adverse impacts resulting from draining and filling wetlands. Inappropriate logging practices from the past, road building, and overgrazing result in soil compaction and erosion. In working wildlands, snowmelt is accelerated when the tree canopy is opened or eliminated[1], and runoff increases as soil infiltration declines. Reduced soil infiltration reduces bank storage (groundwater recharge), causing decline or cessation of summer and fall low flows in streams. Thus, increased stream flows after storms and snowmelt, combined with increased sediment inputs from erosion degrade stream channels, which evolved in dynamic equilibrium with the geological, biotic and climatic conditions of their drainages. These changes in stream flows and sediment inputs often destabilize stream channels, mobilizing more sediment from their beds and banks. Stream restoration efforts applied solely on the stream and its riparian corridor will not succeed or persist if the degraded condition of the tributary watershed is not addressed beforehand or simultaneously.

Physical and ecological *processes* create stream channel and floodplain *structure*, in which habitat *functions* for fish and wildlife, and all other ecosystem components occur. These include the interaction of water, sediment and wood that create channels and shoreline structure, which are geomorphic processes. Geomorphic processes include hydrologic response, sediment transport, wood influences, erosion and accretion, fire, and channel evolution and migration. Changes in the behavior and routing of water in the watershed result in changes in geomorphic processes in stream systems. Biological processes that interact in complex pathways with geomorphic processes include nutrient cycling, riparian and upland vegetation dynamics, soil building and species mediated habitat-forming processes such as beaver activity.

Native fish and wildlife, including anadromous and resident salmonids, have coevolved and adapted to exploit the habitats created by these processes. Sustaining wild, naturally occurring populations of these species depends on sustaining the biotic and geomorphic ecological processes of watersheds and their aquatic ecosystems.

Watershed scale physical and ecological processes have been altered or lost historically in the Pacific Northwest, resulting from a broad array of human activities, including intensive beaver trapping, urban, suburban and industrial development, agriculture, timber harvest, mining, overgrazing, structural flood control and channelization, surface water withdrawal for agricultural irrigation, domestic, commercial and industrial use, construction and operation of roads, railroads, pipelines, electrical distribution lines, and construction and operation of dams and reservoirs for irrigation and power generation. Our society as a whole bears responsibility for these impacts, which have both, accompanied development of the region’s diverse economy, and diminished our ecological resources, and the economic and recreational opportunity based on these assets. These impacts have also decreased potential for future economic opportunities.

Diverse land use and economic activities compete for water and floodplain real estate, while these same resources are vital for restoring and sustaining aquatic ecosystems, including those that support wild anadromous salmon and trout. While these guidelines suggest and recommend modifying land use activities within the watershed to restore the processes that create and maintain stream habitat, in-depth discussion of these issues lies outside the scope of these pages.

The Watershed Planning Act, RCW 90.82, was passed in 1998, providing a framework for developing local solutions to meet the water supply needs, including instream flows, for each watershed. It primarily addresses water quantity, but the watershed plans may also address water quality and habitat issues. Watershed Planning is being implemented in 42 of Washington’s 62 water resource inventory areas (WRIAs). The Growth Management Act (GMA), RCW 36.70A, and Shoreline Management Act (SMA), RCW 90.58, also specifically address protecting fish and wildlife habitat through analyzing and regulating land use with locally developed and implemented programs. Under the Watershed Planning Act, instream flows are established. Under the GMA and SMA, fish and wildlife habitat areas are to be protected and managed with appropriate buffers and regulations. The SMA guidelines for developing and adopting new Shoreline Master Programs (WAC 173-26) require inventory and analysis of landscape scale ecological, hydrologic and geomorphic processes which determine shoreline ecological function. They also require that updated Shoreline Master Programs contain a shoreline restoration plan, which may include regulatory and nonregulatory measures, and must also include benchmarks and other measures for assuring that the restoration plan is achieved over time.

1.2 Salmon Recovery in Washington State

As Washington's population has grown, its salmon have dwindled. In 1991, the federal government declared the first salmon in the Pacific Northwest, Snake River sockeye, as endangered under the Endangered Species Act. In the next few years, 16 more species of salmon were listed as either threatened or endangered (http://www.rco.wa.gov/salmon_recovery/listed_species.shtml). By 1999, wild salmon had disappeared from about 40 percent of their historic breeding ranges in Oregon, Washington, Idaho, and California. In Washington, the numbers had dwindled so much that salmon and bull trout were listed as threatened or endangered in nearly three-fourths of the state.

Washington has chosen to tackle salmon recovery in a unique way. To develop salmon recovery plans that address habitat, hatcheries, harvest, and hydropower, people in communities didn't wait for the federal government to write the plans, but organized themselves across the state to address Endangered Species Act listings of fish. This bottom-up approach and scale of their efforts is unprecedented in the United States and has been dubbed "The Washington Way" by those involved in salmon recovery.

The network of individuals dedicated to restoring salmon starts with people in communities and includes watershed groups, regional organizations, state and federal agencies, city and county governments, tribes, conservation districts, nonprofit groups, as well as the legislature, Governor, and Congress.

1.2.1 Regional Organizations

To coordinate the work of recovery planning and implementation, seven regional organizations formed (http://wwwtest2.rco.wa.gov/salmon_recovery/regions/regional_orgs.shtml) and recovery plans (http://www.rco.wa.gov/salmon_recovery/regions/regional_orgs.shtml) in each of those regions have been accepted by the federal government and are being implemented.

1.2.2 Lead Entities

Lead entities are watershed based organizations authorized by the Legislature in 1998 (see Revised Code of Washington 77.85.050 - 77.85.070 at http://apps.leg.wa.gov/RCW/default.aspx?cite=77.85) to develop habitat restoration and protection strategies, and look for projects to meet those strategies. Lead Entity plans are available at http://wwwtest2.rco.wa.gov/salmon_recovery/regions/regional_orgs.shtml) and strategies at http://www.rco.wa.gov/salmon_recovery/lead_entities.shtml.

1.2.3 Project Applicants

Project applicants develop habitat restoration and protection projects based on regional recovery plans or strategies developed by lead entities. Project applicants typically are regional fisheries enhancement groups, local governments, tribes, state agencies, community groups, land trusts, and others. They apply for grants from the Salmon Recovery Funding Board and others to pay for projects to protect or restore salmon and bull trout habitat.

1.3 Habitat Work Schedule

The Habitat Work Schedule (HWS) is a project mapping and tracking database for Washington State's Lead Entities and their partners (http://hws.ekosystem.us). It enables natural resource professionals, project funders, and the public to follow past, current, and proposed projects from concept through implementation and then, once complete, into the monitoring phases. This leaves a legacy of local and statewide salmon recovery efforts and creates a better coordinated salmon recovery effort. Projects across the state are categorized as one of four options: restoration, acquisition, combined restoration/acquisition, or non-capital projects. Project can be searched in the HWS database by name, region, Lead Entity, project category, or status. Alternately, you can browse a list of projects, a hierarchy of project folders, or mapped project locations.

The HWS was directed by RCW 77.85.060 to be a

> *"…habitat work schedule that ensures salmon habitat projects will be prioritized and implemented in a logical sequential manner that produces habitat capable of sustaining healthy populations of salmon."*

…and to

> *"…identify and coordinate with any other salmon habitat project implemented …"*

…and

> *"…include the start date, duration, estimated date of completion, estimated cost, and …species…"*

…and to be

> *"…updated on an annual basis to depict new activities."*

Many Lead Entities are continuously adding projects to the HWS. Data is updated frequently, so check back often! You can also contact the Lead Entity staff or project sponsors for more information (http://www.rco.wa.gov/salmon_recovery/lead_entities.shtml).

1.4 Aquatic Habitat Guidelines Program

The *SHRG* are part of a series of guidance documents produced through the Aquatic Habitat Guidelines (AHG) program. The AHG program is a joint effort among state and federal resource management agencies in Washington, which include the Washington Departments of Ecology, Fish and Wildlife, Natural Resources, Recreation and Conservation Office and Transportation. The Aquatic Habitat Guidelines are designed to address the urgent need for increased and broadly accepted technical guidance, to ensure that stream restoration efforts, including those for salmon and trout recovery, and watershed restoration are strategic, ecologically appropriate, and optimize the effective investment of public and private resources. Aquatic Habitat Guidelines do not replace existing regulatory requirements, though they are designed in part as technical guidance supporting regulatory streamlining, and grant application review for stream restoration proposals. Other AHG guidance documents include the *Integrated Streambank Protection Guidelines*[2], *Design of Road Culverts for Fish Passage*[3], *Fishway Guidelines for Washington State*[4], *Protecting Nearshore Habitat and Functions in the Puget Sound*[5], *Land Use Planning for Salmon, Steelhead and Trout: A Land Use Planner's Guide to Salmonid Habitat Protection and Recovery*[6], and *Fish Protection Screen Guidelines for Washington State*[7]. All of these may be viewed at the AHG website, maintained by the Washington Department of Fish and Wildlife (WDFW) at: http://www.wdfw.wa.gov/hab/ahg/. This website also presents an overview of the AHG program, executive summaries of the White Papers, AHG Guiding Principles, and draft guidance documents.

Many of the ecological and resource management issues addressed in these guidance documents have been explored in a series of state-of-the-knowledge white papers produced by regional and national experts as part of the AHG program series. These White Papers may also be viewed and downloaded from the AHG website.

A companion document to the Stream Habitat Guidelines is the *River Restoration Analysis Tool*[8], or RiverRAT, developed by the National Oceanic and Atmospheric Administration (NOAA). RiverRat is a river project development and evaluation tool. It was developed to facilitate consistent and thorough evaluation of the potential impacts of proposed projects on river habitat. The tool is supported by a source document that provides a comprehensive synthesis of the watershed and river sciences relevant to restoration planning and design, a project risk evaluation matrix, and a separate comprehensive checklist of information necessary to review project proposals. RiverRat is referenced throughout SHRG and can be accessed at http://www.restorationreview.com/.

1.5 The Watershed Approach

As with all of the AHG documents, informed by the AHG Guiding Principles, the SHRG emphasizes analyzing and characterizing physical and ecological watershed processes, leading to process-based stream habitat restoration or rehabilitation. Watersheds usually cover multiple land ownerships, often complex patchworks of private and public lands latticed with networks of transportation infrastructure and utility easements. Planning stream restoration requires some level of participation by the many different stakeholders in the watershed, leading to public consensus and support for the work, which dramatically increases the likelihood of success and positive long term outcomes. These guidelines do not address the specifics of public participation in watershed planning and stream habitat restoration design, but focus primarily on the technical aspects of ecological process evaluation and restoration design. The interested reader should consult the excellent multi-agency federal publication, *Stream Corridor Restoration: Principles, Processes, and Practices*[9].

Additional guidance for local public participation is available through Watershed Planning Units, local governments planning under the Growth Management Act and Shoreline Management Act, local Conservation Districts and Resource Conservation and Development entities, and other local resource management units working at the watershed scale.

1.6 Restoration or Rehabilitation

Veterans of resource management and historical efforts at ecological restoration have long been aware that restoring ecosystems and habitats which existed prior to Euro- American settlement is supremely difficult, and rarely if ever achieved. Achieving aquatic ecosystem *restoration* is a worthy goal, yet it implies a clear understanding of what ecological conditions were before Euro-American settlement, and current and future circumstances which will allow full restoration, including full control of all human and economic activities in the affected watersheds. These conditions are approximated only in certain park and wilderness areas, not in the region's working landscape.

In most cases, soil profiles, soil microbial and mycorhizal communities, plant communities, and hydrologic conditions are permanently altered or subject to unpredictable fluctuations driven by urbanization and other watershed hardening, irrigation diversions, wetland reductions, etc. Sediment inputs are also frequently increased from elevated erosion, or reduced in tailwater streams below dams. Additional missing or greatly attenuated ecological processes include nutrient cycling from reduced or lost anadromous fish runs. Other altered conditions that won't be immediately improved include water quality parameters. Accelerated action toward water pollution reduction under the federal Clean Water Act is underway in the form of Total Maximum Daily Load (TMDL) plans, emphasizing control of nonpoint sources. However, these plans will be years in implementation. Thus, the watershed based analysis and characterization yields awareness that conceptually, stream habitat *rehabilitation* is a more accurate, achievable and defensible approach in most cases.

There will be circumstances where restoring a stream's natural channel morphology from a ditched and straightened condition is a highly feasible opportunity, with regard to planform geometry or meander form, and longitudinal profile including pools, riffles, runs and sediment composition. In these cases *creation* is a legitimate design approach.

Stream *restoration* may also be best implemented in riparian corridor protection through livestock exclusion, acquisition in fee simple, or less than fee alternatives like conservation easements, in circumstances where the degree of degradation is moderate enough to facilitate a healing response without requiring invasive earth moving, structural measures or revegetation. Other measures include critical area designation under the Growth Management Act, or appropriate environment designation and restoration planning under the Shoreline Management Act and local Shoreline Master Programs, as noted above.

Protective measures voluntarily executed through fee simple acquisition or conservation easements are often more durable and effective than regulatory measures. Protective measures may also result in rapid stream corridor response if adequate evaluation of the watershed and treatment reach has been conducted. Additional protective measures include addressing watershed degradation in uplands, including land use, agricultural best management practices, improved grazing and range restoration, and improved timber harvest and road building practices. The importance of considering and addressing degraded conditions and ecological processes throughout the watershed cannot be overstated, and is critical to any stream habitat restoration design.

1.7 Restoration Sequencing

Stream habitat restoration or rehabilitation begins with an adequate assessment of watershed conditions, and fits within a continuum ranging from passive measures such as modifying land use activities within the watershed to aggressive channel realignment and structural measures, all evaluated and designed in the context of an adequate assessment of watershed conditions. The essential first step in stream habitat restoration is to conduct an adequate comprehensive watershed analysis and assessment, which characterizes watershed processes outlined in preceding paragraphs. Many such efforts are completed or underway throughout Washington, supporting or implementing the Salmon Recovery Act (ESB 2496), (Regional Organizations implementing Salmon Recovery Plans),Washington Department of Natural Resources watershed assessment, watershed planning under RCW 90.82, subbasin assessment conducted as part of the Interior Columbia Basin Ecosystem Management Plan, Shoreline Master Programs updated comprehensively updated under the new Shoreline Master Program Guidelines of 2003, and many others. Watershed-scale assessment should include adequate evaluation of hydrology and geomorphology of the subject stream system, to characterize flows and extent of channel degradation or relative integrity.

In all cases, the preferred approach to stream habitat restoration or rehabilitation should be stream restoration accompanying watershed restoration. Less invasive design approaches including riparian livestock exclusion and ecologically appropriate revegetation are preferred over more invasive and aggressive channel modifications or structures, including log or root wad placement. Channel modifications require terraforming and expensive machine time, in addition to extensive engineering, hydraulics and hydrologic design, and construction oversight.

Instream restoration activities as stand-alone restoration techniques are only appropriate if the cause of stream degradation can be isolated to a specific in-stream cause. Creating habitat features that existing watershed and channel conditions cannot maintain produces only short-term benefits, if any, and usually requires long-term maintenance. When the cause of stream degradation lies outside the stream, such as excessive stormwater runoff from the watershed, restoration activities should focus on watershed and riparian restoration to reinstate the processes that naturally create and maintain stream habitat over the long term. Watershed and riparian restoration activities are less intrusive and disruptive to the aquatic ecosystem than aggressive in-stream activities, thus posing less environmental risk. Restoration planners should also note that streams have a remarkable ability to heal over time once the cause of their degradation is removed. For this reason, approaches that address degrading and destabilizing changes in the watershed, such as modifying land use within the watershed to reduce surface erosion of fine sediment into the stream, are often sufficient and more appropriate than aggressive instream activities to “clean” fines from gravels. Restoration sequencing is discussed in detail in Chapter 4 of this document, *Developing a Restoration Strategy*.

1.8 Monitoring and Adaptive Management

To optimize probability of success, stream restoration and rehabilitation efforts must adequately provide for and assure ongoing long term monitoring. Monitoring protocols must be based on developing easily observed and measures parameters of success, including water quality, channel morphology, stability after high flow events, progress in establishing native plant communities, measuring fish and wildlife use and presence. Since stream restoration and rehabilitation will inevitably proceed in the face of some technical uncertainties and unforeseen circumstances, the principles of adaptive management should be incorporated into watershed restoration plans.

Adaptive management is *not* a trial and error approach. Adaptive management is predicated on designing and monitoring resource management programs and ecological restoration using principles of experimental design, so that adequate data are gathered and statistically analyzed to identify effective alterations to a management program or rehabilitation project. In stream restoration and rehabilitation, this means testing the hypotheses that a rehabilitation program or design is based on a good understanding of watershed processes, and appropriately addresses adverse changes in these processes and ecological functions. Monitoring stream restoration and rehabilitation efforts at adequate levels of scientific rigor costs money, and must be conducted for years after the initial fencing, construction, or plantings are completed. These costs should be anticipated and incorporated into overall project design and grant proposals. Stream restoration efforts which are part of larger watershed restoration initiatives are more likely to succeed not only because of the availability of good watershed analysis and characterization, but also from the increased likelihood of adequately funded long term monitoring, which should be based in principles of adaptive management.

CHAPTER 2

STREAM PROCESSES AND HABITAT

Chapter 2. Stream Processes and Habitat

Process (n):

1. **:** a natural phenomenon marked by gradual changes that lead toward a particular result <the process of growth>
2. **:** a natural continuing activity or function <such life processes as breathing> (from Merriam-Webster On-line Dictionary)

Included in the history of human-caused disturbance of stream channels is a record of intervention undertaken to improve aquatic habitat. Among these, notably in the cases where stream processes were not understood, exists a legacy of expensive failures. Most attempts to directly build habitat elements into streams have failed due to a lack of understanding of the dynamic processes that build, maintain, and destroy habitat.[1] Too often, these attempts have further **degraded** the habitat they sought to restore. Sustainable habitat restoration requires that the full array of stream processes be maintained within, or restored to, a range of variability similar to that occurring naturally. These stream processes in turn require that riparian and watershed processes are similarly maintained or restored. Growing recognition exists that actual recovery of our stream ecosystems requires understanding and working effectively with the physical and biological processes that form and maintain habitat.[2,3,4,5,6,7] This chapter provides a simplified overview of the watershed and stream/floodplain processes that create aquatic and riparian habitat, and briefly describes characteristics of stream habitat.

2.1 Watershed Processes

In physical terms, a watershed is an area from which water drains to a common point. This trait results in a set of physical and biological interactions and processes that causes the watershed to function as an ecological unit. Watersheds can be viewed across a range of nested scales, beginning with the area contributing to a small first-order stream (i.e., a stream with no tributaries - refer to the *Hydrology* Appendix for a discussion of stream order) and culminating with the world's great river basins (such as the Amazon, Nile, Congo, Mississippi, Columbia, etc). Ultimately, stream processes that create habitat integrate the physical and biological processes occurring across a particular watershed.

2.1.1 Watershed Components

Across landscapes, two controlling factors - climate and geology - create three basic ecosystem components: soil, vegetation, and water (*Note: the effects of animals on soil and vegetation will be ignored for the sake of simplicity*). These components are overlaid on, and influenced by, **topography** that is also shaped by climate and geology. Within watersheds, the interactions of these components result in yields of streamflow and sediment with patterns of timing, quantity, and quality characteristic of each watershed. These yields of water and sediment, in turn interacting with riparian vegetation (and, in steep, forested watersheds, large wood delivered from upland sources), form the stream channel and associated aquatic habitat.

Soil

The genesis of mineral soil is physical and chemical weathering (breakdown) of rock at the earth's surface. Physical weathering includes such actions as the grinding of glaciers, the rolling of cobbles in a streambed or the expansion of ice freezing inside cracked rocks. Chemical weathering is the result of reactions between rock and chemicals from the atmosphere (e.g., oxygen, water) and biological activity (e.g., acids). In flat or gently sloping areas, soil can develop in place as the underlying rock (parent material) gradually weathers. In contrast, the depth of soil development on steep slopes is limited by slope instability that causes episodic mass wasting (e.g., landslides). Soil development also occurs through deposition of material transported from elsewhere by wind or water. The soil mantle is a natural storage reservoir for water delivered to the watershed, absorbing rain or snowmelt and gradually transmitting it down slope. Thus, water stored in the soil is a primary source of streamflow between storms or periods of snowmelt. The storage capacity of soil depends on its depth and texture, (i.e., the total pore space available). The rate at which soil water is delivered to the stream system depends on slope, and soil texture and structure. Well-developed soils have many sizes of pores with varying degrees of connectedness. Large pores allow rapid **infiltration** and drainage of water to and from the soil mass; small pores absorb water more gradually and retain it longer, making water available during dry periods for use by plants, or for slow seepage into the stream system.

The development and characteristics of soil depend upon geology, topography, time, climate, disturbance factors, and biological agents (e.g., vegetation and soil organisms). The protective vegetative cover above ground and stabilizing strength of roots below ground are critical to soil development and stability, particularly on steep slopes.

Vegetation

Vegetation performs a wide variety of functions on the watershed scale. It provides strength and roughness across the surface of the watershed, thereby slowing the movement of water and increasing resistance to **erosion.** The strength created by roots in the soil profile can maintain the stability of slopes at steeper angles than could otherwise be sustained. By reducing erosion rates, vegetation promotes the development of deep soils, increasing the capacity of the watershed to store water.

Vegetative litter slows **overland flow** and protects the soil surface from raindrop impacts, preventing splash erosion and the sealing of surface pores. Root channels increase infiltration capacity. The presence of decayed vegetation and other organic matter characterizes the topsoil and greatly influence its properties and structure.

The vegetative canopy and litter on the ground both intercept **precipitation**, allowing a portion to evaporate before reaching the soil. Thus, a given rainfall event must exceed the combined interception capacity of the canopy and litter before it becomes effective in sustaining soil moisture. However, the canopy and litter also collectively inhibit subsequent evaporation of water from the soil.

Within the continental US, water use by vegetation (evapotranspiration) utilizes a significant proportion of the total precipitation received[8] reducing soil moisture and total runoff from the associated land areas. However, the combined influences of vegetation and soil also greatly attenuate the movement of water through the watershed, dampening **peak flows**, sustaining streamflow during dry periods and maintaining high water quality.

<u>Water</u>

Quantity, quality and timing of water discharged from a watershed are integrated results of watershed processes. Distributed across the landscape in the form of rain or snow, water is transported through the watershed, leaving by way of transpiration, evaporation, streamflow and **groundwater** flow. Climate, topography, soil and vegetation control the processing of water through the watershed. Because the combination of these factors is unique to each watershed, the characteristic timing and magnitude of flows through the stream system constitute the ‘signature’ of the watershed. For example, besides sparse vegetation, arid watersheds typically have thin, poorly developed soils with low infiltration rates and little water-holding capacity. Where arid conditions are combined with steep terrain, runoff tends to occur rapidly following precipitation events, resulting in a ‘flashy’ **hydrograph** that peaks and declines swiftly. Conversely, where climate supports dense vegetation, an undeveloped watershed with gentle relief will tend to gradually yield high flows that gently peak and taper off into strongly sustained base flows. Characteristic elements of the hydrologic "signature" of watersheds include: 1) high flows - reflecting snowmelt, prolonged or intense rainfall or rain-on-snow events; 2) rates of **recession** from peak to low flows; and 3) low flows – reflecting groundwater discharge, or water released from natural storage features such as wetlands and lakes.

Snow packs provide significant water storage in many Pacific Northwest watersheds. At one extreme, high-elevation glaciers are long-term features that produce the greatest streamflow during the hottest part of the year. At the other extreme, low-elevation, transient snow packs may accumulate and melt several times during a single season, creating brief mid-winter high flow events. Intermediate between the two are seasonal snow packs that accumulate during late fall, winter, and early spring and melt during late spring and early summer. These produce a snowmelt runoff pattern that gradually increases until late spring or early summer and then steadily declines.

In watersheds where rainfall is the dominant form of precipitation, runoff occurs in response to storm events and the ability of the watershed to store precipitation. To a large degree, this ability is dictated by soil moisture conditions prior to the onset of the storm. Obviously, frozen and saturated soils have virtually no storage capability, and rain falling on them will be quickly delivered to the stream system. Conversely, rainfall delivered at the end of a long dry period may do no more than replenish soil moisture, causing little response in streamflow.

2.1.2 Influence of Disturbance on Watershed Processes

The concept of disturbance is so central to understanding ecosystem functioning that it is worth defining the term:

> *"Any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment"* (Society of American Foresters, 1996).

Periodic large- and small-scale disturbance is critical to ecosystem functioning, resetting the '**successional** clock' and preventing the vegetative community from maintaining a homogeneous climax state. Under natural circumstances, disturbances (e.g., fire, insect outbreak, landslides, and flooding – see Figure 1) within an ecosystem occur with characteristic frequencies, intensities, and extents. Thus, every ecosystem evolves with a particular **disturbance regime**. Within a given ecosystem, the variability of size, intensity, and frequency of different disturbance events creates a mosaic of vegetation at various successional stages. Such mosaics have characteristic sizes and distributions of patches of vegetation at various successional stages.

Figure 1.

(a) Fire. Source: T. McCoy

(b) Insect outbreak leading to tree mortality

(c) Deep-seated landslide

(d) Aftermath of flooding

Over a landscape scale, the disturbance-driven vegetative mosaic tends to remain in dynamic equilibrium during a given climatic period. It is the diversity inherent in this mosaic that provides diverse habitat.[9,10,11]

For example, many species of plants and animals are dependent on early- to mid-successional stages (biological diversity commonly peaks at the mid-successional stage). The availability of mid-successional habitat limits the populations of numerous species.

Vegetation, in turn, interacts with the disturbance regime. For instance, among plant communities, the accumulation, distribution, and type of fuel vary greatly. These are major factors in fire frequency and intensity, which in turn strongly affects the species composition and structure of the plant community. For example, the grasses in Ponderosa pine/grassland systems quickly generate continuous, low, fine fuels that support frequent, low-intensity ground fires. This type of disturbance, maintained by the fire-adapted plant community, in turn maintains the plant community by thinning young, fire-sensitive Ponderosa pines, rejuvenating the grasses, and preventing fire-intolerant plant species from establishing.

At the other extreme, the interval between natural fires in the forests of the maritime Northwest is likely to be hundreds of years, allowing the eventual dominance of late-successional, fire-intolerant species such as western hemlock. In these ecosystems, however, fires frequently occur with an intensity that kills the overstory trees and burns the organic litter on the forest floor. This fire behavior allows the establishment of early-successional plant species such as Douglas-fir and Ceanothus that require full sunlight and bare mineral soil.

Because disturbance plays a dominant role in shaping the vegetative community, it is also critical to watershed functioning.

2.1.3 Erosion and Sediment Yield

Erosion is a natural process made inevitable by gravity, wind, the weathering of rocks and the energy of flowing water. Erosion processes and rates are controlled by climate, topography, soils, and vegetation; natural erosion and deposition are ecosystem attributes that contribute to the disturbance regime and create geomorphic features such as drainage networks, fans and valley bottoms. Forested landscapes normally undergo little or no overland flow or surface erosion, with the organic litter on the forest floor sustaining infiltration rates greater than rates of rainfall or snow melt. In contrast, in arid or semi-arid landscapes with partially exposed, poorly developed soil, surface erosion may be the dominant erosional process.

Erosion rates tend to be episodic and linked to disturbance and weather. Substantial **surface erosion** occurs following the removal of vegetation. Extreme rates of surface erosion occur after severe fire consumes the protective organic layer and exposes bare mineral soil. **Mass-wasting** (i.e., landslides, debris flows, etc.) is the result of the gradual accumulation of soil in unstable locations combined with a triggering mechanism, such as soil saturation, that activates the event.

Streambank erosion, the process by which water loosens and wears away soil and rock from the edge of a stream, generally occurs during high flow events. Figure 2 illustrates the different types of erosion. All three types of erosion peak during storms or periods of rapid snow melt.

Figure 2.

(a) Surface erosion from a road (b) Mass-wasting

(c) Bank erosion. Source: Paul Bakke

Sediment, alternating between moving in brief pulses and being stored in channels or floodplains, is a major watershed product naturally transported and discharged by stream systems. In the same way that a given watershed produces a characteristic streamflow regime, it also has a characteristic sediment budget over time. The budget, consisting of both sediment quantity and quality (i.e., the distribution of particle sizes transported), is largely a reflection of the climate, geology, topography, vegetation, and disturbance regime across the watershed.

2.1.4 Land Use Effects on Watershed Processes

The effects of widespread land use tend to accumulate within watersheds, both over time and in the down slope/downstream direction. Any land use altering one of the three basic watershed components - soil, vegetation, or water - will affect watershed functioning. Due to interactions among the three components, alteration of one almost inevitably affects the other two. Land use (e.g., logging, grazing, farming and urbanization) broadly alters vegetation and often intercepts and diverts the movement of water. Land use, particularly urbanization, may also directly affect the soil through compaction and the creation of impermeable, unvegetated surfaces. Besides removing vegetation, exposing soils, and creating impermeable surfaces, road building in steep watersheds can drastically alter the routing of water through those watersheds. This alteration includes intercepting groundwater flow at road cuts, capturing surface flow in ditches and concentrating diffuse flow through drainage culverts. Besides speeding runoff and drying previously wet areas, this often causes significant erosion and can cause slope instability. Historic road building practices in steep watersheds have been implicated in accelerated mass wasting and stream degradation.[12, 13,14,15] Numerous attempts to increase runoff by removing vegetation have had serious unintended consequences such as greatly increased erosion, earlier, flashier runoff and correspondingly decreased base flows (i.e., more water when it is not desired and less water when it is in short supply).

Reduced vegetation, soil compaction, soil exposure, and increased velocity of water movement result in increased erosion. Erosional processes, once altered, often accelerate over time: overland flow across exposed soils creates **rills** that rapidly develop into **gullies**; sheet flow becomes channelized (expanding the drainage network) and more erosive. Expanded **drainage networks** reduce soil water storage by capturing water at the soil surface (reducing infiltration) and intercepting soil water (draining the soil mantle). Soil erosion in excess of soil formation, and compaction that lowers the ability of the soil to absorb water combine to reduce the water storage capacity of the soil mantle. Severe erosion can alter both soil depth and quality and cause irreversible changes to the vegetation.

Quantity, quality and timing of streamflow are the result of overall watershed processes. In the absence of climate change, changes to watershed processes and to the resultant aquatic habitat reflect the cumulative effects of land use. A general effect of many land uses is to reduce the resistance offered to water as it moves through the watershed, speeding runoff, increasing peak flows and decreasing low flows. Examples of this include intensive timber harvest, road building, grazing and urbanization. An exception to this phenomenon occurs when a significant portion of a watershed undergoes conversion from one plant community to another that is more water-consumptive. An example of this is the conversion, through fire suppression, from an open fire-tolerant forest stand to a densely stocked, closed canopy, fire-intolerant forest stand. In this case, the entire range of flows produced by that land area may significantly decline. A case in point can be found in eastern Oregon, where widespread conversion from sagebrush-steppe vegetation to juniper woodlands has resulted in formerly perennial streams converting to **intermittent** (i.e., seasonal) flow patterns.

Ecologically, land use represents a change to the disturbance regime of an ecosystem. Fire may become much less frequent due to grazing and fire suppression. The magnitude and frequency of flooding may change. The effects of droughts may become more severe due to soil loss, soil compaction and faster delivery of water to the stream system. Landsliding may increase due to destabilization of slopes following logging and road building (See Figure 3).

Agriculture and urbanization represent major disruptions of native plant communities and ecosystems; additionally, irrigation and other water uses inevitably result in alterations to streamflow and groundwater.

Figure 3. Erosion initiated by poor road drainage. Source: Paul Bakke

Aquatic and terrestrial ecosystems evolve within a natural range of disturbance frequency and intensity. Each system has some resistance to change and some resilience in recovering from disturbance. If the effects of human activities substantially differ from those of the natural disturbance regime, the ecosystem will be substantially altered. Ecosystem degradation is the result of imposing disturbances that are beyond the system's ability to resist or recover from.

2.2 Stream/Floodplain Processes and Attributes

2.2.1 Stream Types

A corollary to the concept that stream systems are an integration of upstream watershed processes is that channels and floodplains reflect their landscape setting. Between the extremes of high gradient mountain streams coursing down boulder-strewn beds and meandering low gradient rivers is an array of typical stream morphologies (see *Fluvial Geomorphology* Appendix for a more detailed discussion of stream morphology). These have been described in a variety of typing systems.[16,17,18,19,20,21,22]

For the purposes of this discussion, one overridingly important stream type concept exists. Alluvial (or unconstrained) stream channels are formed in sediments previously transported and stored by the stream. The boundaries of these channels can be adjusted by the forces inherent in the streamflow. Alluvial streams are also characterized by the presence of floodplains. Non-alluvial (or constrained) stream channels are controlled by materials they cannot mobilize, such as bedrock or large boulders (see Figure 4). Constrained stream channels tend to be very stable and resistant to change (for better or worse). As such, constrained streams are rarely the targets of stream restoration efforts.

Figure 4.

(a) An alluvial or unconstrained stream
Source: E. Salminen

(b) A bedrock-controlled or constrained stream. Source: Paul Bakke

Broadly speaking, the morphology of alluvial streams is a reflection of interactions among available energy, water, sediment, and structural elements (such as large wood and beaver dams). These are mediated by the stabilizing influence of vegetation and sometimes the extent of the available floodplain. Channel geometry of alluvial streams (i.e., the varying width, depth, slope, and **planform**) adjusts toward an equilibrium whereby the energy of the streamflow during **bedload**-moving high flows is just sufficient to maintain a balance between sediment delivery to the reach and sediment export from the reach.[23,24,25]

Alluvial channel geometry alters in response to changes in independent factors such as streamflow, the supply of large wood or sediment, or to disturbance. The need for restoration of unconstrained streams is usually created by channel adjustment (i.e., **degradation** caused by excessive erosion or **deposition**) in response to changes imposed by human activities. Likewise, it is usually unconstrained streams that ‘misbehave’ through flooding or channel adjustments, motivating human manipulations. The remainder of this chapter refers primarily to alluvial stream/floodplain systems.

Alluvial channel reaches commonly adopt distinctive planforms, controlled largely by stream gradient and the character of the sediment. Four patterns (straight, meandering, braided and island-braided) with varying degrees of channel stability are described by Beechie and colleagues.[26] The first two (straight and meandering) are characterized by a single, dominant channel and moderate to high stability.

The **sinuosity** (i.e., the ratio between the length of the channel and the length of the corresponding valley floor) of these streams can vary widely. Though arbitrary, a sinuosity of 1.5 or greater is a good approximation of a meandering channel form. At a sinuosity of less than 1.5, a channel is considered ‘straight’[27] (see Figure 5). A straight channel is highly stable because the stability of banks and bed exceed the erosive energy of the streamflow whereas a meandering channel tends to undergo gradual change as the meanders evolve.

Figure 5.

(a) A high sinuosity, low gradient, fine sediment stream reach Source: © 2001 Robert Glenn Ketchum

(b) A low sinuosity, high gradient, coarse sediment stream reach. Source: G. McCoy

The second basic form is the **braided** stream with multiple channels active at **base flow**. The exposed areas between channels can range from highly unstable unvegetated bars to moderately stable, vegetated islands (see Figure 6; respectively classified by Beechie and colleagues[28] as 'braided' and 'island braided'). The channels associated with unstable bars may shift with every high flow. Although the channels associated with vegetated islands are more persistent, the relative dominance of such channels can shift frequently due to unpredictable development or break up of woody debris jams, usually accompanied by deposition or erosion of bed material. Conditions that promote frequent channel change involve relatively steep gradient, large quantities of coarse bedload and an abundant supply of wood.

Figure 6.

(a) A braided stream with extensive unvegetated bars, indicating frequent channel change. Source: T. McCoy

(b) A braided stream with partially vegetated bars, indicating an intermediate level of channel stability. Source: USGS

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(c) A braided stream with vegetated islands and multiple stable channels. Source: Image Courtesy USGS Photographer-Bruce Molnia; Image Source-Earth Science World Image Bank http://www.earthscienceworld.org/images

Braided channels also display a wide range of sinuosity, although it is difficult to quantify. Coarse-bedded braided streams with shifting, unvegetated bars are effectively 'straight', while multiple, stable channels associated with low-gradient, fine sediment stream reaches tend toward higher sinuosity.

2.2.2 Stream/Floodplain Development

For the purposes of the routing and storage of water and sediment, alluvial streams and their associated floodplains comprise a single system. Under equilibrium conditions (occurring over the timeframe of years to decades) the system is self-regulating, balancing imports and exports of water, sediment and energy through adjustments to channel geometry.

An example of such an adjustment is meander development whereby bank erosion on the outside of the bend and sediment deposition on the inside of the bend (i.e., the point bar), lengthens the channel while maintaining stable width and capacity. This lengthening reduces the channel slope and therefore the velocity and erosiveness of flow. As the meander matures bank erosion ceases, stabilizing channel length, slope and planform. Because alluvial channels are, by definition, sculpted out of previously transported sediment, properly functioning channel development requires both high flows capable of mobilizing sediment and an available sediment supply (including bank material).

All else being equal, as depth of flow increases, velocity also increases. Furthermore, the kinetic energy of flowing water increases with the square of the velocity. Thus, swift, deep **bankfull** flows occurring during severe storms or spring **freshets** represent an extreme concentration of energy within the channel (refer to the *Hydrology* Appendix for a description and definition of bankfull discharge). As water flows down slope, it must ‘use up’ the energy imparted to it by the force of gravity (otherwise it would accelerate indefinitely). The major mechanisms of energy dissipation are: 1) friction between the water and its channel (i.e., through surface resistance), 2) turbulence generated by channel form, such as drops over obstructions, and variations in channel cross-section and direction of flow (i.e., through form resistance), and 3) sediment transport. Generally, alluvial channels in balance with their flow and sediment loads have developed relatively ‘sophisticated’ means of dissipating energy. This includes a high degree of form resistance generated by complex channel geometry such as alternating pools and riffles, meander bends, mid-channel bars and structural elements such as large wood and beaver dams (See Figure 7) (not coincidentally, these ‘sophisticated’ energy dissipation mechanisms are associated with high quality aquatic habitat). Secondly, bank stability - generated by a combination of root strength, vegetative roughness and, in fine textured soils, soil **cohesion** - is adequate to resist flow velocities that are capable of mobilizing bed material. This allows the expenditure of energy in bedload transport. As previously noted, sediment transport through equilibrium stream reaches is balanced, thus scouring of the bed during high flow is offset by subsequent filling with sediment transported from upstream. Finally, channels in equilibrium tend to have a high degree of connectivity with their floodplains, allowing excess flood flows to spread and slow.

Figure 7.

(a) Complexity in this stream segment includes meander and point bar development and log jams.

(b) Local scour creates small-scale complexity

(c) Multiple channels in a high-energy stream are maintained in equilibrium by a vigorous riparian plant community.

(d) Simplified channel a short distance from Figure 7c. The constraining influences of the hill slope (shown) and a highway encroaching into the floodplain from the other side (not shown) have eliminated most of the complexity from this stream segment.

Interactions between channel and floodplain are key to the health of the aquatic ecosystem. Natural streams tend to develop channel capacities roughly equal to the peak flows occurring every 1½ to 2 years.[23] In a study of 76 streams in the Pacific Northwest, Castro and Jackson[29] observed the mean bankfull discharge recurrence interval for the Pacific Northwest to be 1.4 years (ranging from 1 to 3.1 years) (see Figure 8). Patterns varied by **ecoregion**; the humid areas of western Oregon and Washington had a mean value of 1.2 years, while the drier areas of Idaho and eastern Oregon and Washington had a mean value of 1.4 to 1.5 years.

Figure 8. A stream reaching bankfull flow. Source: Yakama Nation

The tendency to flood during relatively frequent high flow events is highly protective of the stream system; higher flows are distributed across the floodplain rather than focused in the channel. Attempts to restrict flood flows from floodplains, typically by diking or dredging, cause a great deal of stream degradation (simplification) due to the increase in energy confined within the channel. It should be noted that not all floodplains are expansive, flat valley bottoms typical of large low-gradient rivers (see Figure 9). Depending largely on valley slope and the degree of confinement imposed by the valley walls, floodplains can be relatively small and even discontinuous. In narrow valleys or canyons where the active channel occupies a significant portion of the valley bottom, the associated floodplain is a major part of the interplay between channel geometry and energy expenditure. In these systems, reduction of the available floodplain can precipitate drastic channel degradation.

Figure 9.

(a) A broad, relatively flat floodplain

(b) A combination of low, vegetated floodplain, exposed bars, and high-flow channels provide flood capacity; A high terrace bounds the floodplain

(c) Multiple high-flow channels provide flood relief for moderate floods
Source: Yakama Nation

(d) Distributary channels convey flood flows on an alluvial fan.
Source: Yakama Nation

Two fundamental processes, lateral and vertical accretion, create floodplains. Lateral accretion consists of the deposition of sediment on **point bars**. As erosion occurs along the **cut bank** of a **meander bend**, the bed material derived from this erosion generally transports down the same side of the channel to the next submerged point bar.[27] This process tends to balance erosion from the cut bank on the outside of a meander bend with accretion on the opposing point bar, maintaining channel width and elevation throughout the progression of **meander migration**. When meandering streams are in equilibrium, point bar crests approach the elevation of the opposite floodplain. This indicates that the surface newly formed by lateral accretion is matching the elevation of the feature undergoing erosion so vertical equilibrium is being maintained. Conversely, point bar development that does not crest near the level of the opposing floodplain is symptomatic of an incised and degraded channel (See Figure 10). Under equilibrium conditions, lateral accretion does not add to or subtract from the area or height of the floodplain.

Figure 10. A formerly straightened channel reestablishes a meander pattern. Source: Yakama Indian Nation

Vertical accretion is caused by floodwaters carrying sediment out of the channel and depositing it on the floodplain (see Figure 11). Consequently, vertical accretion is responsible for building valley bottoms. The quantity and quality of deposited sediment relates to the energy of the floodwater carrying sediment out of the channel and the degree to which floodwaters are slowed by the floodplain.

Figure 11.

(a) Lateral accretion: sand and silt deposited on the point bar of the meander shown in Figure 10. Source: Yakama Nation

(b) Vertical accretion: fine sediment captured on a floodplain.

Avulsion, or an abrupt change in the alignment of a channel, occurs when floodwaters carve a new course across the floodplain. As with other instances of erosion, this is typical aspect of channel evolution that can be accelerated by human activities. Chute-cutoff, the most regular and predictable form of avulsion, is a result of tortuous meander development.

The paired processes of cut bank erosion and point bar development cause progressive channel lengthening and a corresponding decrease in gradient. Eventually, the stream's ability to transport sediment is reduced, leading to in-channel deposition and a loss of channel capacity. As channel capacity declines, the floodplain conveys correspondingly greater flows. These flows are conveyed straight down the valley gradient, rather than along the relatively flat, sinuous course of the channel. When the velocity of flows conveyed down the floodplain overcomes the shear strength of the floodplain surface, a new, shorter, higher gradient channel is eroded that cuts off the old meander. This process is the origin of oxbow lakes (see Figure 12).

Figure 12. Oxbow lakes resulting from meander cutoff. Source: USGS

Less predictable is a major re-routing of the channel across the floodplain along a course not significantly shorter than the previous route. These events are normally associated with major floods, when extreme amounts of water, coarse sediment and debris overwhelm channel capacity and force a large proportion of the total flow across the floodplain. Again, the erosive energy of the flood flows must be greater than the resistance of the floodplain to erosion for avulsion to occur. Conditions that promote avulsion include reduced channel capacity, devegetation of the floodplain and an incised channel at the downstream location where flood flows return to the channel. Reduced channel capacity obviously causes more overbank flow; devegetation reduces the floodplain's ability to resist erosion and an incised channel at the point where flood flows return allows for the initiation of **headcutting**.

Headcutting is erosion of the streambed that progresses in the upstream direction. It occurs when a portion of the bed is too steep to remain stable under the flow conditions to which it is subjected. Where the slope of the bed is only moderately oversteepened, the shear forces imposed by high velocity flow erode the bed material. Where a vertical or near-vertical discontinuity exists in the streambed, the turbulence created by the plunging water undercuts the vertical face. Waterfalls are the most dramatic forms of vertical headcuts. Flood flows returning to an incised channel create short-term waterfalls. When this occurs, the bank material is rarely fully resistant to the erosive forces; a headcut is initiated that works upstream toward the source of the overbank flow (see Figure 13). If the flood duration is sufficient to allow the headcut to progress upstream to the main channel, a complete channel avulsion is a possible outcome. However, headcutting is also responsible for the development of complex features in well-vegetated floodplains, including side-channels, backwater channels, and springbrooks.

Figure 13.

(a) Headcut created through basalt bedrock by the Missoula floods.

(b) Headcut from floodwaters returning to the stream channel. The conversion from woody riparian vegetation to row crops has drastically reduced both floodplain surface roughness (increasing flood flow velocity and shear force) and strength (reducing its resistance to erosion). Source: Yakama Nation

The strength and roughness provided by vegetation in riparian areas is crucial to stream/floodplain development and functioning. The roots of streamside vegetation provide strength to the soil mass, greatly increasing bank stability. Roots protruding from banks also create roughness that lessens near-bank flow velocities and erosiveness. In combination, these attributes allow the development of complex channels (e.g., deep, narrow and sinuous, with undercut banks) having comparatively limited capacity and frequent overbank flows (see Figure 14).

Figure 14.

(a) An undercut bank maintained by woody riparian vegetation

(b) Multiple layers and species of riparian vegetation

(c) A narrow riparian corridor typical of a Small stream in a semi-arid setting

(d) A rush and sedge riparian community in a recovering (i.e., aggrading) system. Previous overgrazing caused channel incision and drainage of a wet meadow. Source: Yakama Nation

Floodplain vegetation slows overbank flows, reducing erosion and promoting the capture and stabilization of fine sediments. The development of relatively fine-textured soils in turn supports increasingly dense and vigorous riparian vegetation. The deep soil developed by sediment deposition provides near-stream soil-water reservoirs (i.e., ***bank storage***) that are recharged during flooding (thereby attenuating flood peaks). During dry periods, clean, cool water stored in near-stream soils return to the channels, contributing in both quantity and quality to ecologically critical base flows.

2.2.3 Hyporheic Flow

The hyporheic zone is the volume of saturated sediment beneath and beside streams where ground water and surface water mix. Hyporheic flow (i.e., water flowing through near-stream sediments that can freely mix with surface flow) occurs most effectively in relatively coarse-textured sediments and under flow conditions with enough stream **gradient** to drive flow through the available pore spaces. The hydraulic conductivity of the hyporheic zone increases with sediment size and the degree of sorting of particle sizes (sorting of particle sizes is another result of structural and hydraulic complexity). Fine sediment can effectively seal the pores of the streambed and drastically reduce hyporheic flow. Thus, land uses that increase fine sediment inputs to streams, particularly during low-flow periods when fines can readily settle into the streambed, can impair hyporheic functioning. Hyporheic exchange between surface water and shallow groundwater blends the thermal and chemical characteristics of the two environments, buffering the temperature regime and adding nutrients to the stream. Hyporheic functioning can be a crucial element in the most productive salmonid habitat. For instance, the hyporheic zone of the Flathead River in Montana extends as far as 1.2 miles away from the active channel and supplies more nutrients to the river than do the surface waters.[30]

Hyporheic flow operates at various scales. On a valley scale, flows **downwell** into relatively deep **alluvium** downstream of transitions from shallow to deep bedrock, and **upwell** upon reaching the next shallow groundwater obstruction. Canyons typically indicate shallow bedrock where most groundwater is forced to the surface. Strongly downwelling zones commonly occur downstream from the outlets of canyons, where depth to bedrock greatly increases. Flow paths can be long and relatively deep, and are often concentrated in buried former channel courses known as **paleochannels**.[31]

Reach-scale hyporheic flow is generally driven by variations in depth to the **water table**. Where the water table is above the water surface in the stream, an upwelling zone occurs, and hyporheic flow is delivered to the channel. Where the water table is below the water surface in the stream, a downwelling zone occurs, with some streamflow penetrating the bed and bank and becoming hyporheic flow. Because the depth to the water table can fluctuate seasonally, upwelling and downwelling zones may also seasonally expand and contract along the length of the channel. Typically, the water table gradually rises throughout the high runoff period, particularly during flooding, and falls after the peak seasonal flows. Extreme downwelling occurs where the water table is below the bottom of the channel and the alluvium is coarse. For example, steep canyon streams discharging onto coarse alluvial fans commonly are strongly downwelling through the upper portion of the fan. In extreme cases, a stream reach can be so strongly downwelling that virtually no lateral seepage from the stream exists and a hole dug only a few feet from the water’s edge will remain dry.

Near-stream vegetation is sometimes an indicator of reach-scale hyporheic functioning, particularly in more arid environments. Due to the depth to the water table during the growing season, strongly downwelling zones may support no more than sparse riparian vegetation, or even upland vegetation, on the streambanks. Because these sites are not conducive to revegetation, evaluating whether this is a cause of apparent riparian degradation can be critical to developing recovery or restoration plans. Conversely, due to the sustained accessibility of a shallow water table, degraded riparian vegetation associated with upwelling reaches may require no more than improved management to achieve rapid recovery. Smaller-scale hyporheic flow occurs in response to variations in the streambed. Flow penetrates the streambed gravels where the channel is decreasing in depth, such as at the **tailout** of pools, and travels through the bed along shallow flow paths that are intercepted at the next deepening of the channel, such as the upstream end of the next pool.[32] Small-scale hyporheic exchange increases with increasing complexity of channel plan- and bed-form[21.]

The distribution and extent of hyporheic zones depend upon the volume and texture of sediment underlying the channel and floodplain. Hyporheic functioning of sand and finer bedded streams is minor compared to those that are gravel and coarser bedded.[21] In many cases, the hyporheic zone is of limited extent, but in some settings, such as broad alluvial valleys comprised of permeable gravel, the hyporheic zone can be quite extensive.[33] For a more thorough discussion of hyporheic flow, refer to the *Hydrology* Appendix and the work of Edwards.[34]

2.2.4 Influence of Vegetation on Stream Morphology

For the reader familiar with the preceding sections of this chapter, it is redundant to note the key role that vegetation plays in the formation of equilibrium channels. However, the subject is so central to stream restoration that it merits its own section.

Influence of Live Vegetation on Stream Morphology

The influence of live vegetation on channel form changes as streamflow and channel size increases. Small forested streams lack the hydraulic power to erode their tree-lined banks so their plan form is usually relatively straight. Bank erosion and meander development begin to occur when sufficient discharge exists that the channel depth becomes greater than the rooting depth of the vegetation on the banks. As channel size increases bank vegetation plays a diminishing role in controlling channel form.[35] Note that island-braided systems, by splitting flow amongst multiple channels, are more influenced by streambank vegetation than where equivalent flow is contained in a single channel. Floodplain vegetation plays a vital role in the stability of the full array of alluvial channels by stabilizing the floodplain and reducing the frequency of avulsions.

As with other factors relating to stream morphology (i.e., hydraulics, sediment transport), the localized effects of streambank vegetation are very complex and not fully understood. However, on the larger scale it is clear that vegetation greatly increases bank strength and roughness, thereby maintaining lower channel width and greater channel depth than would otherwise be the case. Hence, removal of riparian vegetation normally triggers widening of the channel through bank erosion that is not offset by sediment deposition along the opposite bank line.

Channel Response to Loss of Riparian Vegetation

The loss of bank vegetation generally results in channel widening and increased capacity, reducing the connection with the floodplain. Widening (i.e., bank erosion not matched by corresponding sediment deposition) increases the sediment supply while reducing depth and velocity of flow and thus the erosive force on the streambed. This reduces stream's sediment transporting 'competence' (i.e., the maximum particle size of sediment that the stream is able to move at a given flow). When the eroding bank material is of a finer texture than the bedload supplied from upstream, the additional load of easily transported fine sediment occupies more of the stream's sediment transporting 'capacity' (i.e., the total quantity of sediment that the stream is able to move at a given flow). The combined reduction of stream competence and available capacity causes coarser bedload to deposit in the widened channel. The resulting coarse and relatively immobile mid-channel bars tend to force flow against the banks, further increasing erosion and channel widening.

The capture and stabilization of fine sediment is one characteristic of a highly functioning stream system, indicating good interactions between the channel and floodplain. The substitution of coarse mid-channel sediment deposits for the eroded bank material composed of fine sediment previously stored in the floodplain represents degeneration of the system to a simplified (degraded) stage of development. Eventually the channel widens to an extent that near-bank flows are no longer erosive. The higher portions of recently deposited bars begin to support early-successional vegetation and develop into low floodplain through capture and stabilization of fine sediment: recovery has begun. At that point, however, the previous floodplain may have converted to a terrace that supports only upland vegetation and the long-term valley building processes have regressed to a stage wherein the active floodplain is lower, more confined and less productive than prior to channel widening.

Besides a general understanding of the mechanics of the interactions between streambank vegetation and flow, the stream restoration practitioner needs an appreciation of the specifics of the ecological niches present within the system to be restored, the vegetation appropriate to those niches, the physical characteristics of those species as they relate to channel stability (e.g., root strength, structure, density, depth and longevity), the successional role of those species (i.e., pioneering, mid-successional and late-successional), the species likely to succeed them and the role of disturbance in influencing the species composition of the riparian community. In other words: riparian plant ecology is a fundamental (and often underappreciated) component of stream restoration.

Influence Large Wood (Debris) on Stream Morphology

Forested alluvial streams are often heavily dependent on physical interactions with large wood for channel development and stability. Besides live trees stabilizing stream banks, large wood frequently exerts a major influence on stream channels.[36] Stream cleaning (i.e., the removal of large wood) has been one of the most destructive practices for aquatic habitat. For example, numerous coastal streams drain watersheds underlain by sandstone. With sediment loads largely consisting of sand-sized material, alluvial streams are heavily dependent on large wood to capture and retain sediment. Typically, when ‘cleaned’ of large wood, these streams quickly erode their bed until reaching bedrock. This represents a drastic change in stream processes and aquatic habitat.

The function of large wood changes in the downstream direction, as the ratio between the length of available large wood and channel width decreases. Where channel width is less than the length of the elements of large wood, individual pieces are able to span the channel. Over the course of time channel-spanning large wood may be incorporated into the streambed, creating natural drop structures that ‘stair-step’ the streambed (see Figure

15). In effect, the stair-stepping creates **channel units** with lower gradient conditions than the overall stream gradient. Energy dissipation and sediment transport are greatly affected by these natural structures; finer bed material is captured in the backwaters of these structures and plunging flow scours pools downstream. Energy dissipated in the plunge is then unavailable for erosion and sediment transport.[22, 37]

Figure 15. Natural large wood drop structure. Source: Yakama Nation

In larger streams, where the length of the available large wood is less than channel width, the wood is apt to be mobilized at high flows. Large pieces anchored by a heavy **rootwad** or lodged on an obstruction tend to collect floating debris, leading in time to structurally distinctive log jams[38] (see Figure 16) with tremendous habitat value. These jams generate complex local hydraulics, creating low-velocity depositional areas and high-velocity areas subject to **scour**. Their influence may promote side channel, point bar, or island development and increase **avulsion.**[22, 38]

Log jams play a particularly significant role in the formation and dynamic functioning of island-braided streams. Jams tend to accumulate at the head of channels where the splitting of flow results in multiple smaller channels. These jams can completely or partially block one channel and redirect flow that then causes the enlargement of the other (the ensuing bank erosion adding more trees to the channel). The blocked channel subsequently becomes a different feature such as a backwater channel that eventually fills with sediment and turns into a low, vegetated floodplain surface. Later, the jam that created the blockage may fail under high flow conditions, reactivating and re-enlarging the relic channel.

Figure 16.

(a) Channel-spanning log jam

(b) Log jam accumulated along the bank

(c) The key piece in this jam is a large tree that toppled into the stream while remaining rooted in the bank. Wood accumulated along the outside of a bend in a high energy system. Spanning pieces have minimal interaction with the flow.

(d) A log jam that has formed on a low bar outside of the low flow channel. This jam interacts with moderate and higher levels of flow. Note the plume of sand that has accumulated in the 'lee' downstream of the Jam. Source: Paul Bakke

Irrespective of channel width, trees falling directly into the channel from the banks (as contrasted with those delivered from the uplands by mass-wasting) often are anchored to the bank by roots. Depending on the orientation of the trunk, the tree may provide protection to the bank by reducing flow velocities. Conversely, it may cause bank erosion by directing flow toward the bank or by causing an eddy. Although large wood has the potential to increase local erosion, on the larger scale it reduces erosion by dissipating energy. In a survey of 41 channels in north-western Washington and Alaska, Montgomery and Buffington (1999)[39] found significant fining of streambed sediments associated with the presence of large wood and other roughness features (indicating increased energy dissipation). The species of trees available to the stream has a strong influence on the interactions between wood and the channel. Tree size is an obvious factor influenced by species: the larger the wood, the greater its ability to physically affect the stream. Buoyancy, which differs among tree species, also relates to the behavior of large wood when it enters the stream. Low-density wood, such as spruce or western red cedar is more readily floated than higher-density wood such as Douglas fir.

Over the course of time, waterlogging increases the density and stability of large wood in the channel.

Another significant variable is the longevity in the stream environment of large wood. Old-growth conifers such as western red cedar and Douglas fir, noted for their resistance to decomposition, can persist in streambeds for hundreds of years, contributing significantly to long-term stability. At the other extreme, Big Leaf maple - a riparian hardwood common in the stream corridors of western Washington and Oregon - although achieving a large size, decomposes quickly unless continuously submerged and so rarely has a long-term influence on the stream.

Another factor involves the typical characteristics of large wood pieces that are delivered to the channel. Some tree species, including most of the conifers that dominate the riparian communities of western Washington streams, tend to remain relatively intact as they fall; others tend to shatter. In systems where the available trees tend to shatter, the formation of channel-spanning steps is limited to relatively small channels, whereas the greater quantities of mid-sized and finer material promotes formation of various debris accumulations. These typically develop around key pieces in the channel, at the heads of high flow channels, along the outside of meander bends, on bars and on floodplains. Western hemlock, a common late-succession conifer species in the maritime Northwest with an increasing tendency to shatter as it ages, commonly delivers segments of trunk to stream channels.[40] Cottonwood, the dominant riparian tree throughout much of the inter-mountain west, is large but relatively short-lived. Although the trunks of cottonwood trees are often delivered intact to the stream, the tops of mature trees tend to break both while still standing and when the trees topple, producing substantial quantities of smaller wood. Thus, log jams in these systems, while often developing on large key pieces, are typically relatively dense, due to the accumulation of finer material.

As previously noted, large wood can be a key component in maintaining channel stability and structure in forested watersheds. Variations in the quantity and quality of wood naturally available to streams are significant for energy expenditure, erosion, deposition, channel geometry, and the tendency to avulse; in other words, wood supply can be a driving factor in channel processes and aquatic habitat formation. As with the other stream system components, the characteristics of the existing supply of wood should be considered when restoration plans are formulated.

2.2.5 Influence of Beaver Activity on Stream Morphology

Beavers have exerted a significant influence on the development and form of many small- to medium-sized stream systems. In semi-arid regions where large riparian trees are naturally lacking along many small streams, beaver dams may play a role as significant as that of large wood in forested streams. Similarities in physical function include: flattening of local stream gradients, increasing interactions between the stream and floodplain, increasing bank storage, capturing of relatively fine sediment in the channel, pool formation, and hyporheic exchange. Beaver dams represent structural elements within stream channels (see Figure 17). In some cases, the strength and energy dissipation provided by these structures is an essential element of the stream’s equilibrium. Removal of beaver from these systems can have the same drastic consequences as the removal of large wood from forested streams.

Figure 17.

(a) West-side beaver pond (b) East-side beaver pond

In larger stream systems, beaver activity is principally limited to side channels and floodplain features. Although the direct effects of their activities on the stream are reduced as stream size increases, indirect effects on stream processes can still be significant through influences upon the riparian plant community. Herbivory by beaver, especially on dominant species of trees, affects both structure and composition of the plant community. Furthermore, beaver ponds affect both floodplain soil development through sediment capture and soil chemistry by promoting saturated conditions - again influencing the plant community.

2.2.6 Disturbance and Stream Processes

Natural Disturbance

Stream corridors are the most dynamic, frequently disturbed component of the landscape. To a degree even greater than in the surrounding uplands, the disturbance regime drives ecosystem structure and function. Channel adjustments triggered by natural disturbances are fundamental to the creation and renewal of the physically complex habitat that supports biologically diverse ecosystems of the riparian corridor. Primary among the disturbance factors is flooding. The energy inherent in high flows does the work of shaping the channel and floodplain, maintaining channel capacity, and transporting and depositing sediment (see Figure 18). Flooding serves as the principal mechanism for creating, maintaining, and destroying channel and floodplain features such as pools, islands, bars, oxbows, side channels, and off-channel ponds.

Figure 18.

(a) Extensive flooding in a low-gradient system. Source: Yakama Nation

(b) High flows generated by a rain-on-snow event. Source: Yakama Nation

(c) Flood damage. Excessive coarse sediment deposition is usually not associated with proper floodplain functioning.

Other disturbance factors commonly affecting stream corridors include: mass-wasting (i.e., landslides and debris torrents), fire, drought, ice jams, severe wind, and insect and disease outbreaks. Each disturbance factor has the potential to affect the riparian plant community, thereby affecting strength and roughness characteristics of the stream corridor. Some, such as mass-wasting and ice jams, have the potential to mechanically alter stream channels. Channel-altering disturbance may cause a temporary loss of the dynamic equilibrium in channel geometry and sediment transport described in the previous section. Following such disturbance, streams typically undergo a period of recovery during which equilibrium channel geometry gradually reestablishes. For example, channels that widen and straighten in the course of a large flood, through the processes of revegetation and sediment capture will gradually narrow and regain sinuosity. Equilibrium, once reestablished, persists until the next channel-altering event.

Some disturbances are so severe, or chronic, that the energy dissipation characteristics of the channel/floodplain system undergo a long-term alteration. For example, disturbance that removes natural structure from a stream channel (e.g., channel scouring following the breaking of a debris dam, stream cleaning, or beaver dam removal) may trigger channel incision and a long-term loss of floodplain connection.

The frequency of channel-changing disturbance, rate of recovery, and therefore the proportion of time the stream system persists in equilibrium vary among ecosystems. Climate plays a dominant role in the occurrence, magnitude, and frequency of most disturbance factors. It also has a major influence on the rate of stream recovery between disturbances. Generally, the relative fluctuation between high and low flows in a stream system is inversely proportional to average annual precipitation. With increasing aridity, stream systems are subject to increasingly extreme flow fluctuations. In the semi-arid regions of the interior Pacific Northwest, the combination of comparatively ‘flashy’ flow - with rapid runoff and low base flow - and relatively unfavorable conditions for revegetation results in rather slow recovery following disturbance. Recovery from major disturbances may be measured in decades in these systems; some streams may essentially be in a perpetual state of recovery, with severe disturbances recurring before equilibrium can be achieved. Conversely, streams in the humid, temperate maritime regions are generally more resilient and quicker to recover. Figure 19 provides examples of base flows in different systems.

Figure 19.

(a) Typical small, humid-system stream at base flow. Source: Paul Bakke

(b) Typical semi-arid system stream at base flow.

Human-Caused Disturbance

A range of human activities have the potential to alter the disturbance regimes of stream systems. Alterations to the storage and delivery of water, sediment, or large wood from the uplands tend to occur synergistically rather than independently, and can result in substantial cumulative effects. For instance, widespread soil compaction results in reduced infiltration rates and loss of soil moisture storage capacity, affecting the vegetative community, runoff patterns (i.e., increasing peak flows and decreasing base flows) and erosion. Similarly, changes to the vegetative community affect water use, soil stability and possibly the supply of large wood.

Human activities within stream corridors involve direct disturbance to channels through manipulation (e.g., diking, filling, straightening, bank armoring and wood removal), and indirect disturbance through changing streambank and floodplain characteristics (e.g., reducing the strength and roughness of the banks and floodplain by converting from native vegetation to agricultural crops.). See Figure 20 for examples of direct and indirect channel disturbance.

Human activities tend to result in chronic disturbances that lack the power of episodic, high intensity natural disturbance events. River regulation is a prime example: peak flows are reduced, moderate high flows are extended, low flows may be increased for delivery to downstream diversions, while downstream of the diversion points low flows may be far less than historic natural flows. Affected ecosystems are rarely adapted to such chronic alterations, which may represent major changes to the disturbance regime and result in altered stream processes, habitat formation and ecosystem functioning.

Figure 20.

(a) Channel straightening

(b) Floodplain converted from native vegetation to pasture.

As previously discussed, stream/floodplain systems in dynamic equilibrium have ‘adapted’ to their particular supplies of water, sediment, and structural elements. Human-caused disturbances generally disrupt, to varying degrees, the processes governing the delivery of these supplies.

2.2.7 Climate Change and Stream Processes

Climate is a fundamental driver of ecosystems at all scales from landscape-level to microsites inhabited by individual plants. Not only does climate directly dictate the mix of species that *can* inhabit a landscape, it also indirectly shapes the composition of the vegetation that *does* occupy the landscape through its dominant role in the disturbance regime. Climate change is both natural and inevitable and it leads to ecosystem change. Its effect on ecosystems is a product of the magnitude and rate of change.

Stream systems will be directly affected climate change through alterations in the amount and timing of streamflow and sediment yield, and indirectly through changes to the plant communities affecting the hydrologic cycle. Many drainage systems show evidence of previous climate change. For example, high **terraces** composed of alluvial materials (indicating a lowering of the base level of the stream system), are often relics of an earlier climatic period. Stream channels are continually adjusting to climatic inputs. Channels in equilibrium make minor adjustments in response to individual channel-forming events. Climate change that modifies the natural range of variability will alter channel characteristics, sometimes to the extent of completely changing the channel type (e.g., from single thread and sinuous to braided).

The potential effects of significant, rapid, human-caused climate change on watershed and stream functioning may represent the most profound disruption caused by human activities. Of particular significance to many streams in the Pacific Northwest are the implications of changes, due to global warming, in the accumulation and distribution of snow packs. Even assuming that precipitation patterns remain the same, reductions in the quantity of water temporarily stored in snow packs would translate into higher, earlier annual peak flows and longer, lower base flows,[41] i.e., more severe flooding and drought. Climate change and its effects on Pacific Northwest ecosystems are addressed in the *Climate Change* Appendix.

2.2.8 Channel Degradation and Recovery

Channel degradation (i.e., simplification) occurs due to cumulative effects, local disturbance, or a combination of both. Cumulative effects can be difficult to identify, particularly when they are superimposed upon local disturbance. Recognizing the underlying causes of degradation often requires expert interpretation of existing conditions and historical information. Similarly important, and also requiring substantial expertise, is the identification of trend in channel condition. Degraded channels can be grouped into three categories, based on trend: 1) those that are actively undergoing degradation, 2) those that are degraded but stable, and 3) those that are recovering. Long-term familiarity with the system involved is extremely valuable in accurately identifying channel condition and trend.

The concept of a *threshold of stability* may be useful when thinking about channel degradation. Until a threshold is reached, small changes in the factors driving a system cause small responses by the system. When the threshold is reached, a small change in the driving factors elicits a major change in the system. For example, progressive encroachment into a broad floodplain that increasingly restricts flooding correspondingly increases the depth and velocity of flood flows throughout the remaining floodplain and in the channel. This may result in little observable channel change until in-channel velocities increase to a degree that the stream banks or bed are no longer stable. As that threshold is exceeded, rapid change may occur that drastically alters channel characteristics. Essentially, the previous equilibrium state has been disrupted and the channel is adjusting the balance among the different mechanisms of energy dissipation toward a different, and simplified, equilibrium. The adjustment period corresponds to the ‘actively degrading’ trend mentioned above (see Figure 21).

Figure 21. A widening channel. Much of the channel has cut down to bedrock, leaving little opportunity to expend energy transporting bedload. Hence, the erosive energy of high flows is expended on the banks, which have destabilized.

In contrast to complex stream systems with variable geometry, structural elements (e.g., wood and boulders), and a high degree of connectivity with their floodplains, degraded streams that are comparatively simple in plan, cross-section and profile and expend energy in relatively 'crude' ways. Energy dissipation in degraded streams is generally dominated by surface resistance and/or excessive erosion and deposition. Surface resistance increases as the channel widens and flows become shallower. Additionally, it is increased by coarsening of the bed material. This occurs as energy dissipating mechanisms are lost (for instance, by removal of large wood); greater available energy winnows the smaller sizes of material from the streambed and transports the mobilized material through the reach. By selective removal of the fine material, the bed coarsens until it becomes resistant to the new energy regime.

Unbalanced sediment transport (i.e., erosion and deposition) is characterized by channel downcutting, where bed materials are more easily eroded than the banks, and by widening, accompanied by unstable mid-channel bars, in coarse-bedded stream segments. Stream channels undergoing rapid erosion are likely to also exhibit excessive sediment deposition and instability at a downstream location where a flattening of the slope or a widening of the cross-section available to the channel exists.

Degraded but stable streams have completed their adjustment to a new balance of energy dissipation, but, similar to terrestrial desertification, they lack recovery pathways to their former state. Or, the rate of recovery is too gradual to be meaningful for our purposes. Degraded but stable streams generally have lost the ability to capture and stabilize fine sediment (see Figure 22). Examples include channels that have eroded to bedrock and developed a width just sufficient to transport available water and sediment; and coarse-bedded streams that have straightened and widened, through bank erosion, to such a degree that high flows are retained within the banks and stabilizing perennial vegetation is continually scoured.

Figure 22. A channelized stream that is in a degraded but stable condition. Source: Paul Bakke

Degraded but recovering streams are often recognizable by the establishment of young perennial riparian vegetation appropriate to the site. Pioneer species, such as various species of shrubby willow, colonizing exposed bars in the active channel are often the first sign that recovery processes are underway. Note that in order to 'count' toward recovery, vegetation must have survived through at least one high flow period. If persistent through high flow conditions, these pioneers, by increasing roughness, create zones of reduced flow velocity and promote deposition of finer sediment. Such sediment capture is key to initiating floodplain development and succession of riparian plant species.

Under most circumstances, a vigorous riparian plant community - being the means to stabilize sediment - is key to natural channel recovery and long-term stability; it is always necessary, and often sufficient. Where cumulative effects are causing degradation, however, the native plant community may not be adequate to maintain stability; in these circumstances, off-site practices must be altered before recovery can proceed. It should be emphasized that a vigorous plant community includes a range of age classes. Often, when site conditions change, the established vegetation remains healthy, but the conditions necessary for propagation have been eliminated. Thus, the community ages and eventually declines if proper site conditions are not reestablished. The long-term implications for stream stability are serious. A well-known example is the decline in cottonwoods in many western stream corridors. Cottonwoods rely on floodwaters to distribute their seeds onto freshly deposited sediments. They are adapted to synchronize release of their short-lived seeds with the peak spring runoff period. River regulation and loss of floodplain connection have drastically reduced the recruitment opportunities for cottonwoods along many western streams. Excessive grazing can also inhibit regeneration. Large, old cottonwoods persist along many streambanks where there are no young cottonwoods to be seen. Figure 23 contrasts vigorous and decadent cottonwood communities.

Figure 23.

a) A vigorous cottonwood-dominated riparian community with various age classes represented;

(b) A decadent cottonwood community on a stranded floodplain. It has been many years since regeneration occurred at this location.

2.3 Stream Habitat

2.3.1 Habitat Requirements of Salmonids

Salmonids need appropriate habitats to feed, hide and spawn. Depth and velocity of flow are key habitat attributes, along with the availability of food and cover for protection from predation and favorable water quality and temperature. Naturally, these attributes vary throughout the year, particularly with fluctuating streamflow. Physically complex channel/floodplain systems offer a range of hydraulic conditions (i.e., depth, velocity and turbulence) throughout varying levels of flow. Hyporheic flow can do much to buffer stream temperatures through the climatic extremes of summer and winter.

Spawning habitat requirements usually involve clean gravel within a narrow range of sizes that allows for hyporheic flow; the tailouts of pools where flow upwells through gravels are often selected. The gravel must be small enough for the spawning female to excavate her nest (redd), but small material is also prone to be scoured at high flows, so for maximum safety it should also be the largest that she can excavate. In other words, depending on the species and size of the fish: not too big, not too small, but just right. Although the activity of excavating redds provides some sorting of the bed materials by removing the fine sediments, the occurrence of gravels falling within the ‘right’ range of sizes is often a function of complex hydraulics associated with complex channel geometry.

Feeding and hiding habitat characteristics and scale vary through the differing stages of fish growth and development, beginning within the interstices of gravel/cobble streambeds and in the shallow margins used by fry and ending with deep pools favored by adults. Small fish tend to utilize shallow areas that larger competitors or predators cannot access. Preferred feeding habitat involves low velocity areas immediately downstream of food sources. For example, riffles that provide habitat for the aquatic insects that are a prime food source are too swift for many juvenile salmonids to occupy, but downstream tailout pools can provide excellent opportunities for feeding (riffles and pools have been described, respectively, as ‘kitchens’ and ‘dining rooms’). Cover in proximity to feeding and spawning areas, in the form of roots, overhanging banks and vegetation, debris accumulations and pore spaces within the streambed, is needed to provide protection against predation.

Side channels and off-channel features within the floodplain provide vital habitat to many juvenile salmonids. Besides relatively sheltered rearing habitat, floodplain features provide important low velocity refugia during periods of high flow when fish remaining in the main channels are washed away (outmigrating smolts take advantage of such high flows to quickly move downstream).

2.3.2 Habitat Complexity

A fundamental characteristic of ecosystems is that biological complexity (i.e., diversity) requires habitat complexity. In the case of aquatic ecosystems, features such as channel structure, bed material, flow velocity, water quality, temperature, and nutrient availability influence **biotic** diversity.[42,43,44] Structural complexity creates an array of microhabitats that provide for the needs of an assortment of species throughout their various life stages. Conversely, community diversity in streams with simple habitat is lower than in those with higher habitat complexity.[45]

The frequency and magnitude of floods is the primary driver of structural complexity within stream corridors, periodically creating and destroying the various features within the channel and floodplain. Complex channel/floodplain structures generate hydraulic complexity (i.e., varying flow velocity, depth, and turbulence) throughout a range of flow conditions (see Figure 24). This is critical to meeting the diverse needs of aquatic organisms through all life stages. Complex hydraulics, interacting with sediment and vegetation (including roots and large wood), create and maintain ecosystem structure. Effectively, structural complexity, hydraulic complexity and high quality habitat are related characteristics of a properly functioning stream/floodplain system.

Figure 24. High quality aquatic habitat is the result of structural and hydraulic complexity.

2.3.3 Habitat Connectivity

Connectivity within the stream corridor is not only essential for salmonids and other migratory fishes; it is also of critical importance to a host of resident aquatic species. The needs of aquatic organisms for food, shelter, and reproduction through the range of varying flow conditions motivate movement longitudinally (i.e., upstream/downstream), vertically through the water column and into the porous streambed and laterally from the main channel to the margins and off-channel floodplain features.

Longitudinal Connectivity

An obvious characteristic of stream/floodplain systems is longitudinal connectivity across the landscape (originating near watershed divides and generally terminating at the ocean). The ecological implications of this connectivity are profound. Besides storing and routing matter in the downstream direction, these systems provide continuous habitat and migration corridors essential to many aquatic and terrestrial species.

Historically, the upstream migration and subsequent spawning of anadromous fish imported huge amounts of ocean-derived nutrients to the watersheds of the Pacific Northwest, enriching not only the stream systems but also the uplands (think humans, bears, eagles and ravens feasting on fish).[21]

Longitudinal connectivity is vital to ecosystem resilience: the ability to recolonize sites after severe disturbance. Generally, small- to medium-sized, high-gradient streams are subject to infrequent but severe disturbance (*sensu*, Benda and colleagues[46]) that can eliminate much of the aquatic and riparian life within a stream reach. This most commonly is caused by multiple disturbances, such as when a high intensity rain or snowmelt event occurs several years after fire, clearcutting or road construction. The combination of reduced root strength and soil saturation may trigger landsliding and debris torrents capable of scouring and damming channels. It should be noted that extremely infrequent and severe events might affect even relatively large streams, such as in 1980, when the Toutle River was overwhelmed by mud and debris flows triggered by the eruption of Mt St. Helens. Connectivity within the system is key to re-colonizing these sites following severe disturbance.[47] When habitat connectivity is lost, migratory species may be excluded, and disturbance can lead to local extinction of resident species (see Figure 25).

Figure 25.

(a) Natural fish passage barrier (b) Human-created fish passage barrier

Lateral Connectivity

The lateral dimension of the stream corridor extends across the channel and floodplain. Riparian/ floodplain habitats may consist of side channels, off-channel ponds and wetlands, perennial or intermittent streams and springs and periodically flooded grasslands and forests.[33] These riparian/floodplain habitats offer feeding, reproduction, and refuge habitat for invertebrates, fish, amphibians, reptiles, birds, and mammals. Flooding provides periodic or episodic surface connection between the various floodplain features and the active channel, allowing the exchange of organisms and materials (e.g., wood, sediment, solutes). Figure 26 illustrates the simplification caused by diking.

Figure 26. Dikes have been used throughout history to disconnect channels from their floodplains.

Vertical Connectivity: The Channel and Hyporheic Zone

The vertical connectivity of in-stream habitat refers to the physical, chemical, and biological interconnectedness of the water column in the channel and throughout the hyporheic zone. As noted in the Section 2.2.3 *Hyporheic Flow*, the hyporheic zone is the volume of saturated sediment beneath and beside streams where ground water and surface water mix. Geomorphic and hydrologic processes within a watershed result in a systematic distribution of sediment within the stream system. These processes dictate the location, quantity and quality of sediment deposits, ultimately controlling the occurrence and degree of hyporheic functioning.[32] The ecology of gravel-bedded streams appears to be heavily influenced by hyporheic functioning. In natural stream systems, the quality of hyporheic flow is typically high and the temperature is buffered. These characteristics provide significant benefits to aquatic habitat benefits.[21, 48]

Recognition of the hyporheic zone and its importance is relatively recent and much is still poorly understood. According to a literature search by Edwards[4932], the ecological significance of hyporheic zones includes:

- Affecting surface water quality,
- Influencing the retention and processing of solutes,
- Contributing to the decomposition of organics,
- Providing habitat to diverse and abundant organisms and serving as refuge, buffering organisms from disturbance in discharge and food supply, and
- Providing one of the dominant links between the riparian zone and the stream channel.

Physical and hydraulic complexity are the interacting, interrelated components of diverse habitat that supports the range of species and life stages of Pacific Northwest aquatic ecosystems. Salmonid habitat needs are such that high quality habitat indicates highly functioning stream and riparian processes discussed in previous sections of this chapter.

2.4 Summary

Channel and floodplain structure, and by extension, aquatic habitat, are created, maintained, and destroyed by the energy inherent in high flows. Energy is expended through erosion, sediment transport, and various forms of friction. Critical to stream channel characteristics are the proportions of the different types of energy dissipation. These are the result of interactions among streamflow, sediment quality and quantity, channel and floodplain geometry, stream corridor vegetation, and structural elements. Complex patterns of sediment erosion and deposition, created by these interactions, underlie diverse, productive aquatic and riparian habitat.

A stream reach in dynamic equilibrium has developed a geometry that balances the energy available for sediment transport with the supply of sediment being delivered to the reach. This does not imply that sediment transports through the reach without stopping. Rather, it indicates a balance between erosion and deposition. With balanced rates of erosion and deposition, individual channel and floodplain features are created and destroyed but overall channel characteristics such as sinuosity, gradient, width/depth relationships, and pool and riffle frequency are maintained. The stabilizing role of vegetation in channel development and maintenance cannot be overemphasized. Channel complexity, having a large effect on energy dissipation, exerts a major influence on erosion, sediment transport, and deposition. Thus, complexity is intimately intertwined with maintenance of a dynamic equilibrium.

A stream reach undergoing simplification of overall channel characteristics is in disequilibrium. The balance between erosion and deposition has been disrupted. This may be the result of major disturbance, changes to riparian vegetation, or to the supply of water, sediment or structural elements. Disequilibrium can also be caused by local disturbance or channel manipulation. If the changes or disturbance are temporary, the stream will often recover its former characteristics. If the changes are chronic, the stream will eventually reach a new, often simplified, equilibrium.

Effective restoration of aquatic habitat depends upon reestablishing watershed and stream processes to a range of variability that maintains a complex channel/floodplain system in dynamic equilibrium. This endeavor requires a body of knowledge encompassing geomorphology, hydrology and plant ecology, and also the societal will to adopt sustainable land use practices. At this time, it is not clear precisely to what degree ranges of natural variability can be tampered with before significant habitat simplification occurs; moreover, different stream ecosystems vary their resilience capabilities. Alterations to watershed and stream processes exceeding the natural range of variability of those processes will inevitably alter the stream habitat and ecosystem. The degree of alteration we collectively find acceptable is the outstanding question.

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CHAPTER 3

STREAM HABITAT ASSESSMENT

Chapter 3. Stream Habitat Assessment

Stream habitat is created and maintained by the dynamic interplay of multiple physical, chemical and biological processes that function at diverse spatial and temporal scales (Chapter 2 of this document). Historically, restoration efforts were primarily quick fix, in-channel engineering efforts that were implemented without adequate knowledge of watershed and ecosystem processes and characteristics. These restoration efforts were often conducted at inappropriate locations or at inappropriate spatial and temporal scales and ignored the processes that were limiting habitat quality or species survival. Hence, structural and functional failures were common. Appropriate habitat assessments could have prevented many of these failures.

The purpose of a habitat assessment is to characterize the present (and/or historic) state of habitat and the processes that create and maintain it so that problems and appropriate restoration options and obstacles can be identified and prioritized. It provides the technical basis for making decisions concerning land management as well as restoration and mitigation policy, planning, and project development. In light of the limited resources available for restoration, the risk of project failure, and the risk of unintended detrimental habitat and infrastructure impacts when watershed processes and conditions are poorly understood, some degree of assessment should be conducted for all projects in order to maximize the likelihood of their long-term success. Assessment costs should be an intergral part of project implementation costs, and therefore, should be included in the project budget. It is invariably more cost effective to adequately assess watershed conditions before project implementation rather than after a project has failed to meet expectations, but especially if more than one project can benefit from the endeavor.

The objectives of this chapter are to:

- Describe types of information to be gained through expanding scales of assessment,
- Describe typical components of an assessment,
- Provide tips on selecting an appropriate scale of assessment,
- Identify references concerning various assessment methodologies, and
- Identify available resources to help in your assessment.

Because the goals of assessment and the depth and scale of analysis vary with the problem(s) being addressed, specific instructions on how to conduct an assessment are not addressed below.

3.1 Role of Assessment

Stream habitat assessments are typically conducted at three scales: 1) watershed, 2) reach, and 3) site, because the processes responsible for creating, maintaining, and connecting stream habitat operate on multiple spatial and temporal scales. For instance, sediment found at a particular site may be derived from adjacent bank erosion (site-scale process), upstream channel incision (reach-scale process), or mass-wasting events in the watershed (watershed-scale process). The other reason is that the impacts of activities within the watershed are cumulative and propagate downstream (e.g., water quality impairment), upstream (e.g., channel incision), and laterally (e.g., channel migration). Hence, what goes on elsewhere in the watershed may influence the effectiveness of a restoration project. Similarly, the effects of an individual or series of restoration project may extend beyond the project area.

3.1.1 Watershed Assessment

Watershed assessments provide the context for evaluating the spatial and temporal variability of watershed inputs (water, sediment, organic material, energy, and solutes), their effects on watershed -, reach-, and site -level habitat conditions and species populations, and their relationship with past, current, and future land management. Understanding this relationship is useful to evaluate cause and affect relationships and to differentiate between anthropogenic and natural shifts in habitat and population conditions. Identifying the root cause(s) of habitat degradation is necessary to successfully restore stream ecosystems. Projects that address only the symptom of a problem, rather than functional causes, will provide only short-term and localized benefits.

Reid[1] lists the following questions as examples of what watershed assessments can best address:

- "What areas are important for fish [and wildlife], and why?
- Where has habitat been impaired?
- What aspects of the habitat have changed?
- What caused those changes?
- What is the relative importance of the various habitat changes to fish [and wildlife]?
- What is the present trend of changes in the system?
- Which changes are reversible?
- What is the expected effectiveness of the potential remedies?
- What are the effects of those remedies on other land uses, [infrastructure], and ecosystem components?
- What are the relative costs of the potential remedies over the long term?"

Watershed assessments may also assist in:

- Identifying watershed-wide constraints and opportunities for habitat restoration, enhancement, and preservation (Habitat restoration is of little long-term value in a watershed incapable of supporting the processes that create and maintain habitat conditions),
- Integrating planning efforts to avoid the problems and inefficiencies that result from multiple actions within a basin performed in isolation of each other,
- Developing prioritized restoration strategies that target projects and drainages that offer the greatest potential for collectively achieving long-term restoration goals at the lowest cost,
- Determining the appropriate scale in which implementing restoration, rehabilitation, enhancement, and preservation efforts, is most effective, and
- Developing monitoring strategies and objectives to determine the individual or collective effectiveness of restoration measures conducted throughout the watershed. Such measures are necessary to monitor and adaptively manage the watershed's overall restoration strategy.

3.1.2 Reach Assessment

A reach assessment characterizes conditions found within a specific length of stream. It may be limited to the stream channel itself, or it may extend laterally to adjacent contributing areas. Channel reaches are typically many channel widths in length and exhibit similar geomorphic characteristics throughout, such as channel pattern, slope, confinement, flow, and sediment size.[2]

Reach assessments can be used to collect information essential to project planning, development, and implementation. Reach assessments identify, quantify, and evaluate the condition of species, and the abundance and quality of habitat contained within. They can describe the relationship between species inhabiting the area, existing habitat conditions, and the habitat-forming processes acting within that reach. They can identify constraints and opportunities for restoration within the reach. Reach assessments are useful in characterizing factors that constrain the abundance and diversity of species that spend their entire life cycle within a reach. However, the limited scope of a reach assessment may not be adequate to characterize the factors affecting migratory species, which spend part of their life cycle in multiple stream reaches. Thus, restoration treatments designed to address habitat degradation from reach-scale assessments may only partially address impacts or be limited to addressing the symptom of a problem rather than the cause. Because reach assessments, by definition, cover a larger area than site assessments, they are better able to predict the impacts a project might have on upstream, downstream, and adjacent habitat and infrastructure, but they are limited in characterizing cumulative watershed effects.

3.1.3 Site Assessment

Sound project design requires knowledge of the condition and layout of the project site. For instance, riparian planting projects require knowledge of soil type and condition; light and moisture availability; the extent, frequency, duration, and depth of flooding; land management; and wildlife use of the area, among other variables. Such knowledge enables the designer, to select appropriate plant species and site preparation and maintenance techniques. Besides being a necessary design tool, site assessments are capable of identifying, quantifying, and evaluating the condition of species and the abundance and quality of habitat at that particular site. They can explore the spatial relationship among various in-channel habitat components, such as the proximity of cover to spawning habitat, or the connectivity of off-channel and in-channel habitat. They can also identify site-based restoration constraints and opportunities.

But site assessments are inadequate for identifying limiting factors to species health and abundance unless the species spends its entire life cycle within that particular site (e.g., vegetation, certain macroinvertebrates). They are also incapable of identifying the cause of any problems that originate from outside the site. For instance, although plants are stationary, their health, species composition, distribution, and extent are influenced by the availability of light, water, and nutrients, patterns of sedimentation and inundation, and the type, magnitude and frequency of disturbance. Each of these factors may be controlled by site, reach and/or watershed-scale processes. Likewise, site-scale assessment may be inadequate to predict how an individual project may influence upstream, downstream, and adjacent habitat, infrastructure, and channel stability. Hence, well-intentioned projects implemented to enhance habitat may inadvertently damage or impair other habitat or biota, destabilize the channel bed or banks, or put nearby infrastructure at risk if factors in restoration planning are not considered at a broader scale.

3.2 Conducting Assessments

Humans can alter habitat and habitat availability within the stream corridor directly through channelization, bank armoring, stream cleaning, and levee construction activities, among others, or indirectly through landuse activities within the watershed. The cumulative impact of land use activities and natural disturbance events (e.g., floods, landslides, fire, or debris torrents) may cause a series of channel and watershed responses that destabilize the stream or degrade habitat conditions, water quality, or fish and wildlife productivity. Because cumulative impacts vary both within and between watersheds, every assessment is unique, even if the reasons for conducting the analysis are the same. Assessments must address specific objectives, and include land use and naturally influenced disturbances.

3.2.1 Assessment Topics

Stream habitat assessment includes the reconnaissance, measurement, and documentation of existing conditions, historic conditions, and predicted future conditions as they relate to fish and wildlife species population and distribution, and the processes that influence and determine stream habitat. The habitat of an organism is defined by its physical (e.g., velocity, depth, substrate), chemical (e.g., dissolved oxygen, nutrient, and contaminant levels), and biological (e.g., predator-prey, competitive, and symbiotic relationships) characteristics.[3] Hence, an assessment of the value, distribution, abundance, and accessibility of stream habitat may include physical, chemical, and/or biological surveys. Which components are evaluated and to what extent depends on project and restoration objectives, site, reach, and watershed conditions, and the scale(s) of analysis. Collecting and analyzing historical data and applying it for restoration purposes is challenging, but it can provide a context for understanding the capacity of the site to produce quality habitat. The Puget Sound Nearshore Ecosystem Restoration Project[4] (PSNERP) provides an applied example of how historical assessments can be useful in identifying restoration potential of marine shorelines.

Landuse throughout the watershed directly and indirectly influences habitat conditions, and it may disturb (e.g., noise, artificial light), limit migration (e.g., dams, culverts, levees, tide gates), or create dangerous situations (e.g., roads) for fish and wildlife. Thus, habitat assessments are often conducted in conjunction with landuse, land management, landowner, and infrastructure assessments. Importantly, it can be difficult to establish clear causality between cumulative land use activities,[1] especially with regards to biological response (establishing a link between watershed activities and physical channel response may be more clear). Lag time between action and response can be years or decades, and the greater the lag time, the more opportunity for additional influences to come into play. For example, it may take decades for sediment inputs associated with logging to accumulate in downstream sites[5].

3.2.1.1 Physical Habitat Assessment

A physical habitat assessment describes the structure and composition of a landscape. Physical habitat assessment is basal to assessing stream habitat restoration efforts because it evaluates the structure being restored directly, it is necessary to support biological assessments, and it is an intrinsic element of setting environmental flows using instream flow methods, which may also be used for physical habitat assessment.[6] Physical habitat assessment may consist of:

- Documenting physical characteristics of the land and stream such as topography, feature dimensions, soils, stream bed and bank characteristics, channel characteristics (entrenchment, sinuosity, channel migration zone), vegetation, and drainage basin boundaries, size, and shape.

- Evaluating channel stability. Is the channel actively aggrading or incising?
- Evaluating the abundance, distribution, proximity, condition, and accessibility of various types of habitat. Is there potentially productive habitat that is currently inaccessible because it lies behind levees or upstream of impassible culverts, tide gates, dams, or other stream or floodplain obstructions?
- Documenting landuse, land cover, and infrastructure, including those that place constraints on the channel, floodplain, or habitat-forming processes.
- Documenting the extent, type, and location of direct stream and floodplain modifications (e.g., channel straightening, dredging, diking, armoring, or cleaning; dams; floodplain fill) that have occurred.
- Identifying barriers and constraints to fish and wildlife passage between critical habitats (e.g., culverts, roads, levees, high flow velocities, low flow depths). Are they temporary, partial, or complete barriers?
- Determining physical habitat deficiencies that constrain fish, wildlife, and plant productivity within the stream corridor.

Consider current conditions as well as how each of these characteristics has been altered from historic conditions and how they will change over time if current landuse activities, regulations, and trends continue. Many characteristics vary over time and space in response to variations in climate, geology, vegetation, the frequency, magnitude, type, and proximity of disturbance, and site-, reach-, and watershed-scale processes. Therefore, evaluation of the processes that determine the physical characteristics of an area is an integral component of physical habitat assessment. Principal processes that influence channel morphology and physical habitat conditions include the delivery and routing of:[7,8,9]

> **Sediment**: Evaluation may include identifying, locating and determining the relative dominance of current sediment sources to the stream (e.g., mass-wasting events, channel incision, bank erosion, surface erosion), predicting where future erosion is likely to occur, evaluating whether individual sources are temporary or long-term, sediment size distribution, suspended sediment concentrations, or the rate of sediment transport to and from the site, reach, or watershed (sediment budget). Consider also how these have been altered from historic conditions and how they will change over time. What are the natural and human causes of changes between historic and current conditions? How is the supply of sediment affected by other controls and processes (e.g., surface runoff, vegetation, stream discharge)? How does the supply of sediment affect other processes (e.g., wood recruitment) and channel stability? Assessments concerning sediment supply and erosion may include inventories of landslides, roads that present a landslide hazard, and surface erosion hazards (e.g., unvegetated or disturbed soil areas),[7] calculations of road density.[8] or identification of dams, reservoirs, and instream detention basins that prevent downstream sediment transport. Refer to Chapter 4.6.1, *Sediment Supply,* of this document for information on the function and value of sediment in a stream, potential human impacts to sediment supply and transport, and potential techniques to address those impacts. Refer to the *Sediment Transport* Appendix for further information on evaluating sediment transport. [7,10]

Water: Evaluation may include determining the rate and timing of discharge to and from (water withdrawals) the stream; the frequency, depth, duration, and extent of floodplain inundation; and the routing and storage of water within the watershed, determining peak flows, dominant flows, and minimum flows, and locating special hydrologic features such as springs and groundwater recharge areas. Is the flow comprised dominantly of surface water or groundwater? Is the watershed subject to rain-on-snow events? Consider also how these have been altered from historic conditions and how they will change over time. What are the natural and human causes of changes between historic and current conditions? How is discharge affected by other controls and processes (e.g., vegetation, fire, floodplain connectivity, channel roughness)? How does discharge affect other processes (e.g., species migration, channel migration, sediment delivery) and channel stability? Assessments concerning stream flow regime may include an evaluation of how the flow regime has been affected by dams, water withdrawals, stormwater drainage networks, wetland drainage and fill, floodplain drainage and fill, land cover changes, stream channel and floodplain modifications, and by increasing amounts of impervious surface in the watershed. Or it may include an assessment of the connectivity of stream channels, floodplains, wetlands, side channels, and other off-channel habitats. How much of the floodplain is no longer accessible to overbank flows? Refer to Chapter 4.6.2, *Flow Regime*, of this document for information on the function and value of water in a stream, potential human impacts to water supply and transport, and potential techniques to address those impacts. Refer to the *Hydrology* Appendix for more information on evaluating watershed hydrology.[7,8,10]

Organic material (large wood and detritus): Evaluation may include the age, extent, species composition, and distribution of riparian and upland plant communities, or the distribution, abundance, species, and size of large wood in the stream. Consider also how these have been altered from historic conditions and how they will change over time. What are the natural and human causes of changes between historic and current conditions? How is the organic material supplied to the stream affected by other controls and processes (e.g., fire, wind throw, mass wasting, flooding, vegetation)? How does it affect other processes (e.g., sediment storage, scour, channel migration, primary productivity, disturbance, species migration) and channel roughness, gradient, and stability? Assessments concerning organic inputs to the stream may include riparian vegetation and in or near-stream large wood surveys, the history of fire, fire suppression, landslides, bank erosion, flooding, blow down, and other recruitment mechanisms for large wood, the history of stream cleaning, timber harvest, and land cover changes, and inventories of obstructions to large wood transport (e.g., culverts, bridges, dams). Refer to the *Large Wood and Log Jams* technique and the *Riparian Restoration and Management* technique for further information on instream wood and riparian habitat, respectively.[7,8,10]

Energy (light and heat): Evaluation may include the degree of shade provided to the stream, or the turbidity (as turbidity increases, light penetration decreases), temperature, and flow of the stream, its tributaries, and other natural or artificial discharges to the stream. Consider also how these have been altered from historic conditions and how they will change over time. Is the dominant source of water to the stream groundwater or surface water? What are the natural and human causes of changes between historic and current conditions? How is the energy supplied to the stream affected by other controls and processes (e.g., vegetation, discharge, hyporheic flow, sediment supply)? How does it affect other processes (e.g., biotic productivity, dissolved oxygen content)? Assessments concerning energy inputs to the stream may include inventories of the temperature, turbidity, and flow regime of the stream and natural and artificial discharges to the stream, the rate and timing of water withdrawals (shallow water heats up faster than deep water), the extent and nature of modified channels (over-wide and flat bottomed channels will have relatively shallow flow), direct measurements of shade or indirect measurements based on the height, extent, species composition, and canopy cover of nearby vegetation that provide shade to the stream. It may also include an inventory of natural and artificial impoundments that allow water to heat up. Does the water released from those impoundments come from the surface of the reservoir (where it will be warmest) or from lower down?

Physical habitat inventories may be conducted at a watershed-, reach-, or site scale. However, evaluation of the processes that create, maintain, and connect those habitats will likely need to occur on a watershed-scale.

3.2.1.2 Chemical Habitat Assessment

The concentration of solutes (substances capable of dissolving in water) in a stream is a major factor in determining the quality of habitat for aquatic organisms and for terrestrial and avian species that drink the water or prey on aquatic species. Some solutes may be beneficial or necessary to support life within a certain range of concentrations (e.g., dissolved oxygen, nutrients) while others have only detrimental impacts above a certain threshold concentration. Where water quality is impaired, restoration of physical habitat in the absence of water quality improvement measures will provide minimal benefit, if any.

Chemical habitat assessment may include:[8,10]

- Monitoring water quality. Are the surface water quality standards described in WAC173-201A being met? If not, how often and under what conditions are they out of compliance?
- Identifying the source, fate, and transport pathways for solutes of interest. As solutes are derived from numerous natural and anthropogenic sources, evaluation of land use activities within the watershed may be a necessary component of chemical habitat assessment. How have changes in land cover, land use, hydromodification, stream and floodplain modifications, and legal and illegal effluent discharges to the stream altered the source, fate, and transport of pollutants? Documenting current and historic escapement levels of anadromous fish may be necessary in streams deficient in marine-derived nutrients supplied by anadromous fish carcasses.
- Monitoring streamflow, which directly influences the concentration of solutes in the stream.
- Defining any associations between water quality and the present condition of species in an area. Is water quality a limiting factor to fish, wildlife, and plant productivity within the stream corridor?

- Determining how water quality is affected by other controls and ecosystem processes (e.g., mass wasting, flooding, stream flow, shade, vegetation, soils).
- Identifying beneficial uses that are dependent on water quality (e.g., fish and wildlife species that dwell in or drink from the stream, near-shore, or marine environment; fish, wildlife, and people that consume fish and wildlife that dwell in or drink from the stream, near-shore, or marine environment; drinking water; irrigation water, swimming).

Consider current conditions as well as how each of these characteristics has been altered from historic conditions and how they will change over time if current landuse activities, regulations, and trends continue. Refer to Chapter 4.6.7, *Water Quality*, of this document for information on potential human impacts to water quality, and potential techniques to address those impacts.

Chemical assessment can be conducted at the watershed, reach, or site scale. Impairments to water quality can be expressed as a function of the catchment area above the sample site. Because water quality varies with flow and with processes that influence the supply, transport, and fate of solutes in a stream, the frequency and timing of measurement is one of the biggest determinants of the value of the data, no matter what scale of assessment is conducted.

3.2.1.3 Biological Habitat Aassessment

Biological assessments should be conducted as an ecosystem assessment. Too frequently, biological assessments are focused on single species, single life history stages, or limited geographic distribution. To the extent possible, assessments should include multiple species, life histories, and spatial extents to achieve restoration project objectives while minimizing impacts to non-target species. Biological assessment may include:[10,11]

- Determining the relative abundance and distribution of species present in, or dependent upon, the stream corridor, including identification of threatened or endangered species, native and non-native species, resident and migratory species.
- Identifying species that have been extirpated.
- Identifying biotic invaders that may impede or preclude recovery.[1]
- Measuring the age, size, growth rate, and condition of species present. Condition may refer to physical ailments or abnormalities, the presence of parasites or pathogens, or to the genetic integrity of stocks. What factors are responsible for this condition?
- Documenting the life histories of species, including how and when they use different parts of a stream network (the needs of the individual species may vary from season to season and from year to year).
- Determining interactions among species present, including dependency (e.g., predator/prey, parasitic, or symbiotic relationships) and competition among species for available habitat or resources.
- Documenting current and historical hatchery and harvest management influences.

Consider current conditions as well as how each of these characteristics has been altered from historic conditions and how they will change over time if current landuse activities, regulations, and trends continue. Because people, pets, and livestock also make up part of the biological community, their proximity and role as predator, prey, and disturber of fish and wildlife, should be evaluated as part of a biological assessment.

Biological assessment can be conducted at the watershed-, reach-, or site-scale, depending on the assessment goals. Certain objectives require large-scale analysis. Such analysis may go beyond the watershed to encompass entire flyways (e.g., migratory birds) or marine and near-shore environments (e.g., anadromous fish).

3.2.2 Determining the Scale of Assessment

Information gleaned from an assessment varies with the scale of analysis. Information from multiple scales complements one another. Habitat assessment at a site or reach scale may reveal the effects of impacts to watershed-scale processes. Similarly, limitations to habitat potential at the site or reach scale may identify watershed assessment needs. For instance, a decrease in the abundance of pool and cover habitat within a particular stream reach may trigger a watershed assessment of instream wood, riparian vegetation, and sediment supply to determine the root cause of the change. Broader scales of analysis allow individual sites, issues, and concerns to be viewed in a larger context,[10] increasing the likelihood of identifying and addressing core problems and fully assessing how a potential project will impact, respond to, and function within the landscape. Unless a problem, its cause, and its potential treatment impacts are clearly limited to a specific site (e.g., water quality degradation immediately downstream of an industrial discharge pipe), focus on restoration of individual sites is only appropriate after developing some understanding of how those sites fit within the broader landscape.[8] A watershed analysis that identifies broader ecosystem problems is recommended prior to initiating isolated restoration activities, though such analyses do not necessarily need to be extremely detailed or costly.

Even watershed assessments can be conducted at multiple scales. A watershed-scale assessment extends from the mouth of the stream to the upstream reaches of its drainage basin. Because the watershed of a small tributary stream is nested within the watersheds of successive larger streams, watershed-scale assessments may mean different things to different people. Its focus may be limited to the tributary or it may encompass the entire river basin including the main-stem and all tributaries. The size of watershed included in an assessment varies with the study objectives, topics to be addressed, and the physical, biological, and social complexity of the system[10]. A site or reach-specific problem, such as water quality concerns or insufficient instream cover or pool habitat for resident aquatic species, requires an assessment only of the local watershed to determine the cause of the problem, though risks and benefits to habitat and infrastructure associated with proposed treatments should also be considered as the effects of individual projects may extend up- or down-stream. Other topics, such as fish and wildlife population studies, or limiting factors for the productivity of migratory fish and wildlife species (e.g., migratory waterfowl, anadromous fish species) require assessment at larger scales, and may include the marine and nearshore environments.

Reid[1] provides a comprehensive description and evaluation of a number of approaches and procedures for watershed assessment, ranging from “ad hoc” approaches that focus on specific issues in specific areas to broad watershed analyses that seek to understand watershed conditions and identify issues of concern. She describes two of the most widely accepted and implemented watershed assessment procedures that are applied in Washington State:

> *Ecosystem Analysis at the Watershed Scale: Federal Guide for Watershed Analysis.*[10] This guide was completed under the direction of the Regional Interagency Executive Committee and the Intergovernmental Advisory

Committee, representing multiple federal agencies. It describes a 6-step process that focuses on seven core analysis topics (erosion processes, hydrology, vegetation, stream channel, water quality, species and habitats, and human uses) as well as specific problems or concerns identified in the watershed. Analysis teams identify and describe ecological processes of greatest concern, establish how well or poorly those processes are functioning, and determine the conditions under which management activities, including restoration, should and should not take place. The analysis itself is not prescriptive, but it provides the objective background information from which later management decisions and environmental impact assessments can be based. This analysis has a broad scope, capable of providing information to evaluate a range of land use issues.

Standard Methodology for Conducting Watershed Analysis Manual, Version 5.0.[12] This method was developed by a multitude of state agencies, tribes, members of the forest products industry, small private landowners, and environmental groups who were participating or otherwise involved in the Timber, Fish, and Wildlife Agreement. The assessment method presented is stepped and iterative, consisting of two parts—resource assessment and management prescription. A series of key questions provides a framework to develop information and interpret the condition and sensitivity of public resources within the watershed, including fish habitat (salmonid emphasis), water quality, water supply, and public works. These findings then feed into a prescription process where local land managers and agencies develop a tailored forest management plan for the watershed that responds to the identified resource concerns. The manual also includes modules that describe how to evaluate mass wasting, surface erosion, hydrologic change, riparian function, fish habitat, water quality, and public capital improvements. The procedure currently focuses on impacts to aquatic habitat. Terrestrial habitat may be addressed at a later date.

Two watershed assessment methodologies developed in Washington State since Reid's publication[13] include:

State of Washington Guidance on Watershed Assessment for Salmon.[9] The Joint Natural Resources Cabinet, representing multiple state and tribal agencies and planning councils, developed this document. The guidance provided is oriented towards identifying problems and issues in salmon recovery for specific watersheds. It presents three stages of watershed assessment: 1) Habitat Conditions--what habitat conditions are limiting salmon production? 2) Causes of Conditions--what processes or land uses are causing the habitat conditions?, and 3) Salmon Response to Conditions--what linkages exist between salmon and habitat conditions? Successive stages of assessment build on one another and support increasingly complex issues and decisions with regards to habitat preservation and restoration. Though the focus of the document is on salmon habitat, products may have broader application. The guidance does not explain how to assess various parameters, however, it contains an appendix that lists the various types of assessment that may be necessary and their relation to existing statewide information sources.

> *Enhancing Transportation Project Delivery Through Watershed Characterization: Methods and SR522 Case Study. Review Draft Report to the Transportation Permit Efficiency and Accountability Committee.*[8] The Watershed-Based Mitigation Subcommittee, created by Washington's Environmental Permit Streamlining Act in 2001, developed this report. It summarizes a scientific framework and set of procedures being developed at multiple watershed scales to identify and prioritize sites having potential to mitigate for transportation impacts. The framework consists of three parts: 1) Project site assessment –understanding the transportation project's potential environmental impacts, 2) Watershed characterization and cumulative impact assessment – characterizing effects of land use on ecological processes and aquatic and terrestrial resources, and 3) Identify and assess potential sites – ranking potential mitigation sites and selecting the preferred mitigation site. Each part includes a series of generalized steps that form the scientific framework for watershed characterization. Recovery efforts focus on recovery of ecosystem processes that create and maintain habitat in order to maximize the environmental benefit and longevity of mitigation activities.

The following is not a watershed assessment. However, when applied at a watershed scale, it can be used to rapidly identify stream reaches that appear to be functioning well and are candidates for protection and preservation, and those that are functioning poorly and require further review and assessment to reveal the cause of impairment and identify potential remedies.

> *Process for Assessing Proper Functioning Condition (PFC).*[14] PFC, first developed by the Bureau of Land Management, was adopted by all other federal land management agencies. It is a qualitative assessment system used to evaluate how the stream is handling the energy flowing through it. Assessment is based on hydrology and geomorphology, riparian vegetation, and soils. It results in a classification of streams, reach by reach, as exhibiting "proper functioning condition", "functional, but at risk", "nonfunctional", or "unknown". Non-functional stream reaches are those that lack adequate vegetation, landform, or large wood to dissipate stream energy, indicative that the channel itself or the processes that create, maintain, and connect habitat within such reaches have likely been altered from historic conditions. The strength of PFC lies in its relatively rapid application.

Each of the watershed assessment methods described above was developed with specific objectives in mind. Despite their differences, they share a common philosophy that:[1]

1. General patterns exhibited through a watershed are more important to consider than specific details.
2. Understanding of interactions among watershed components and processes is more important than understanding of the individual components.
3. Qualitative descriptions and order-of-magnitude estimates are often of greater value than precise numbers.

The choice of which watershed analysis to use depends on the problems being addressed and the objectives of the assessment.[1] Planners are encouraged to review the inherent assumptions, potential application, limitations, and required time, cost, and expertise of a procedure, as well as the utility prior to making a selection.

Conducting an assessment costs time and money, both of which increase with the number of parameters studied, the level of detail required to describe each parameter (e.g., quantitative vs. qualitative analysis), and the geographic extent of the study. Limited resources may limit the scope and scale of assessment. But the cost and time associated with assessment must be weighed against the amount and type of data necessary to provide meaningful results. The success of an assessment is measured by its utility to decision makers and resource specialists applying the results.[10]

Where available time and funding for watershed assessment is limited, it may be appropriate to limit its scope to that necessary to plan, design, and implement low risk restoration activities that offer a high likelihood of success. Roni et al.[7] reviewed the effectiveness of various restoration methods for improving salmonid habitat. Results, summarized in **Table 3.1**, suggest the highest likelihood of success is associated with preserving high quality habitat; reconnecting isolated high quality instream, floodplain, and estuary habitats that are currently inaccessible as a result of barrier culverts, dams, levees, or other artificial structures; and restoring ecosystem processes and controls through projects such as road abandonment and improvement, and riparian restoration. With that in mind, if a full culvert assessment has not been done in a low gradient watershed, a culvert assessment might be a good place to start. In watersheds with a history of mass wasting and identified sedimentation concerns, consider conducting a mass wasting assessment. In an area subject to urban growth, identification and assessment of undeveloped riparian zones and floodplains that can be acquired represents important opportunities that may soon be lost. Information from similar watersheds, in conjunction with the help of professional scientists and resource managers with previous experience in the region can play an important role in prioritizing watershed assessment efforts, when prioritization in necessary. Areas with similar geology, geography, landuse, and climate often have similar needs for restoration.

Table 3.1. Typical response time, duration, variability in success, and probability of success of common restoration techniques. Adapted from Beechie et al.[15] as modified from Roni et al.[7]

Restoration type[a]	Specific Action	Years to achieve response	Longevity of action (years)	Variability of success among projects	Probability of success
Reconnect Habitats	Culverts	1-5	10-50+	Low	High
	Off channel	1-5	10-50+	Low	High
	Estuarine	5-20	10-50+	Moderate	Moderate to High
	Instream Flows	1-5	10-50+	Low	High
Roads and land use	Road removal	5-20	Decades to centuries	Low	High
	Road alteration	5-20	Decades to centuries	Moderate	Moderate to high
	Change in land use	10+	Decades to centuries	Unknown	Unknown
Riparian restoration	Fencing	5-20	10-50+	Low	Moderate to high
	Riparian replanting	5-20	10-50+	Low	Moderate to high
	Rest-rotation or grazing strategy	5-20	10-50+	Moderate	Moderate
	Conifer conversion	10-100	Centuries	High	Low to moderate
Instream habitat restoration	Artificial log structures	1-5	5-20	High	Low to High[b]
	Natural LWD placement	1-5	5-20	High	Low to High[b]
	Artificial log jams	1-5	10-50+	Moderate	Low to High [b]
	Boulder placement	1-5	5-20	Moderate	Low to High [b]
	Gabions	1-5	10	Moderate	Low to High [b]
Nutrient enrichment	Carcass placement	1-5	Unknown	Low	Moderate to high
	Stream fertilization	1-5	Unknown	Moderate	Moderate to high
Habitat creation	Off channel	1-5	10-50+	High	Moderate
	Estuarine	5-10	10-50+	High	Low
	Instream	See various instream restoration techniques above			

Where sustained long-term funding is available, assessments may be incremental, with efforts focusing on new sub-basins within a watershed, or issues and effects not previously assessed. However, it is important to integrate incremental assessments with previous information to get a better handle on the cumulative effects and cause and effect relationships between physical, chemical, and biotic processes operating at a watershed scale.

The following considerations are recommended when determining the necessary scope and scale of assessment for restoration and project planning:

Restoration Planning:

- What are your assessment goals? Is there a particular issue you are trying to address (e.g., elevated nitrogen and low dissolved oxygen concentrations in the nearshore environment) or is your objective to identify and prioritize issues and restoration/management initiatives in the watershed? Is your objective restricted to project-specific reconnaissance?
-

- How much is already known about the stream, its watershed, and the fish and wildlife that it supports? Have other studies been conducted such that the proposed assessment is unnecessary or its scope can be limited to avoid redundancy of effort? Can the current assessment fill critical data gaps identified in previous analyses?
- Are other restoration projects likely to occur in the watershed that can benefit from the assessment? Encourage and pursue opportunities for coordinated and cooperative analysis efforts.[10] Because watershed analysis promotes the long-term viability of an overall restoration strategy, it may be practical to pursue cost-sharing of assessment among numerous smaller projects.
- What is the spatial and temporal scale of the problem? Is it localized or system-wide?
- What is the spatial and temporal scale of the cause of the problem? Keep in mind that limitations to habitat potential at the site or reach scale may sometimes be explained only by assessing watershed-scale processes. The scale of assessment should match the scale of the underlying cause of the problem if it is to be correctly identified and addressed. For instance, sedimentation of spawning gravels resulting from watershed-wide land use impacts will require watershed assessment to identify dominant sources and prioritize potential remedies.
- What funds are available to conduct an assessment? Could the cost be shared among multiple projects and stakeholders? Could the scope or scale of assessment be modified to attract more funding?

Project Planning:

- What factors and conditions will influence the success or failure of the project?
- What are the nature and scale of impacts associated with the proposed project? What are the possible impacts (including unintentional impacts) to habitat, infrastructure, and fish, wildlife, and human life? How far reaching will those impacts be? What is the likelihood of their occurrence?
- What is the risk of, and associated with, project failure? What is the nature and scale of impacts to habitat, infrastructure, and fish, wildlife, and human life if the project should fail? What is the likelihood of project failure? Many projects have a high risk of failure when the watershed processes and conditions are not well understood. Higher risk projects warrant higher levels of assessment.
- What are the risks associated with a delay of project implementation during the time necessary to conduct an assessment (e.g., further habitat degradation or species extinction)? Studies may take years to accomplish effectively, during which time valuable resources may be lost.

3.2.3 Special Case Assessments – Urban Streams

Urban streams provide unique challenges to restoration and assessment efforts. Water chemistry, physical habitat characteristics, and riparian vegetation have been discussed in previous sections of this chapter as important considerations in stream habitat assessments. However, urban streams are uniquely influenced by the source, rate and timing of stream flow (Konrad and Booth 2005[16]). Impervious surfaces, including roads, can direct precipitation away from natural drainages and magnify the amount of water that reaches the channel by reducing or preventing soil infiltration rates. Resulting increased stream flows during storm events can cause downcutting of the channel bed and coarsening of stream substrates. During summer months, less ground water is available to the stream because ground water storage during winter months is retarded. Biotic responses to these changes can result in decreased fish and aquatic insect production. Additionally, urban streams more commonly have armored stream banks than non-urban streams, which can exacerbate stream flow effects on fish and fish habitat.

3.2.4 Limitations of Assessments

Assessment, on any scale, can provide valuable insight into the conditions and issues of concern in a watershed and the underlying cause of those conditions. However, the ability of an assessment to accurately and fully reveal an understanding of what's going on in the watershed, and to provide meaningful results can be limited by any number of constraints. Nevertheless, narrowing the number and significance of assessment uncertainties can improve restoration project performance. Some limitations of assessments include :

- Property ownership and access may limit the area of study. Contact with landowners early in the process with an outline of assessment objects can be helpful in accomplishing habitat assessments while meeting landowner needs. Also, assessments that feature partnerships with local restoration groups, such as Regional Fisheries Enhancement Groups (RFEG's), tribes, Lead Entities, or County extension services may be helpful to some landowners.
- The type and resolution of data collected may be limited by time, money, or the limited objectives of those conducting the assessment. Although they may not match your assessment objectives, existing assessments conducted for a similar purpose or in a representative location or scale may supplement limited assessment capabilities.
- Most of our understanding of restoration project success (and failure) comes from case-study assessments. Due to large variations among restoration projects and their site conditions, aquatic habitat response to these actions is highly variable. Although among the least desirable monitoring tools, narrative discussions of project effectiveness at the site scale can be incorporated into all restoration projects. Even anecdotal information should be conveyed in a public forum, such as the Lead Entity Habitat Work Schedule (refer to Chapter 1), so that others can continue to understand how their project's effectiveness can be maximized. No single discipline covers the many influencing variables that are involved in restoration project planning, and thus, assessments are improved when they involve an interdisciplinary team of professionals.
- Rare events that occurred in the past or elsewhere in the watershed may influence sites a considerable distance downstream, many years or even decades later. Consequently, the temporal and spatial scope of analysis should be sufficient to identify remote or historic influences.
- Lack of historical records may limit our understanding of past conditions. In many areas of Washington, aerial photos date to the 1930's. Local or state libraries and historical societies are often productive sources of these valuable resources.
- The quality, accuracy, and precision of data are dependent upon the knowledge and skill of those collecting and interpreting the data. Training is essential to minimize human error and ensure consistent application of data collection methods.
- The quality, accuracy, and resolution of data are influenced by the tools and methods employed for data collection.

3.3 Assessment Methodologies

Several resources exist that provide comprehensive guidance and instruction in how to conduct an assessment of stream habitat for restoration purposes. As discussed previously, a basic issue for stream habitat assessments lies in deciding the level of detail needed for a worthwhile yet cost-effective assessment. Approaches range from rapid assessment methods that involve reconnaissance-level surveys to more complex appraisals. Based on the Conducting Assessment section (3.2), a robust assessment should touch on the physical, chemical and biotic elements of habitat. In this synoptic introduction to assessment methodologies, some approaches collectively integrating these habitat elements are introduced here, and assessment resources that address individual habitat elements are introduced in the following subsections.

Despite their name, integrated approaches have foci that range from narrow to broad, so their use depends on project-specific needs. For example, the USGS National Water-Quality Assessment Program[17,18] characterizes stream habitat in an integrated physical, chemical, and biological context, but its goal is to relate these habitat factors specifically to describing water-quality conditions. Evaluation is based on a spatially hierarchical framework that incorporates habitat data at basin, segment, reach, and microhabitat scales. This framework provides a basis for consistency in collection techniques while allowing flexibility in assessment within individual study units. Procedures are described for collecting habitat data at basin and stream segment scales that encompass use of GIS databases, maps, and aerial photographs.

On the broader end of the spectrum are different iterations of watershed analysis, several of which were discussed in section 3.2.2. Watershed analysis is a procedure used to characterize the human, aquatic, riparian, and terrestrial features, conditions, processes, and interactions (collectively referred to as “ecosystem elements”) within a watershed.[19] One of its original uses was one of the principal analyses for implementing the Aquatic Conservation Strategy set forth in the Northwest Forest Plan.[20] In Washington State, its primary use has been to develop a forest practices plan for individual Watershed Administrative Units.[21] In general, a watershed analysis approach may be beyond what is needed for assessment on a restoration project, but many aspects of watershed analysis can be quite useful in restoration project assessment. The state of Oregon uses Watershed Assessment,[22] which is similar to watershed analysis.

A number of other excellent watershed-based integrative analysis approaches exist, but some are focused on specific targets, such as salmon and salmon habitat. Some good examples of the latter are the river basin analysis of the Skagit and Samish Basins that was developed by The Habitat Restoration and Protection Committee of the Skagit Watershed Council,[23] the ecosystem planning and recovery document developed for listed salmon by Beechie and colleagues,[24]and the ecosystem approach to salmonid conservation by Spence and colleagues.[25] If one chooses an integrative analysis for assessment, whether such an analysis assesses over a broad wildlife brush, is salmon-specific, or focuses on other stream-associated wildlife should be a primary consideration in assessment choice.

3.3.1.1 Physical Habitat Assessment

Similar to integrative assessment methods, methods that focus exclusively on assessment of the physical habitat exhibit a large range in complexity and cost. Rapid assessment methods, which involve reconnaissance level surveys (such as the habitat mapping approach) identifying, mapping and measuring key habitat features over long stretches of river in a relatively short space of time, are tools that have been developed by EPA[26]. Diverse intermediate levels of assessment also exist[27,28] and more complex appraisals, such as the Physical Habitat Simulation System (PHABSIM),[29] require more detailed data on microhabitat variation in flow.[30,31] A key aspect of assessing the physical habitat of streams is basing them on biologically meaningful features to enable a connection that aids evaluating the biological integrity of the stream (see section 3.3.1.3).

3.3.1.2 Chemical Habitat Assessment

Chemical habitat assessment of streams addresses diverse water quality parameters. Similar to other aspects of assessment, the detail with which chemical habitat assessments can be done varies enormously. The National Water-Quality Assessment Program (NWQAP)[32] provides an excellent structure to enable understanding the chemical and spatial diversity in stream sampling for diverse assessments. Discussed are sampling structures for what are termed Basic versus Intensive Sites. Basic Sites involve measurement of general water quality parameters (dissolved oxygen (DO), pH and alkalinity, specific conductance, and temperature), suspended sediments, and major constituents (dissolved solids, major ions and metals, nutrients, and organic carbon). In contrast, Intensive Sites, besides the water quality parameters measured at Basic Sites, include measurement of a diverse suite of contaminants (herbicides, pesticides, etc.), contaminant derivatives, and other compounds. The choice of what water quality parameters to measure will be project-specific and dependent on *a priori* knowledge of anticipated inputs to the stream, costs, and other conditions. For these reasons, the number of parameters measured at Basic Sites, the number of Basic Sites sampled, and whether or not measurement of any Intensive Sites are even used will also depend on the project. Lastly, a number of water quality parameters, such as temperature and dissolved oxygen, are temporally labile, so careful attention needs to be paid to what kind of temporal profile is needed to measure labile parameters.

3.3.1.3 Biological Habitat Assessment

Chemical habitat assessments are diverse, but approaches to biological habitat assessment are even more so, largely because of the combination of biotic diversity and its spatial complexity. The book edited by Rosenberg and Resh is a particularly useful tool.[33] Macroinvertebrates are favorite target biological habitat assessments in streams, in part because both their numbers and their diversity allow much better assessment resolution that any vertebrates and in part because they can be targeted even in streams lacking fishes. The approaches to sampling them for the purpose of biological assessments are diverse. Rapid assessment approaches for sampling macroinvertebrates are numerous as well,[34] and contrasts of the advantages and disadvantages of different rapid assessment methods have been done.[35] Also, the Washington Department of Ecology has an established protocol for macroinvertebrate assessment in rivers and streams.[36] Biological assessments using fish assemblages have been developed,[37] and can be useful under selected circumstances as long as sampling is spatially and temporally adequate. Using fish in biological assessments is often more costly that using macroinvertebrates and as indicated above, they cannot be used where fish are absent. Use of other groups, such as amphibians, may be useful under selected circumstances, but stream-associated amphibians have restricted distributions that prohibit their widespread use, and they suffer from many of the same problems as sampling fishes, often to a greater degree. Suggested Sources of Data and Information.

When conducting an assessment, always start with existing information and previous watershed assessments and inventories to avoid duplicating efforts. Most watersheds in Washington State have undergone previous assessment and restoration planning. However, the scope, scale, or quality of the assessment may be inadequate for some purposes. Considerable data may exist for many components of the assessment. Other components may require considerable original field data collection and data from remote sources. Be aware that the scale and scope of assessment is greatly influenced by the objectives of those conducting it. For instance, methods employed and data collected during a reach assessment that evaluates channel migration over time will differ from that collected during a reach assessment of available pool habitat, large wood, spawning redd counts, or dissolved oxygen levels. Assessments conducted at a site level will likely be highly project specific as site assessments are conducted primarily for the purpose of implementing a project.

Besides published assessments, a wealth of publicly available information exists that may be useful. These include, but are not limited to:

- Air photos
- GIS maps
- Satellite photos
- Historic records
- USGS stream gage and water quality data (also available from the Washington Department of Ecology)
- Landslide and unstable slope information (available from the Department of Natural Resources)
- Fish passage barrier data (available from WDFW)
- Reach-scale gradient and confinement data (available from the Northwest Indian Fisheries Commission and WDFW)
- Fish distribution maps and GIS data (available from the Northwest Indian Fisheries Commission and WDFW)
- Previous restoration efforts (from the Recreation and Conservation Office)
- Current conservation and restoration planning efforts (available from local government offices and Lead Entity organizations – see WDFW for a map of these resources)
- Literature search
- Priority habitat species maps (available from WDFW)
- Anecdotal information. Speak with local city, county, and agency experts (biologists, geomorphologists, historians, etc) and landowners

The quality of information directly influences its utility. Therefore, those conducting an assessment should consider the following factors before using such information:[9]

- Are the data relevant to the assessment question or issue being addressed?
- Are the data compatible with other relevant analyses?
- Are the data of an appropriate age?
- Are the data of sufficient quality?

Consider the accuracy, completeness, data collection, handling, and analysis methods prior to conducting assessments.

We strongly encourage those conducting watershed, reach, or site assessments to make the results of their work publicly available so that others may benefit and build upon them.

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CHAPTER 4

DEVELOPING A RESTORATION STRATEGY

Chapter 4. Developing A Restoration Strategy

Restoration of stream habitat refers to actions taken to enable physical and biological processes to operate free from artificial constraints[1] and to return the stream to a self-sustaining condition resembling conditions that existed prior to anthropogenic disturbance[2]. Restoration actions also commonly include enhancement - habitat creation or stabilization - where the full restoration of processes is not possible within acceptable timeframes. This chapter presents a process and considerations for development of a restoration strategy that accounts for varying spatial and temporal scales of impact, disturbance, and opportunities for recovery, and identifies a prioritization of key restoration strategies. The next Chapter (5) narrows the focus from a strategy level and the selection of component restoration techniques to development of designs for a set of specific restoration techniques to meet specific project objectives.

Stream ecosystems are dynamic in space and time; an effective strategy for restoration of stream habitat therefore requires consideration of the influence of past, current, and future events and activities on the processes that create and maintain habitat and access to that habitat. The natural variability of these processes through a watershed and over time is a critical consideration in development of a restoration strategy, and indeed, serves as a conceptual foundation for developing restoration strategies[3]. Considering the dynamic nature of the stream environment, these guidelines echo the recommendations of other researchers[4] [5] [6] [7] [8] when suggesting that stream ecosystem restoration activities focus less on recreating and maintaining specific instream habitat *forms,* and more on reestablishing the *processes* responsible for creating and maintaining natural patterns of habitat diversity, often by reducing or removing constraints to these processes.

The physical processes that shape and create habitat (refer to Chapter 2 of this guideline entitled *Stream Processes and Habitat*) act as a form of natural disturbance to the system, where disturbance refers to any degree of change and may occur at any scale. Habitat complexity is a result of interactions between natural disturbance events and natural succession. Regular disturbance sustains a dynamic network of habitat that is spatially and temporally diverse. Disturbance can occur as a rare catastrophic event, such as a volcanic eruption, or from more frequent seasonal events, such as from the periodic input of sediment from a steep cutbank or from seasonal flood events. Spatially, disturbance may occur on a local scale, impacting an individual pool, or on a larger reach or watershed scale. Restoration strategies should strive to provide sustainable long-term benefits to the stream ecosystem, not just a target species, by maintaining natural succession and disturbance regimes, which, in turn, support long-term habitat viability and biological diversity[9].

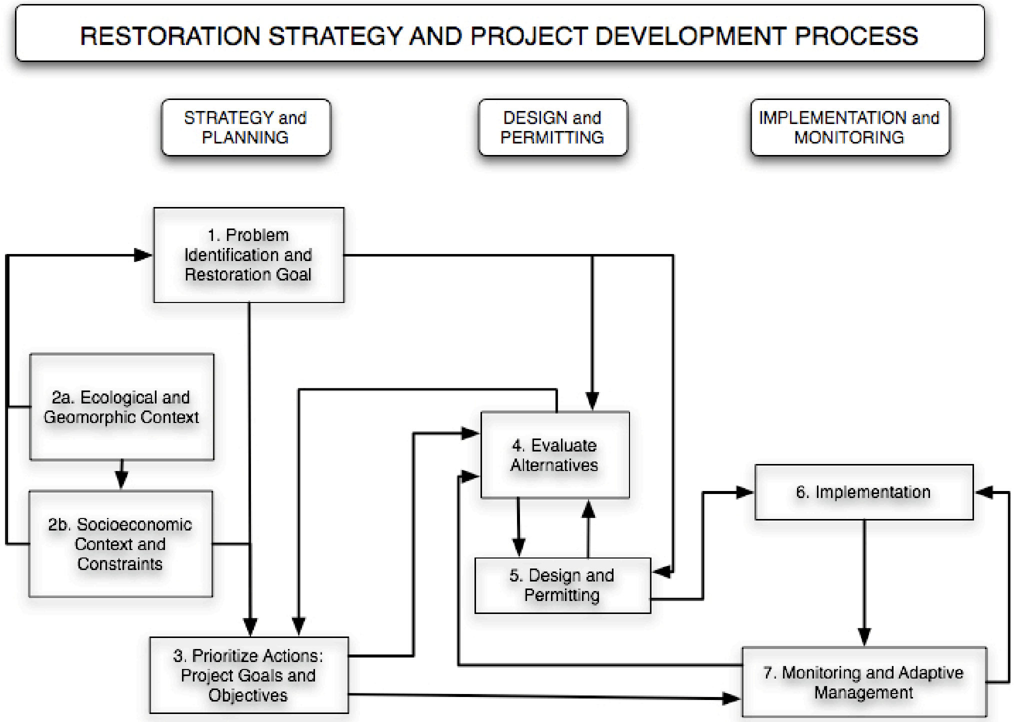
Restoration of stream ecosystems requires a coordinated and comprehensive strategy to reestablish and sustain the natural physical, chemical, and biological processes and interactions that have been compromised by human activities. Individual projects must be considered within the context of the overall restoration strategy, developed at a watershed scale, to ensure that their incremental gains will collectively achieve restoration goals. The reason for this is two-fold. First, aquatic and upland ecosystems are interconnected and interdependent; the varying processes and range of native species that comprise a functioning aquatic ecosystem cannot be reasonably or effectively treated separately. Further, the condition of wetlands, lakes, or streams reflects the cumulative effects of activities and events within their watersheds. Consequently, ecosystem recovery efforts will be most effective when implemented on a scale that encompasses the entire range of affected species and the full extent of activities that have led to their decline. The restoration strategy should take into account cumulative impacts to habitat abundance, quality, connectivity, and diversity on a watershed or other landscape scale appropriate to the affected plant and animal species.

Though the goal of restoration is to return stream processes to a close approximation of pre-disturbance conditions by addressing the root causes of degradation and constraints on processes that sustain habitat, circumstances may exist that preclude full recovery. Restoration strategy development must consider the various scales at which constraints such as existing infrastructure, invasive species, limited native species abundance and extinction, and past, current or future land use occur. Where impacts and constraints exist primarily as site- or reach-scale conditions, restoration strategies may include reconfiguration, removal, or avoidance of these constraints. However, where watershed-scale impacts and constraints affect restoration potential and are relatively irreversible, such as those associated with urban development or climatic change, restoration strategies may instead focus on adaptation to an altered watershed condition and enhancement of existing conditions and processes rather than return to pre-disturbance conditions.

Diverse approaches to development of a restoration strategy exist[10] [11] [12] [13] [14], all of which rely fundamentally on watershed assessment as the basis for determining restoration options in the context of land use and socio-economic constraints. The phases of restoration strategy and project development, depicted in Figure 1, include:

1. *Problem identification and restoration goal*. A restoration strategy is developed to achieve a restoration goal, ideally focused on addressing causes of the identified problem. Goals are defined by specific objectives - measurable outcomes that can also serve as the basis for effectiveness monitoring.
2. *Consideration of watershed context and constraints*. Root causes of the problem are identified through watershed assessment and inform selection of restoration strategies. Socioeconomic factors may impose constraints and define opportunities.
3. *Prioritization of restoration strategies*. A restoration strategy consists of coordinated and prioritized projects and actions, each with specific goals and specific objectives.
4. *Evaluate alternatives for specific projects.* Multi-disciplinary technical analyses are used to evaluate alternative approaches and techniques with respect to their capacity to meet project-specific objectives.
5. *Design and permitting projects.* Technical analyses are used to design and integrate project elements. Designs are adapted to meet permitting regulatory expectations and constraints.
6. *Implementation of projects.* Implementation is conducted according to plans and specifications.
7. *Monitoring and management.* Effectiveness monitoring evaluates restoration relative to specific objectives and guides adaptive management and communicates lessons learned.

Figure 1. Restoration strategy and project development process. The outcomes of Strategy and Planning are prioritized and coordinated restoration actions and projects with defined goals and measurable objectives. (Adapted from RiverRAT).



The outcome of the restoration planning process will typically consist of a general restoration goal and a strategy, or plan of action that includes a prioritized set of specific restoration actions and projects. For each specific action or project identified, project-specific goals and objectives are necessary to guide design, implementation, and monitoring of individual projects. Individual restoration projects are, therefore, components of a restoration strategy that prioritizes actions and projects within a watershed context. The restoration strategy development and planning process (Steps 1-3) is described in this chapter; design development, permitting, and approaches to restoration actions (Steps 4-6) are described in Chapter 5; monitoring and adaptive management (Step 7) is described in the *Monitoring* Appendix.

4.1 Problem Identification and the Restoration Goal

The call for stream restoration is often initiated when there is a compelling reason to address an observed problem, such as declining recruitment of native fish or deteriorating water quality. Articulating a problem is a subjective exercise. Lack of habitat, for example, is not inherently a problem unless you are a fish; flooding is not a problem unless human property is affected. From this subjective perspective, ‘problems’ can be characterized as limited or exacerbated conditions that affect the interests of native aquatic species or humans. Common problems that lead to a call for restoration include degradation of water quality, declining population, recruitment, or range of native species, and property loss or damage.

The *problem* should serve as the basis for defining restoration goals; the *root causes* of the problem should inform the selection of restoration strategies and actions. Differentiation of problems (conditions) from their root causes (processes) is critical to developing appropriate restoration strategies for two reasons: first, it is often unreasonable to expect problems not to recur if their causes have not been addressed; second, ecosystem processes are often inappropriately classified as problems when in fact they are within the natural range of variation, and therefore not inherently problems from an ecosystem perspective. Defining problems and root causes can be facilitated by two lines of questioning:

1. Problem definition: Ask “Why is it a problem and for whom?” For example, if a problem is initially articulated as loss of habitat diversity, this question will lead us from “For whom is loss of habitat diversity a problem?” to “How is this problem affecting that population?” to the ultimate problem – a declining population of native fish. Similarly, if a problem is initially articulated as excessive bank erosion, this question may lead us first to conclude that excessive sediment impacts habitat quality, and then to the ultimate problem – a declining aquatic community. Alternatively, similar questioning may reveal that, where data do not indicate that sediment is in fact affecting the aquatic community, the ultimate problem may be a human one – loss of property – rather than an ecological problem. Clarification of the ultimate problem may lead to differing restoration strategies and priorities.

2. Root causes: Ask “What is the cause of that?” and repeat the query for each subsequent explanation, until the ultimate *root* cause is derived. For example, considering the problem of a declining fishery each subsequent response may result in the sequence: a declining fishery may be attributed to degraded habitat; degraded habitat may be caused by channel incision; channel incision may be caused by increased magnitude and frequency of high flows; and increased frequency of high flows may be caused by urbanization. Urbanization, therefore, is the root cause. Alternatively, an incised channel may be the result of a change in channel slope, the root cause being channelization. Restoration strategies that are developed for any of the intermediate explanations may be limited in their success. Where restoration strategies cannot reasonably reverse the ultimate cause, they can be developed for intermediate causes with the understanding that not addressing root causes has limitations.

Exploring a series of queries about root causes reveals the significance of scale in assessing the relationship between problems and causes. The scale of an identified problem may be different than the scale of its root causes. The previous example illustrating different causes of incision indicates different scales of causes (watershed-scale urbanization versus reach-scale channelization), and therefore implies different restoration strategies. Rehabilitation measures that treat only the scale of the symptom of the problem (e.g. incision) and not scale of the cause (e.g. urbanization or channelization) may provide only short-term benefit. Addressing the root cause at an appropriate scale will ultimately provide a more sustainable and effective strategy. Identification of activities and events that lead to habitat constraints or degradation generally requires a thorough watershed assessment of impacts and changes to dependent and independent variables at varying scales (see Chapter 2 for discussion of variables and Chapter 3 of this guideline entitled *Stream Habitat Assessment*), unless the cause can be absolutely attributed to a specific activity on a more local scale. Examples of common causes of habitat problems are listed in Table 1.

Table 1. Example root causes of habitat loss or degradation at varying scales. Assessed or observed habitat loss or degradation can usually be attributed to disruption or constraint of processes that create and maintain habitat. Impacted processes can often be attributed to a root cause, which may occur at a site, reach or watershed scale. This table lists common root causes of impacts to the processes that in turn result in loss or degradation of stream habitat. Ideally, restoration actions are directed to addressing root causes to prevent additional or recurring habitat impact.

SCALE of IMPACT	IMPACT/CAUSE	PROCESS/VARIABLE AFFECTED
Watershed	urbanization	hydrology and sediment supply
	climate change	hydrology
	forestry and roads	hydrology and sediment supply
	agricultural conversion	hydrology and sediment supply
	dams and diversions	hydrology and sediment supply
Reach	channelization	slope and sediment transport
	levees	hydraulics and floodplain inundation
	snag removal	hydraulics, sediment transport and storage
	channel training and armoring	bank stability, hydraulics, sediment transport and storage
	riparian vegetation management/removal	bank stability, hydraulics, sediment transport, supply and storage
	infrastructure encroachment	bank stability, hydraulics, sediment transport and storage
	grazing and trampling	bank stability
Site	bank armoring	bank stability, hydraulics, sediment transport and storage
	Infrastructure, stream crossings, and building encroachment	bank stability, hydraulics, sediment transport and storage
	snag removal	hydraulics

Watershed-scale causes often impact independent variables of hydrologic regime and sediment regime. Root causes at this scale can profoundly affect stream habitat conditions throughout a watershed by upsetting the equilibrium between hydrologic and sediment variables and boundary conditions, resulting in channel instability and associated habitat degradation. Where restoration strategies cannot address causes at this scale, reach-scale strategies must account for changes in the independent variables that govern stream processes and associated habitat availability and character. Reach-scale root causes often affect boundary conditions (e.g. bank stability, substrate character, slope) and in-channel variables (e.g. hydraulics and sediment transport rates). One of the most common and problematic reach-scale impacts is the confining of a channel migration zone (e.g. levees) or a channel's ability to adjust (e.g. streambank protection), effectively constraining processes that create and sustain habitat through channel migration and associated riparian and in-stream habitat succession. Impacts to boundary conditions can upset equilibrium conditions and set in motion a series of channel adjustments and associated habitat degradation that may extend up- or down-stream. Site-scale causes are similar to reach-scale causes, but are limited in extent to a few habitat units.

4.1.1 Restoration Goals and Objectives

The goal of restoration is to remedy observed problems, ideally by addressing their root causes. Ideally, restoration goal statements should articulate desired outcomes and who or what benefits from those outcomes. Articulating a goal in the context of the subject of the identified problem can greatly facilitate development of restoration strategies. Consider the following two similar goal statements developed to address the problem of a declining fishery where habitat has been determined as a dominant limiting factor:

1. Restore the extent and diversity of aquatic habitat to pre-disturbance conditions.

2. Restore ecosystem processes that contribute to the recovery of native salmonids.

The first example goal addresses the problem of limited habitat. Strategies to address this problem may include a variety of habitat creation and enhancement techniques. However, the goal statement does not explicitly indicate that this is for the benefit of fisheries or any other aquatic species. As such, it is feasible to achieve the goal of restored habitat without any benefit to the fisheries - if the processes that create and maintain habitat are not in place, if the habitat is not adequately connected, or if habitat is otherwise unavailable to the fishery, the ultimate problem, and goal, of a diminished fishery will not be achieved. The second example goal statement articulates the problem and the goal in terms of the ultimate beneficiary – native species. Strategies developed to achieve this goal, therefore, will require consideration of all processes necessary for recovery, including those that create and maintain habitat.

Restoration goals are more likely to lead to success if they are developed with consideration of multiple perspectives. Restoration goals can be developed considering four models of experience or perspective[15]:

1. *Scientific model*: the scientific model is based on what is feasible ecologically and geomorphically; it is a rational model that relates cause to observed effect and establishes restoration strategies based primarily on what is possible.
2. *Social model*: the social model is based on what is acceptable socially; it relates what people, politicians, and agencies expect from restoration, which may or may not be scientifically tenable or sustainable, but needs to be considered in restoration planning. It also considers cultural expectations, public attitudes and awareness of environmental concerns, and whether people feel part of restoration.
3. *Economic model*: the economic model considers what is sensible economically; it has to do with the cost of a project and who pays for it, and also whether the local economy can accommodate restoration. Reversing degradation trends may require some degree of economic restructuring.
4. *Philosophical model*. The philosophical model considers what basic principles guide restoration priorities. Basic philosophies for prioritizing strategies may be founded on establishing the greatest gain in available habitat for species of concern, or may be primarily opportunistic, such as a willing landowner model, which seeks to maximize community participation above maximizing ecosystem recovery.

Goals are typically refined with ancillary objectives. Where goals may be to restore water quality or to re-establish normative sediment delivery and transport processes, objectives support and refine these goals, breaking them down into smaller steps. Objectives may define, for instance, which particular water quality parameters are to be targeted (e.g., temperature, turbidity, dissolved oxygen, fecal coliform), or which sediment supply processes are primarily responsible for excessive sediment loading to the stream (e.g., road-related mass wasting events, clear-cut-related mass wasting events, surface erosion off agricultural fields).

Objectives help to define the strategies and actions necessary to achieve a stated goal. Where goals may drive the selection of strategies and multiple projects, objectives may drive the actions of a single project or elements of a single project. Development of clear objectives is a critical step in ensuring that restoration goals are communicated among stakeholders. The following “S.M.A.R.T” criteria guide the development of restoration objectives:

1. **S**pecific – objectives are clear, concise statements that specify what you want to achieve.

2. **M**easurable – objectives use parameters that can be measured before and after project implementation.
3. **A**chievable – objectives are geomorphically and ecologically possible.
4. **R**elevant – objectives are clearly related to and support the project goal.
5. **T**ime-bound – objectives are bound by a specified time frame.

Of these, the ‘measurable’ and ‘time-bound’ criteria are essential for establishing monitoring and management strategies. Monitoring can be used to evaluate restoration effectiveness only if objectives articulate measurable outcomes and define when those outcomes are anticipated. Similarly, adaptive management can only be effective if objectives are clear enough to establish when restoration is diverging from its stated goal – which requires measurable outcomes and timeframes.

4.2 Watershed Context and Constraints - Factors to Consider in Developing Restoration Strategies

Stream habitat restoration will be most successful if restoration strategies are developed with consideration of the social, ecological, and physical watershed contexts that define opportunities and constraints for restoration. These contexts facilitate the prioritization and coordination of restoration actions within an overall restoration strategy.

4.2.1 Stakeholders

Successful restoration often requires involvement from numerous stakeholders early in the process of developing a restoration strategy. Stakeholders represent the various interest groups and may include all impacted, interested, and involved parties. Examples of typical stakeholders include:

- State and federal resource agencies, including permitting agencies,
- Local government,
- Landowners,
- Tribes,
- Community and related businesses,
- Hunters, anglers and other recreationists, and
- Environmental advocacy organizations.

Inclusion of stakeholders in developing a restoration strategy will help to identify opportunities and constraints in advance of selecting specific restoration actions, and thereby reduce the potential for unanticipated obstacles in the planning process. Each stakeholder brings to the table their own set of interests, which may or may not conform to the restoration goals. Early stakeholder involvement ensures that any concerns, negotiations, or major decisions can be addressed in a cost-effective and timely manner, especially since the cost of changing strategies or designs increases as details are developed. Stakeholder involvement may also yield restoration strategies and opportunities that address multiple interests and further expand restoration goals. Early involvement provides each stakeholder with a sense of ownership that helps to bolster community support and encourages donations of money, materials, and services to design, construct, monitor, and maintain restoration projects. The longer stakeholder involvement is delayed, the more likely the project will be rejected and design modifications will be required to proceed. Stakeholders may also indicate concerns regarding public safety of proposed actions, particularly where wood or other structures are included in strategies. While public safety concerns may at times conflict with restoration objectives, they nonetheless must be addressed in planning and design (see *Public Safety* Appendix for further discussion).

4.2.2 Ecological and Geomorphic Context

Habitat restoration, ideally, will result in conditions where natural geomorphic and ecological processes maintain habitat function and condition. However, "natural" processes must be viewed in the context of current and future land use within a watershed. Natural, in its purest sense (i.e. ecological and geomorphic conditions in the absence of significant human alteration), may be impossible to achieve given permanent or predicted landscape changes. Thus, strategies for achieving desired conditions must be considered within the context of constraints on the ecological and geomorphic processes.

Geomorphic context includes the consideration of the extent to which physical watershed and stream processes and the variables that govern these have been impacted, and whether these impacts are functionally reversible or not. Land use within a watershed affects both hydrologic and sediment regimes, the building blocks of stream processes. In significantly developed watersheds these impacts may be effectively irreversible, leading to permanent change in hydrologic and sediment regimes. In such circumstance, practical restoration strategies may be limited primarily to stabilization and enhancement efforts with long-term maintenance. While there may be opportunities to set back levees and infrastructure and to mitigate impacts to hydrologic regime through stormwater detention, these will likely not be sufficient to reverse cumulative impacts. When developing restoration strategies within watersheds that have been, or are in the process of being subjected to permanent or semi-permanent landscape change (such as urban development or widespread agricultural land use), achieving natural conditions may be limited to managing a channel system to promote natural process and function under the new hydrologic and sediment regime. Alternatively, where a watershed has been impacted primarily by agricultural conversion or forestry, and land ownership is concentrated among a few landowners, there may be opportunities to establish unconstrained stream corridors and manage land use to sufficiently reverse historical and cumulative impacts to geomorphic inputs and variables.

Ecological context refers to past, present, and future processes and conditions that characterize the interaction of organisms with each other and their environment, and includes primarily biological and environmental quality factors. Water quality issues can continue to limit progress toward a goal, even where physical habitat concerns have been adequately addressed. Likewise, impacts to nutrient or energy supply and transfer can affect all trophic levels regardless of physical conditions. One of the most profound and irreversible changes that may occur in an ecological context is the introduction of non-native species that may displace, compete with, or inter-breed with native aquatic and riparian species. The introduction of riparian species, such as Japanese knotweed or reed canarygrass, can greatly complicate restoration opportunities by constraining the potential for recovery of native riparian species that may be critical to ecological and geomorphic stream processes. Similarly, addressing competition or inter-breeding of non-native species may involve consideration of passage within a stream network; maintenance or creation of a passage barrier, while counterintuitive, may be an integral component of a recovery strategy for a native population.

Climate change represents an additional layer of geomorphic and ecological context, in that it is contributing to changes in watershed processes and species assemblages. Particularly where watersheds are transitional (e.g. between rain and snow-dominated zones) or where streams are near threshold conditions for certain aquatic species (e.g. near upper temperature limit for salmonids), climate change will likely impact both ecological and geomorphic variables. Climate change is discussed further in the *Climate Change* Appendix.

4.2.3 Considerations of Scale

Restoration strategies may consist of one or many restoration actions, or projects. Stream habitat restoration may be implemented at virtually any scale, ranging from removal of a single passage barrier to alteration of watershed-wide land use practices. Ideally, individual actions will be scaled to address root causes of identified problems at the appropriate scale. Site-specific disturbances may be remedied on small scales; systemic disequilibrium and watershed-scale causes of stream degradation generally require watershed-wide restoration activities to yield measurable benefits.

Many restoration endeavors require cumulative level of implementation before measurable benefits are realized. For instance, if livestock are fenced from the stream on one property, but continue to have unlimited access to the stream on a number of other properties, the resulting water quality improvement expected in response to the single treatment may be negligible. That is not to say that restoration activities to address large-scale problems must occur all at once to be effective. Even small improvements may be beneficial. Habitat improvements, like habitat impairments, are cumulative. Incremental improvements resulting from multiple small-scale projects over time can collectively achieve restoration goals. Additionally, pilot projects are often fruitful in demonstrating the efficacy of an approach and gaining acceptance among stakeholders.

Despite the value of incremental gains, the logistics of certain restoration activities require some threshold scale of application to be worthwhile. Where the scale of a restoration strategy is constrained by property ownership, jurisdictional boundaries, and funding limitations, these limitations must be weighed against the reduced potential for success that they impose. For example, if lack of willing landowner participation will limit a proposed levee setback or removal project to a few select or discontinuous properties, careful consideration must be given to whether such limited or disjunct application of the treatment will contribute to achieving project goals. Logistics may make it difficult to apply such a treatment on an incremental property-by-property basis as additional landowners choose to participate over time.

4.2.4 Timeframe for Recovery

Selection of restoration strategies must balance the urgency stated in restoration objectives and the practical limits of rates of ecosystem recovery. Strategies may include a combination of structural measures, intended to address urgent objectives, and actions that restore processes, intended to address sustained recovery objectives. Structural measures, such as reconstruction of channel form or addition of habitat features, are implemented to create immediate benefits, but generally provide only short-term benefit if they do not also address root causes. Actions that restore processes that create and maintain habitat benefits indefinitely are selected to provide long-term recovery goals, but may require years to decades or even centuries to produce measurable results. Oftentimes, passive restoration is all that is necessary for successful long-term ecosystem recovery and is generally less expensive and invasive than active restoration techniques that achieve the same goal. However, during the time lag between restoration activities and habitat recovery, opportunity to reestablish habitat function and value may be lost. Depending upon the urgency for realizing short-term benefits and the likelihood of the system to fully recover, planners may choose to implement a strategy that combines direct habitat creation techniques (providing relatively immediate, though possibly short-lived, benefits) with others whose benefits will be longer-lived but require years to be fully realized.

The development of restoration goals and objectives and selection of strategies will benefit from consideration of the time required for various restoration actions to generate intended results. In particular, legacy impacts such as splash damming, beaver removal, floodplain logging, and systemic snag removal, may have created conditions and constraints on processes that will require decades, or even centuries, to restore full habitat potential and biological productivity. For example, a century of removal of beaver and willow complexes in semi-arid regions to maximize floodplain agriculture has created conditions that will require decades for adequate recovery. The absence of expansive willow complexes limits the potential for beaver recruitment even with active reintroduction because of limited food. Moreover, absence of beavers may diminish the recovery potential of willow complexes, even with aggressive planting, if water tables are depressed due to lack of beaver dams and limited recharge of shallow aquifers exists. A combination of immediate actions, including riparian planting and beaver reintroduction, may be necessary to jump start the restoration trajectory and accelerate natural recruitment. Nonetheless, repeated efforts and long (decadal) time intervals may be required to fully recover processes, habitat value, and productivity associated with beaver-dominated semi-arid streams. Similarly, even with aggressive planting efforts, more humid stream systems that historically had old-growth conifer forests on the floodplain may benefit from addition of wood structures to stabilize the channel bed and provide habitat during the decades to centuries that may be necessary to restore their full habitat potential and biological productivity through natural processes.

4.2.5 Climate Change

Documented and projected rates of climate change suggest the importance of accounting for this change when selecting restoration strategies. However, accounting for change is difficult because predictions are uncertain, and incorporating uncertainty in restoration planning is problematic. Most predictions suggest that current trends are likely to continue or accelerate. Observed and predicted trends in the Pacific Northwest include warming of average annual temperatures and increased cool-season precipitation[16]. This is likely to lead to fundamental shifts in the hydrologic regime, including lower summer flows and shifts from snowmelt hydrologic regimes to rain-dominated hydrologic regimes. In coastal streams, restoration strategies must also consider the potential for climate change to affect sea level and associated tides.

This is significant in that sea level rise can change a stream's base level, leading to uncertain morphological response and channel adjustment. Climate change will likely impact[17]:

- Precipitation – annual average, inter-annual variability, seasonality, intensity and duration
- Vegetation and evapotranspiration
- Rainfall-runoff relationships
- Base level for sea level and lakes

In the face of this uncertainty, strategies to account for climate change in restoration emphasize resilience of channel processes, reducing or minimizing regulation or impacts to flow regimes, restoring habitat diversity, and adaptive management (refer to the *Climate Change* Appendix for further information). RiverRAT[1] offers the following guiding principles for accounting for climate change; refer to RiverRAT Appendix 2.4.1 for detailed discussion of these principles:

1. Remove as many artificial constraints as possible to allow the stream to respond to climate change through adjustments of all channel form dimensions and variables.
2. Provide additional space for morphological adjustment to lower risks to habitat, people, and property along the stream.
3. Redesign remaining artificial constraints within the channel (road crossings, grade control,

bank protection) to allow for future and unknown changes in flow and sediment regimes.
4. Implement monitoring to support adaptive management of climate change impacts as they occur.

4.3 Prioritization of Restoration Strategies

A restoration strategy is a plan of action for working toward a restoration goal. The selection of appropriate restoration strategies is informed by the previously described social, ecological, and physical watershed context and factors, and bounded by the extent of opportunities and constraints imposed by these factors. At a watershed scale, restoration efforts should focus first on projects that offer the greatest potential for success[18 6]. Roni et al.[8] suggests the following prioritization of stream habitat restoration strategies:

1. *Protect habitat*. Protect areas with healthy, high-quality habitat (strongholds, refugia, and key sub-watersheds) to prevent further degradation. Secure, expand, and link protected areas.
2. *Connect habitat*. Connect and provide access to isolated habitat, including instream, off-channel, and estuarine habitat made inaccessible by culverts, levees, or other man-made obstructions.
3. *Restore habitat-forming processes*. Employ land use recovery and watershed restoration techniques to restore processes that create, maintain, and connect habitats, including restoration of sediment dynamics, large wood dynamics, flow regimes, adequately sized healthy riparian zones, floodplain connectivity, water quality, and channel evolutionary processes. Employ a combination of passive and active restoration techniques, as necessary.
4. *Create or enhance habitat*. Modify or create stream habitat by such measures as installing instream structures, reconfiguring channel planform, cross-section or profile, or constructing a new side channel.

This prioritization lists strategies generally in order of their potential sustainability, effectiveness, cost-efficiency, and minimization of risk. Sustainability in this context refers to strategies that are self-maintaining and whose benefits persist indefinitely; effectiveness refers to the likelihood of providing desired habitat value; cost-efficiency refers to the relative cost of each strategy relative to outcomes; and risk refers to the potential for harming natural resources either as a collateral aspect of the restoration process or unintentionally, as resulting from project failure. The above approaches are not mutually exclusive. An actual restoration plan may include a combination of some or all four strategies in order to ensure that short- and long-term restoration and recovery goals are met. A similar listing of strategy attributes is listed in the ‘Project Impact Potential” factors described in the RiverRAT Screening Matrix[1.] The screening matrix is a mechanism to consider the potential for impact to the resource based on restoration actions and context, and suggests that the more active the action, the more risk is assumed by the ecosystem and the more carefully a project needs to be supported by detailed analysis and review. The prioritization of strategies is also roughly hierarchical, emphasizing first those strategies that focus on watershed-scale connectivity and habitat-forming processes, with site- or reach-scale enhancement strategies being secondary. A 2009 report of the reach-scale effectiveness monitoring of Washington Salmon Recovery Funding Board (SRFB) funded projects concluded that while the monitoring has been somewhat inconclusive in most biological measurements, reach-scale projects are generally showing some degree of success with respect to largely physical parameters measured[19]. The report emphasizes the effectiveness of fish passage and other channel connectivity efforts in particular, and recommends that these be combined with constrained channel projects. Monitoring of fish habitat enhancements has generally been inconclusive, presumably due to monitoring constraints.

The focus of the following sections is on identification of appropriate strategies given watershed context, opportunity, and addressing anthropogenic (human-made) root causes of stream and habitat degradation. For each strategy, associated specific stream habitat restoration techniques are suggested for consideration. These techniques are broad suggestions and are not intended to dictate a particular approach. Rather, they are intended to provide a palate of alternatives to the designer that need evaluation in a site-specific context. Specific projects contributing to a strategy may include a combination of techniques to fully address restoration goals and objectives. Details of select techniques are described in Chapter 5 of this guideline entitled *Designing and Implementing Stream Habitat Restoration Techniques*. Because the combination of socio-economic, ecological, and geomorphic conditions and variety of impacts and constraints is unique to each watershed, no cookbook or clear path exists establishing specific habitat restoration strategies and associated techniques.

4.4 Habitat Protection

Protection of relatively intact, functioning ecosystems is a far more cost-effective approach to conserving the integrity of biological communities than restoring an ecosystem after it has been degraded. Considering the mixed success of past recovery efforts and the limited knowledge and understanding of interactions among physical, chemical, and biological processes, protection also offers a greater chance of success[18] and may be comparatively easier to implement. Habitat protection helps to conserve biodiversity, reference conditions, and a source of locally derived native plants, fish, and wildlife to re-colonize nearby restored areas.

Doppelt et al.[18] suggest that priority for protection be given to:

1. Remaining healthy key biotic refuges, benchmark watersheds, floodplains, and riparian areas. Refuges are discrete ecologically intact areas that support biodiversity; larger refugia may encompass an entire watershed. Biological hotspots are smaller in scale and typically consist of isolated patches of relatively undisturbed habitat. Benchmark watersheds are remaining undisturbed watersheds. They represent ecosystem potential and can be used to establish restoration goals and measure restoration effectiveness.
2. Other biological hotspots that provide critical habitat for certain life stages of biodiversity or that control dominant physical, chemical, or biological processes.
3. Potential biological hotspots in close proximity to existing biotic refuges and hotspots that may be rapidly colonized as conditions become suitable following restoration activities.

Protection strategies may be adopted at any scale. However, because watershed-scale protection is generally impractical, the most pragmatic scale, is reach-scale protection of floodplains, riparian corridors, and channel migration zones (CMZs). CMZ and floodplain protection is critically important in developing basins where continual social pressure exists to develop within floodplains, and where development leads to constraints on stream processes. Protection of a river corridor and the associated riparian vegetation community promotes resilience by providing the stream sufficient room to adjust to disturbance, whether natural or anthropogenic.

Protection often takes the form of land acquisition; however, it may also include such measures as conservation easements, zoning, or other land use policies and regulations, particularly those that pertain to floodplains. Further detail on techniques to protect land and water supply are provided in the *Dedicating Land and Water* technique (Chapter 5).

Protection also goes beyond preventing or limiting potentially destructive activities on protected areas; management measures (such as prescribed fires or invasive weed control) may be necessary to maintain ecosystem structure and function. It will also be necessary to reduce or eliminate threats to ecosystem integrity caused by past, current, and future activities both inside and outside the protected area. Such measures may include repairing or eliminating unstable road crossings, reforesting unstable slopes, and implementing best management practices for stormwater management and construction. Once the integrity of the protected areas is secure, restoration activities should focus on improving the condition of land between protected areas in order to effectively connect them.

4.5 Restoring Habitat Connectivity

Connectivity within a stream system refers to "the flow, exchange, and pathways that move organisms, energy, and matter through these systems"[20]. Survival of a species depends on the existence of, and access to, its reproductive, feeding, and refuge habitats. Habitat requirements vary among aquatic species and among life stages of individual species; seasonal use of different habitats is common. Therefore, connectivity among habitats is essential. The movement of organisms, energy, and matter may occur in three physical dimensions: longitudinally (up- or downstream), laterally (between the channel, floodplain, and adjacent upland areas), or vertically (into and out of the substrate). Fish passage is a common and specific objective for many projects focusing on connectivity.

Connectivity may be limited by biological (e.g., invasive species, extinction of species), chemical (e.g., water quality), or physical barriers (e.g., culvert). This section focuses on physical barriers to habitat connectivity. Physical barriers to the movement of organisms are typically classified as complete, temporal, or partial. Complete barriers block the movement of the entire population of an organism all of the time; temporal barriers block the movement of the entire population of an organism some of the time; partial barriers block only the smaller or weaker individuals of a population all of the time, limiting the genetic diversity that is essential to support a robust population[21].

Reduced connectivity results in habitat fragmentation that reduces large expanses of habitat into a matrix of small, disconnected refugia. As patches of undisturbed areas become smaller and more isolated, the amount of "fringe" habitat (the interface between interior habitat and the outside world) increases relative to that of "interior" habitat. The exposure to non-native plant and animal species also increases, along with the proximity between adjacent patches. As a result, fish and wildlife traveling between patches of less altered habitat are subject to greater exposure to predators and other hazards (e.g., roads). Habitat fragmentation favors those species requiring a relatively small range to meet their needs and opportunistic species capable of adapting to the new environment. Sensitive interior species will be most affected by habitat fragmentation.

Strategies to restore habitat connectivity should focus first on root causes of disconnection and should be conducted at appropriate scales. For example, where an in-channel structure creates a fish passage barrier, a site-scale strategy (i.e. removing or reconfiguring the structure) will likely be adequate. Similarly, where connectivity is impaired at a reach-scale (e.g. due to channelization that eliminates velocity refuge for upstream fish migration), a reach-scale strategy will be necessary. And lastly, habitat disconnection related to a watershed-scale impact, such as low instream flows caused by numerous upstream irrigation diversions, may require a watershed-scale strategy to repair.

Besides restoring connectivity, consideration is given to the condition and quantity of the disconnected habitat. Priority should be given to restoration of connections to abundant, high-quality, and sustainable habitat. Where disconnected habitat is degraded or only provides very limited additional capacity, then restoring connectivity may be of little value unless habitat restoration or restoration of habitat processes is integrated in the restoration strategy.

Table 2, while not exhaustive, suggests techniques that may be appropriate for restoring connectivity given common physical barriers and constraints. Additionally, the *Fish Passage Restoration Technique* and the *Design of Road Culverts for Fish Passage Guidelines*[21] provide detailed information and considerations for channel and structure design to facilitate fish passage.

Table 2. Selection of techniques to restore connectivity of habitats, based on causes of impacts. Causes and solutions presented are not exhaustive, but provide examples of techniques to consider in addressing causes at varying scales. Causes listed are not necessarily root causes. For example, channel incision* may impact habitat and connectivity, but typically has a root cause of either channelization or watershed-scale change to sediment or hydrologic regimes.

Impact/Cause*	Scale of Impact	Connectivity Dimension	Solution	Restoration Technique
Diversions or other weirs	Site	Longitudinal	Removal or reconfiguration of structure	Instream structures; Channel modification, Fish passage, Dedicating Land and Water
Culverts	Site	Longitudinal	Removal or reconfiguration of structure	Instream structures; Channel modification; Channel profile, Fish passage
Dams	Site; reach	Longitudinal	Removal or reconfiguration of structure; install fish ladder	Instream structures; Channel modification, Fish passage
Tide gates	Site	Longitudinal, Lateral	Removal or reconfiguration of structure	Fish passage
Levees	Reach	Longitudinal, Lateral	Levee removal, breach levees	Floodplain and Channel Migration Zone Restoration; Floodplain fencing, Riparian restoration; Dedicating land
Floodplain fill	Reach	Longitudinal, Lateral	Remove fill, Riparian revegetation	Channel modification; Side channels; Riparian restoration; Dedicating land
Channelization	Reach	Longitudinal, Lateral, Vertical	Reconfigure the channel; raise channel bed	Channel modification; Instream structures; Channel profile; Dedicating land
Channel incision*	Reach	Longitudinal, Lateral, Vertical	Reconfigure the channel; raise channel bed	Channel modification; Instream structures; Channel profile;

				Dedicating land
Bank stabilization	Reach	Lateral, Vertical	Remove stabilization features; reconfigure channel and banks, riparian revegetation	See Integrated Streambank Protection Guidelines; Channel modification; Riparian restoration; Dedicating land
Hydrologic or Sediment regime	Watershed	Longitudinal, Lateral, Vertical	Restore regime, reconfigure channel, stabilize channel	Channel modification; Instream structures; Channel profile; Dedicating land

4.6 Restoring Habitat-Forming Processes

The third priority for habitat restoration strategies, following protection and connection of existing habitats, is the restoration of habitat-forming processes. Habitat is an outcome of a hierarchical set of inputs, processes, and variables – sustainable habitat restoration therefore requires restoration of the inputs, processes and variables that create and maintain habitat [1]. Habitat consists of physical, energy, and water quality elements. While the following sections emphasize strategies to restore physical processes, strategies for restoration of energy and water quality processes are also discussed. Restoration of degraded habitat requires that the root cause of degradation be identified and addressed at appropriate scales if the treatment is to provide long-term, sustainable results[6,7].

At the watershed scale, processes are governed primarily by the sediment regime and the hydrologic regime (Chapter 2, Hydrology and Sediment appendices), consequently, restoration strategies may focus on restoring or modifying sediment inputs and the hydrologic regime. In instances where land-use and development patterns at the watershed scale preclude significant reversal of impacts to the sediment and hydrologic regime, such as in the case of wide-scale agricultural conversion of historic forestland or urbanization, it may be practically impossible to restore the character of the regimes that drove channel processes. In this case, alternatives are to adapt the channel, or allow the channel to adapt, to new sediment and hydrologic regime, or alternatively to adopt a strategy of “managed inputs”. Restoring hydrologic regime, sediment regime, and managed inputs are described in following sections.

Two common expressions of impacted sediment and hydrologic regimes are incised channels and aggrading channels (refer to Chapter 2, the Geomorphology Appendix, and to RiverRAT Section 2-6.3, Channel Incision and Evolution). Determining an appropriate strategy to address incised or aggrading channels will require detailed watershed-scale assessment, supplemented with reach-scale sediment transport analyses to establish cause-and-effect relationships. While incision and aggradation are generally indicative of fundamental changes in watershed inputs, these changes may result from natural changes in watershed condition (such as due to volcanic eruption, major landslide, loss of glaciers in headwaters, or extensive fire alteration of vegetation) or may be the result of direct or indirect human impacts that affect hydrologic or sediment processes. Incised and aggrading reaches may warrant reach-scale restoration strategies in addition to restoration of hydrologic and sediment inputs, or where restoration of these inputs is impractical. Strategies for addressing incised and aggrading channels are also described in following sections.

At the reach scale, habitat-forming processes are governed by boundary conditions – the soils, vegetation, floodplain, and geological conditions within which dynamic channel processes and disturbances create and maintain habitat. Beaver can also be a dominant influence on boundary conditions. The processes of erosion and deposition are moderated or accelerated by the character of boundary conditions. Impacts to these boundary conditions, such as by vegetation removal or alteration, stabilization of the bed or banks, levee encroachment, or through other channel modifications that alter channel conditions can often be addressed at a reach scale. Restoration of floodplains is a critically overlooked and underemphasized restoration strategy, and often more important than channel restoration. Emphasis should be given to floodplain processes – restoration of floodplain connectivity, floodplain revegetation, and floodplain roughness – as an alternative to or supplement to channel restoration strategies. In alluvial systems, efforts to stabilize or restore stream channels may provide only short-term benefits where floodplain processes have not also been restored or reconnected.

Restoration strategies for restoring habitat-forming processes may be largely passive, or may require more active measures. Passive measures include activities such as implementing best management practices (BMPs) to reduce stormwater runoff from urban areas, improve water quality, or reduce water withdrawals from a stream for irrigation, drinking water, or other purposes; modifying the rate and timing of water released from dams; reduce erosion from construction sites, agricultural fields, and timber harvest areas; or stopping livestock grazing in the riparian zone. In systems with a potential for rapid natural recovery, passive restoration alone may be sufficient to reach long-term restoration goals. However, if recovery is unlikely to occur within the desired timeframe as a result of passive restoration efforts, or if the system is so badly degraded it cannot recover on its own, active restoration measures that accelerate the natural recovery of habitat-forming processes or stabilize degradation trends should be considered.

4.6.1 Sediment Supply and Transport

Sediment supply is described in Chapter 2 as one of two watershed-scale dominant factors (hydrologic regime being the second) forming stream channels and associated habitat. Sediment makes up an important element of stream habitat (e.g. spawning gravel, pools, bars) and moderates the supply and transfer of water, energy and nutrients to floodplains and through hyporheic exchange. Disruptions to sediment supply can profoundly disrupt the processes governing formation and sustainability of stream habitat, channel stability and water quality. Restoring sediment supply may be a critical element to the restoration of stream habitat and to establishing processes that create and maintain stream habitat. An understanding of sources of sediment and sediment transport and associated assessment and analytical methods is essential for developing strategies for sediment supply restoration. The role of sediment, sources and forms of sediment, and mechanisms for sediment transport are detailed in Chapter 2 and the Fluvial Geomorphology and Sediment Transport appendices.

Watershed-scale sediment supply impacts include any activities that affect the delivery of sediment from uplands to the channel. Activities that alter soil structure, vegetation, or topography often increase the delivery of fine and coarse sediments to streams. Such activities include road construction, maintenance, and use; livestock grazing; placer mining; urbanization; agriculture; timber harvest; and general land clearing. Increases in sediment supplied to a stream may be chronic, via accelerated rates of surface erosion, and/or abrupt, via mass wasting events. Refer to Chapter 3, Stream Habitat Assessment, for methods of determining impacts leading to changes in sediment supply or sediment transport capacity. Conversely, watershed-scale actions may also contribute to a reduction in sediment supply, such as by paving or other armoring of upland or in-channel sediment sources, or from a dam, which can prevent all downstream sediment transfer. Reduced sediment supply may ‘starve’ a channel of sediment, leading to channel degradation, widening, incision and loss of fine-sediment delivery and associated nutrients to floodplains and other off-channel aquatic and terrestrial habitats.

Watershed-scale activities and impacts may also affect the sediment transport capacity, primarily by affecting the hydrologic regime and associated stream energy that in part determines sediment transport capacity. Watershed-scale impacts, such as increases in peak flows associated with urbanization, can cause increases in sediment transport capacity, leading to channel incision or widening and associated loss of habitat, impacts to water table, riparian vegetation, and channel stability.

At the reach-scale, impacts to sediment supply may be caused either by alterations to sediment supply from the channel bed and banks, or sediment transport capacity. Reach-scale actions that may limit sediment supply include primarily armoring of the channel bed or banks that reduce natural recruitment of sediment from within the channel and floodplain or installation of structures that impede sediment transport by creating sediment traps (refer to Sediment Transport and Hydraulics appendices for further information). Reach-scale actions that may increase sediment supply include primarily the removal or alteration of stabilizing riparian vegetation that may increase recruitment of sediment from channel banks. Actions that alter sediment transport capacity may include channel alterations that change the cross-section, roughness, or slope of the channel and thereby affect stream energy at the reach level. Generally, any actions that increase stream energy may lead to increases in transport capacity and associated channel degradation or incision; actions that reduce stream energy may lead to decreases in transport capacity and associated channel aggradation.

The most effective long-term solution to restoring impacts to stream sediment supply must address the cause of altered supply at an appropriate scale (i.e., watershed-scale impacts may require watershed-scale strategies). Solutions must also consider the sediment transfer dynamics inherent in a given stream type. For example, stream channels on alluvial fans or in braided stream channels are inherently defined by aggradation processes, where sediment supply exceeds transport capacity, and therefore may not warrant efforts to reduce or contain sediment deposition. In contrast, alluvial systems characterized by channels that migrate through floodplains are defined by a balance between sediment supply and sediment transport, and therefore may warrant efforts to restore a balance between supply and transport by restoring supply rates, or by transport rates, or both. Restoration of sediment supply and transport processes is a complex undertaking and will require careful watershed- and reach-scale assessment of supply and transport processes and rates. Because of the complex of variables influencing sediment supply and transport, it is impractical to offer a solution to every possible impact. However, where clear relationship between cause and effect can be determined, certain strategies can be applied.
Examples of strategies to address sediment related causes of habitat concerns are provided in Table 3.

Table 3. Examples of strategies and techniques to address general sediment-supply or transport problems and causes

Problem	Causes	Strategy	Relevant techniques
Watershed-scale problems, causes and strategies			
Excess sediment	Forestry, agricultural practices	Upland forestry or agricultural BMPs to stabilize soils and reduce runoff	Riparian Restoration, Dedicating land.
	Systemic instability	Sediment detention basin, No action	Sediment detention basin; Dedicating land
Decreased sediment; increased transport	Urbanization; Dams	Channel stabilization to check incision; channel modification to balance transport with supply; Dam removal; sediment augmentation	Instream structures; Large wood; Channel modification; Spawning gravel; Beaver reintroduction; Dedicating land
Reach-scale problems, causes, and strategies			
Excess sediment	Riparian vegetation impacts	Revegetation; land-use BMPs	Riparian restoration; Dedicating land
	Channel incision	Stabilize channel and banks; Reconfigure channel	Riparian restoration; Channel modification; Instream structures; Dedicating land and water
Decreased sediment; increased transport	Bank armoring; Channelization	Remove armoring and channel constraints; Reconfigure channel and banks; restore channel roughness	Riparian restoration; Channel modification; Instream structures; Beaver reintroduction; Dedicating land

4.7 Flow Regime

The flow regime refers to the characteristic seasonal and inter-annual variation of volume and timing of stream flow (see also Chapter 2). Stream flow provides the energy that drives stream ecosystem processes, including the creation and maintenance of habitat and provides the energy to transport and distribute water, sediment, organic material, nutrients, and thermal energy within the stream corridor[22]. Together with sediment supply, the flow regime is the dominant watershed-scale factor governing the formation of stream channels and associated habitat. Flow regime is commonly characterized using flow statistics including magnitude, frequency, timing, and duration of flows (refer to the *Hydrology* Appendix for further description and methods for analyzing flow regime). Despite its importance as a dominant variable that influences habitat-forming processes, flow regime restoration is one of the most neglected aspects of stream restoration[5].

Besides in-channel flow, the flow regime influences the water level of nearby groundwater and surface water bodies (such as wetlands, lakes, and ponds) and dictates the frequency, extent, and duration of floodplain inundation. These, in turn, influence the distribution and composition of riparian vegetation and wildlife, and the exchange of nutrients, water, sediment, vegetation, contaminants, organisms, and organic material between the floodplain and the stream. High flows transport sediment, control vegetation encroachment into the active channel, and influence the structural stability of streambanks. They also contribute to the disturbance regime of a stream serving as a mechanism for creating and maintaining diverse aquatic floodplain, and riparian habitat [20] [23].

Flow also determines the amount of available aquatic habitat for a given point in the channel over time. At its simplest, aquatic habitat is living space or volume; habitat volume generally increases with flow volume. However, the quality of living space (or spawning or incubation space) is determined by other flow-related factors, such as depth, velocity, cover, bottom material (substrate), and water quality[20]. Despite the variability of streamflow during the course of a year, the seasonal timing of high and low flows (i.e., the flow regime) may be quite predictable. Native fish and wildlife have adapted to, and in some cases are dependent on, the natural flow regime to provide them access to suitable feeding, reproduction, and refuge habitat, and to serve as a cue for breeding or other features in their life cycle. For instance, the timing of returning salmon to western Washington streams in the fall coincides with the start of the rainy season. The fall freshets are necessary in some streams to provide the salmon passage to their spawning grounds. Streamflow controls the movement of fish and aquatic wildlife up and down the stream corridor, and between the floodplain and the stream.

Alterations to a stream's flow regime, usually associated with development or other land use change or by flow regulation (dams), can lead to altered flow regimes that effectively increase stream energy and sediment transport, leading to incision, excessive bank erosion, or other channel stability disturbances that can greatly affect the quality or quantity of available habitat. Increased flows can also flush fish, wood, food, and substrate out of a reach. Flow regime can also be affected by the withdrawal of water for municipal, industrial, or agricultural use. Depleted stream flow can increase fish vulnerability to predators, heighten competition for food, and may dewater redds or cause stranding. In addition, low flows during warm weather often lead to warmer water temperatures and reduced oxygen levels, potential contributors to increased fish mortality[24]. Low flows during cold weather can lead to freezing, which can kill eggs in the gravel, depending on conditions. For a more thorough review of the importance of streamflow in the context of stream ecology, refer to *Instream Flows for Riverine Resource Stewardship*[20] or to RiverRAT Section 2-3.2.7, Anthropogenic impacts on flow regime[1].

The relationship of stream flow to channel condition and channel habitat can also be affected at the reach-scale, even when the flow regime (timing and volume of flow input to the channel) has not been affected. Channel modification (changes to width, depth, slope or roughness) or any modification to floodplains, including levees, can alter stream energy by confining or dispersing flow. Even where the flow regime has not been affected at a watershed scale, physical changes to the channel or floodplain can result in changes in stream energy. Channel and floodplain modifications can also affect infiltration rates and consequently aquifer recharge rates, which may affect base flow conditions. Historical or ongoing removal of beavers, wood jams, and other natural features that attenuate flows can also affect stream energy and aquifer recharge.

Because flow regime is the dominant variable influencing stream channel type and character, habitat restoration strategies at any scale must consider the flow regime and changes to flow regime as a possible explanation for degraded conditions. Where flow regime has been altered, habitat restoration efforts may provide little value or fail if the altered flow regime has not been addressed. Strategies to address altered flow regimes should focus first on addressing root causes. With the exception of flow regulation of dams, root causes of alterations in stream flow regimes are the result of cumulative impacts to the watershed. Therefore, restoration of stream flow generally requires a watershed-scale land restoration and management strategy. In highly urbanized areas and in stream reaches with water regulated by active dams, it may be impossible to restore the flow regime to pre-disturbance conditions. However, strategies can be employed to reduce the impacts of existing infrastructure and to minimize or eliminate the impacts of future development. Restoration strategies may include changes to watershed land use and management, changes to flow management from dams, retrofitting of storm flow management to moderate runoff in urbanized or developing watersheds, or changes to off-channel diversions.

Where addressing root causes is impossible or impractical, or where channels have been drastically de-stabilized due to flow regime change, reach-scale channel stabilization or reconfiguration will likely be necessary to check any further degradation and to create a channel type that is more appropriate for the 'new' flow regime. Similarly, where changes to flow conditions are primarily the result of reach-scale changes to channel or floodplain condition, reach-scale strategies may be appropriate. Because the variables influencing flow regime and channel response to changes in regime are so complex, it is impractical to outline restoration strategies for every conceivable impact. However, where a clear relationship between impacts to flow regime and channel or habitat effects can be determined through watershed and hydrologic assessment, restoration strategies can be selected. Examples are provided in Table 4.

Table 4. Examples of strategies and techniques to address general flow regime problems and causes

Problem	Causes	Strategy	Relevant techniques
Watershed-scale problems, causes and strategies			
Increased flow and stream energy	Development, urbanization	Stormwater and runoff management; Channel stabilization and enhancement	Instream structures; Large wood; Bank protection
	Land conversion	Land use BMPs, Riparian buffers; Channel stabilization and enhancement	Instream structures; Large wood; Bank protection; Dedicating land
Increased flow variability	Development; urbanization	Stormwater and runoff management; Channel stabilization and enhancement	Instream structures; Large wood; Bank protection; Dedicating land and water
Depleted low flow	Diversions, dams	Flow regulation management; Dam or diversion removal or retrofit	Channel modification
	Reduced recharge from beaver removal, other floodplain modification	Beaver restoration; Levee removal; Floodplain restoration	Channel modification; Levee modification; Beaver reintroduction; Riparian restoration; Dedicating land and water
	Aggradation	See Table 7 - Strategies to address aggradation	See Table 7
Decreased high flows (effective discharge)	Dams	Dam removal, retrofit, or flow management	Channel modification, Dedicating land and water
Reach-scale problems, causes and strategies			
Increased flow and stream energy	Levees, confined or modified channel	Levee removal or breach; Channel restoration; Floodplain restoration	Channel modification; Floodplain and CMZ Restoration; Riparian restoration; Dedicating land

4.7.1 Managed Inputs – Gravel, Wood, and Nutrients

Instances may exist where inputs to processes that are essential to ecosystem health have been disrupted or disconnected and cannot recover to pre-disturbance levels within reasonable timeframes. Where inputs to processes may require years to decades to be restored, these processes may be artificially augmented through a deliberate, managed input of material to the stream.

Commonly applied strategies include supplemental input of sediment, wood, or nutrients to the stream. Instream flow requirements (e.g. spring floods or minimum instream flows) can also be considered as deliberate managed inputs, but are not explicitly discussed in this guideline. In these guidelines, supplementation is defined as the input of materials to a channel without specialized or secured placement.

Material supplementation in alluvial streams generally relies on flow events to distribute materials through the channel and floodplain; in colluvium dominated streams material is contributed and distributed primarily from mass wasting events. This strategy, therefore, requires careful consideration of the stream type and character and impacts to the flow regime and any changes in channel and floodplain conditions, including the timing and probability of flow events necessary to distribute materials. This strategy, therefore, requires careful consideration of the character and impacts to the flow regime and any changes in channel and floodplain conditions, including the timing and probability of flow events necessary to distribute materials. It may take weeks, months, or years before benefits are realized, depending on the magnitude and timing of flows. As hydrology is difficult to predict, the timing, extent, and longevity of material distribution is also difficult to predict. A risk of unintended consequences also exists if material is deposited or forms jams where it compromises infrastructure, property, public safety, or existing valuable habitat (refer to *Public Safety* Appendix).

Sustained benefits to fish and wildlife from a managed inputs approach can only be achieved through periodic re-application for as long as the natural supply and delivery of material to the system is constrained. In some instances, supplementation may require a substantial commitment of resources to achieve the desired result in both the short- and long-term, especially in instances where the disturbed processes will likely never be restored. Examples of strategies to address common inputs' constraints on channel and floodplain processes are provided in Table 5.

Table 5. Examples of strategies to address deficient inputs* to stream processes.

Problem	Causes	Strategy	Relevant Techniques
Sediment starved	Dams	Dam removal; Sediment augmentation for small streams	Channel modification, Dedicating land and Water
	Channel armoring	Channel re-naturalization; Sediment augmentation for small streams; Dedicating land	Channel modification, Dedicating land and water
Marine-derived nutrients	Passage barrier	Fish passage restoration (Barrier removal or passage); -Nutrient supplementation	Fish passage (AHG)
Large wood starved	Riparian logging; Channel armoring; Dams/impoundments	Riparian restoration; Channel modifications; Large wood inputs; Dedicating land	Riparian revegetation, Channel modification, Large Wood, Dedicating land and water

* Input deficiency may occur at any scale.

4.7.2 Incised Channels

Channel incision is the progressive lowering of the channel bed relative to its floodplain elevation. Incised channels are transitional forms between one dynamic equilibrium channel form and another[25]. Through typical geomorphic evolution, incised channels commonly expand laterally as they form a floodplain relative to the incised channel elevation. Incision and associated expansion results in the erosion of the bed and banks, the delivery of considerable quantities of sediment to downstream reaches, dewatering of the riparian zone[26], destruction or degradation of existing aquatic habitat[27], and the undermining of infrastructure such as bridges and utility crossings.

Tributaries to incised channels may also incise (i.e., 'headcut') as they adjust to the lower base level of the main channel. This process can propagate long distances upstream and upslope, extending throughout the drainage network. Channel incision processes are further detailed in Chapter 2, the Geomorphology Appendix and in RiverRAT Section 2-6.3, Channel Incision and Evolution, which describes common indicators and management strategies for incised channels. RiverRAT Appendix1.2

– Geomorphic Analyses also lists common indicators of incision.

Channel incision is typically initiated by either a change in the balance of sediment transport leading to erosion of the channel bed, or due to lowering of base level. An increase in channel bed erosion can be caused by a decrease in sediment, such as downstream of a dam, removal of natural or artificial stabilizing features (i.e. wood jams, culverts), or an increase in stream energy, which can result from a change in hydrology (urbanization increasing frequency and magnitude of flows) or a change in channel conditions (i.e. an increase in slope, decrease in roughness, or change in channel dimensions). Causes of incision may occur at watershed or reach-scales. Reach scale channel incision is generally initiated by the removal of grade control, roughness elements (including large wood), or channelization. Watershed scale channel incision may result from intrinsic factors, such as the evolution of the valley slope and geology, or extrinsic factors, such as a change in hydrologic or sediment regime or base level change.

Assessment of incision should first determine whether incision is active or whether a new and equilibrium grade has been attained, and second, whether incision is the result of human impacts or part of a natural channel evolution. The assessment of human impacts assessment can be complicated by legacy human impacts that may have caused or contributed to channel incision many decades previously, but which are no longer obvious. For example, historic and systematic removal of beavers and dams, particularly from arid systems in Washington, is believed to have contributed to widespread channel incision[28, 29]. Similarly, the practice of splash damming over a century ago effectively wiped out channel grade control provided by pervasive log jams in forested watersheds. Where incision is determined to be largely a natural phenomenon, it may be appropriate to allow the process to play out without intervention. Objections to allowing natural stream evolution to bring about equilibrium include the length of time required to reach equilibrium (considered to be on the order of decades[30]) and the increase in width necessary for the reestablishment of a functioning channel at the new elevation. Many situations exist in which allowing the channel to evolve to a new equilibrium creates unacceptable risks to property, infrastructure, and habitat[31].

Generally, where incision is ongoing, a strategy of stabilization may be warranted to prevent further degradation and associated degradation or loss of habitat. Stabilization of the channel, however, may be effective over the long term only if the root causes are also addressed. Otherwise, stabilization can lead to additional problems. A stream system that is incising due to excess stream energy, and whose bed has been stabilized, may erode its banks excessively. Where an incised channel has reached a stable channel grade, but remains entrenched, and where human impacts can be attributed to the cause of incision, restoration strategies may be warranted. Three fundamental approaches exist to incised channel restoration where human impacts have caused incision: (1) restore the channel bed to its former grade through channel filling and reconstruction or through the installation of regular check dams, (2) lower the floodplain to the incised, existing channel grade, or (3) allowing the channel to evolve to an equilibrium condition, typically at a lower grade and abandoning old floodplain surfaces as terraces. Raising of the channel bed to historical grade is generally appropriate only when the factors leading to incision have been fully restored.

This practice may require significant stabilization of the bed and banks to prevent re-incision. Lowering of the floodplain can effectively accelerate the natural evolution of incised channels. This latter strategy may be particularly appropriate in the case of legacy impacts or where incised channel evolution has progressed significantly. Table 6 provides examples of strategies to address incision associated with common, general causes.

Table 6. Examples of strategies and techniques to address channel incision

Problem	Causes	Strategy	Relevant Techniques
Watershed-scale problems, causes and strategies			
Ongoing incision	Urbanization	Stabilize channel; restore flow regime	Channel modification; Instream structures; Dedicating land and water
	Dams or other sediment traps	Stabilize channel; Augment sediment; Remove structure	Channel modification; Instream structures; Large wood, Dedicating land and water
	Removal of wood, beavers, or other natural stabilization	Stabilize channel; restore wood, beavers	Channel modification; Instream structures; Beaver reintroduction; Large wood; Riparian restoration; Dedicating land
	Base level lowered	Stabilize channel and restore base level; Reconfigure channel for new base level	Channel modification; Instream structures; Large wood; Riparian restoration; Dedicating land and water
Incised channel with stable grade	Urbanization	Lower floodplain; Enhance channel	Channel modification; Instream structures; Large wood; Riparian restoration; Dedicating land and water
	Dams	Lower floodplain; Enhance channel; Remove structure	Channel modification; Instream structures; Large wood; Riparian restoration; Dedicating land and water
	Loss of natural stabilization (e.g. large wood jams)	Raise channel grade; Lower floodplain; Restore natural stabilizing features	Channel modification; Instream structures; Large wood; Riparian restoration; Dedicating land
	Base level lowered	Reconfigure channel for new base level	Channel modification; Instream structures; Large wood; Riparian restoration; Dedicating and water
Reach-scale problems, causes and strategies			
Active incision or Incised channel with stable grade	Channelization or Dredging	Restore channel	Channel modification; Instream structures; Large wood; Riparian restoration; Dedicating land
	Removal of local grade control	Stabilize channel; Restore channel	Channel modification; Instream structures; Large wood; Riparian restoration; Dedicating land

4.7.3 Aggrading Channels

Aggradation is the progressive accumulation of in-channel sediment resulting in increased channel bed elevation. Aggrading channels indicate that an excess of sediment exists relative to a stream system's capacity to transport that sediment and is typically a reach-scale phenomenon. Characteristics of aggrading streams are covered in Chapter 2, the Geomorphology Appendix and RiverRAT Appendix1.2. Channel response to aggradation commonly includes increased rates of bank erosion and lateral migration. Aggradation can impact infrastructure and habitat through increased flood elevations, reduced bridge capacity, channel widening with associated bank erosion, temporary loss of fish habitat, increased summer stream temperature due to decreased depth, or channel migration into developed land.

Aggradation occurs at the point where stream energy is insufficient to transport sediment delivered to a system. In undisturbed watersheds and stream systems, aggradation typically occurs in one of two environments: alluvial fans and deltas. In both cases, aggradation occurs at a break in channel grade, at the point where the stream slope decreases significantly without any change in hydrology, such as at the mouth of a steep canyon (alluvial fan) or at the mouth of a river at a lake or the ocean (delta). Aggradation may also occur in response to reductions in effective discharge (e.g. in regulated rivers), increases in sediment supply (e.g. from excessive erosion due to land use impacts, from in-channel mining, or downstream of a headcut or incising channel), or upstream of channel modifications or structures that reduce a channel's capacity to transport sediment, such as dams or undersized crossings that cause backwatering.

Assessment of aggradation should focus first on determining whether it is occurring naturally, due to geomorphic position in a watershed, such as in an alluvial fan or delta environment, or locally as a result of dynamic equilibrium alluvial channel processes. Little, if any, habitat justification exists for developing strategies to mitigate aggradation where it is naturally occurring – aggradation mitigation typically requires trapping or dredging sediment, both of which require continual or repeated practice and can result in significant habitat impacts. Where anthropogenic disturbances are attributed to causes of aggradation, the selection of a strategy will depend on whether aggradation is the result of watershed-scale disturbance or site- or reach-scale disturbance. Where watershed-scale disturbance is responsible for aggradation, strategies should first address sources or causes of excess sediment at the watershed scale through land-use BMPs, or with flow regime management where reduced flows are implicated. Where this is impractical, excess sediment can be dredged or trapped in sediment detention basins, although these strategies require substantial expense and long-term operation and maintenance and can create passage barriers or other significant habitat impacts, and are generally unreliable[32].

Addressing impacts associated with aggradation may be more feasible where it can be attributed to site- or reach-scale impacts, such as upstream of artificial channel constrictions or downstream of an active upstream headcut or incising reach. Appropriate strategies in these cases include first addressing the cause by removing constraints or stabilizing a headcut, and second, by removal of excess sediment from the channel in cases where volumes are manageable and immediate risks associated with aggradation are unacceptable. Where aggradation has also caused significant bank erosion or lateral migration, channel and riparian restoration may also be appropriate.

In some instances, a mass-wasting event may cause a pulse of sediment, leading to localized aggradation and associated channel instability. Localized aggradation resulting from mass-wasting, particularly in otherwise undisturbed systems, will generally self-attenuate without any management. While sediment removal and sediment detention basins have been used in the past to manage unacceptable risk or consequences of aggradation, these measures are generally extremely expensive, require significant maintenance, provide only short-term benefit, and may have significant collateral impacts to habitat. As an alternative, it may be possible to store excess sediment in the channel by creating numerous site-scale structures (e.g. large wood jams) that can trap and hold sediment indefinitely. This may be particularly applicable where such channel storage has historically been eliminated or reduced through splash-damming or snag removal. Table 7 summarizes potential strategies and techniques to apply to various causes of aggradation.

Table 7. Examples of strategies and techniques to address channel aggradation

Problem	Causes	Strategy	Relevant Techniques
Watershed-scale problems, causes and strategies			
Ongoing aggradation	Dams and flow regulation	Manage flows for sediment transport	* NA
	Land use related increase in sediment	BMPs or management to reduce sediment inputs	Sediment detention basin; Dedicating land
Reach-scale problems, causes and strategies			
Ongoing aggradation	Upstream active headcut or incision	Stabilize headcut; remove aggraded material	Instream structures; Channel modification (to remove aggraded material); Dedicating land
	Downstream channel constriction	Remove or reconfigure constriction; allow natural erosion of aggraded material	*NA – though infrastructure reconfiguration may require some degree of Channel modification
Aggraded reach	Upstream arrested headcut	Remove aggraded material; allow natural erosion or channel avulsion	Channel modification (to remove aggraded material); Dedicating land

* Not applicable – While watershed-scale management practices and those focusing on management of inputs to the channel are critical restoration strategies, they are generally not discussed as habitat restoration 'techniques', per se.

4.7.4 Energy Inputs

Energy inputs to the stream consist primarily of light and heat, which provide for habitat quality (temperature) and regulate primary productivity through photosynthesis. Light and heat are controlled primarily by climate, the degree of shade, and the source of water. Loss of riparian forest shade can increase stream temperatures dramatically[33]; normative groundwater exchange moderates stream temperature through the year; and the temperature of stormwater, irrigation returns, and other discharges to the stream may differ significantly from that of the stream. Energy inputs may be affected by land use, urbanization, riparian management, channel modifications, irrigation returns and industrial wastewater, impacts to hyporheic exchange, and flow management from reservoirs. Additionally, climate change is attributed to a general warming of streamflow in Washington regardless of other impacts (refer to *Climate Change* Appendix). Increases in temperature and light are generally more common impacts, and may be of specific concern for populations of cold-water fishes.

Watershed assessment and temperature and light modeling can be applied to derive likely causes and impacts, and the scale of these causes. Strategies to address excess energy inputs may be necessary at both watershed and reach scales. Watershed-scale strategies include primarily BMPs for land use and stream corridor management that promotes natural riparian forest condition, hydrologic connectivity through floodplain inundation and hyporheic exchange, and attenuation and infiltration of runoff. Reach-scale strategies include primarily restoration of riparian and floodplain corridor processes that promote normative flooding, hyporheic exchange, and riparian vegetation succession, or channel manipulation to reduce width:depth ratios where channel width has increased, such as due to stock trampling of streambanks.

4.7.5 Water Quality

Water quality refers to the physical and chemical characteristics of water that are critical factors to survival, productivity, and diversity of aquatic life in a stream. Water quality parameters include temperature, turbidity, dissolved gases, nutrients, heavy metals, inorganic and organic chemicals, pH, and biota (pathogenic bacteria, viruses, etc.). If the magnitude or concentration of any of these factors falls outside the natural range for a specific location and time of year, biological processes may be altered or impaired[34]. Water quality is regulated by, and can be affected by, inputs to the stream system and dynamic physical and chemical stream processes, including flooding, hyporheic exchange, and primary productivity.

Water quality standards for surface waters of the state of Washington (Washington Administrative Code (WAC) Chapter 173-201A) are intended to protect designated uses, such as drinking water supplies or cold-water habitat. However, they do not offer the same degree of safety for survival and propagation at all times to all organisms within a given ecosystem[35]. The Washington Department of Ecology has reported that nearly 50% percent of all river and stream reaches monitored did not meet state water quality standards[36]. The primary water quality problems identified were temperature, pH, and fecal coliform bacteria. (Water quality and quantity assessments are available at: http://www.ecy.wa.gov/programs/wq/links/wq_assessments.html

Water quality can be affected by both point- and non-point sources of pollution. Point sources are those that can be traced back to a discrete discharge, such as an industrial outfall. Non-point pollution stems from diffuse inputs to a water body with the pollutant traveling via air, groundwater, or surface water runoff. In Washington, approximately 20% of water quality problems in streams that do not meet water quality standards can be traced to point sources[37]; the rest are attributed to non-point sources of pollution. While most lake and groundwater pollution is also attributed to non-point sources, point sources are the dominant cause of estuary pollution. Common non-point sources of water quality impairment are summarized in Table 8.

Table 8: Sources of Pollution by Land Use Activities[38]

Non-point Source	Nitrogen	Fecal Coliform	Sediments	pH	Dissolved oxygen	Pesticides	Flow	Temperature
Agriculture								
Animal Feeding Operations	X	X	X	X	X			
Dryland	X		X			X		X
Irrigation	X		X	X	X	X	X	X
Non-commercial	X	X	X					X
Forest Practices								
Road construction			X			X	X	X
Timber harvesting			X				X	X
Reforestation	X					X		X
Urban/Rural								
Construction			X					X
On-site sewage systems	X	X		X	X			
Stormwater runoff	X		X	X		X	X	X
Hydromodification								
Channelization			X		X		X	X
Dams			X		X		X	X
Wetlands and riparian Areas								
Vegetative clearing			X		X	X	X	X
Draining of wetlands	X		X				X	X
Recreation								
Marinas and boats	X	X	X	X	X			
Off-road		X	X					
Hiking, fishing		X						

Strategies for addressing water quality impairments are linked to point- or nonpoint sources. Point sources of pollutants are best addressed at the source through improvements to water treatment before it is released to the stream. Non-point sources can be addressed through a combination of riparian buffer zones, dilution, and upland land use best management practices. Riparian zones buffer waterways from disturbances in the watershed; moderate water temperature and, thus, dissolved oxygen concentrations; limit the rate of bank erosion; and provide wood to streams that control the instream storage and transport of sediment and organic matter. Vegetated riparian zones, along with vegetated uplands and wetlands, increase flow complexity and, therefore, travel time to the stream, increasing the opportunity for pollutant uptake, degradation, sorption, and transformation. They filter sediment, pollutants adsorbed by the sediment (e.g., phosphorus, heavy metals), and insoluble pollutants from overland flow and from flood flow. Aerobic and anaerobic processes operating within a wetland allow certain chemicals to volatilize or precipitate out of the water column. And, the accumulation of organic matter that occurs in many wetlands provides a permanent sink for many chemicals. Restoration of riparian buffers (see Riparian Restoration technique) can provide substantial benefit to streams impacted by non-point sources of pollution.

Once the pollutant reaches the stream, its impact on stream water quality depends, in part, upon its dilution by flow. As the amount of water mixing with the pollutant increases, the pollutant's concentration decreases. Thus, activities that remove water from the stream (e.g., for irrigation or domestic or industrial water supply), that regulate flow (e.g., dams), and that limit base flow (e.g., development of impervious surface which limits groundwater recharge opportunities) increase the likelihood of pollutants impacting water quality. Where streamflow has been depleted, strategies to address water quality may include restoration of flow through flow management, particularly during critical low-flow periods (see Flow Regime section). Flow management that restores sediment transport and floodplain flooding processes can also mitigate water quality impairments. In the stream, nutrients and contaminants may cycle between a dissolved form, a gaseous form, and a particulate form (as a precipitate, sorbed to organic matter, or contained within living organisms). As a particulate, their movement is influenced by downstream fine particle transport[39]. Thus, depositional sites that provide temporary or long-term storage of sediment and organic matter also provide storage for particulate forms of contaminants. Depositional areas include floodplains and floodplain features (e.g., relic channels, alluvial wetlands and ponds) [40] [41] [42], backwater areas, alluvial fans, bars, log jams[43] [44] [45] [46] [47], and low gradient channel reaches[48]. The duration of storage may range from a few days to hundreds of years or longer, depending on the type of storage site, the frequency, magnitude, and duration of storm events, stream power[49], and sediment supply. During storage, many contaminants degrade, transform, are taken up by plants, bacteria, fungi, and other organisms, or become buried in sediment and organic matter. However, others may retain their toxicity and pose a further threat when disturbed by erosion or released back (desorbed) into the water column. Note that, during storage, contaminants may pose a threat to the organisms that reside there. Activities that simplify the channel or limit the extent, frequency, or duration of floodplain inundation will reduce the magnitude and alter the distribution of storage sites within the stream corridor.

Non-point source pollution is derived from diffuse sources spread throughout a watershed and is, therefore, more difficult to control than point source pollution. The specific water quality restoration technique employed to control non-point source pollution depends on the specific water quality parameter that has been identified as causing impairment, its source(s), the pollutant's transport pathway, and it's eventual fate within the ecosystem. Effective management of non-point source pollution can best be achieved through a combination of: 1) land use management that restricts the type of activity allowed in an area (e.g., zoning restrictions, land use plan development and implementation), and 2) the use of best management practices that minimize contaminated runoff and sediment inputs by controlling sources and transport. Because of the vast array of sources of non-point source pollution and the complexity of its control, the restoration of stream water quality impacted by non-point source pollution requires a watershed-scale land restoration and management strategy. Some of the many resources available for guidance on the prevention and management of non-point pollution are listed below.

- *Washington's Water Quality Management Plan to Control Non-point Source Pollution* (http://www.ecy.wa.gov/biblio/0510027.html) describes a holistic approach to controlling and cleaning up non-point source pollution. The document describes current laws, regulations, programs and technical assistance available to control non-point pollution as it relates to agriculture, forest practices, urban areas, recreation, hydromodification, and loss of aquatic ecosystems.
- *Stormwater Management and Design Manuals for Eastern and Western Washington*(http://www.ecy.wa.gov/programs/wq/stormwater/municipal/StrmwtrMan.html) The objective of this manual is to provide a commonly accepted set of technical standards and guidance on stormwater management measures that will control the quantity and quality of stormwater produced by new development and redevelopment.

4.8 Creating and Enhancing Stream Habitat

The fourth strategy priority for habitat restoration (after protection, connection, and process restoration) is to restore, create, or enhance habitat at the site- and reach-scale. Creation or enhancement of stream habitat may be appropriate where:

1. the natural processes that create and maintain habitat have been severely constrained or eliminated and cannot be effectively restored;
2. opportunity exists to provide short-term benefits during the years, decades, or longer timeframes necessary for certain processes to fully recover; or
3. recovery plans for listed species identify specific habitats as critical and urgent for near-term recovery objectives.

Common causes of loss or degradation of habitat and strategies to address these causes have been detailed in previous sections. Generally, efforts to create or maintain habitat will be most effective over the long term if these causes are addressed first, or where creation is used to supplement or complement strategies to address causes. While some short-lived habitat enhancement measures in dynamic systems may be appropriate in certain circumstances, created habitat will provide the longest benefit in relatively stable channels and watersheds that are not undergoing rapid change.

Constructed or enhanced habitats often address only symptoms of a system that no longer creates and maintains a sufficient extent and variability of habitat.
Stream habitat, in naturally functioning stream systems, is an *outcome* of episodic disturbances and dynamic stream processes of erosion, transport, and deposition of sediment and wood that continually create new and variable habitat conditions. Consequently, the application of strategies to create and enhance stream habitat should be applied with the understanding that such strategies may provide only short-term benefit and may require significant cost relative to more sustainable strategies, particularly when adopted to meet long-term habitat goals. Constructed habitat features may be abandoned by a shifting channel, buried by depositional processes, or they may fail or wash out during high flow events. Rigid structures have a limited ability to adjust and adapt to dynamic stream conditions and, so, are more prone to failure or creating a barrier to fish passage when conditions around them change over time. Rigid structures may also serve to prevent or limit natural habitat-forming processes from occurring, including channel migration and sediment transport. Besides generally providing only short-term benefit, the construction of physical habitat features may result in unanticipated or undesirable outcomes, particularly when they are constructed to be non-deformable and unable to withstand stream energy associated with high flow events. The hydraulics created by such structures and their interaction with other dynamic processes can be difficult to predict, and may lead to unintended consequences by causing channel avulsion, meander migration, or bed and bank erosion or deposition.

Recovery plans often specify *specific* habitat types as critical to recovery, driving the need to create such habitats where other restoration strategies are unable to do so in an adequate timeframe. Habitat can be loosely categorized as providing opportunity for forage, refuge, spawning or rearing; different species will require or prefer different specific habitat conditions to meet each of these needs. For example, because of different food requirements and spawning habits, different species will require different depth, velocity, cover, and substrate conditions for feeding and spawning. Additionally, the proximity of different habitat types can affect habitat suitability; spawning fish may find otherwise acceptable spawning habitat unsuitable if there is not adequate refuge immediately adjacent to spawning habitat. As a general strategy, reach-scale restoration of habitat should emphasize diversity of habitat elements (i.e., depth, velocity, cover, and substrate size and sorting). Providing a diversity of habitat conditions will increase the likelihood of providing for specific habitat preferences through a range of flow conditions, providing for a variety of native species, providing a variety of forage and cover, and providing connected or adjacent habitats that improve specific habitat viability. Many of the strategies and actions discussed in previous sections will lead to processes and conditions that create and sustain habitat diversity. However, recovery plans often specify the restoration, or creation, of spawning or rearing habitat as a priority strategy for species recovery. The following sections describe considerations for creation or enhancement of these specific habitat types.

4.8.1 Salmonid Spawning Habitat

The suitability of salmonid spawning habitat is determined by substrate size, water velocity, water depth, gravel permeability, surface and sub-surface flow conditions (e.g., up sloping microhabitats with downwelling flow), dissolved oxygen, water temperature, and cover. And while a given species may key in on the same spawning habitat criteria from stream to stream, the processes governing the formation and maintenance of these site characteristics varies among stream types. Spawning habitat in low gradient channels with meandering pool/riffle morphology is typically associated with abundant deposits of gravel in pool tailouts, riffles, and point bars. In contrast, spawning habitat in steeper channels is often limited to small patches of coarse gravel stored above channel obstructions, such as large wood or rock steps.

Creation of spawning habitat, therefore, must be designed with the specific stream type in mind, and must provide for continued hydraulic conditions to renew and maintain appropriate gravels and sub-surface conditions.

Because salmonids spawn in gravel substrate, the condition, character, and availability of gravels is of primary concern in creating or enhancing spawning habitat. Condition of gravels is most commonly degraded by fine sediment that can bury gravel or limit flow through gravel. The character of gravel refers to the gradation, or variation in sizes of gravels in the stream bed; impacts to stream environments may limit the availability of appropriate size class of gravel for spawning. Availability simply refers to the quantity of gravel in a stream and whether it is accessible for spawning. Table 9 relates the problems, cause and potential solutions for constraints on spawning related to gravel.

Table 9. Examples of strategies and techniques to address spawning gravel constraints

Problem	Causes	Strategy	Relevant Techniques
Fine sediment impairs gravel condition	Upland land management contributes excess fine sediment	Upland best management practices; riparian buffers; restore beavers to trap fine sediment	Riparian restoration; Beaver reintroduction; Spawning gravel cleaning; Dedicating land
	Insufficient stream energy	Reconfigure channel to create hydraulics that promote flushing and mobilization of fines	Channel modification; Instream structures; Large wood; Spawning gravel cleaning
		Reconnect depositional areas (floodplains, bars, etc.) to trap fine sediment	Channel modification; Spawning gravel cleaning; Dedicating land
		Restore flushing flows	Flow regime restoration; Dedicating land
Inadequate gravels of appropriate size	Insufficient supply of gravel	Remove armoring and stabilization to allow gravel recruitment	Channel modification; Riparian restoration; Bank protection; Dedicating land
	Insufficient stream energy	Create variable hydraulics to promote redistribution and sorting of gravel	Channel modification; Instream structures; Large wood; Dedicating land
		Restore flushing flows	Flow regime restoration
Constraints on supply of gravel	Loss of in-channel gravel storage	Add channel roughness; allow migration and bar development	Channel modification; Instream structures; Large wood; Dedicating land
	Supply constrained by channel armoring	Remove channel armor or stabilization features	Channel modification; Riparian restoration; Dedicating land
	Dams	Remove dam or provide supplemental gravel	Channel modification

Besides constraints related to gravels, spawning habitat may be limited by access due to passage barriers, by general loss of habitat due to channelization, constraints on dynamic channel processes, and removal of instream structure, and by loss of cover (riparian and instream cover associated with large wood or other in-channel features). Strategies to address these constraints are presented in previous sections. The suitability of spawning habitat can also be diminished by impacts to water temperature, water quality, stream flows (rates of change and seasonality of flows), and trampling by humans or stock.

4.8.2 Salmonid Rearing Habitat

Rearing habitat is the second habitat element commonly specified as a restoration priority in salmon recovery planning. Rearing habitat is critical to the survival from fry to juvenile and adults for all species; for some salmon species rearing habitat also provides a critical path in the transition from freshwater to saltwater habitat. Characteristics that make habitat suitable for rearing include lower energy and lower velocity stream environments with ample cover and forage and suitable water quality. Cover may be provided by structural complexity (wood and substrate), instream and bank vegetation, riparian vegetation, and bubble screens from complex hydraulics. Freshwater rearing habitat may occur in the channel along channel margins and around large wood jams, in side-channels and sloughs, in beaver ponds, within estuaries and during prolonged seasonal high flows inundating floodplains. Specific rearing habitat requirements will depend on the target species.

Significant loss of rearing habitat has occurred as a result of stream channelization that reduces overall habitat availability and channel complexity and connectivity, bank and bed armoring that limits edge complexity and associated low energy habitat, levees that affect seasonal overbank flow and associated floodplain rearing habitat, dams that affect rates of change in flow that may strand fish, beaver removal, and many other actions discussed previously that limit natural channel processes and associated habitat complexity, variability and succession. Addressing the causes of the majority of rearing habitat loss or degradation will require priority strategies presented previously, namely reconnecting of available habitat and restoration of dynamic channel processes that create and maintain the succession of habitats. However, where rearing habitat cannot be restored or where habitat-forming processed cannot be adequately restored, the creation of rearing habitat can contribute to alternative species recovery strategies. Measures for creating specific types of rearing habitat include:

- *Off-channel rearing habitat*. Groundwater fed channels, sloughs, ponds and wetlands can be constructed to provide valuable off-channel rearing habitat for coho and chum salmon when these areas will no longer be created or naturally maintained as a consequence of hydro-modification, development, levee construction, or bank armoring that limit flooding and channel migration. The key element of these sites will be their perennial flow of generally cooler water in summer and warmer water in winter that increases fish survival and growth. Relevant techniques include *Side Channel, Channel Modification,* and *Beaver Reintroduction*.
- *Main channel rearing habitat*. Instream structures that create depth, velocity and substrate variation and provide cover with mainstem channels can be built using a variety of techniques. Relevant techniques include *Channel modification*; *Large wood,* and *Instream structures*.
- *Estuarine rearing habitat*. Within the estuary, opportunities may exist to restore or improve juvenile fish access to sloughs and distributary channels through removal or modification of tide gates and levees, dike removal, breaches and setbacks, and restoration of estuarine channels and structural features. Relevant techniques include *Channel modification*, *Levee removal,* and *Instream structures*.
- *Nearshore rearing habitat*. Nearshore areas can be improved by removal of bulkheads to restore natural shoreline vegetation and beach processes including gravel enrichment that provide the necessary substrate for rearing of some species. Nearshore islands can also be built to provide shallow water habitat rich with eelgrass that mitigate for permanent loss of high quality shoreline habitat.
- *Beaver pond rearing habitat*. Rearing habitat can be significantly increased and improved through reintroduction of beavers[50] and their resulting ponds, particularly in side channels and tributary streams.

4.9 Monitoring

The science and practice of habitat restoration is an uncertain and developing science – there is generally an inadequate base of knowledge and empirical data from which to predict outcomes with certainty. Consequently, restoration plans are effectively hypotheses that the selected strategy will result in the intended outcomes; the implementation of restoration strategies should be considered tests of those hypotheses[51]. Monitoring is, therefore, a critical element of the development and testing of restoration strategies. Furthermore, because restoration outcomes are difficult to predict, a philosophy of adaptive management is prudent for any restoration strategy.

Adaptive management requires monitoring relative to project goals and objectives to determine whether strategies are resulting in intended restoration trajectories.

Monitoring is listed as the seventh phase of restoration strategy development process (see introduction to Chapter 4). Yet, as depicted in Figure 1, the development of monitoring plans and implementation of monitoring is an iterative process. Monitoring plans must be developed hand-in-hand with development of restoration strategies. In particular, monitoring metrics should be derived directly from stated restoration objectives (see previous section on Restoration Goals and Objectives) – this ensures that monitoring can be used to test project outcomes relative to objectives, and to meaningfully inform adaptive management practices. Monitoring is conducted specifically to measure success through performance indicators that have been defined relative to project objectives. Performance guides adaptive management, which may require additional or ongoing management actions. And beyond adaptive management, monitoring is documented to communicate lessons learned from implemented restoration strategies.

RiverRAT Section 3-8 Monitoring and Management provides an overview of the various functions of monitoring with an emphasis on the application of monitoring to an adaptive management framework. The Washington SRFB Reach-Scale Effectiveness Monitoring Program provides valuable perspective on effectiveness of monitoring protocols intended to measure reach-scale restoration effectiveness using both biological and physical parameters[19]. Besides the *Monitoring* Appendix of this SHRG, numerous resources are available to support the development of monitoring plans, including:

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3. Skinner, K., Shields Jr, F.D., Harrison, S. 2008. Measures of success: defining the outcomes. IN S.E. Darby and Sear, E. (eds.) River Restoration: Managing the Uncertainty in Restoring Physical Habitat. John Wiley & Sons, pp. 187-208.

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CHAPTER 5

DESIGNING AND IMPLEMENTING STREAM HABITAT RESTORATION TECHNIQUES

Chapter 5. Designing and Implementing Stream Habitat Restoration Techniques

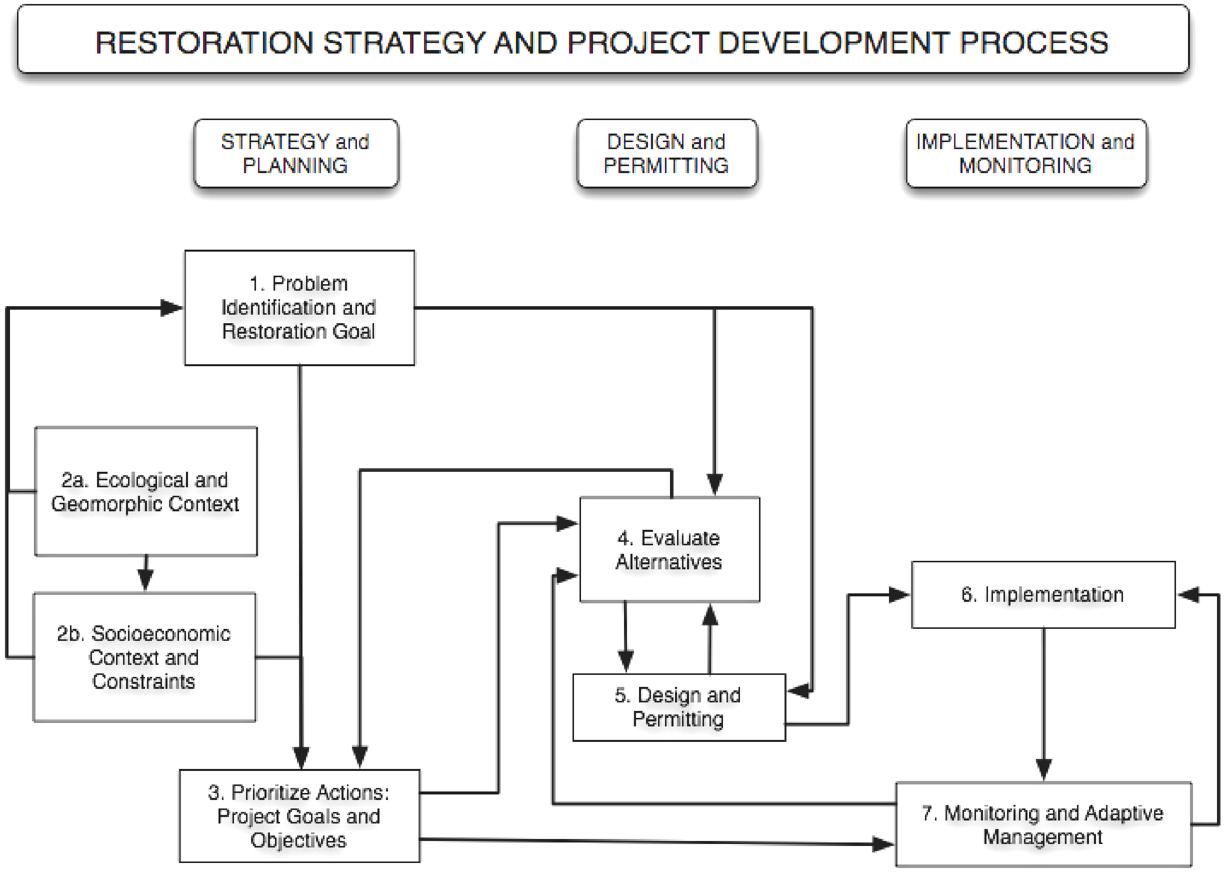
Restoration strategies, presented in Chapter 4, may include site- or reach-scale projects intended to increase or improve habitat or the processes that create and maintain habitat. Chapter 5 is an introduction to the development and design process for stream habitat restoration projects. Individual restoration projects are components of a restoration strategy and may include combinations of specific restoration techniques. Chapter 4 describes considerations and a process for identifying appropriate restoration techniques, as components of a strategy. This chapter describes a process for development and design of restoration techniques selected as part of the overall watershed- or reach-scale strategy, and provides details of design and implementation considerations for commonly applied techniques.

The restoration strategy and project development process (Figure 1) includes three phases: Strategy and Planning, Design and Permitting, and Implementation and Monitoring. The first phase, Strategy and Planning (see Chapter 4) identifies specific types of actions and projects that contribute to an overall restoration strategy, and develops goals and objectives for these specific priority projects and actions. This chapter focuses on the middle Design and Permitting phase, including evaluation of alternatives and project design. It presents a process for conducting project design, building on preliminary assessments and specific, measurable project objectives. The outcome of the project design process is a set of implementation plans that satisfy restoration objectives and priorities. Following the Design and Permitting stage, which is described in this chapter, the project development process enters the Implementation and Monitoring phase. Considerations for Implementation and Monitoring are discussed in the individual technique sections and the Technical Appendices.

Restoration projects often short-circuit the project development process by jumping from an observed problem directly to selection and design of a solution, skipping the critical steps of reach or watershed assessment, definition of project goals and specific objectives, and careful consideration of alternative strategies for meeting objectives. Even where assessment has been performed, restoration design may fail to meet objectives if the findings of assessment are not explicitly integrated in the design process. This chapter presents a design approach that addresses these shortcomings.

Chapter 5 introduces specific design considerations for component restoration techniques that may contribute to a restoration project. The information presented in these techniques is intended to assist landowners, land managers, and other stream restoration practitioners in developing designs and implementing various components of stream habitat restoration projects. Chapter 5 offers details to guide design of specific component techniques where reach-scale projects have been identified. It is important to consider that reach-scale projects and component techniques may be limited in their utility or may offer only short-term benefits where causes of problems have been identified at broader scales. For example, installation of large wood can create habitat in stream systems that lack large wood. However, unless constraints on recruitment of additional large wood are addressed, installed large wood may provide only temporary benefit.

Figure 1. Restoration strategy and project development process. The outcomes of Strategy and Planning are prioritized and coordinated restoration actions and projects with defined goals and measurable objectives. (Adapted from *RiverRAT*).



Prior to embarking on designs for specific techniques, the restoration practitioner should have already completed a site, reach, and watershed assessment to identify probable causes of observed or perceived problems, to determine constraints to addressing these problems, and to frame the project in the broader context of a watershed restoration strategy (Chapter 4). Because restoration practice is most effective when it address *root causes* of problems rather than observed symptoms, a robust assessment that looks at potential causes at site-, reach- and watershed-scales will contribute to a more effective restoration strategy. Where project scale is small and associated planning budgets are small, project planning and design should include a minimum level of watershed-scale assessment sufficient to identify probable impacts to hydrologic and sediment inputs as well as geomorphic constraints in upstream reaches. In addition, design should only proceed when project goals and specific objectives have been clearly defined and a restoration strategy has been developed to meet these objectives. The restoration strategy identifies appropriate restoration actions and techniques, and ensures that the identified project is a priority in the context of broader watershed plans. Site- or reach-scale techniques may ultimately provide little value if they are not consistent with overall watershed priorities.

Besides the techniques presented in this chapter, other resources exist that provide detailed information on specific methods of analysis, additional sources of information, and general background on related sciences and other components of project planning, design, and implementation; these include appendices to this document, related Aquatic Habitat Guidelines white papers (http://wdfw.wa.gov/hab/ahg/ahgwhite.htm), and *RiverRAT* resources[1] (Section 3 Project Development, Appendix 1 Investigative and Design Analyses, and Appendix 2 Design of Stream Channels and Streambanks, www.restorationreview.com). The *RiverRAT* resources constitute a considerable supplemental resource by providing a comprehensive suite of references and examples of project development, project design, analytical techniques and resources. In particular, the Project Screening Matrix presented in *RiverRAT* provides a tool that can assist the restoration planning team in evaluating the relative risk to aquatic resources depending on inherent stream characteristics (stream response potential) and project characteristics (project impact potential), and the *RiverRAT* online tool provides a framework for guiding and evaluating the project design process.

5.1 Design Process For Stream Habitat Restoration

Design, in the context of stream habitat restoration, generally refers to the process of characterizing existing processes governing stream dynamics and associated habitat, using technical analyses to predict outcomes associated with alternative design details, and developing plans and specifications to describe techniques to be implemented. Restoration design is often an iterative process, where each step in the process builds on initial analyses and provides additional information or perspective that may warrant some degree of circling back to previous steps in the process.

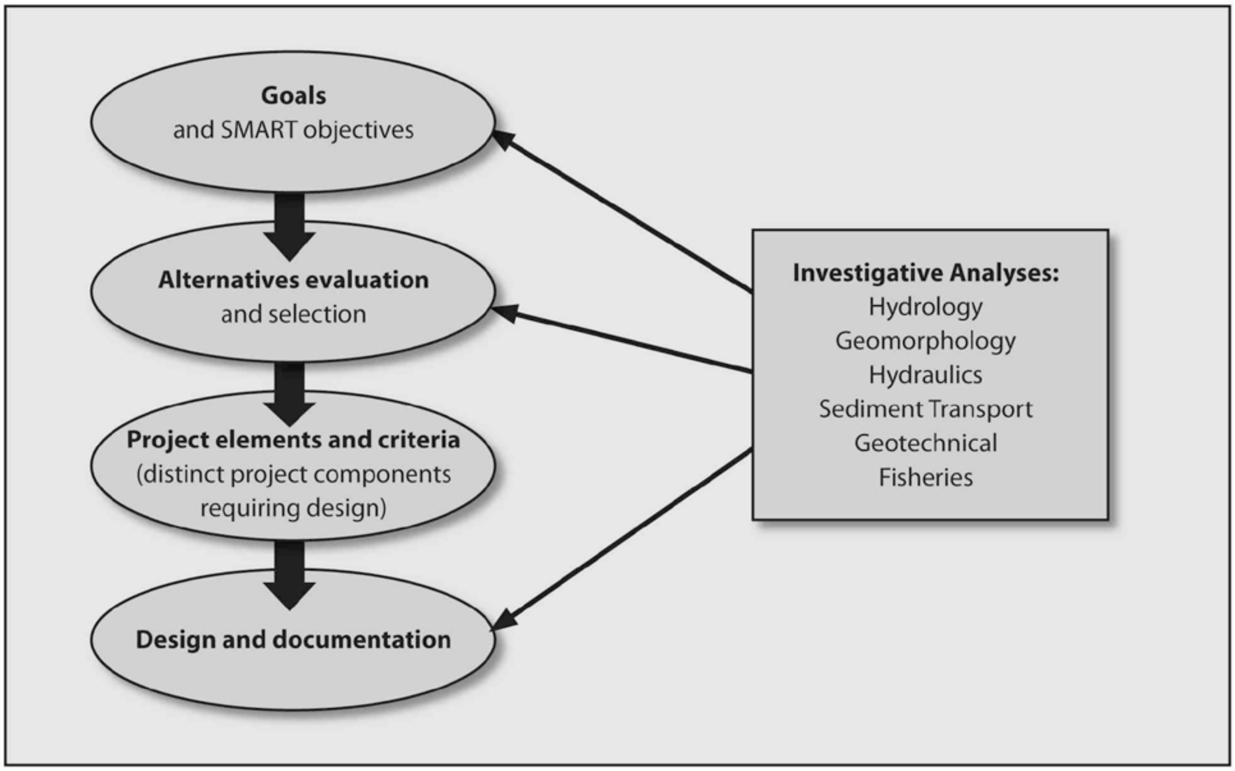
This chapter presents the following roughly sequential steps and components of project design process (the steps presented here cumulatively represent Steps 3-5 of the overall restoration development process depicted in Figure 1):

1. **Goals and objectives** define the purpose and specific desired outcomes of a restoration project. They are typically developed as part of the strategy and planning process and are discussed in greater detail in Chapter 4. However, specific and measurable objectives may be further refined as part of the design process, or may need to be revised as the design process provides more detailed information and context to project stakeholders.
2. **Survey and analysis** serves as the technical foundation for the entire design process; survey gathers necessary site and historical data and technical analyses are conducted to characterize and analyze existing conditions, derive input values for subsequent design analyses, and to predict restoration outcomes relative to project objectives for alternatives analysis and final designs. [Note: Technical analyses developed initially in early phases of design are refined and expanded throughout the remainder of the design process (Figure 2).]
3. **Conceptual alternatives evaluation and selection** first develops concept-level restoration techniques, or combinations of techniques, and then evaluates them relative to project objectives. For the selected alternative, specific project elements that require detailed design are identified.
4. **Design criteria** are specific, measurable attributes developed to clarify design and performance expectations and intent for selected project elements; design criteria guide

the design process toward specific outcomes for each project element that are consistent with project objectives. [Note: The process of defining design criteria may warrant iterative development with the selection of project elements; likewise, subsequent design analyses may warrant iterative development with design criteria.]

5. **Design** involves the iterative analyses based on an appropriate technical design approach for each project element and the development of design products necessary for permitting and sufficient to explain and justify proposed designs and guide implementation. Design stages and milestones vary by project, but typically involve a concept level design (see Alternatives), a draft or preliminary design that is integrated with permitting requirements, and a final design. Design plans, specifications, and reports are often prepared at draft and final stages.

Figure 2. The design process. (Adapted from Figure 35 in *RiverRAT* Appendix 2) Technical analyses (referred to as 'Investigative Analyses' in this figure) are developed to support all phases of design.



The discussion of a design process outlined in this chapter emphasizes:

- Selection and development of an adequate level of analysis and design to address causes of problems or constraints identified through preliminary reach-scale and watershed-scale assessments;
- Selection of appropriate technical approach to design based on project goals, existing and predicted watershed processes and ability to characterize these processes;
- Relation of project elements and their design to defined project objectives; and

- Documentation and portrayal of designs that fully explain and justify the design approach and outcomes.

5.1.1 Survey and Analysis

The first step in stream habitat design is the characterization of historical and current processes contributing to or limiting stream habitat. This typically requires historical data analysis and detailed existing site survey information to characterize and analyze existing conditions and to derive input data for various technical analyses. Review and analysis of historical data is generally required to characterize the hydrologic regime and watershed- and reach-scale change in stream processes (see Chapters 2 and 3). Survey may include varying degrees of topographic survey and channel or geomorphic survey (see *Fluvial Geomorphology* Appendix), sediment sampling, vegetative or aquatic sampling, and location and characterization of constraints such as infrastructure. The type, extent, and level of detail of survey and data needed to conduct analyses and design is dependent upon project goals, objectives, scale, and context and cannot be easily or characterized or summarized. The technical appendices (Hydrology, Fluvial Geomorphology, Sediment Transport, and Hydraulics Appendices) provide further information needed to perform assessment and analysis.

Project design is conducted using a variety of technical analyses, which initially serve to characterize channel processes, and ultimately are used to predict outcomes and responses to the implemented project. Initial technical analyses are conducted to evaluate existing and future or proposed conditions and to derive input data for design analyses; technical analyses are refined and further developed throughout the design process to evaluate and select alternatives and develop design details (Figure 2). Technical analyses are used to:

1. Determine causes of identified problems, particularly where the causes occur at a location or scale beyond the observed problems and anticipated project area,
2. Determine input values for the design process, such as design discharge values or sediment supply and transport rates,
3. Identify project constraints at varying scales, such as watershed changes that have affected hydrologic regime, channel confinement due to infrastructure, or wood recruitment limits,
4. Develop detailed designs, such as channel dimensions, streambank configuration, and placement of large wood,
5. Test or predict outcomes of various alternatives and for proposed designs through scenario modeling,
6. Estimate project costs,
7. Establish baseline conditions as the basis for monitoring, and
8. Evaluate risks to the environment, infrastructure, property, and public safety associated with both existing and predicted future (restored) conditions, as well as the probability of failure of project elements.

Four types of technical analyses serve as the foundation for restoration design related to physical processes that create, modify and maintain stream habitat:

- *Hydrology*. Hydrologic analyses are used to characterize and explain streamflow and streamflow interaction with groundwater. Hydrologic analyses can determine the impact of watershed change on the hydrologic regime and can help identify where hydrologic change has caused impacts, constraints or other change in habitat. Hydrologic investigations are used to establish design flows – the discharge(s) used as the basis for design of channel, habitat, and floodplain features and components. Hydrologic analyses are foundational in habitat restoration design, as virtually every other design analysis requires the input of design discharge(s). Hydrologic analyses should be informed by watershed-scale assessment of land use that may impact hydrology as well as consideration of probable future climate change impacts (see *Climate Change* Appendix).

- *Hydraulics*. Hydraulics refers to the study of the behavior of fluids and energy associated with streamflow, which strongly influence habitat. Hydraulics is typically evaluated at the site and reach scale. Stream velocity and energy are a function of the interaction between flowing water and the channel boundary; stream energy affects erosion, deposition, and sediment transport, and also directly influences instream habitat conditions. Hydraulic analyses are typically performed through modeling and are important design resources and tools. Hydraulic models facilitate rapid comparison of many scenarios, including different alternatives or variable flows within a design. Hydraulic analyses are necessary for bank design (see Integrated Streambank Protection Guidelines), habitat design, sediment transport analyses, and predicting inundation and flood potential under varying flows.
- *Geomorphology*. Geomorphology is a geologic science that focuses on the processes that create landforms. Fluvial geomorphology is a specific discipline within geologic sciences focusing on river process and resulting forms. Geologic and geomorphic analyses are used to explain observed changes in channel forms and associated habitat, and to predict channel form outcomes. Geomorphologists identify inputs to and controls on channel processes and forms, such as sediment sources, natural grade control, and boundary characteristics. Geomorphologists evaluate the stability of the stream channel and how stability is influenced by human changes to the watershed, the channel, or its floodplain, and can assist in predicting channel and associated habitat outcomes from restoration actions.
- *Sediment Transport*. Sediment transport analyses are used to evaluate sources of sediment and the movement of sediment within a channel. These analyses are used to identify causes of channel stability problems and are useful for evaluating the performance of varying design scenarios. Sediment analyses are used to determine whether sediment transport capacity is balanced with sediment supply, and is frequently used as the basis for channel design. Sediment transport analyses require hydrologic and geomorphic information and may require expertise of both geomorphologists and engineers.

Besides the technical analyses described above that are necessary to perform many restoration designs, project development and design will benefit from interdisciplinary input and review from related scientific, engineering, and implementation disciplines, including:

- *Fish biology and aquatic ecology, including aquatic entomology*. Aquatic life scientists are essential for evaluating habitat conditions, determining species-specific life stage requirements, conducting population studies, and evaluating species community dynamics. The ultimate objective of many stream restoration projects is to restore aquatic habitat conditions, which highlights the importance of this discipline in the design process.

- *Botany and plant ecology*. Plant ecologists and botanists evaluate riparian condition, which determines the availability and quality of riparian habitat and influences channel stability, habitat structure, available energy, water quality, and hydrologic variables. This discipline is also crucial to the development of achievable riparian restoration objectives, methods, designs, and management.
- *Wildlife and conservation biology*. Wildlife biologists provide information and analysis of terrestrial, amphibian, and avian species that depend on and influence stream and riparian habitat.
- *Landscape Ecology/Watershed Science*. Landscape ecologists compile and evaluate broad-scale ecological and land use data using remote sensing, GIS, and other technology. Such data is useful to 1) determine the extent and distribution of habitats and problems within a watershed or ecosystem, 2) identify likely causes to those problems and threats to habitat, and 3) to make recommendations to preserve, restore, and enhance habitat.
- *Engineering*. The evaluation and design of restoration, rehabilitation, and other stream habitat projects often relies on analysis, modeling, and assessment provided by professional engineers with expertise in hydraulics, civil, environmental, sediment transport, and geotechnical engineering. Sediment transport analysis is typically conducted within engineering disciplines.
- *Geotechnical*. Geotechnical engineers evaluate soils and soil characteristics, particularly within streambanks, and their susceptibility to erosion under various flow conditions. Geotechnical analyses are critical to restoration design where streambanks are an integral component of a project or where hyporheic flow and exchange is an important consideration.
- *Construction*. Individuals familiar with construction are skilled at evaluating access availability, equipment requirements, and construction feasibility.
- *Survey and Drafting*. Survey and drafting expertise is often necessary or greatly facilitates the collection of base survey data for technical analyses, and is often necessary for construction implementation.
- *Project Management*: Restoration planning, design and implementation is a complex team process that requires experience with organizing, facilitating, and coordinating of multiple disciplines, schedules, permitting, budgeting, and construction and implementation.

The ecological and physical complexity of stream systems requires an understanding and appreciation of many disciplines within the natural sciences and engineering. The complexity of physical and ecological processes at play in a stream system may blur the distinction among disciplines. For example, analysis of sediment transport may require the expertise and perspective of *both* engineers and geomorphologists. A geomorphologist may be better able to assess watershed scale sediment balance and dynamics, whereas an engineer may bring added analytical expertise to conducting sediment transport analyses at the reach scale and in a modeled analytical framework. Similarly, a fish biologist may be best able to characterize habitat limitations, whereas a geomorphologist may be better able to determine the causes of those limitations from a channel-process perspective.

Further information on sciences fundamental to restoration, as well as relevant technical analyses, is presented in Appendices within this document as well as appendices within the *RiverRAT* document and appendices. The SHRG and *RiverRAT* appendices both provide a primer on the application of the science to stream habitat restoration, as well as deeper technical information. *RiverRAT* appendices also provide considerations for design and project review – including a set of questions intended to assist practitioners and reviewers to ensure they are considering the implications of the analysis. While these guidelines and *RiverRAT* represent a fairly complete discussion of fundamental sciences and analyses, readers may find that some related fields of science (e.g. conservation biology, aquatic entomology, landscape ecology) and engineering applications (e.g. surveying, drafting, project management) will require additional research beyond what is provided or referenced herein.

5.1.2 Conceptual Alternatives Evaluation and Selection

For any given habitat project identified in a restoration strategy, myriad alternatives, or suites of project components and techniques may exist to remedy the problem. Alternatives consist of different concept-level approaches to achieving project goals, and may include different combinations of techniques as well as a ‘no action’ alternative. An alternatives evaluation compares a number of concept-level designs and serves to justify the selection of treatments for stakeholders, permitting agencies, and funding entities, and documents the relationship between proposed actions or treatments and project objectives. Any or all alternatives may be valid. For example, where channel incision resulting from straightening of a channel has reduced habitat and hydrologically disconnected the floodplain, alternatives may include restoring the historical channel alignment and grade, installation of check dams and habitat features on the channelized reach to reconnect the floodplain, or lowering of the floodplain coupled with channel reconfiguration and habitat enhancement. A restoration plan may include any or all of these alternatives.

Chapter 4 presents restoration project development as a seven-phase process (see Figure 1), where design follows an evaluation of alternatives. In fact, alternatives evaluation is not necessarily separate from design, but rather often serves as concept-level design by identifying concept-level project elements. In analyzing alternatives, a conceptual level of design is developed and tested. The process is also iterative, where design analyses and details may reveal constraints or opportunities that compel changes to the restoration strategy, selected techniques, or other elements of the selected restoration concept.

The process of developing and evaluating alternatives may lead to preferred solutions that are ultimately more efficient to design and implement and reduce risk.

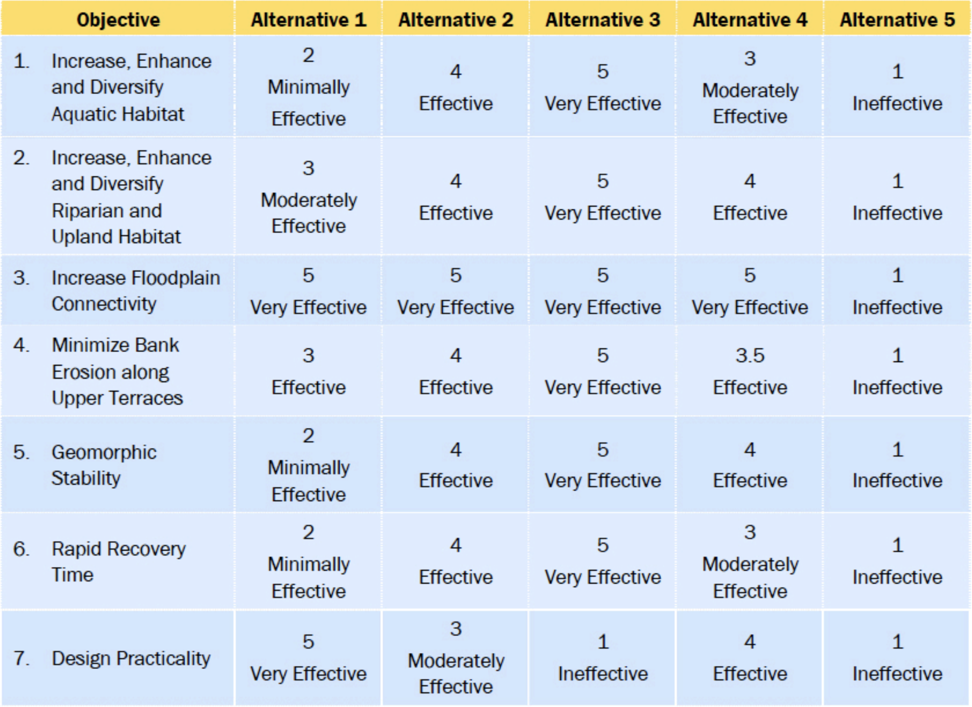
No project should proceed without formal consideration of alternatives that includes a no-action alternative. It is common practice for restoration practitioners as well as for project proponents to present only a single approach for consideration and to embark on design without due consideration of other alternatives. The risk inherent in this is that the preconceived best approach may not be the approach that best addresses all project objectives, all stakeholder interests, and all risks. Failure to evaluate alternatives can, and often does, lead to implementation of disruptive or unnecessary techniques, excessive cost, and potentially greater risks. Furthermore, an alternatives analysis can reduce the potential for bias, whether intentional or unintentional, on the part of either a design or implementation contractor that may have vested interest in alternatives that require a greater level of design or implementation. Even when a particular restoration project approach appears to be the obvious solution to all stakeholders, an alternatives analysis provides thorough justification for the selected approach, particularly where projects are publicly funded.

An alternatives evaluation includes a comparison of three essential components - (1) effectiveness, or benefits, based on predicted outcomes for each of the project's defined objectives; (2) risks, and (3) cost.

Effectiveness

Stream habitat restoration projects often proceed with little attention to predicting outcomes, on faith that implemented techniques and actions will achieve project objectives. Ideally, an alternatives evaluation will predict and compare outcomes relative to each project objective for each alternative. For example, where the restoration or creation of a particular habitat type is an explicit project objective, an alternatives evaluation will predict the actual amount of that habitat type for each alternative. While prediction of outcomes is a fundamental component of evaluating alternatives, the level of detail and confidence in predicted outcomes will depend on the extent of design conducted to evaluate alternatives. Purely conceptual alternatives, developed with a minimum of technical analysis, may require largely subjective predictions of probable benefits and effectiveness of each alternative. Table 1 shows a comparison of effectiveness of each of 5 alternatives for habitat enhancement of the Walla Walla River, WA,[2] where each alternative is evaluated somewhat subjectively, and given a rating ranging from ineffective to very effective.

Table 1. Comparison of alternatives for habitat enhancement of the Walla Walla River, WA[3],



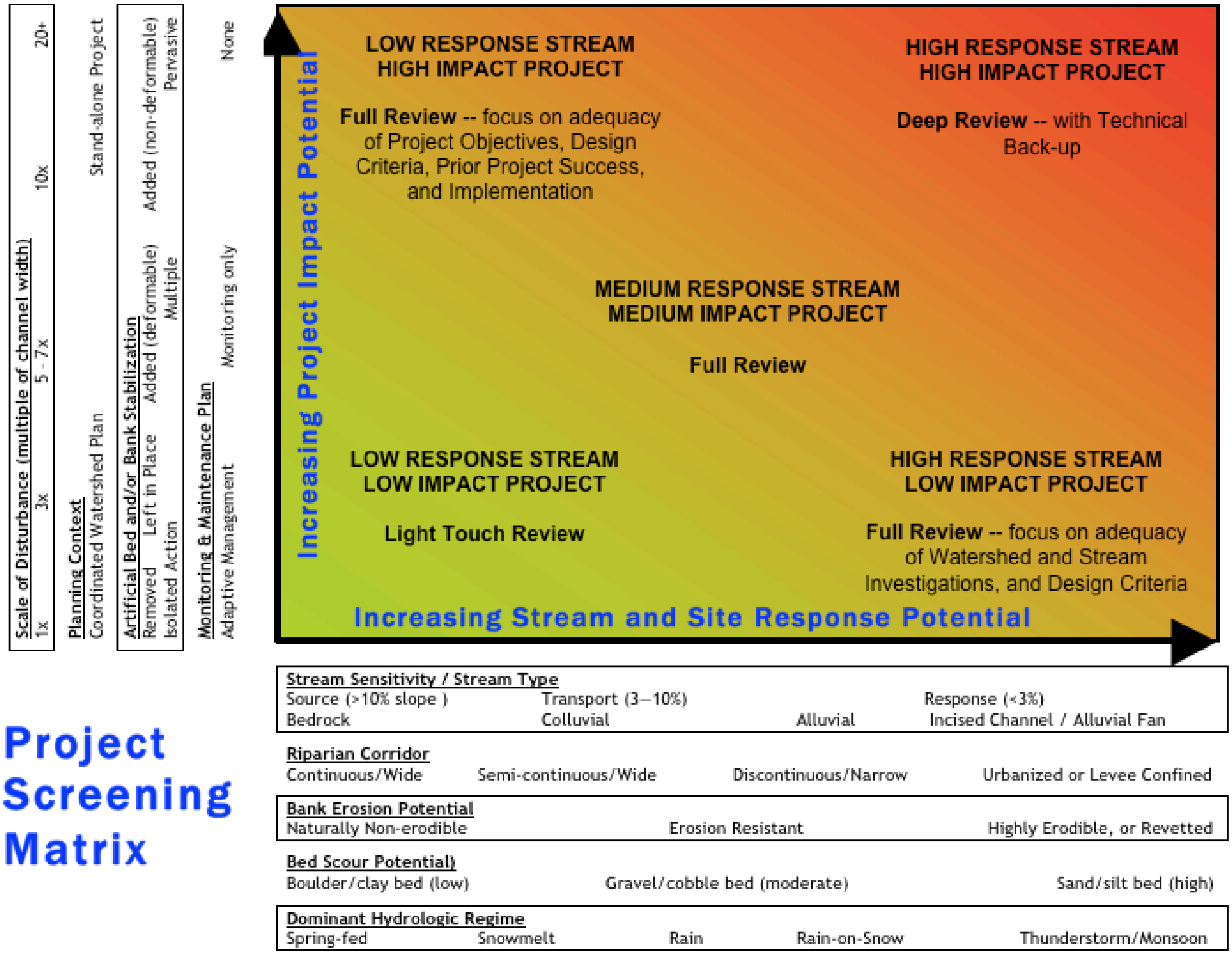
Objective	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
1. Increase, Enhance and Diversify Aquatic Habitat	2 Minimally Effective	4 Effective	5 Very Effective	3 Moderately Effective	1 Ineffective
2. Increase, Enhance and Diversify Riparian and Upland Habitat	3 Moderately Effective	4 Effective	5 Very Effective	4 Effective	1 Ineffective
3. Increase Floodplain Connectivity	5 Very Effective	5 Very Effective	5 Very Effective	5 Very Effective	1 Ineffective
4. Minimize Bank Erosion along Upper Terraces	3 Effective	4 Effective	5 Very Effective	3.5 Effective	1 Ineffective
5. Geomorphic Stability	2 Minimally Effective	4 Effective	5 Very Effective	4 Effective	1 Ineffective
6. Rapid Recovery Time	2 Minimally Effective	4 Effective	5 Very Effective	3 Moderately Effective	1 Ineffective
7. Design Practicality	5 Very Effective	3 Moderately Effective	1 Ineffective	4 Effective	1 Ineffective

The sustainability of an implemented strategy is an important element of its effectiveness. Sustainability refers to the capacity of a strategy or project to continue to be effective over time with a minimum of maintenance or interference. Activities that restore the natural rates and types of habitat-forming processes rather than creating specific habitats will generally result in greater sustainability. The design life (longevity) of most direct habitat creation projects, and particularly structural treatments such as log and boulder placements, will be related to the magnitude of hydrologic events and other disturbance events that may destabilize them. Because the magnitude of disturbance events is a largely unpredictable variable, particularly in light of changing climate conditions, it may be impossible to determine the longevity of created habitat. Furthermore, structural approaches may have design lives that exceed functional life. For example, while a structural approach may survive a design flow event, and last through a predicted design life, the function provided by that structure may be lost due to a change in the channel relative to the structure. A logjam placed to create scour, deposition and provide cover and spawning habitat may be left high and dry by a natural shift in channel location. Strategies that promote processes that create and maintain habitat will be more sustainable, and therefore effective, over long time periods.

Risk

Risk evaluation is an important element of evaluating alternatives. Risk can be defined generally as the combination of the probability of a particular event and the consequence of that event. Risk can be evaluated relative to aquatic species of interest (and the processes that support them), risk to property owners or infrastructure, public safety risk (refer to *Public Safety* Appendix), and social risk associated with perceptions of failure. Evaluation of risk is often a subjective, qualitative, and uncertain process. Nonetheless, it is a critical part of the process of comparing alternatives. For the purposes of alternatives evaluation, it may be sufficient to rank relative risk subjectively as ‘acceptable’, ‘tolerable’, or ‘unacceptable’ for each alternative. *RiverRAT*: Appendix 3.5 of the *RiverRAT* resource provides a comprehensive overview of uncertainty and risk, including techniques for accommodating uncertainty and risk in restoration planning and actions. *RiverRAT* also provides a Project Screening Matrix tool intended to help restoration planners evaluate the relative risk of a strategy or project to stream resources. The *RiverRAT* screening matrix (Figure 3) demonstrates that risk to aquatic resources is not a quality that is inherent to a given project type, but rather is dependent on the stream type and project context. (Refer to *RiverRAT* Section 1-1.1 for more information on the screening matrix.)

Figure 3. *RiverRAT* screening matrix. The screening matrix is intended to assist project reviewers in determining an appropriate level and emphasis for project review. It can also be used in project development to determine aspects of a project what may pose greatest risk to the aquatic resource. For detailed information on the screening matrix and its application, refer to *RiverRAT*.



Risk should be considered in both the long-term and short-term. Short-term risks are those associated with project implementation. Construction projects invariably involve some degree of disturbance. Long-term risks include those associated with the eventual failure of structural features or the potential for the project to have unexpected impacts over time. For example, elements of a constructed logjam may wash downstream and damage downstream property or infrastructure such as bridges. Long-term risks may also include anticipated or unexpected impacts upstream, downstream and adjacent to the site. For instance, installing a series of boulder clusters may constrict flow and cause bank erosion and flooding along a roadway. Risks that are commonly associated with specific techniques are discussed in the individual technique descriptions included as part of this chapter and in the *Public Safety* Appendix.

Cost

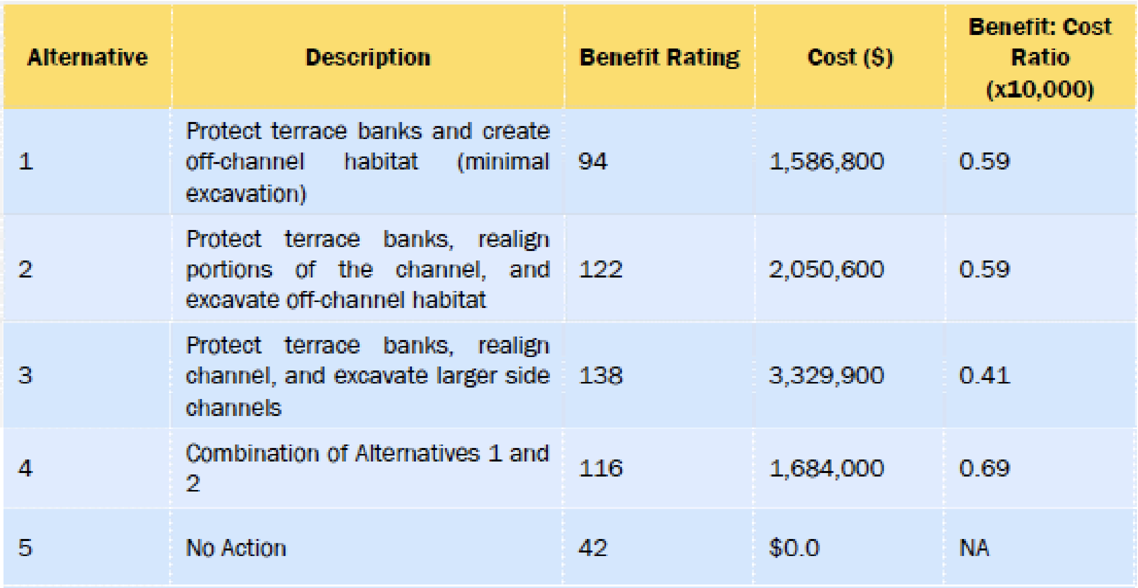
The cost of a project relative to the benefits it provides is one of several criteria commonly used to evaluate and prioritize alternative restoration projects and to examine the trade-off between pursuing restoration and maintaining current conditions. Ideally, a cost comparison will include all project-life costs, from the cost of assessment and design to implementation, and including long-term monitoring, operations and maintenance. Design costs can vary by alternative, and therefore should be incorporated in alternatives analysis. The cost of design for habitat restoration projects generally ranges from 15 to 50 % of implementation costs. This may be higher than that for traditional civil engineering works. The reason for this is that: 1) the same analysis is generally necessary whether the project is large or small so the percentage of implementation cost will be larger for smaller projects, and 2) habitat restoration projects are very site specific and it is generally not possible to apply designs used on previous projects to new ones. Monitoring, operations and maintenance are often excluded from cost comparisons, with the ultimate result that projects are typically not monitored, and operations and maintenance costs are not adequate.

A cost-benefit analysis has traditionally been employed where the value of benefits is expressed as a monetary equivalent or as a specific rating along some other numerical scale. The challenge in consideration of cost-benefit ratios lies in determining the monetary value of the benefit. Costs can usually be readily determined in dollar units; however, benefits are often impossible to translate to monetary benefit. Rather, benefits are usually based on anticipated recovery of habitat and production values for which a monetary work is, at best, difficult to ascribe. For example, benefits may be expressed as quantity of various habitat units created or expected increases in biological productivity (e.g. recruitment). Additionally, ancillary benefits may exist, such as a stabilized channel that prevents the future need for rock armoring or dredging, that cannot be easily measured. Consequently, the costs of varying alternatives are often considered independently of benefits and relative to available budget.

Comparison of alternatives

Alternatives evaluation is often best summarized using a matrix table that compares alternatives to project objectives and other evaluation criteria. Additional evaluation criteria may include implementation and maintenance cost, funding opportunity, sustainability or long-term persistence of restoration actions, timetable for achieving objectives, and social acceptability of alternatives. To facilitate the interpretation of alternatives comparisons, values derived for each objective under each alternative are often normalized and summed, producing a single value for each alternative. Alternatively, normalized values can be weighted to emphasize the importance of certain objectives or other evaluation criteria. In either case, a total benefit rating can be derived, and compared to cost, for a cost:benefit ratio. Table 2 illustrates the benefit rating, cost, and benefit:cost ratio for a habitat enhancement project on the Walla Walla River, WA[2].

Table 2. Benefit rating, cost, and benefit:cost ratio for a habitat enhancement project on the Walla Walla River, WA[2]



Alternative	Description	Benefit Rating	Cost ($)	Benefit: Cost Ratio (x10,000)
1	Protect terrace banks and create off-channel habitat (minimal excavation)	94	1,586,800	0.59
2	Protect terrace banks, realign portions of the channel, and excavate off-channel habitat	122	2,050,600	0.59
3	Protect terrace banks, realign channel, and excavate larger side channels	138	3,329,900	0.41
4	Combination of Alternatives 1 and 2	116	1,684,000	0.69
5	No Action	42	$0.0	NA

5.1.3 Design Criteria for Project Elements

Stream habitat restoration typically involves the design and integration of a suite of discrete project *elements* that are identified during concept-level design and that require design. Design criteria are used to define the intent and expectations for each project element. Design criteria are specific, measurable attributes of project features that clarify the purpose of each project element and articulate how each element will contribute to meeting project objectives.[4] Examples of project elements that warrant design criteria include streambanks, large wood structures, channel cross-section, channel planform, floodplain topography, floodplain revegetation, levee set-back, and connections to off-channel features.

The design process is typically segmented into discrete designs for each element, which are then integrated to form a complete design. For example, cross-section design can be performed using hydraulic models and specified discharge, such as a channel-forming discharge. Large wood structures can similarly be designed to fit in the design channel and to withstand anticipated forces derived from channel designs. These two elements must then be integrated – large wood structures will affect channel *roughness*, which will affect channel cross-section design. The integration of discrete project elements thus requires an iterative design process. The detailed design of each project element determines *how* the project meets specific objectives; the integration of project elements determines how the project meets overarching project goals.

Examples of design criteria include:

- Large wood structures will be constructed entirely from native and locally derived species and remain in place and functional under all flows up to the 25-year discharge for a minimum of 5 years.
- Created habitat will provide rearing refuge of specified species of native fish and will not strand adult fish.

- Installed/constructed habitat structural elements will be constructed using only materials native to the site or contributing watershed.
- Drop structures will provide for upstream passage of all native species during migratory periods.
- Created side-channel habitat will be accessible during all flows greater than 100 cfs.

For further examples of design criteria applied to specific techniques and project elements, refer to *RiverRAT* Appendix 2, or to Chapter 13 in Restoration of Puget Sound Rivers.[5]

While design criteria are often implicit in the design process, distinct advantages exist to the explicit definition of design criteria. Design criteria serve the primary purpose of clarifying the intent of each project element as well as its expected performance. This encourages dialogue among project stakeholders, project sponsors, design team, and permitting agencies, and facilitates a shared vision of how a project is intended to perform. Design criteria can greatly facilitate the integration of engineering practice with restoration practice by articulating specific design and performance expectations to engineers conducting design.[6]

Where design criteria serve the primary purpose of clarifying project objectives for the design team, design criteria also establish measurable attributes for project elements that can serve as the basis for post-project monitoring. Ideally, post-project monitoring will be conducted to determine whether a project has been successful and to learn what design and implementation methods worked. This can be greatly facilitated with design criteria that provide specific measurable attributes to evaluate during monitoring.

Design criteria for stream habitat restoration and design can be categorized relative to the process they are intended to define or the objective they are intended to meet. For example, the following attributes can be defined using design criteria:

- *Channel form*: Design criteria define channel capacity, variability, and channel geometry characteristics.
- *Deformability*: Design criteria define the degree to which a channel can adjust its boundaries vertically and laterally, the degree to which it is allowed to migrate within a defined corridor, and within what timeframe.
- *Floodplain function*: Design criteria define the frequency, timing, and duration of floodplain inundation as it relates to stream stability, riparian vegetation, and fish and wildlife habitat.
- *Aquatic habitat*: Design criteria define what species, life stages, or limiting factors are targeted, or what degree of habitat and species diversity is to be achieved.
- *Timeframe*: Design criteria define the timeframe during which objectives are to be met, and may specify both durability and longevity.

Design criteria for many project components of channel and stream habitat design can be related to hydrologic events, such as the design flood, dominant flow, high fish passage design flow, or low flow conditions. Projects requiring full channel restoration or reconstruction may require a suite of design discharges to adequately meet project objectives. A low-flow design discharge may be necessary to design certain habitat elements (such as pool depth); a high fish passage design flow will be necessary to ensure individual structures (such as culverts, fishways, and drop structures) provide unobstructed fish passage; a dominant-flow design discharge may be necessary to design channel components that relate to geomorphic function (such as cross-section and planform); and a flood-level design discharge may be necessary to design certain habitat elements within the floodplain (such as off-channel habitat) and project components in the channel or floodplain that are expected to remain stable up to some maximum flood event.

Two classes of design criteria exist – performance criteria and prescriptive criteria. Performance criteria define *what* a project will achieve and the duration of benefits, while prescriptive criteria define *how* the project will be undertaken. Performance criteria "describe the required performance or service characteristics of the finished product or system without specifying in detail the methods to be used in obtaining the desired end result."[7] The difference between the two types of design criteria can be illustrated by considering the following set of paired performance and prescriptive criteria:

Performance Criteria	Prescriptive Criteria
Large wood structures will remain stable through all flows up to the 25-year discharge	Log structures will be constructed with cables and anchors
Constructed habitat will support specified species of juvenile fish for 10 years	Create 10 acres of off-channel rearing habitat varying in depth from 1 to 3 feet
Provide upstream passage for adult chum during all migratory period flows	Install drop structures of 0.8-foot or less at all flows during all migratory period flows
Floodplain inundation of at least 50% of floodplain area will occur with an average frequency of 2 years.	Create a channel with a width:depth ratio of between 12 and 16

Design Criteria and Monitoring

Design criteria developed as performance criteria can facilitate the development of a monitoring plan capable of measuring project performance relative to the established project goals and objectives. For example, performance criteria for a channel modification project intended, in part, to enhance salmonid spawning habitat may include the expectation that a minimum number of redds will be established by a specified species over a specified timeframe. Monitoring plans to evaluate these performance criteria will include redd counts and will document species and timeframe. Monitoring plan and protocol development is further discussed in the *Monitoring* Appendix.

Prescriptive criteria can also be used as the basis of a monitoring plan, though such monitoring is better suited to evaluating the applicability of specific practices to specific circumstances rather than to evaluating project success. For example, prescriptive criteria may dictate the number of logjams placed and the method of anchoring. (In contrast, performance criteria associated with logjams may specify fish use of habitat created by the jams over time). By comparing post-project counts of logjams to pre-project prescriptive criteria, the success of individual project components can be evaluated (e.g., that the prescribed anchoring method was adequate for the setting). However, this may not provide any meaningful information regarding the project objective of providing habitat, as this does not indicate fish or wildlife use. Only *performance* criteria can be used to determine if the project objectives related to fish or wildlife usage of habitat created by the logjams were achieved.

Carrying this example further, with prescriptive criteria dictating the number and anchoring method of logjams, a project may be deemed unsuccessful if the jams became dislodged before the end of the intended project life. Yet the jams may re-form in another location, with the same wood, in the same reach and continue to provide desired habitat function. Thus, monitoring conducted using a plan that is based on habitat-related performance criteria may indicate project success; while monitoring conducted using a plan based on structure-related prescriptive criteria may indicate a failed project, even though project objectives (increased habitat associated with logjams) were achieved.

5.1.4 Design Stages, Products and Approach

Project design involves developing specific requirements for all project elements, integrating these elements into a comprehensive design, and articulating expectations for project implementation through design products, i.e. plans, specifications, and a design report. The following sections describe typical and generalized: (1) design stages (conceptual design, draft design and permitting, and final design); (2) design approaches (analog, empirical and analytical); and (3) design products (plans, specifications, and reports).

5.1.4.1 Design stages

Project design typically occurs in a number of stages, generally categorized as concept-level design, draft or intermediate design, and final design. The Washington State Salmon Recovery Funding Board (SRFB) suggests a similar and parallel sequence for development of project design stages, referenced in Table.[8] The nomenclature applied to phasing of the design process varies depending on specific nature of the project, requirements of funding entities or project sponsors, and among design teams. The simple categorization described in Table 3 represents a generalization that captures the general intent of most project design phasing – that is to provide interested parties opportunity to review and provide input to the design process as it progresses. The varying nature of permitting requirements and stakeholders' interests may suggest more, or less, intricate phasing and involvement through the process. Some entities define design phases according to percent complete – this refers generally to the percent of total effort and design budget allotted for each phase. The correlation of percent complete to project phases also varies substantially.

Table 3. Design Stages. Project design stages vary significantly by project, but can be generally categorized as three stages. The percent complete refers primarily to level of design effort and budget expended. Likewise, products expected or required for each stage vary significantly among projects.

Stage	Percent Complete	Intent	Products
Conceptual design (feasibility study)	10-30%	• Description of problem and the project site • Develop concept-level project elements • Evaluate, compare, and select preferred alternative • Indentify project goals and objectives • Identify project elements • Define design criteria for all project elements • Communicate and document selected design alternatives and project elements to stakeholders, including permitting and pubic safety	• Evaluation of alternatives and discussion of the pros and cons of each alternative • Concept-level plans depicting all project elements • Design criteria for all project elements • Rough cost estimate
Preliminary design	30-70%	• Data analysis and develop preliminary designs for all project elements; ensure they are consistent with project objectives • Provide sufficient justification and detail for permitting submittals (depending on permit) • Communicate and justify design methods, approach, and assumptions for stakeholders and permitting	• Evaluation of alternatives and selection of preferred alternative. • Draft plans depicting all project elements • Draft design report • Preliminary cost estimates
Final design	90-100%	• Provide final details and ensure integration of all project elements • Provide final permit requirements (depending on permit) • Scenario modeling to ensure final design will provide for project objectives • Prepare plans and specifications for contracting and bidding • Relate project design to monitoring requirements • Communicate and document design methods, assumptions, and justification of all design details for stakeholders and posterity	• Final design report • Plans and specifications • Contracting and bidding documents • Monitoring plan • Final cost estimate

Conceptual designs are commonly developed to identify and communicate project components as they relate to project objectives. A concept level of design is used for alternatives evaluation, where a number of concepts are developed sufficiently to address project feasibility and to predict outcomes of each concept and to select an alternative. It is typically portrayed using plan schematics that illustrate all proposed project elements and an accompanying concept report that explains and justifies the elements and how they were selected. This level of design provides a platform for the project owner, permitting agencies and other stakeholders to review project components at an early stage and to develop consensus on an implementation approach. A selected concept will then be carried forward to identify all necessary design components and to develop design criteria for these components. Development of conceptual designs typically requires sufficient level of technical analysis of topographic information, hydrology, geomorphology and hydraulics to ensure feasibility of proposed concepts. Conceptual design may represent as much as 30% of design effort and budget. In the SRFB categorization, the analysis and selection of alternatives may be conducted either in the context of conceptual design or carried into preliminary design.

Preliminary design is an intermediate step between concept design and final design and may be necessary or adequate for permitting. This phase of design typically includes plan views and profiles of any project elements and standard details for their implementation. Individuals reviewing intermediate plans should be able to interpret exactly where the project will be built and where project impacts will occur. It typically involves conducting technical analyses sufficient to determine how design of each specific project element will meet design criteria for those elements, and ensures the integration and compatibility of project elements. The extent to which preliminary designs are reported and presented depends on expectations and requirements of varying audiences, and may require multiple intermediate phases for complex project designs. Preliminary designs may be adequate for permitting requirements. Where permitting requires further level of design detail and justification, preliminary designs should be submitted to permitting agencies where opportunity still exists to accommodate permit-specific interests without the costs and time associated with making those changes later in the process.

Ideally, preliminary design involves scenario modeling to ensure that the predicted outcomes of the proposed restoration project are consistent with project objectives. Prediction of outcomes is a fundamental element of project design and can often be evaluated with little additional design effort using existing design analyses and models, and through scenario modeling, which simply entails running the same outcome models with varying input values. For example, a hydraulic model used for design of a channel configuration will indicate water surface elevation and velocity for a given input discharge and a given roughness coefficient. Once the design model is established, running scenarios, such as varying roughness to account for increases in vegetation over time, can be useful for predicting outcomes. The scenario models developed during draft design can be further refined through the final design process.

Final design includes conducting detailed design analyses sufficient to develop all final design details, including plans and specifications necessary for implementation. The required level of analysis in design will depend greatly upon the technique selected, site conditions, project goals and objectives, who will be conducting construction oversight, and the acceptable level of risk. Regardless of the level of analysis conducted during the design process, the designs should be sufficient to ensure that the established criteria can be met. Final design products typically include plans and specification sufficient to support contracting and bidding, or perhaps the contracting and bidding documents themselves. Additionally, final design may include a monitoring plan, or draft monitoring plan. The development of monitoring plans in conjunction with final design documents promotes monitoring that is feasible and appropriate to measure project objectives.

5.1.4.2 Design products

Design products include primarily plans and specifications and design reports. It is common to develop sequential, or draft versions of these products in conjunction with the design phases described previously (see Table 3). In total, design products at any phase need to be sufficient in detail to explain and justify the project plans and to describe the project to varying audiences, including:

- Stakeholders, project owner, and funding entity
- Permit agencies
- Project implementation team, including contractors and project engineers
- Monitoring team

Plans and Specifications

Plans typically include a location map, plan views of existing and proposed conditions with boundaries and survey controls, drawings of project elements, their spatial arrangement and placement, and details of how to construct or implement them, as well as the locations of project areas including staging, protected areas, and project sequencing information. Specifications are detailed descriptions of how to implement elements, descriptions of acceptable or required materials, methods for placement, sequencing and timing requirements, and methods of measurement and payment for contracting. Examples of plan drawings are provided for most techniques. Further information regarding construction is provided in the *Construction* Appendix.

Plans and specifications may be presented in draft and final formats, in conjunction with draft and final designs. The amount of information and detail provided in the plans and specifications should reflect the level of design analysis, the risks associated with project implementation, and the objectives of the project. For example, a project involving the installation of large wood to address a deficiency of wood in a remote stream may include typical installation guidelines (e.g., obstruct X% of the bankfull channel, stabilize the logs by burying X% of their length, interlocking the logs, or pinning them between two or more live trees on the bank), and specify the number and general location of large wood complexes (e.g., along the outside bank of meander bends) and the number of pieces of wood within each complex, but ultimately rely on the experience and judgment of the construction supervisor to select the specific location and orientation of each individual log and the installation methods. Alternatively, a large logjam structure placed in close proximity to critical infrastructure (e.g., upstream of a bridge) that is intended to protect a streambank in addition to providing related habitat may require detailed plans and specifications that illustrate the placement and orientation of each piece of the structure, anchoring methods, depth of installation, and other design details.

The contracting mechanism and nature of the project will also dictate the necessary level of detail in plans and specifications, or vice versa. A contracting mechanism that solicits lump sum bids for completed project elements will require substantial detail in plans and specifications, sufficient in detail for a contractor to determine all implementation costs in advance, while a contracting mechanism that solicits time and materials unit cost bids may allow for lesser detail in plans, and rely on the construction supervisor to implement according to his/her judgment.

Design Report

A design report documents the design process - it explains and justifies the design methods and analyses applied, describes outcomes for each project element, and documents assumptions applied in the design process. Detailed outputs from analyses and modeling are often included as appendices. A design report provides the critical function of relating the design process to project objectives and design criteria, and creating a record of how specific designs were developed. Design reports may be developed in stages that parallel the design process (Table 3 above). For example, the concept design process often includes preparation of an alternatives evaluation report that documents the process and justifies the selection of a preferred alternative. The amount of detail required in a design report at any stage of design will vary among projects and audiences, but should be sufficient in detail for a reader not previously involved in the project to understand how *and why* a design was conducted and how and why each project element contributes to meeting project objectives. When reviewing project performance in future years, a lack of detail in design reports makes it difficult to determine the reasoning used in preparing the project design or what the original problems were. For each project element and design analysis, a design report should address *why* a design analysis was performed, *how* it was performed, *who* performed the analysis, and *when* in the process it occurred.

An example final design report outline is provided below. Design reports vary in their organization and level of detail. Design reporting commonly follows a sequential or scientific organization. The outline suggested below, however, focuses on making information accessible to a broad audience (permitting, stakeholders, researchers) by emphasizing information that justifies the selected project elements relative to watershed conditions and project objectives. It also provides for detail in description of the design process, methods, assumptions and outputs in two levels of detail – as a summary of analyses as they relate to project intent within the report, and as appendices to the report that document details of design analyses and computations.

Example Design Report Outline

A. Purpose and need for the project
  - Goal
  - Objectives

B. Existing conditions
  - Problem description - description of habitat or process constraints that are limiting
  - Watershed description and summary of watershed, biological and water quality factors as they relate to project conditions
  - Site history and constraints that have led to observed problems and present challenges to restoration
  - Cause of problem assessment – description of identified causes of constraints at multiple and relevant scales

C. Preferred alternative selection-rationale
  - Summary of alternatives considered
  - Justification of selected alternative

E. Project description – Techniques to be applied

- Project elements – a listing and description of project elements (techniques) as they relate to objectives
- Sequencing and implementation – description of the implementation process that addresses anticipated permitting requirements, work windows, access, constraints, and other construction considerations

F. Design considerations and analyses
  - Design criteria for project elements – listing of specific design criteria for each element
  - Design methods and references – justification and documentation of design methods applied, including assumptions that facilitated design
  - Design output – analytical *results* of all technical and design analyses and how these are translated to project element designs

G. Final design drawings and construction estimate

H. Appendices
  - Technical analyses– summary of data sources, limitations and assumptions necessary to conduct analyses
  - Computations relating design to analysis, and assumptions
  - Analytical and model output summaries
  - Permitting activities and how review comments were addressed in the final design
  - Construction strategies to address implementation risks

The advantage of providing comprehensive design reporting are many: it allows for design review by varying audiences including internal team review, permit agency review, and future post-project appraisal review of design as it relates to eventual project performance. The *RiverRAT* resources provide a comprehensive *Project Information Checklist* of information to be included in a design report. The information listed in the RiverRAT checklist is roughly organized according to requirements or guidelines for reporting a Biological Assessment, but can be adapted to design reporting for virtually any application.

5.1.4.3 Design approach

Stream restoration design is an evolving and multidisciplinary field, where the specific expertise, training, or lack of training of those involved often dictates the emphasis on approaches to design. While a number of stream restoration guidelines and manuals exist, no accepted standard of practice exists.[1] While approaches to design of natural channels and associated project elements are varied, a general categorization[9,10,11,12,13] indicates three generalized approaches: analog, empirical, and analytical. The primary differences among these approaches, and the appropriateness of their application to varying levels of design, relates to the availability of information and data about the physical processes governing the project area and the extent to which these processes and watershed conditions have changed over time. These approaches are summarized below; for additional discussion and details regarding the limitations and opportunities afforded by each approach, as well as questions to ask in review of technical approaches, refer to *RiverRAT* Appendix 2. (http://www.restorationreview.com/downloads/Science_and_Tools_Appendices_2010.pdf). The three approaches can be applied at any scale, from the design of a single project element or structure to reach-scale channel reconstruction. For many project elements, the design process may warrant application of a combination of these approaches. Similarly, different approaches may be used for different project elements, such that a complete design applies varying approaches appropriate to varying project elements.

Analog approach

The analog approach uses templates from adjacent or historical channel characteristics as the basis for design of habitat elements or natural stream channels. It is also referred to as the "reference reach," or "template" approach. Analog design is the most intuitive approach, as it is based on copying observed patterns from similar or desired channel forms in adjacent or historical channels. They can be applied with a minimum of analysis at virtually any scale. However, they must inherently be based on an assumption, or confirmed through analysis, that the reference reach is in equilibrium *and* is representative of the flow, sediment, and boundary conditions at the project site. Where the analog approach can greatly simplify design, a significant discrepancy between any of the major variables (flow, sediment, boundary conditions, slope) of the analog and project reaches generally invalidates this approach. Similarly, it is important to consider that an analog approach may be inappropriate when considering probable change in future conditions resulting from climate change, particularly in watersheds that are likely to experience significant change in hydrologic parameters.

Empirical approach

The empirical approach uses empirically derived equations, derived from local, regional or global data sets, that relate various stream and channel parameters (e.g. channel width as a function of watershed area). It is also referred to as a 'hydraulic geometry' approach. Empirical equations represent average conditions by reducing the range of variables from multiple observations to derive predictive formulas. The empirical approach is similar to the analog approach in that it uses observations from existing stable stream systems as the basis for design of a project reach. As such, the same limitations on applicability of the approach apply – the major variables governing channel processes among the empirical data set must be similar to those at the project site. Integrity in application of empirical approach necessitates careful examination of the source of empirically derived data as well as the confidence limits and range of values represented by empirical equations.

Analytical approach

Analytical approaches to design apply theoretically-derived equations for flow hydraulics and sediment transport to develop channel geometry that balances sediment transport with channel configuration. It is also referred to as the 'predictive' or 'process-based' approach. A distinct advantage is that the analytical approach allows for the simulation of process-response mechanism in channel design. This is particularly useful for unstable or rapidly evolving stream systems. Limitations on the applicability of the analytical approach are less restricted than for analog and empirical because no pre-requisite of stable or equilibrium conditions exist. The dominant limitation on the analytical approach is the availability of data sufficient to characterize input variables of hydrology, sediment, and boundary conditions.

Stream habitat restoration design, in practice, often requires a hybrid approach, where elements of analog, empirical and analytical design are applied as appropriate, generally dictated by the relevance of analog conditions and availability of data. Analog, empirical, and analytical design may be applied independently among project elements; however, an analytical approach is generally required to predict and test outcomes.

5.2 Techniques Included in this Guideline

Chapter 5 describes a suite of techniques commonly applied to stream habitat restoration projects. Any given project may involve one or more of these techniques as part of an overall restoration project plan. Chapter 4 presents an approach to developing a restoration strategy, including selection of appropriate projects and their component techniques. It is important to note that any given technique is not a restoration strategy in and of itself, but is instead a part of an integrated strategy that has been developed through the analysis and design processes described in Chapters 2 through 5. A variety of techniques that can be incorporated into a comprehensive strategy, either individually or in concert, are described below. Information presented for techniques is intended to describe how the technique can be applied to a restoration strategy, special considerations for design and permitting of the technique, implementation considerations and costs, monitoring and maintenance considerations, and specific project examples. The techniques present what the authors consider to be the best available science, as well as the most practical resources, for each method. The information provided represents the integration of material available through other guidelines and the literature, as well as the experience of the authors and contributors to this document.

The intent of the following techniques is not to provide a “cookbook” that walks you through every analysis that may be required to design and implement a technique. The reason for this is that design of many of the techniques described herein generally requires substantial input from an interdisciplinary team. Attempting to serve as a complete resource for practitioners with varying levels of knowledge of each discipline would be a daunting task both for the readers and the authors. Additionally, many projects will require site-specific and project-specific criteria to meet varying interests, objectives, and constraints. As such, the following techniques focus on providing readers with a comprehensive list of factors to consider when planning, designing, and constructing stream restoration work. Design criteria are suggested and, when appropriate, references for additional design guidance are provided.

Techniques detailed in these guidelines include:

1. Dedicating Land and Water to the Preservation and Restoration of Stream Habitat
2. Channel Modification
3. Levee Modification and Removal
4. Side Channel / Off-Channel Habitat Restoration
5. Riparian Restoration and Management
6. Fish Passage Restoration
7. Nutrient Supplementation
8. Beaver Re-introduction
9. Salmonid Spawning Gravel Cleaning and Placement
10. Instream Structures
11. Large Wood and Logjams
12. Bank Protection Construction, Modification, and Removal
13. Instream Sediment Detention Basins
14. Floodplain Fencing

The suite of techniques listed includes those that are typically associated with process-based approaches as well as those associated with structure-based approaches that do not necessarily restore underlying processes. In the later case, these techniques are nonetheless included because they have other utility in their application, particularly in situations where true restoration of channel processes may be impossible given political, social, and physical land use constraints, such as those found in highly urbanized stream systems. For example, stable instream structures are commonly incorporated in restoration strategies where channel stability has been significantly compromised by channel manipulation or changes in watershed controls. In this sense, they are stabilizing features intended to constrain the stream and create static, rather than dynamic, habitat conditions. This may be appropriate or necessary in severely degraded systems. Similarly, techniques that address only the symptoms of habitat degradation (e.g., instream sediment detention, spawning gravel cleaning, bank stabilization) are included here because they have some application to stream habitat restoration under limited circumstances or when used in conjunction with other techniques.

The collection of techniques presented herein is not a comprehensive list of all stream habitat restoration, rehabilitation, enhancement, and creation techniques, nor is it intended to limit the designer. It does not include:

- Watershed management and Best Management Practices (BMPs). These include a wide range of watershed management techniques that address point and non-point source pollution and runoff, slope stability, and changes in sediment supply, large wood supply, and flow regime. Although these are not included, they may be necessary to address the root cause of habitat degradation as outlined in Chapter 4.
- Land use planning and establishment of protective regulations that is critical to the long-term success of restoration.
- Wetland restoration. Wetlands are often integral components of stream and floodplain systems, but are not presented here except where channel, riparian, or floodplain habitat can be considered wetland habitat.
- Estuary Restoration (topic of a proposed future Washington State guideline)

5.3 Information Included Within Each Technique

Each technique in this guideline includes the following information:

1. *Description*: A general explanation of the technique.
2. *Physical and Biological Effects*: A discussion of the potential benefits and impacts resulting from implementation of the technique.
3. *Application*: When, where, and why to use the technique, and under what conditions it may be appropriate or inappropriate.
4. *Risk and Uncertainty*: A discussion of the risk to habitat, to infrastructure and property, and to public safety (see *Public Safety* Appendix), and of the uncertainty in application of the technique.
5. *Methods and Design*: How to design a project using the selected technique, including data to collect, analyses to conduct, variations and methods of application, and references to additional resources for design guidance.
6. *Permitting*: Permits that are typically required to implement the technique. A more thorough discussion of permitting considerations is presented in the *Typical Permits Required for Work In and Around Water* Appendix.
7. *Construction Considerations*: Aspects of the technique that may require special

consideration with regards to construction. A more thorough discussion of construction considerations that are common to all or most techniques is provided in the *Construction* Appendix.

8. *Cost*: A typical range of costs for materials and construction and the elements that affect cost variability. The cost of materials, hauling distances, and site access can differ dramatically among projects and can overwhelm typical project costs.
9. *Monitoring*: Special considerations for monitoring that are not otherwise presented in the *Monitoring* Appendix.
10. *Maintenance*: Short and long-term maintenance requirements.
11. *Examples*: Descriptions and photos of example projects using each technique are presented. Conceptual drawings are also provided.

5.4 References

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TECHNIQUE 1

DEDICATING LAND AND WATER

Dedicating Land And Water

1 DESCRIPTION OF TECHNIQUE

Dedicating land and water refers to the protection of watershed and stream corridor lands and instream flows for the primary purpose of supporting stream ecosystem processes and functions. Land and water protection is generally a priority strategy for stream restoration and conservation (see Chapter 4). Dedicating land or water for stream conservation or restoration requires the integration of conservation planning with legal aspects of land ownership, land use, and water rights.

The Dedicating Land and Water technique may be the main emphasis of a stream habitat restoration project, or it may be a component of a broader set of techniques implemented in concert. Dedicating land or water is often an important supplemental action to ensure that other actions are viable. Because restoration practice is most effective when it addresses the root causes of problems rather than the observed symptoms, a robust assessment that looks at potential causes at site-, reach- and watershed-scales will contribute to a more effective restoration strategy.

Dedicating Land

Three realms for land protection exist in descending order of scale, they are:

- Upland – to protect against land use impacts to hydrology and sediment.
- Channel corridor – to provide dynamic geomorphic channel processes, floodplain connectivity, or shallow aquifer recharge.
- Riparian buffers – to provide a buffer for water quality, protect against erosion, provide a source of large wood, provide shade, and potentially improve hydrologic storage capacity.

Generally, the most practical and important is protection of the stream corridor. Stream corridors are often delineated as a channel migration zone (CMZ). Protection of the CMZ or a portion thereof provides:

- Riparian buffer – water quality buffer, shade, water storage capacity, wood and organic recruitment
- Floodplain and riparian habitat and function
- Floodplain and side channel connectivity and function
- Resiliency – the capacity to rebound from disturbance, including room for stream to adjust to stochastic disturbance or disturbance trends such as from climate change

Mechanisms for protecting land may be permanent or temporary. General mechanisms for permanently dedicating land include:

1. Conservation easements – a legal agreement between a landowner and a qualified land trust or government entity that permanently limits uses of the land to protect its conservation values. Conservation easements allow the landowner to continue to own the land, offer great flexibility, and can be crafted to accommodate the interests of conservation and the property owner.
2. Fee simple – the most common way to own land and usually the most complete and enduring form of protection. When a conservation entity holds a property in fee simple, it can protect the property against development or detrimental use. Deed restrictions may be placed on the property to ensure management in perpetuity consistent with conservation objectives.
3. Public lands – transfer of ownership to a public entity or agency whose intent in management is conservation.

Additional land protection programs focus on land use for some finite term, rather than permanently and include:

- Temporary land use restrictions – agreements between landowner and some other entity to restrict land use within stream corridor or upland that affects the stream, such as riparian fencing and grazing agreements.
- Conservation Reserve Program (CRP) (http://www.fsa.usda.gov/FSA/webapp?area=home&subject=copr&topic=crp). The Conservation Reserve Program is a federal program aimed at reducing sedimentation in streams and lakes, improving water quality and establishing wildlife habitat. CRP encourages farmers to convert highly erodible cropland or other environmentally sensitive areas to native habitat. Farmers receive an annual payment for the term of a multi-year contract.
- Conservation Reserve Enhancement Program (CREP) (http://www.fsa.usda.gov/FSA/webapp?area=home&subject=copr&topic=cep). The Conservation Reserve Enhancement Program (CREP) is a voluntary land retirement program that helps agricultural producers protect environmentally sensitive land, decrease erosion, restore wildlife habitat, and safeguard ground and surface water. CREP is an offshoot of CRP that addresses high-priority conservation issues of both local and national significance and may emphasize riparian restoration.

Dedicating Water

Dedicating water refers to actions taken to restore or protect instream and normative flows for the primary purpose of protecting instream habitat. A normative flow regime consists of a range of flows that perform many environmental functions related to habitat and aquatic ecosystem function, including low flows that provide aquatic habitat, channel-forming flows that create and maintain physical channel habitat, and flood flows that maintain many instream and riparian functions (refer to *Hydrology* Appendix for further discussion of types of flows). While the expression ‘normative flow’ is defined and used differently by different jurisdictions and scientists, it is generally used to characterize a range of flows needed to meet a range of environmental functions. Normative flows and instream habitat are affected when water is taken out of the stream or its connected aquifer for traditional uses (agricultural, municipal, and industrial), or when flow is impounded and regulated thereby changing the timing, duration, and magnitude of flows.

Dedicating water to instream habitat may involve preservation or restoration of instream flows through water rights mechanisms, such as Trust Water Rights (Chapters 90.38 and 90.42 RCW), or short-term leasing of a water right to benefit flows during a drought, or changing the management of impounded flow – this technique emphasizes instream water rights opportunities. Management of regulated flow is an important tool for habitat management, but often requires substantial and sophisticated multiparty legal negotiations and analysis (refer to the *Hydrology* Appendix for resources for analysis of regulated flows). Efforts to restore or protect instream flows are often focused on minimum flows and an emphasis on protecting summer base flow. However, instream flow rules also address channel maintenance flows and fish life history stages such as spawning, incubation, and rearing. Channel maintenance flows, flows needed to sustain varied ecological processes, as well as those necessary for specific life stages of specific species, are sometimes collectively referred to as *environmental flows*[1]. In regulated rivers, these other components of the flow regime may be significantly altered and impacting stream processes and habitat. In recent years stream ecologists, hydrologists, and geomorphologists have attempted to provide guidance for less frequent higher flow needs of streams[2]. However, environmental flow determination should give careful consideration to other interests. As mentioned above under Dedicating Land, protecting the natural landscape and vegetation in the upper watershed is essential to maintaining the hydrology that provides the diverse functions of environmental flows.

2 PHYSICAL AND BIOLOGICAL EFFECTS

SHRG and other stream restoration guides emphasize restoration of physical habitat elements and the processes that create and sustain habitat. Processes are facilitated by and often require ‘healthy corridors’ to be fully functional. Functional corridors can only be guaranteed by dedicating land through some mechanism that protects land within the corridor from development, channel or bank armoring, or other constraints. Restoration of habitat within the channel may provide only short-term value if the processes that sustain the habitat are constrained, or if the stream does not have sufficient room within its corridor for dynamic processes (Refer to Chapter 2 and *Fluvial Geomorphology* Appendix). Protection of stream habitat restoration investments, through easements, zoning, and buffer strips, and instream flow protection, is listed as a guiding principle of stream management and restoration in RiverRAT[3]. Particularly in light of the uncertainty resulting from future climate change, the capacity for streams to rebound from disturbance in restored stream systems may depend heavily on the capacity for dynamic evolution within a stream corridor.

3 APPLICATION OF TECHNIQUE

Protecting stream ecosystems from constraints imposed by development of floodplain and riparian lands, encroachment of infrastructure, and from intensive land use within floodplains, especially fill, is a critically important stream habitat restoration and conservation strategy, simply because it provides for the dynamic floodplain and stream processes that create and maintain instream habitat. Equally important is the protection of instream and normative flows. Stream processes within a protected corridor may be constrained by flow regulation that constrains channel-forming flows and existing physical habitat may be rendered inaccessible or inadequate due to depleted flows. Where streams have the opportunity to adjust their boundaries and channel character in response to disturbance or to evolve in response to changing inputs and boundary parameters (such as from climate change or land use within the watershed), the need for restoration can be greatly reduced, and the effectiveness of restoration can be significantly improved. Dedication of land and water should be considered as a supplemental project objective on every project. Without protections in place, no way exists to ensure that restoration efforts will provide lasting benefit. Federal stream mitigation policy (administered under the Clean Water Act Section 404) typically requires that lands used for mitigation be placed under easement to ensure mitigation value in perpetuity.

The protection of lands and water associated with stream restoration or fishery restoration goals is most important to protect (1) habitat designated as refuge for aquatic species or as priority watersheds for native species conservation, (2) streams or stream segments designated as critical habitat under habitat conservation plans or for species recovery plans, and (3) for projects whose objectives explicitly include reconnecting floodplains, setting back levees, creating or reconnecting side channels, and enhancing or restoring riparian habitat or buffers.

Diverse plans designating priority conservation areas exist in Washington, including but not limited to the following:

- *Ecoregional assessments*. WDFW and WDNR partnered with The Nature Conservancy to develop ecoregional assessments for nine ecoregions that cover Washington. Each assessment identifies priority conservation areas. (http://waconservation.org/projects/planning/)
- *Washington Freshwater Assessment*. The Nature Conservancy conducted an assessment of freshwater biodiversity in Washington as a conservation planning resource and identified priority watersheds for conservation of aquatic biodiversity. (http://waconservation.org/projects/planning/)
- *Wildlife Action Plans*. WDFW has developed Wildlife Action Plans as a conservation planning tool. (http://www.wdfw.wa.gov/conservation/cwcs/)
- *Columbia River Instream Atlas Project (CRIA)*. WDFW compiled existing data products and best professional knowledge to provide tools (workbooks, maps, reports, GIS data) to aid in prioritizing stream reaches for flow restoration and augmentation. CRIA provides detailed information for 189 stream reaches in eight fish- and flow-critical watersheds in Eastern Washington: Okanogan, Methow, Wenatchee, Upper Yakima, Naches, Lower Yakima, Walla Walla, and Middle Snake Rivers. (http://www.ecy.wa.gov/biblio/1112015.html)

4 RISK AND UNCERTAINTY

No inherent risk exists associated with protecting land and water as part of a restoration strategy. Dedicating land and water will generally *reduce* the risks associated with inherent uncertainty and may be the strongest approach to addressing uncertainty associated with future events. Where uncertainty in the design or application of other restoration techniques exists, land and water protection can greatly mitigate the risks associated with that uncertainty. The dedication of the channel migration zone (CMZ) or riparian land to stream restoration can reduce risk to private landowners by providing a buffer between the stream and private resources, reduce risk of impacts from erosion and flooding by providing sufficient room for natural erosion and flooding, and perhaps most importantly, reduce the risk of failure relative to project objectives. Providing protected land and water resources in association with other restoration actions will generally improve the probability of the success of those actions.

5 METHODS AND DESIGN

Protecting Land

The process of dedicating land includes first identifying what specific land or water resources to protect, and then putting legal protections in place. For any site- or reach-scale stream habitat restoration program, as much of the CMZ adjacent to the project as is possible or practical should be protected. Ideally, CMZ or buffer protections will extend upstream and downstream of the project area.

Resources for delineating CMZs and floodplains include:

- CMZ delineation: “A Framework for Delineating Channel Migration Zones”[4]; http://www.ecy.wa.gov/biblio/0306027.html
- Floodplain mapping: http://www.ecy.wa.gov/programs/sea/floods/fema.html

Protecting land within a floodplain or CMZ from development or any specific land use to allow for dynamic channel processes, floodplain inundation and riparian succession typically requires a conservation easement. A conservation easement is a voluntary, legal agreement between a landowner and a qualified land trust that provides the land trust with a legal right to use the land for conservation purposes by restricting uses that are inconsistent with conservation outcomes. The landowner retains ownership of the property but voluntarily agrees to restrict their uses on the property. The land trust is the “holder” of those rights, and enforces the restrictive terms of the conservation easement in perpetuity. The landowner may sell or pass their property on to their family, but the conservation easement remains in place. Tax benefits may exist associated with a donation of a conservation easement to a qualified, nonprofit land trust. Or, depending on the conservation values of the property, a land trust may be able to compensate a landowner for placing a conservation easement on their property. Many land trusts also accept land in ‘fee simple’, or holding ownership, in which case the land trust would own the property and manage it for conservation purposes. Land trusts that hold and enforce conservation easements are called generally called “Conservation Land Trusts.”

Conservation easements can be written to restrict or limit armoring of the stream channel or streambanks. For stream habitat projects, this is a particularly important element of easement restrictions; unless an easement expressly indicates this restriction, the easement may actually be of limited value from a channel process perspective. Easements crafted to limit bank armoring can thereby be used to specifically allow for erosion into the CMZ. In these instances, traditional land uses may be permitted within the CMZ, but protection of the land by armoring or levees is prohibited, and land lost to erosion cannot be restored. Ideally, the easement will also restrict uses of the floodplain to promote full floodplain function afforded by undisturbed riparian vegetation or buffers.

The following can provide more information regarding easements and resources for putting easements in place:

- Land Trust Alliance: offers a suite of resources and publications for understanding and planning conservation easements: http://www.landtrustalliance.org/
- Land trusts in Washington: a list of approximately 40 local, regional, and national land trusts in Washington: http://findalandtrust.org/states/washington53
- The Forestry Riparian Easement Program compensates eligible small forest landowners in exchange for a 50-year easement within riparian forests. Through this program the landowner effectively leases trees and their associated riparian function to the state: http://www.dnr.wa.gov/BusinessPermits/Topics/SmallForestLandownerOffice/Pages/fp_sflo_frep.aspx

Protecting Water

Ecology has authority to set instream flows for river basins by regulation under three statutes (Chapters 90.22, Minimum Water Flows and Levels Act, 90.54 Water Resources Act, 90.82 Watershed Planning, RCW). Setting instream flows can include the following elements: flow levels, maximum allocation, closures, reservations, mitigation and storage. Flow setting recommendations are often the result of watershed planning efforts. Ecology uses the recommendations from watershed planning units to develop rules for instream flows. Instream flow rule development is often complex and controversial, and requires extensive staff time. Furthermore, Ecology has a limited budget and as a result two thirds of the Water Resource Inventory Areas in the state have not had instream flows set. Ecology considers completion of a watershed plan, readiness to proceed and resource protection when developing a schedule for locations for instream flow rule making.

Dedicating water to instream flow typically involves a change in the 'beneficial use' from traditional out-of-stream uses, to instream use. This is typically accomplished by the sale, lease, donation or transfer of a water right to the Washington State Trust Water Rights Program (TWRP) – the transfer may be temporary or permanent. Trust waters are governed under the Trust Water Rights Program (Chapters 90.38 and 90.42 RCW). Trust water rights are similar to traditional water rights: they retain their priority date, have a designated place of use (a section of stream or a body or groundwater), a designated purpose of use (instream flow or groundwater preservation) and a designated period of use. Trust water rights differ from traditional water rights primarily in the designation of instream flows as the purpose of use, and place of use is the water body in the original water right. When donated to the TWRP on a temporary basis, it is protected from relinquishment while it is in trust, retains its priority right, and the holder can begin their previous use again once the term of donation expires.

Water can be protected instream using the TWRP in two ways:

1. It is protected from the 5-year use-it-or-lose-it relinquishment statute (RCW 90.14.071, 90.14.130, 90.14.160-180, 90.42.040(6)).
2. The Washington Department of Ecology has authority to protect water from withdrawal by junior water rights users (RCW 90.03.005, 90.03.400, 90.42.040(1))

In Washington, minimum instream flows are commonly determined using the Instream Flow Incremental Methodology (IFIM), which operates on models of physical stream habitat at different streamflows, collectively called PHABSIM (physical habitat simulation). Normative or environmental flows[5] encompass a range of flows necessary to sustain ecological functions. Guidelines[6] for environmental flows are useful but actual implementation depends on site- and stream-specific circumstances.

The following non-governmental organizations and web sites (NGO) can provide more information regarding water rights and instream flows:

- The Washington Water Trust is an organization that facilitates market-based water rights transactions and partnerships that benefit stream resources. http://washingtonwatertrust.org/faq/frequently-asked-questions
- Trout Unlimited – Washington Water Project is an organization that facilitates market-based water rights transactions and partnerships that benefit stream resources. http://www.tu.org/conservation/western-water-project/washington

6 PERMITTING

Dedicating land and water typically involves legal protections as described previously. While legal transactions to put protections in place may be involved, permits are not necessarily required. If water will be *permanently* held instream, an application must be submitted to a regional office of Ecology for a change of use for the water right. A new certificate will be issued to deposit the water into the state trust water right program. This will protect the water right from relinquishing. Temporary donations of a water right also require an application, but do not require an extensive review or result in a new certificate. Interested parties should consult Department of Ecology Water Resources Program about process details for temporary trust.

7 CONSTRUCTION CONSIDERATIONS

Not applicable. Dedicating land and water typically involves legal protections that are passive measures.

8 COST ESTIMATION

The costs associated with dedicating land or water are highly variable and site specific. Some general considerations are provided below. It is important to keep in mind, however, that from the perspective of conducting restoration, and fostering restoration of channel processes and associated habitat, protecting land and water will usually be the most cost-effective means to accomplishing restoration goals and objectives over long timeframes. More active strategies, particularly those requiring manipulation of the channel or installation of structures, may provide only short-term or initial value, and without associated land or water protection, their value may diminish rapidly over time.

Cost of dedicating land

The costs of conservation easements are highly variable and depend on the nature or agreement of protection. Most conservation easements are donated to land trusts or governmental entities. Through donation of a conservation easement to a qualified, non-profit land trust a landowner may qualify for federal income tax benefits, local property tax reductions, or estate tax savings. Less frequently, land trusts or governmental entities may be able to pay landowners for conservation easements. Grant funding to purchase conservation easements may be available for high quality habitat for a variety of purposes: fish and wildlife habitat, wetlands conservation, protection of farmland, protection of river corridors, or other specific purposes.

Costs to either donate or sell conservation easements may include appraisals, surveys, title insurance, legal fees, real estate transaction costs, mortgage subordination, and environmental assessments. In the case of a purchased conservation easement, these costs may or may not be covered by grant funding. Additionally, land trusts often require stewardship contributions from landowners. When the land trust agrees to hold a conservation easement, it agrees to enforce the terms of the conservation easement in perpetuity. In order to enforce the terms of the easement, land trusts generally monitor their conservation easement properties at least annually and they may have staff and legal costs when enforcement situations arise. A stewardship contribution from the landowner provides the land trust with funding to ensure protection of their land in perpetuity.

Cost of dedicating water

The costs of water acquisition for environmental benefit are highly variable and depend on the complexity of the transfer and attributes of the water right. Costs to either donate, sell or lease water rights to the trust water program may include appraisals, legal fees, and environmental assessments. In some cases, funds exist to assist with the water acquisition. In cases where the water is donated in perpetuity, the donator is eligible for a federal tax credit.

9 MONITORING

Land trusts generally monitor their conservation easement lands at least annually. Land trusts pre-arrange monitoring visits with landowners, and may include visiting the property with the landowner, walking the property and boundaries, taking photographs at photo-point locations around the property, and writing up a report of their visit. This type of monitoring is called compliance monitoring, and the main purpose of the visits are to ensure the terms of the easement are being followed. Some land trusts may engage in more habitat- or wildlife-based monitoring. When the conservation easement is first placed on the property, the landowner and land trust create what is called a baseline documentation. This baseline is a snapshot of the property at the time of conservation. Future monitoring visits may compare current conditions to those of the baseline.

Monitoring may also be necessary to verify that transferred water rights are honored. Compliance monitoring of water rights is typically conducted by measuring streamflow both in the channel and at points of diversion for other users, to verify that instream rights remain in the stream. Streamflow measurement may require the installation of weirs on smaller streams, or other gaging devices on larger streams. Biological monitoring is also recommended to compare pre-project to post implementation biological conditions. Refer to the *Monitoring* Appendix for further description of monitoring methods and outcomes.

10 MAINTENANCE

Land and water protection are passive approaches to stream habitat restoration, and as such require minimal maintenance. The primary maintenance concern for either is in monitoring required to ensure easements and water rights are adhered to by property owners and water users, and to measure effectiveness, particularly where public funds are provided.

11 EXAMPLES

Numerous land and water protectionprojects have been completed in Washington State. Information on projects funded through the SRFB can be found at the SRFB Habitat Work Schedule website (http://hws.ekosystem.us). A few case studies in Washington State are presented below.

11.1 Canyon Creek, WA Case Study[7]

Canyon Creek, for most of its length, is a steep and confined mountain stream in the northern Cascades of Washington, tributary to the North Fork of the Nooksack River. The confluence of Canyon Creek and the North Fork Nooksack River are characterized by alluvial fan morphology, where the steep stream exits a canyon and enters the North Fork Nooksack River valley. Property on the alluvial fan is privately owned and subdivided, and in the 1990s was being subdivided and developed up to the active channel margins. While flooding of properties was not considered a great threat, the chance of significant channel shift, as is characteristic of geomorphic processes on alluvial fans, would result in loss of property and structures, as well as threats to human safety. Previous management of the stream channel to protect property during the 1980s included relocation following erosional events, and installation of a buried rock wall to prevent further channel shifts. These installed structures failed in subsequent high flow events. In response, a rock-reinforced dike was installed to train the river from the mouth of the canyon downstream to below the at-risk properties. While this dike protected the properties in subsequent high flow events, it sustained damage and was in need of repair. In 1999, Whatcom County Public Works commissioned a conceptual alternatives analysis for addressing protection of property from flooding and erosion (Inter-Fluve, Inc. 1999, Jakob and Weatherly 2008).

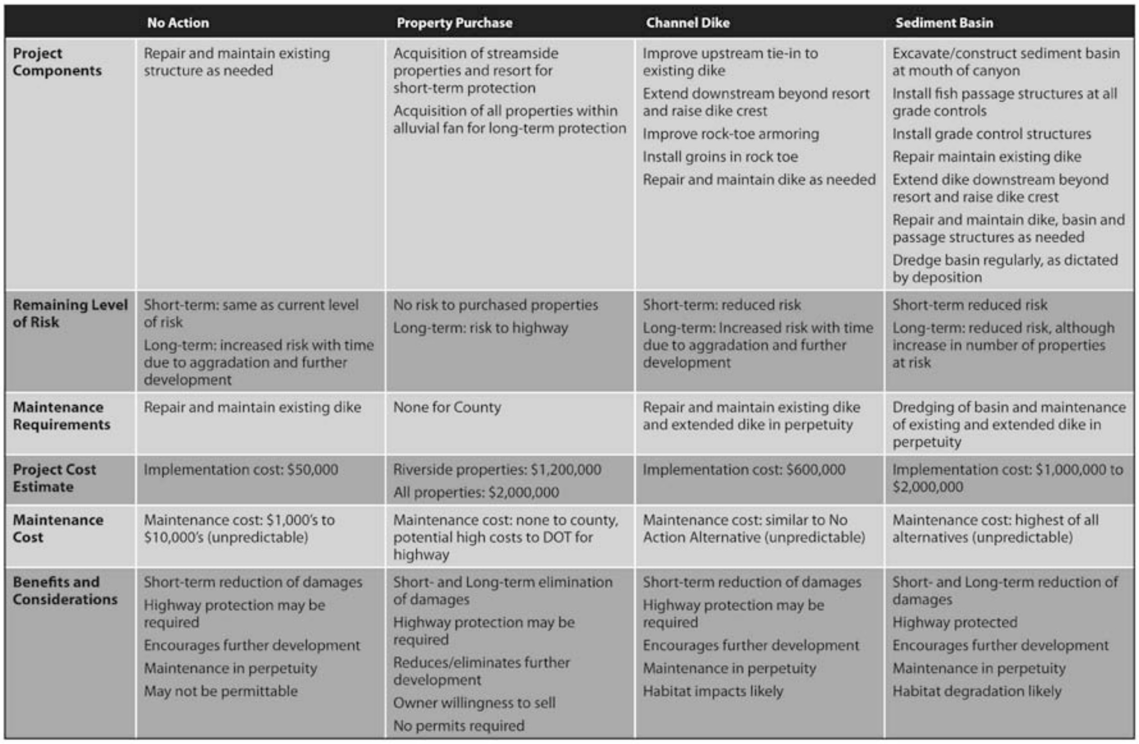
Four alternatives were evaluated to compare costs of initial actions and predicted project maintenance costs and probable outcomes:

1. *No action*. A no action alternative was included as a comparative tool to evaluate costs, benefits, and risks of other alternatives relative to minimal or no further protection.
2. *Purchase property*. The property purchase alternative was included to evaluate the cost of "buying the problem" - in effect converting ownership to public ownership and allowing the stream channel to evolve naturally with no or greatly reduced liabilities, and no long-term cost of maintenance.
3. *Install channel dike*. Installing a channel dike to contain high flows and associated sediment, the traditional approach at this site, was considered with the understanding that engineered approaches had not yet been effective and so would require far greater stabilization measures than previously, and likely perpetual maintenance expenses.
4. *Install sediment basin*. As an alternative to containment and in an effort to include all possible solutions, trapping of sediment at the canyon mouth was evaluated as an alternative to minimize channel erosion and avulsion related to excess sediment (the inherent sediment regime in alluvial fans). Sediment basins require regular and perpetual management to remove trapped sediments.

Table 1 presents a summary and comparison of alternatives, and demonstrates that the property purchase option is economically viable. This option provides the greatest certainty in protection of property and threats by reducing potential for further development of the alluvial fan, and allows for natural, dynamic, and arguably uncontrollable dynamic channel processes. Purchasing of properties was selected as the preferred alternative. Whatcom County, along with a local land trust, have since secured ownership or easements for virtually all of the properties along the channel, allowing the channel to be left largely unprotected and free to adjust and evolve naturally. As of 2008, work continues to remove pre-existing levees and remove barriers to upstream passage[8].

Table 1. Canyon Creek, WA alternatives analysis matrix.

Four alternatives were evaluated to alleviate flooding of a subdivision on an alluvial fan: (1) No action; (2) Property purchase; (3) Channel dike; and (4) Sediment basin. Evaluation of each alternative included a summary of project components, level of risk flood damage, maintenance requirements, project cost and maintenance cost, and summary of benefits and considerations. Risk to resource was not included in the evaluation.

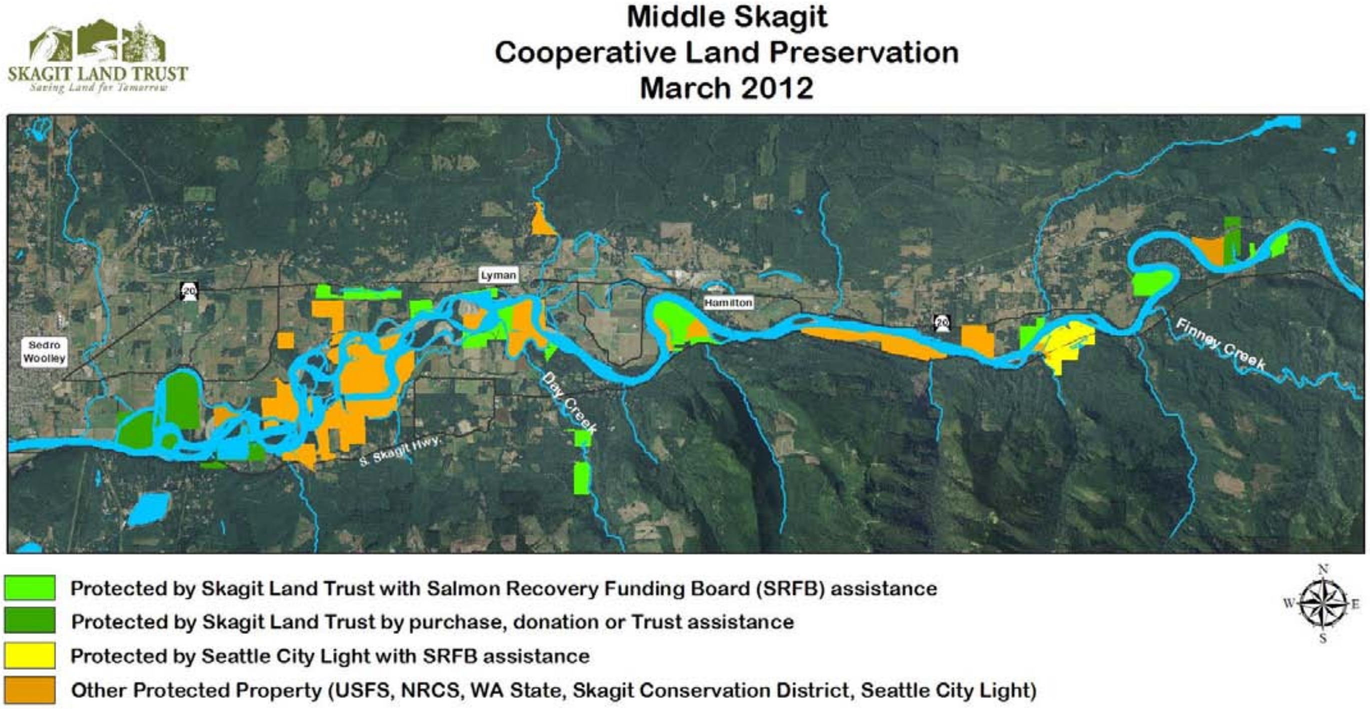


	No Action	Property Purchase	Channel Dike	Sediment Basin
Project Components	Repair and maintain existing structure as needed	Acquisition of streamside properties and resort for short-term protection Acquisition of all properties within alluvial fan for long-term protection	Improve upstream tie-in to existing dike Extend downstream beyond resort and raise dike crest Improve rock-toe armoring Install groins in rock toe Repair and maintain dike as needed	Excavate/construct sediment basin at mouth of canyon Install fish passage structures at all grade controls Install grade control structures Repair maintain existing dike Extend dike downstream beyond resort and raise dike crest Repair and maintain dike, basin and passage structures as needed Dredge basin regularly, as dictated by deposition
Remaining Level of Risk	Short-term: same as current level of risk Long-term: increased risk with time due to aggradation and further development	No risk to purchased properties Long-term: risk to highway	Short-term: reduced risk Long-term: Increased risk with time due to aggradation and further development	Short-term reduced risk Long-term: reduced risk, although increase in number of properties at risk
Maintenance Requirements	Repair and maintain existing dike	None for County	Repair and maintain existing dike and extended dike in perpetuity	Dredging of basin and maintenance of existing and extended dike in perpetuity
Project Cost Estimate	Implementation cost: $50,000	Riverside properties: $1,200,000 All properties: $2,000,000	Implementation cost: $600,000	Implementation cost: $1,000,000 to $2,000,000
Maintenance Cost	Maintenance cost: $1,000's to $10,000's (unpredictable)	Maintenance cost: none to county, potential high costs to DOT for highway	Maintenance cost: similar to No Action Alternative (unpredictable)	Maintenance cost: highest of all alternatives (unpredictable)
Benefits and Considerations	Short-term reduction of damages Highway protection may be required Encourages further development Maintenance in perpetuity May not be permittable	Short- and Long-term elimination of damages Highway protection may be required Reduces/eliminates further development Owner willingness to sell No permits required	Short-term reduction of damages Highway protection may be required Encourages further development Maintenance in perpetuity Habitat impacts likely	Short- and Long-term reduction of damages Highway protected Encourages further development Maintenance in perpetuity Habitat degradation likely

11.2 Skagit River, WA

The Skagit River (WA) presents an example of coordinated and ongoing protection of river-bottom lands for the purpose of habitat protection and restoration. Figure 1 depicts the change in land ownership and protection of the Skagit River and its floodplain above Sedro Wooley between 1976 and 2012. The location of protected river bottom lands reflects both targeted and opportunistic protection of those areas deemed particularly important to salmon habitat for spawning, rearing, or refuge.

Figure 1. The middle Skagit River above Sedro Wooley. Colors represent lands under easements or other protections and under different ownership, ranging from conservation easements on private land to ownership by the Nature Conservancy, Skagit Land Trust, Seattle City Light, and various state and federal agencies.



11.3 Cascade Creek, Orcas Island, WA – Water purchase

A purchase of 0.50 cfs of instream water on Cascade Creek (Orcas Island, WA) by the Washington Water Trust and Department of Ecology represents the first permanent environmental water right purchase in western Washington. The collaborative agreement between the Trust and Orcas Water Holdings includes ¼ cfs to be left in the stream during June, July and August, and ½ cfs during September and October. Even this relatively small amount of water benefits multiple life stages for coho and chum salmon, sea run cutthroat trout, and resident trout by providing instream flows during hot and dry periods.

Since the 1880s, water had been diverted from Cascade Creek for commercial and residential water use and for drinking water for a number of communities. Water rights were established before the need for instream flows was considered. If existing rights were used to their fullest, the stream would be dry in late summer and early fall. The agreement acknowledges the multiple needs of Cascade Creek water for community systems, hydropower, and stream flows for fish and wildlife. The purchase was funded through support from Department of Ecology, WDFW, the Wild Fish Conservancy, San Juan County, and KWIAHT (Center for the Historical Ecology of the Salish Sea).

Other examples of instream water rights can be reviewed at:
http://washingtonwatertrust.org/projects/
http://www.tu.org/conservation/western-water-project/washington/restore

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TECHNIQUE 2

FLOODPLAIN AND CHANNEL MIGRATION ZONE RESTORATION

Floodplain and Channel Migration Zone Restoration

1 DESCRIPTION OF TECHNIQUE

This technique describes the suite of activities that constitute floodplain and channel migration zone (CMZ) reconnection for the purpose of habitat restoration. These activities include the removal or modification of features that confine the active channel, limit floodplain inundation, or inhibit channel planform adjustment. Examples include levee removal or setback, removal of bank armoring, and the restoration of floodplain topography and vegetation conditions. This technique focuses on passive, process-based approaches that remove features that confine channels and encroach on floodplains. It does not include direct measures to restore channel planform, create off-channel habitat, or adjust channel profile. These techniques are included in *Channel Modifications*, *Side Channel and Off Channel Habitat*, and *Instream Structures*.

> The Floodplain and Channel Migration Zone Restoration technique may be the main emphasis of a stream habitat restoration project, or it may be a component of a broader set of techniques implemented in concert. Prior to embarking on designs for specific techniques, the restoration practitioner should have already completed a site, reach, and watershed assessment to identify causes of observed or perceived problems, to determine constraints to addressing these problems, and to frame the project in the broader context of a watershed restoration strategy (Chapter 4). Because restoration practice is most effective when it addresses root causes of problems rather than observed symptoms, a robust assessment that looks at potential causes at site-, reach- and watershed-scales will contribute to a more effective restoration strategy. In addition, design should only proceed when project goals, specific measurable objectives, and design criteria (Chapter 5) have been clearly defined and a restoration strategy has been developed to meet these objectives. A site- or reach-scale technique may ultimately provide little value if it is not consistent with overall watershed priorities or integrated with other techniques as part of a restoration project.

Because most floodplain restoration projects will result in changes to channel and floodplain processes, a thorough understanding of fluvial geomorphology is essential. Refer to the *Fluvial Geomorphology* Appendix and to *Chapter 2: Stream Processes and Habitat*, for further discussion of channel stability and equilibrium. Other techniques presented in SHRG relate to or even fall within the category of Floodplain Restoration. These include *Large Woody Debris*, *Channel Modifications*, and *Instream Structures*. These techniques are briefly discussed in this section as they specifically relate to Floodplain Restoration, but the reader should refer to these separate techniques for additional information. Additionally, *Dedicating Land and Water* should be considered as a complementary technique. This section emphasizes the importance of restoration and protection of floodplain and CMZ (channel migration zone) areas and processes.

1.1 Background

Natural, undeveloped floodplains and CMZs provide important functions including flood energy dissipation, flood water storage, natural sediment transport conditions, nutrient exchange, creation and maintenance of complex habitats, and resiliency to disturbance. Floodplains often provide refuge areas for aquatic species during floods and are excellent habitat for a wide variety of species.

Features that limit floodplain connectivity affect the quantity and quality of aquatic habitat through direct manipulations to habitat as well as indirect effects on channel processes.

Features that limit floodplain inundation and channel migration are common along Washington streams. These features include levees, bank revetments, floodplain fill, dredge spoils, utilities, and infrastructure. Roadways, housing developments, commercial development, and industrial facilities are frequently located within floodplains. Due to their location, however, floodplain structures are subject to damage from flooding and erosion and are, therefore, typically protected from the river by flood control levees and streambank revetments. Although these protection measures may be successful in reducing flood damage to property and structures, they frequently come at the cost of impairments to aquatic habitat and stream ecosystem processes. Furthermore, flood and erosion control features may actually increase the degree of flood damage in downstream areas due to a reduction in floodwater storage and an increase in stream energy. Over time, many flood control features become less effective at flood control and may require frequent maintenance and engineering improvements. The use of levees for flood protection encourages increased development of floodplain areas because of the public perception that the area landward of the levee will not be flooded, which may not always be the case. For instance, Pierce County, Washington, has been identified by the National Wildlife Federation as one of the top 300 locations within the United States where there are repeated flood damages of individual properties in excess of $1,000. Repetitive loss to properties in Pierce County accounted for only 2% of all National Floodplain Insurance Program (NFIP) claims, but sustained 25% of all NFIP losses and received 40% of all NFIP payments.[1] As a whole, Washington ranks 16th for flood disasters compared to the rest of the Country. From 1953 through September 2010, Washington had 214 declared flood disasters (http://www.fema.gov/datasets/data.gov.FEMADeclarations.xls). In some years, Washington has ranked highest in the Country for flood disasters.[2]

Floodplain restoration serves many purposes including but not limited to: habitat restoration, erosion reduction, water quality improvements, groundwater recharge, restoring wildlife migration corridors, and reduction of flood hazard risks. From a restoration perspective, it is preferable to fully restore floodplain and CMZ connectivity. However, complete restoration is often not feasible due to the legacy of past land uses or the presence of permanent infrastructure. In these cases, partial reconnection of processes may nevertheless provide important benefits to the aquatic system.

1.1.1 Relationship between Floodplains and CMZs

Floodplains and CMZs, although similar, are not necessarily synonymous. The areal extent of floodplains is generally defined by the extent of inundation from floodwaters. CMZs, on the other hand, are not limited by inundation extent, and may extend beyond floodplains into hillslopes or terraces that may be eroded via fluvial processes. For this reason, CMZs often have a greater areal extent than floodplains. It is also possible, however, for CMZs to have a lesser extent than floodplains when floodplain surfaces, although inundated by floodwaters, are able to resist erosion either through natural or anthropogenic processes. This may occur naturally in channels where bedrock limits lateral erosion, and it occurs commonly in managed alluvial systems where bank armoring prevents lateral erosion. The aerial extent of floodplains and CMZs is dependent on the time-scale of interest.

For instance, a CMZ defined for a 25-year time frame may be relatively small and represent a narrow corridor that would likely be occupied by the river channel over the next 25-years. In contrast, a CMZ defined for a 500-year time frame may occupy a much wider corridor or even the entire river valley bottom. The Washington Department of Ecology manual for delineating CMZs[3] includes a thorough discussion of CMZs and methods for their delineation.

1.1.2 Regulatory Context

This section discusses regulatory management of floodplains. Additional information, and information specific to permitting floodplain and CMZ projects, is included in Section 6: Permitting.

Current State and Federal laws are intended to limit floodplain encroachment. The National Flood Insurance Act of 1968, which led to the creation of the National Flood Insurance Program (NFIP - managed by FEMA), helps limit floodplain development by providing flood insurance only in communities that adopt ordinances that limit development in flood hazard areas. Washington State further protects floodplains and CMZs by requiring local jurisdictions to adopt a Comprehensive Flood Hazard Management Plan (CFHMP) to qualify for State funds for flood control assistance. CFHMPs are designed to cover federal NFIPs requirements as well as provide additional floodplain and CMZ protections.

Although past NFIP requirements have helped limit floodplain development to some degree, a 2004 court order required that FEMA consult with the National Marine Fisheries Service (NMFS) regarding potential impacts of the NFIP on ESA-listed species. In September of 2008, NMFS issued a Biological Opinion that determined that implementing the NFIP causes jeopardy to several species of Puget Sound salmon and orca whales as well as adverse modification to their habitat. NMFS provided a Reasonable and Prudent Alternative to modify the implementation of the NFIP in a manner that would remove the jeopardy situation. In response, FEMA has been working with the state, tribal, and local interests in developing a model ordinance that incorporates a set of rules to protect human development from floods while minimizing the impact of new construction and redevelopment on aquatic and riparian habitat.

For levee removal or modification projects, it is important to know who has legal authority over the levee. Even if levees are located on private land, the jurisdiction may fall to the US Army Corps of Engineers, a local diking district, or other entity. These entities must be involved throughout the process to ensure that designs are acceptable to the governing organization. Modification or removal of small levee systems owned and built by a private landowner may be easier to accomplish, although impacts to adjacent lands must still be investigated.

1.1.3 Types of Floodplain and CMZ Disconnection

1.1.3.1 Levees

Artificial levees, also commonly referred to as dikes, are embankments built along the bank of a watercourse or an arm of the sea that are designed to protect land from inundation or to confine streamflow to its floodway.[4] In this technique, the term levee refers to artificial levees as opposed to natural levees that form on some stream systems. Natural levees are caused by frequent overbank flooding on streams with heavy sediment load and they are an important component of natural floodplain creation in some systems.

The Natural Resources Conservation Service (NRCS) classifies various types of levees based on their function and their importance with respect to flood protection.[5] The levee types include lateral levees that run parallel to the stream; perimeter or setback levees that are located near the infrastructure they protect; cross-floodplain levees that redirect floodplain flows back into the channel; and tidal levees that are designed to isolate areas from tidal inundation/fluctuations. Transportation and utility corridors frequently function as lateral and cross-floodplain levees. In the early 1900s, many lateral and tidal levees were constructed or authorized by the U.S. Army Corps of Engineers.

The degree of impact of levees on channel processes and habitat depends on many factors, including how much of the floodplain is isolated from flooding, the range of flood levels that are affected by the levee, the degree to which levees prevent recharge of floodplain aquifers, how much off-channel habitat is disconnected from the main river, and how much bank armoring and channel confinement is created by the levee.

1.1.3.2 Floodplain Filling, Grading, and Vegetation Removal

Clearing, grading, and filling of floodplains are typically conducted to facilitate uses such as agriculture, development, or road building. Filling and grading are also used to eliminate floodplain side-channel depressions and irregularities in floodplain topography that are the natural signatures of past channel locations and flood overflow channels. In broad alluvial floodplain valleys, it is common for complex floodplain topography and diverse native vegetation communities to be cleared and replaced by flat, uniform topography. Clearing, filling, and grading may or may not be associated with levees or bank armoring; however, even in the absence of these other confinement features, these practices can have detrimental impacts on channel process and habitat. Geomorphic and biological impacts of clearing, filling, and grading are discussed in Sections 1.2 and 1.3.

1.1.3.3 Bank Armoring and River Training Structures

Streambank armoring and river training structures are designed to prevent erosion and channel planform adjustment. These structures take many forms and are constructed from a variety of materials, including rock, concrete, masonry, steel, and wood. Although bank armoring and river training structures are frequently associated with flood control levees, there are also revetments intended solely for bank protection and not flood control.

The most common type of bank armoring is riprap, which consists of large angular rocks placed along the bank. Riprap can provide effective erosion control; however, riprap typically results in severely degraded channel margin habitat and riparian function. Other common types of bank armoring include rock-filled wire-basket gabions, steel sheet piles, concrete retaining walls, and engineering techniques including reinforced soil and geosynthetic materials. Techniques have also been designed to stabilize banks, provide some degree of habitat value, and, potentially, bank deformation over the long-term. These include wooden crib-walls, rootwad revetments, and a variety of bio-engineering approaches that utilize a combination of vegetation and more naturally integrated means to stabilize banks.

River training structures are designed to move the stream energy away from the streambank in order to reduce erosion and prevent channel migration.

These techniques typically involve multiple structures placed in sequence that either fully or partially span the channel and are designed to deflect stream energy away from the bank. They may be oriented upstream, downstream, or perpendicular to the channel and may be either fully or partially submerged depending on objectives and site conditions. They are typically constructed of rock but are also constructed using concrete or wood. Examples include bendway weirs (aka barbs or vanes), spur dikes (aka groins or jetties), wooden pile dikes, and partially submerged boulder weirs (e.g. cross-vanes and J-vanes).

More information on streambank protection is included in the Integrated Streambank Protection Guidelines (ISPG)[6].

1.2 Geomorphic Consequences of Floodplain and CMZ Disconnection

Structures or modifications that isolate floodplains from flood inundation or inhibit natural channel migration induce fundamental changes to channel processes and aquatic habitat. These changes may be immediate and direct, such as the disconnection of an off-channel wetland via levee construction, or long-term and indirect, such as reducing channel migration dynamics necessary for maintaining complex instream and off-channel habitats over time. In planning and designing floodplain or CMZ restoration, it is important to understand the degree to which geomorphic processes are constrained, the trends in channel response to structures, and the limits imposed by ongoing land uses and the legacy of past practices. The reader should refer to the White Paper – Ecological Issues in Floodplains and Riparian Corridors[7] (http://wdfw.wa.gov/publications/pub.php?id=00058) for a thorough discussion of geomorphic and biological issues associated with floodplain and CMZ disconnection.

1.2.1 Geomorphic Consequences of Levees

Levees are designed to contain high flows within a specified area and have been used universally throughout the world for flood protection along stream systems and in tidally influenced areas. Whereas levees may be effective in providing flood protection to structures and property, they have numerous impacts on channel geomorphology and natural river processes. The degree and type of impact is a function of the levee characteristics as well as the stream type. Levees in low gradient systems with a high sediment load may lead to aggradation within the channel; whereas levees in systems with a low sediment load may lead to incision. These processes are discussed below.

Levees constrain stream flow to a smaller cross-sectional area than the natural channel and may increase velocity and stream energy above pre-levee levels. Increased stream energy can cause higher channel and bank erosion rates, often leading to channel incision in systems where eroded sediment is not replaced by new sediment depositing in the channel. Channel incision, in turn, can lead to accelerated bank erosion and the introduction of additional sediment into the stream system from the goetechnical failure of over-steepened banks. Additionally, deepening of the channel bed reduces connectivity between the stream and the floodplain, thus confining more flow to the primary channel. If the streambed is armored, or a resistant layer is encountered, the channel may preferentially erode its streambanks. Woody vegetation is often removed from levees based upon concerns, real and perceived, that structural integrity will be affected. Shrubs and trees are also removed from areas within levees (i.e. between the levee and streambank) in order to decrease roughness, increase velocities, and hence lower flood stages.

These reductions in energy dissipation further increase stream power and flow velocities, reinforcing the processes responsible for channel boundary erosion and channel incision. In other situations, the presence of levees may lead to sediment aggradation within the channel. Sediment that would be otherwise stored in the floodplain or along the channel margin is routed downstream, increasing the sediment load and triggering additional aggradation. Accordingly, the channel responds to aggradation through channel widening (braiding), lateral migration (if banks are composed of erodible material), or avulsion (a partial or complete shift in the channel location). Over time, levees may become increasingly susceptible to overtopping due to aggradation of sediment within the channel, and levees must therefore be raised in order to maintain flood protection. In extreme examples, the channel bottom can aggrade so severely that it becomes perched above the surrounding landscape, in essence flowing at an elevation higher than its surrounding floodplain. This typically occurs on very low gradient systems with high sediment load. An example of this is the Skokomish River in Mason County, Washington, that drains into Hood Canal; another is the lower Dungeness River that flows into the Strait of Juan de Fuca. During high flows, stream energy is magnified within the constricted channel (as described above) and much of the sediment stored in-channel can be rapidly mobilized. This results in a stream system that has amplified cycles of erosion and deposition. This increase in depth of bed scour allows more frequent adjustment of channel form and may undermine bridges and other channel-spanning infrastructure and has biological consequences (e.g., redd scour).

Even in areas where levees are not present, placement of floodplain fill is frequently used to raise floodplain elevations so that inundation of the floodplain occurs at a higher stage, thus providing flood control even in the absence of a traditional levee. In this sense, floodplain fill has many of the same geomorphic consequences as levees themselves. Filling of floodplain depressions and flood overflow channels also reduces the potential for channel planform adjustment through avulsion.

A geomorphic consequence of levee construction in tidally influenced areas is local land subsidence within the levee system. Land subsidence is the lowering of the land surface within the area confined by the levee system due primarily to a reduction in tidal inundation (due to the levees) and pumping. Subsidence levels in the Columbia River Estuary have been documented at over 5 feet but are likely greater than that for many areas. Although the specific mechanisms of subsidence have not been determined for the Columbia River Estuary, it is assumed to be the same as has been found in the Sacramento-San Joaquin River Delta area of California. Prior to levee construction and agricultural use, the peat soils were saturated and dominated by anaerobic (oxygen-poor) conditions. The drainage of the soils due to levee construction and pumping transformed the soil conditions to more rapid aerobic (oxygen-rich) decomposition which oxidizes organic carbon in the soils. Organic material is transformed to carbon dioxide gas and the land essentially shrinks. Subsidence within the levee system is exacerbated by a loss of fluvial/tidally transported sediment into the area and a lack of organic material contributed from decaying wetland vegetation. Subsidence requires continual raising of levees in order to maintain flood protection and also severely limits the ability to restore diked areas because of the permanent change in land elevations. For example, restoration via levee removal in an area that was historically a Sitka spruce forested wetland may be constrained by permanent elevation changes that will now only support emergent marsh and tidal mudflat habitat.

Levees often fail due to overtopping or due to failure of levee materials. Considerable risk is associated with levee failures including flood inundation of property, houses and damage to public infrastructure. Flood damage typically results from levee failure rather than levee overtopping.[8] If flood stage exceeds levee height, then overtopping occurs. Although overtopping often causes levee failure via erosion of the levee at the point of overtopping, it is more common for a failure to occur prior to overtopping. This occurs as a result of the hydraulic pressure gradient created by the difference in water surface elevations on either side of the levee. This pressure gradient creates seepage through the levee, increasing pore water pressure and reducing the shear strength of levee materials. Mobilization of material creates preferential flow paths allowing even more material to be transported out of the levee (piping) and eventually leads to failure. Once a levee is breached, water courses through the opening at high velocities, entraining material and enlarging its path. The area behind the levee becomes inundated and, depending upon the local topography and the levee system, may not be able to naturally drain.

1.2.2 Geomorphic Consequences of Bank Armoring and River Training Structures

In addition to the geomorphic consequences of floodplain disconnection described above, there are also consequences associated with actions that prevent bank erosion and channel migration. Such actions include bank armoring as well as river training structures such as groins and vanes. The impact of inhibiting channel migration will vary depending on the extent of the historical CMZ and the channel type. Rivers with wide CMZs that experience frequent adjustments in channel position will be more affected than rivers with narrow CMZs and naturally stable planforms. A reduction in channel migration rates affects numerous components of the stream ecosystem, including sediment transport, wood transport, and energy dissipation. Bank revetments that inhibit erosion may reduce the inputs of sediment to the channel and may therefore lead to channel incision. In many low gradient meandering streams in Washington, the recruitment of wood due to meander migration governs stream dynamics and habitat creation. Reducing wood recruitment serves to further simplify the stream system and prevent natural habitat-forming processes from occurring.

1.3 Biological Consequences of Floodplain and CMZ Disconnection

Floodplain and CMZ disconnection affects aquatic habitat through direct and indirect means. Direct impacts are often the most dramatic and immediate and may include blockage of fish passage to off-channel habitats, destruction of channel margin habitat, and elimination of flood refuge areas. However, many of the biological impacts stem from impacts to the physical processes described in the previous section. These impacts may be less direct and may occur over longer time scales. The reader should refer to the White Paper – Ecological Issues in Floodplains and Riparian Corridors[7] (http://wdfw.wa.gov/publications/pub.php?id=00058) for a thorough discussion of geomorphic and biological issues associated with floodplain and CMZ disconnection.

1.3.1 Biological Consequences of Levees

Levees often directly sever fish passage connections to off-channel habitats. For many aquatic species, off-channel habitats are important for rearing, flood refuge, reproduction, or feeding.

The elimination or disconnection of these habitats can have severe consequences to population viability. For instance, the lands behind the levees may provide habitat for a variety of invertebrate, amphibian, and plant species that are an important food source to a variety of predators; however, the great majority of the biomass and organic nutrients cannot be transported out of the area because there is no hydrologic connectivity between these habitats and the river environment. The lack of biomass and nutrient transport to the river may become an ecosystem function-limiting factor in this situation.

In addition to the more direct impacts to off-channel/floodplain habitats, floodplain disconnection also affects instream biological processes. Biological impacts stem from the physical changes to stream energy, sediment dynamics, and channel margin habitat. Streams subjected to floodplain disconnection tend to have less shading from riparian trees, increased water temperature fluctuations, less cover for fish, and less organic matter input. Stream velocities are greater and there are fewer areas available for fish to find refuge from high flows. If the channel has been straightened as part of levee construction, then instream habitats may be fundamentally altered and reduced. For example, a meandering pool-riffle channel may be replaced with a straightened and shorter channel where glide/run habitat dominates and provides little value for fish.

Floodplains also provide important water quality benefits through buffering, infiltration, and biotic processes such as occurs in floodplain wetland areas. For example, floodplain wetlands may provide important sinks for pollutants such as nitrogen and phosphorous produced from agricultural uses.

1.3.2 Biological Consequences of Floodplain Filling and Grading

The process of clearing, filling, and grading of floodplains is typically done to facilitate development or agriculture. This action has fundamental impacts to biological processes. Vegetation removal has direct and obvious impacts on terrestrial habitat as well as riparian function. Even vegetation removal in floodplain areas distant from the stream itself may have long-term impacts to stream biota when considering that channel migration processes may eventually result in a floodplain forest becoming a riparian forest. Clearing or alteration of natural floodplain vegetation also alters the dynamics of nutrient exchange between floodplains and stream channels. Elimination of floodplain depressions, such as relic channel scars and flood overflow channels, directly impacts wetlands and off-channel habitat that may be important for aquatic biota. Juvenile salmon, for example, will seek out the more quiescent waters in floodplain depressions for refuge during high flows. Filling and grading also disrupts relic floodplain channels that serve as pathways for shallow ground and surface water (hyporheic) flow and macro-invertebrate movement.

1.3.3 Biological Consequences of Bank Armoring and River Training Structures

In addition to the biological consequences of floodplain disconnection described above, there are biological consequences associated with actions that prevent bank erosion and channel migration. Bank armoring has a direct impact on channel margin habitat. Bank revetments, such as riprap, transform natural and complex channel margin habitat to uniform, degraded edge habitat. Riparian trees and instream wood are frequently removed as part of bank armoring.

This has direct and immediate effects on habitat and also reduces long-term shading, wood recruitment, and nutrient exchange. Reducing lateral channel erosion also reduces sediment recruitment from streambanks. In many alluvial systems, sediment that is sourced from streambanks is critical for providing pool-riffle morphology and salmon spawning-sized substrate.

In naturally free-formed alluvial channels, inhibiting bank erosion inhibits the processes that create and maintain channel planform and habitat over time. Erosion and deposition are natural processes that are a function of the energy balance of the stream system. Critical components of salmon habitat, such as pool and riffle sequences, are formed and maintained by channel erosion, deposition, and a constantly shifting channel position. Furthermore, relic channels that are left behind due to channel shifting (e.g. oxbow lakes, wetlands, backwater channels) are also critical for fish use, prey production, nutrient exchange, terrestrial habitats, and flood energy dissipation.

2 PHYSICAL AND BIOLOGICAL EFFECTS

Levee removal has many potential physical and biological benefits. Floodplain and channel migration zone restoration can potentially restore natural rates of floodplain inundation, channel migration, erosion, and deposition by allowing the channel to access its floodplain and CMZ. In doing so, the channel can dissipate stream power from overbank inundation and deposition and adjust to variations in watershed inputs (water, sediment, wood) from channel migration (lateral migration and avulsion).

The potential physical and biological effects of floodplain and CMZ reconnection are presented below.

<u>Potential physical effects:</u>

Channel

- Reduction of water surface elevation during floods.
- Reduced flood potential to downstream areas.
- Loss of sediment transport capacity within the reach
- Increase in sediment deposition in the reach.
- Attenuation of sediment transport downstream.
- Greater channel complexity and/or increased shoreline length.
- Changes in channel geometry.

Floodplain

- Increased fine sediment deposition.
- Potential for increases in groundwater recharge.
- Increased wood retention.

Channel and Floodplain

- A more natural energy distribution within the channel and on the floodplain/floodway.
- Increased floodplain flows resulting in more floodplain channels, diversity and interaction with the active channel.

- Increased wood recruitment from floodplain forests with potential to increase supply to downstream reaches.
- Increased rates of channel planform adjustment.

Tidal systems.

- With levee removal, restoration of estuarine functions of temperature, tidal currents, and salinity.
- Reduction in the rate of land subsidence due to re-saturation of soils and restoration of sediment accretion processes.
- Increased habitat abundance from distributary channels.

Potential biological effects:

Habitat

- Formation of new off-channel habitat features through restoration of channel planform adjustment.
- Shift in vegetative community composition and distribution.
- Wider riparian corridors that provide more 1) shade for moderated water temperatures and microclimate, 2) recruitment of wood for instream habitat, 3) organic material, 4) filtering of sediment and nutrient inputs, 5) nutrient cycling, 6) better seed dispersal and 7) travel corridors for terrestrial species.

Fish and Wildlife

- Restoration of flood-flow refuge for aquatic species.
- Restoration of connectivity into tributaries and floodplain habitats for fish and wildlife.
- Reduction of fine sediment detrimental to salmonid eggs.
- Shift in wildlife species composition and distribution.
- Increased primary productivity.

Tidal Systems

- Restoration of an estuarine transition zone (tidal currents, temperature, and salinity) for species migrating through the tidal zone.
- Restoration of saline-dependent plant species and thus increased drainage.
- Restoration of estuarine food production.

It is important to note, however, that levee removal may also cause further instability if the channel has adjusted to the presence of the levee. Simply removing a levee is typically not enough to restore habitat due to fundamental changes the levee may have induced in the stream system. Over time, streams will adjust to the presence of a levee and may reach a new equilibrium with respect to the flow and sediment balance. Examples include sites where floodplain areas have subsided or the channel bed has aggraded and where floodplain reconnection would therefore result in floodplain inundation that far exceeds what existed historically. In addition, if measures are not taken to mimic the natural stability of channel margins and floodplain areas (e.g. if floodplain and riparian areas no longer have native forest vegetation), then levee removal may induce severe instability and erosion.

A long period of adjustment to a new equilibrium may ensue with potentially negative impacts to habitat. A thorough understanding of geomorphic effects of levees, equilibrium conditions, and potential response mechanisms is necessary to ensure a successful project.

3 APPLICATION OF TECHNIQUE

This technique applies to streams that have undergone disconnection or constraint of floodplains or CMZs via the types of structures and practices described in Section 1.1.3. Applying this technique requires a thorough understanding of physical and biological processes. Due to the many inputs and factors involved, as well as the uncertainty associated with floodplain and CMZ restoration, design and planning should be conducted by an interdisciplinary team composed of experts in hydrology, hydraulics, engineering, geomorphology, biology, riparian ecology, and construction methods. Methods and design considerations are discussed further in Section 5.

In general, application of this technique should focus on streams where infrastructure and floodplain development is minimal, but where it may increase in the future. Once floodplains are developed, modification and removal opportunities become limited and more expensive. Areas of specific interest include undeveloped lands, public lands, and parks. These areas favor restoration of natural floodplain vegetation, flood channels, and active side channels. Levee removal or setback is most beneficial in streams that are not incised and are still capable of accessing their historical floodplains at relatively frequent flows (i.e. during the 2 to 5-year flood events). Channels that are incised require careful examination to determine whether trends in down cutting are on-going or have reached equilibrium. In some cases it may be appropriate to augment levee removal or setback with in-channel profile adjustment or floodplain lowering. These strategies are discussed below in Section 5.2.8.

By restoring floodplain functions and processes, floodplain and CMZ restoration can be used in conjunction with many other techniques including but not limited to: 1) channel modification, 2) large wood additions, 3) streambank restoration, 4) land preservation, 5) riparian restoration/management, and 6) side channel restoration. It should also be complemented with acquisition of fee simple title or a permanent conservation easement to ensure that restored CMZ and floodplain areas are protected from future development.

4 RISK AND UNCERTAINTY

Project risk is a function of the probability that the project will result in undesirable outcomes, whereas uncertainty refers to the limits of our knowledge about how a project will perform in the future. (Refer to RiverRAT Appendix 3.5 for a thorough discussion of accounting for uncertainty and risk in stream habitat restoration design and management). The level of risk and uncertainty associated with floodplain restoration will vary depending on the scale of the project, the geomorphic setting, the presence of nearby infrastructure, and the degree to which the stream has adjusted to hydromodification. Risk and uncertainty can be managed by developing a thorough understanding of existing processes and by determining the potential response to restoration. Most floodplain restoration projects will require analyses of stream geomorphology, hydrology, hydraulics, sediment transport, aquatic habitat, and riparian ecology. Structural and geotechnical engineering may also be required when large structures (e.g. levees) are involved.

Important components of a risk analysis will include:

1. Assessment of anticipated changes in channel stability, erosion, and sediment deposition.
2. Assessment of the anticipated hydraulic effects on upstream and downstream reaches and on the floodplain within the project area.
3. Assessment of anticipated changes to flood hazards, including a comparison of inundation extents pre- and post-project.
4. Assessment of stream channel response within the project area.
5. Assessment of changes to aquatic habitat and vegetation conditions.

Where streams have evolved to the presence of a levee, floodplain inundation may occur at a different rate, magnitude, or recurrence interval compared to historical (i.e. pre-levee) conditions. Relating flood frequency to post-project inundation extent will almost always be necessary to manage risk and reduce uncertainty. In streams that have aggraded in response to the constraining effect of levees, levee removal may actually decrease main channel capacity and in extreme cases, there may be no main channel capacity. This situation can result in years of dynamic channel adjustment as the channel works to develop a suitable alignment, shape, and slope. This type of channel adjustment carries with it a high degree of uncertainty with respect to eventual channel form. The level of uncertainty, and the tolerance for it, must be well understood prior to undertaking restoration.

Restoration of channel migration is inherently uncertain with respect to erosion, sediment transport, and the eventual channel position and planform. At the site-scale, removal of bank armoring will initiate erosion and will add sediment to the system. The fate and impact of this sediment needs to be understood. In some cases, interim bank stability may need to be provided over the short-term in order to reduce the risk of rapid erosion and channel instability. At the valley-scale, infrastructure far from the restoration site may be at risk in the future as the channel position changes over time. The entire potential CMZ should be clearly identified and managed for erosion and flood risk if necessary. The potential risk of channel erosion undermining adjacent valley slopes should be included in the risk assessment. Restoration of channel migration will also impact upstream and downstream reaches due to changes to sediment transport, stream energy, and the potential for reach-scale adjustments to channel profile. Risks to upstream and downstream areas should be explicitly addressed as part of project analysis and design.

4.1 Risk to habitat

Risk to habitat is generally low for floodplain and CMZ restoration. Primary risks include bank erosion and longer and more frequent floodplain inundation. If channel migration processes are restored, there may be an increase in bank erosion which could increase sediment contributions to the channel. Restoring channel migration processes should be combined with restoration of the native vegetation community in order to provide natural levels of bank stability. Interim bank protection measures may need to be employed until restored vegetation matures. Changes in inundation patterns may result in changes to vegetative communities and animal assemblages. Most habitat losses will be replaced by increased habitat in other parts of the floodplain and a significant increase in habitat complexity.

The greatest risks to habitat may occur while attempting to restore floodplain topography; excavation of floodplain features can result in fish stranding after high flows. Likewise, proliferation of exotic species, both plant and animal, may be of concern during the initial years of reestablishment. Another risk to habitat is land subsidence due to disconnection of the floodplain from the source of sediment, dewatering, and peat decomposition. Land subsidence is most common in tidally-influenced areas but may also occur in very low gradient non-tidal systems. When reconnecting a subsided floodplain to an active channel, the surface of the floodplain may be too low resulting in constant inundation. If the subsidence is significant, the channel could avulse through the floodplain and again alter the type of available habitat.

4.2 Risk to infrastructure, property, and public safety

One of the primary hydraulic effects of levee removal is the restoration of overbank flows. The anticipated frequency, duration, stage, and spatial extent of overbank flows should be well understood in order to manage flooding and erosion risk. This can be accomplished through hydraulic modeling (refer to the *Hydraulics* Appendix). Combining hydraulic modeling with a GIS (e.g. HEC-GeoRAS), or employing the use of 2-D models, is useful for determining and mapping the spatial extent of flood inundation that will result from floodplain restoration. For situations where flood stage or frequency will change, updates will likely be needed to regulatory flood maps (i.e. FEMA maps) and zoning designations.

For levee removal, flooding and channel erosion may pose a significant threat to infrastructure and property. Levee setbacks are frequently used to maintain flood protection of property. Levee setback can actually improve flood protection for adjacent and downstream property due to an increase in the flood capacity as a result of a greater cross-sectional area and storage volume for the channel and floodplain.

Another aspect to infrastructure and property risk is increased scour and bank erosion within the project area. If scour is significant, the channel could avulse to a new location within the floodplain. Scour is a concern because new areas will be opened to flow and other areas will be more prone to erosion immediately after the construction (or deconstruction) phase. Energy dissipation and bank protection may be necessary in critical areas where scour is not acceptable. Scour analysis models are available to help quantify the risks of erosion and avulsion. See the ISPG[6] for information regarding streambank protection and avulsion risk reduction.

Risk to public safety can be either increased or decreased depending on the project. In most cases, levee setback will decrease flood stage and risk of levee breaching, which will reduce the risk to public safety. If, however, proper analysis of flood stage and routing has not been completed, inadvertent flooding in previously non-flooded areas could decrease public safety. Public education and awareness is a critical component to projects that change flooding regimes along streams.

5 METHODS AND DESIGN

Levee modification and removal generally entails a high level of planning and design that extends well beyond the levee site. Projects may require several years of coordination and planning to obtain environmental clearances, landowner permission, easements, and adequate analyses and designs before being ready for implementation.

Even the implementation stage could be phased over several years depending upon the scale of the project. Basic assessment and data needs are discussed below, although individual project needs may vary considerably.

5.1 Data and Assessment Requirements

Reach-scale geomorphic assessments are essential for predicting the hydraulic and geomorphic effects of floodplain and CMZ restoration (refer to *Chapter 3: Stream Habitat Assessment*). Watershed-level assessments are also necessary at some level to account for potential actions and effects to the reach in question. The degree of risk and uncertainty dictates the amount of data collection and assessment required for a given project.

In evaluating levee modification or removal, a critical component for project feasibility and planning is determining the relative elevation of a channel or estuary to the floodplain surface. For example, removal of levees with a perched channel (e.g. from subsidence or in-channel sediment deposition) will likely require an analysis by a registered professional engineer to determine the effects on flood elevations, scour and deposition, and impacts to adjacent lands. Geomorphic and hydrologic analyses are essential for evaluating how the channel has evolved and adjusted to artificial confinement.

It is also useful to compare current channel geometry to pre-levee geometry to assess the extent of past channel change and the likely extent of future channel change. It is important to note, however, that due to stream channel adjustment to confinement post-restoration geometry may be different than pre-levee geometry. Historical aerial photograph sequences are an excellent tool for determining past rates of change for channel planform and for helping to delineate CMZs, but they are not capable of providing information on cross-section or longitudinal profile geometry.

For most floodplain and CMZ restoration projects, the following data collection and assessments will be required.

Data Needs:

- Hydrology (high and low flow frequency, magnitude, timing, and duration) for analysis of hydraulic and sediment effects. A range of flow levels should be evaluated from low flows to large infrequent floods.
- Topographic survey with cross-sections (including in-channel, levee, floodplain, and surrounding area which will potentially be impacted) for hydraulic analysis, flood inundation analysis/mapping, grading, and for potential realignment design. High resolution LiDAR (Light Detection and Ranging) may be used to supplement field survey data in some locations. LiDAR data is also useful for identifying floodplain areas that have been filled and graded.
- Cross-section characteristics sufficient for backwater hydraulic modeling including expected in-channel debris, channel variability, and bank and floodplain vegetation type and abundance.
- Land use, property ownership, and the location of infrastructure. These information sources are critical in order to help minimize risks and to investigate channel alignment alternatives.

- Channel bed and bank materials for sediment and scour analyses.
- Material used in levee or bank armoring structures. Removal or modification of structures may require specific equipment or techniques depending on material types and quantities.
- Floodplain characteristics (including soils, potential flow paths, vegetation, roughness, infrastructure and natural constraints to channel migration).
- Sediment load and sediment transport characteristics.
- Information from reference sites that may be useful for helping to predict or design the restored channel planform and geometry.
- Habitat types, quantities, and conditions including main channel and off-channel habitat types, LWD, riparian vegetation conditions, and water quality.
- [Tidal systems] Tide data to evaluate tidal inundation frequency and extent. Collecting tidal stage data at the project site and comparing this to nearby NOAA gages with longer periods of record is useful for characterizing the tidal regime.

Assessment Needs:

- Habitat assessment and quantification of anticipated changes to habitat and species assemblages (terrestrial and aquatic). It is also important to assess potential construction related impacts to habitat or species and to develop means to prevent harm. The impact of increased floodplain inundation on water fowl, shore birds, and terrestrial wildlife should be included.
- Assessment of riparian and floodplain vegetation communities and successional characteristics, especially as they relate to habitat, hydraulics (e.g. roughness and flow paths), wood recruitment, and nutrient cycling.
- Hydraulic modeling of impacts to river stage. This includes flood inundation analysis and mapping for the current and restored condition as well as modeling of the impact of the project on stream energy, sediment transport, and erosion potential. Hydraulic analysis will typically require at least a one-dimensional hydraulic model to evaluate impacts; small projects may only require at-a-station hydraulic analysis and large complex projects may require 2-D hydraulic and sediment transport models.
- Identifying the location of ordinary high water (OHW) and the 100-yr flood stage, both pre- and post-project, will help to understand the hydraulic effects of the project within a regulatory context. Post-project monitoring should be used to confirm or adjust design predictions.
- Developing sediment budgets and understanding reach-scale trends in sediment transport, scour, and bank erosion will help to understand the effect the project will have on sediment and channel dynamics.
- Assessment of large wood dynamics in the reach and potential upstream sources for large wood that may affect conditions within the project area.
- Risk assessment to determine potential risk to infrastructure (i.e., roads and bridges) and property located at the site and in upstream and downstream areas. A channel migration hazard study may be needed for establishing potential channel migration extents and the risk that channel migration may pose to infrastructure and property. If necessary, measures should be identified for modifying floodplain topography and vegetation in order to achieve adequate roughness, stability, and habitat conditions throughout the floodplain and CMZ.

- An evaluation of upstream and downstream effects of levee removal/setback, including flood water storage, sediment storage, sediment routing, erosion, planform adjustments, and potential changes to channel profile.
- Geomorphic assessment that evaluates how the stream has responded to the levee and/or bank armoring over time, and identification of secondary restoration activities that may be needed, such as grade control, temporary bank stabilization, realignment of the channel, floodplain roughening elements, and revegetation efforts.
- An assessment of the value of various levels of levee setback in order to determine setback levee location and configuration. Considerations include habitat benefit, potential geomorphic changes, property boundaries, adjacent land-use, infrastructure constraints, and the tolerable extent of flooding and channel migration.
- An assessment of past and future trends in channel dynamics and equilibrium conditions, including channel planform adjustment, bank erosion, sediment aggradation, and channel incision. For example, for a levee removal project it may be important to determine if the channel has achieved a state of equilibrium or if it is continuing to incise or aggrade.
- [Tidal systems] An assessment of the impact of levee removal on existing agricultural drainage and on saltwater intrusion into the water table on land behind the new setback levees.

Hydraulic models (refer to *Hydraulics* Appendix) are available to help predict changes that result from varying restoration scenarios. Many analytical tools are available for flood routing (e.g. HEC-RAS) as well as standard designs for levee construction from entities such as the US Army Corps of Engineers and the Natural Resources Conservation Service. Combining hydraulic modeling with a GIS (e.g. HEC-GeoRAS), or using 2-D models, is useful for determining and mapping the spatial extent of flood inundation that will result from floodplain restoration.

Sediment transport models (e.g. HEC-6 and GSTARS) are helpful for addressing issues associated with sediment movement within the project area and in the upstream reach, but should be used with caution as sediment transport modeling is an inexact science with potentially large margins of error. It is critical for modelers to fully understand model functions and limitations and to qualify results based on data and model uncertainty.

5.2 Considerations for Floodplain and CMZ Restoration Strategies

Floodplain and CMZ restoration projects are intrinsically linked to the naturally dynamic processes of the stream system, including the transfer of water, sediment, nutrients, and wood through the stream. It is essential that projects are evaluated within a broad context and are not restricted to a hypothetical closed system with known variables and assured outcomes. The assessment of probable project outcomes should be expanded well beyond the footprint of the project when evaluating impacts, benefits, and risks. Projects implemented at the reach-scale are preferred over site-specific projects because they restore more floodplain functions and amplify beneficial effects. They are also potentially more cost effective with regard to the amount of increased habitat benefits.

It may be necessary to implement measures in the channel upstream or downstream of the project site prior to removal of levees/bank armoring in order to reduce the potential for undesirable planform or profile adjustments (e.g. incision or avulsion). Specific guidance on modifying in-channel characteristics is provided in the *Channel Modification* Technique.

5.2.1 Levee Removal

Full levee removal typically restores the greatest amount of floodplain and CMZ compared to levee setback or breach. Full levee removals typically occur in agricultural areas that are no longer in production and where there is little or no existing infrastructure that is being protected by the levee. In areas where levees are currently providing flood protection to infrastructure or agriculture, setbacks or selective breaches are more common. Other elements are frequently constructed in combination with full levee removal, including removal of bank armoring, removal of floodplain features, and site re-contouring and revegetation. These associated elements are discussed below in their respective sections.

Removal of levees that lie directly adjacent to active channels will typically require interim bank stability measures to avoid high erosion rates following construction. This may include design of “deformable” streambanks that limit erosion only for a planned time interval. Bio-engineered treatments, including fabric encapsulated soil lifts and large wood, are commonly used to provide interim stability while allowing for the growth of planted streambank vegetation. Eventually, once the original treatment decomposes, the planted vegetation will have matured and will allow for long-term natural rates of bank erosion.

One of the largest components of a levee removal project is the excavation and removal of the levee material itself. Use of a nearby spoils disposal area will generally simplify construction and help to control costs. In some cases, levees have been constructed by excavating material from a borrow ditch next to the levee; these borrow ditches may be suitable for placement of spoils. Keep in mind that there will likely be requirements associated with disposition of materials, such as locating them outside the 100-year floodplain and applying adequate erosion control measures.

The footprint of a removed levee will typically have highly-compacted soils that will not support vigorous vegetation growth. This is because levees built to an engineering standard were compacted during construction. Consequently, this will require ripping the subsoil at the final grade to reduce compaction and allow for vegetative reestablishment. Topsoil removed during construction should be stockpiled for later use on these mineral soil areas.

For levees that have mature vegetation growing on them, there may be significant short-term impacts to habitat due to levee removal. These short-term impacts are usually outweighed by the long-term benefit of removal; however, in highly sensitive areas where short-term impacts cannot be tolerated there may be alternatives to full levee removal. These include leaving remnant islands of levee that contain mature vegetation or constructing multiple breaches that remove only a small portion of the vegetation. When mature vegetation must be removed, attempts should be made to salvage and re-plant the material, or where re-planting will not be successful, incorporate removed vegetation as habitat (i.e. large wood) within the project area.

5.2.2 Levee Setback

Levee setback can be considered for areas where the width of the floodplain can be increased but where there still remains infrastructure that needs protection. Because levee setback typically requires the removal of one levee and the construction of another, the considerations above for levee removal will also apply to levee setbacks. Additional considerations for levee setbacks are mostly related to the construction of the new setback levee.

Levee setback distances will vary greatly and are often dictated by landowners and land managers. Ideally, setback levees will be located as close to the infrastructure as practicable in order to regain the greatest floodplain or CMZ width. The further back the levee is placed, the more floodplain area is protected and unlikely to be developed.

If the material from the original levee will be used in the new setback levee, it will be necessary to determine the adequacy of the material for construction of the setback levee. The material will have to have the proper gradation of sizes and soil types. Borings, test pits and soils testing will have to be done to determine if the material can be reused. Current levee engineering standards may render existing levee materials inadequate. This can significantly increase costs by requiring that old materials be hauled away and new materials brought in. A temporary storage area to stockpile soil material will also be required until setback levee construction is complete. A qualified engineer can help with logistics and plans for levee removal and can also develop design guidance for the new levee.

5.2.3 Levee Breach

Levee removal and setback projects may not be feasible if they are not easily accessible by large equipment, if vegetation is mature and well-established, or if the cost is prohibitively high. In these scenarios, levee breaching may be a viable option. Levee breaches allow for floodplain inundation, floodwater storage, sediment deposition, and off-channel habitat, although these may be limited relative to levee removal or setback.

An analysis for levee breaches will be similar for removal or setback, but may require additional analyses at the breach locations, particularly if erosion of the levee or channel avulsion through the breach cannot be tolerated. The potential for erosion at the breach point is high because of the concentrated energy of the flow and therefore the design of the breach (e.g. size, location, or use of structures) will require careful analysis to minimize the risk of scour and channel avulsion. It will be necessary to calculate breach size using expected volumes and critical flow velocities. If breaches are too narrow, flows are constricted and may result in localized bed scour and channel avulsion. Narrow constrictions may also limit fish passage. Where scour is anticipated, it may be possible to dissipate energy using vegetation, logs, or pilings. It may also be possible to add multiple breaches to reduce shear stress and flow velocities; although this will not necessarily reduce the potential for scour at other undersized breach points. Multiple breaches may also help to reduce the risk of channel avulsion and will provide alternative channels if flow or fish passage through one of the breaches is reduced due to wood or sediment accumulation.

Because many levees also serve as river training structures, there may be a need to maintain some river training function of the levees. In this situation, breaches can be placed in areas that will allow backwatering of the floodplain during high flows without allowing channelized flow to access the historical floodplain. Backwater breaches may also be suitable for areas where seasonal farming will still occur on the floodplain. Floodwaters will backwater crop areas during the rainy season but will freely drain and be available for farming during the dry season. For backwater breaches, the lower half of the inside of a meander bend, where natural deposition is expected, may be a good place to locate the breach. This allows for floodplain inundation while reducing the hydraulic gradient between the floodplain and channel, and helps control avulsion risk

In some circumstances, open breaches are not acceptable, especially in areas where an access road is located on the top of the levee. Culverts or bridges can be used to allow some connectivity to the historical floodplain while maintaining road access. While this is not a preferred alternative, it may nevertheless provide important aquatic and terrestrial habitat benefits. Long-term maintenance for culverts and bridges will have to be factored into the overall cost and design of the project.

Regardless of breach type, breaches should be placed preferentially in low areas or in areas where channel remnants still exist. Natural breaches, as a result of flood events, provide excellent opportunities to increase breach size or to place culverts or bridges. These natural breaches also work well with an adaptive management approach where new breaches are not repaired but are incorporated into an existing project.

5.2.4 Removal of Floodplain Encroachment Features

Typical features that encroach on floodplains and CMZs include roads, houses, buildings, recreational features (e.g. parks and golf courses), and utilities. Such features may or may not include levees and bank armoring but may nevertheless impact floodplain and CMZ processes and off-channel habitat. In some cases, removal of these features will restore floodplain inundation rates, restore natural channel migration, and allow for the development of floodplain channels that are important for off-channel fish habitat.

Removal of floodplain features is often not possible until significant or repeated flooding or erosion threatens or damages property, at which point opportunities arise for floodplain restoration. This has occurred on many Washington streams where encroachment features have been damaged by flooding. It typically requires purchase of property or conservation easements by government or not-for-profit entities. Once encroachment features are removed, the primary elements of restoration include site re-contouring and revegetation. Where utilities are involved, relocation or reconfiguration will often be necessary.

Relocation or setback may be an option for roads, railroads, and utility corridors that confine or otherwise impact floodplains. Relocation of these features to the toe of the valley wall will maximize floodplains and CMZs, but locations that negatively impact wall-based or groundwater-fed channels should be avoided. Road crossings can be moved to natural points of valley constriction or can be replaced with longer bridge spans in order to reconnect more of the floodplain.

5.2.5 Modification or Removal of Bank Armoring

Where feasible, removing bank armoring allows for more deformable channel boundary conditions and restores natural rates of erosion and planform adjustment. This technique is different from habitat-friendly bank protection, of which there are many approaches that are covered thoroughly in the ISPG[6]. In contrast to bank protection, this technique actually allows for more natural rates of bank erosion and channel migration over the long-term.

When removing bank armoring, it is critical to consider post-project channel boundary conditions and stability, which will likely be considerably different than natural, pre-armoring conditions at the site. Most sites subjected to bank armoring have been cleared of vegetation, armored using large rocks or other structures and backfilled with soil. Channel conditions have likely adjusted to bank armoring including deepening and coarsening of the bed. These altered conditions will impact post-project stability and must be considered in design.

It is typically necessary to provide some interim stability to the restored bank so that dramatic instability does not impair habitat or cause unintended consequences to downstream or upstream reaches (i.e. erosion and flooding). Interim stability is provided until a time when replanted riparian vegetation has matured and can eventually provide long-term natural stability. This approach is sometimes referred to as creating "deformable boundaries" and is used as part of various restoration techniques (see *Channel Modifications* technique for more information). Approaches include reconstructing banks using soil encapsulated fabric lifts, large woody debris jams, or other bio-engineering techniques that combine vegetative plantings with soil stabilization measures.

5.2.6 Restoration of Floodplain Topography and Vegetation

Restoring floodplain topography and vegetation may be desirable in order to restore natural flood flow pathways, set the template for future channel planform adjustment, enhance off-channel/floodplain habitat, increase floodplain sediment storage, and restore nutrient exchange pathways. Restoration of topography may include the creation of features found in natural, connected floodplains including swales, natural levees, off-channel features, flood overflow channel depressions, and wetlands. Planting of native vegetation communities is typically conducted to benefit overbank hydraulic conditions (roughness), provide a source for future wood recruitment, and to improve terrestrial and aquatic habitat. Some projects have had success with allowing the restored hydrology (e.g. restored floodplain inundation) to reestablish natural vegetation on its own. This may be particularly effective in tidal areas and where there is not a risk of domination by invasive species.

One of the primary reasons for restoring topography and vegetation is to manage for appropriate floodplain roughness. This is because many developed floodplains have been cleared and graded and natural roughness features have been removed. This creates a risk of significant instability and avulsion potential once floodwaters are reintroduced to the site. A floodplain and channel migration assessment may be necessary for evaluating the risk of avulsion. If flow velocities over the floodplain are high enough to entrain floodplain material and there is low roughness due to prior land-use, then the potential for channel avulsion may be high. Unless avulsion is an acceptable and anticipated outcome, precautions to limit avulsion potential may be required.

Examples include regulating flow at constructed levee breaches to contain most of the flow in the primary channel, placing logs or engineered log structures in the floodplain to increase roughness, and planting dense vegetation within the floodplain (may take years until roughness or stability is provided by vegetation).

It may be advantageous to implement measures within the floodplain and CMZ prior to reconnection activities. For example, converting an agricultural field to a floodplain may require placing stable, properly ballasted wood or planting and managing floodplain vegetation for some period of time in order to provide functional roughness components prior to levee modification or removal.

In some cases, aggressive modifications to floodplain topography can be conducted in order to allow the stream itself to make beneficial planform adjustments in a "passive" approach during floods. An example is the excavation of preferential channel flow paths in the restored floodplain area that the main channel or side-channel will eventually occupy, in effect setting the template for future planform adjustment. This technique is appropriate for systems that have been straightened and confined and where floodplain areas that were historically accessible for channel migration have been filled and graded. This approach can bring about beneficial changes more rapidly than simple removal of confinement features, and it also requires less in-water work for construction; however, it also carries greater uncertainty and requires more analysis to manage for risk.

Despite the potential benefits, restoration of floodplain topographic features may be inappropriate in some situations. Florsheim and Mount[9] documented floodplain topography changes after intentional levee breaches along the Lower Cosumnes River in California, and found that, in this case, excavation of floodplain ponds and other depressional features actually trapped incoming sediment and limited the natural development of floodplain topography.

5.2.7   Floodplain Lowering and Raising the Channel Bed

Floodplain lowering and/or raising the channel bed can be used for areas where floodplains are disconnected as a result of floodplain fill or channel incision. This reconnection technique requires a thorough understanding of watershed inputs, channel processes, the legacy of past land-use, and future trends in channel geometry. If the underlying causes of channel incision are not addressed, then applying this technique may involve a significant risk of failure or may require continual maintenance.

Raising the channel bed can be used to increase the frequency and extent of floodplain inundation. Raising the channel can either be conducted using channel profile adjustment structures (aka grade control; see the *Instream Structures* technique) that protrude from the channel and are designed to aggrade sediment over time, or can be conducted using a combination of structures and fill to bring the channel up to the desired grade. This technique often has considerable uncertainty, especially in urban settings where incision is caused by fundamental changes to watershed hydrology. If hydrologic conditions are the cause of the problem and are not addressed, persistent instability may continue post-project and may once again cause floodplain disconnection through channel widening or re-incision. This technique is most successful where incision is related to local, reach-scale impacts such as channelization, removal of LWD, removal of vegetation, or instream gravel mining.

Floodplain lowering is another means for increasing the frequency and extent of floodplain inundation. This technique includes the excavation and removal of floodplain material in order to lower floodplain elevations. Floodplain lowering is frequently used when raising the channel bed is too costly, uncertain, or otherwise inappropriate, and is usually not cost-effective on large stream systems with extensive floodplains. Floodplain lowering may be appropriate for incised channels that have already progressed through some degree of incised channel evolution and associated widening and incipient floodplain development (refer to the *Fluvial Geomorphology* Appendix for additional information on this process). This technique may also be useful for increasing the amount of available storage for surface water and sediment during overbank floods. This can reduce downstream flooding and sedimentation issues. This technique was used as part of a restoration effort on Johnson and Kelley Creeks in Portland, OR (www.portlandonline.com/bes/index.cfm?a=263660&c=33213) as a means to provide floodwater retention to reduce downstream flood impacts.

6 PERMITTING

Various permits will be required at the local, state, and federal levels. For most projects, the standard suite of regulatory permits will be required. Refer to the *Typical Permits Required for Work in and Around Water* Appendix for further information. This section focuses on permits that are unique to floodplain and CMZ restoration projects.

Any changes to flood elevations or the mapped FEMA floodway will require additional permitting from the local jurisdiction (state, county, or city), and will require a Letter of Map Revision (LOMR) from FEMA that is required in order to revise the FEMA flood hazard maps (Flood Insurance Rate Maps).

For levee removal or modification projects, it is important to understand who has legal authority over the levee. Even if levees are located on private land, the jurisdiction may fall to the US Army Corps of Engineers, a local diking district, or other entity. Approval will be required from these entities before action can be taken to modify the levee. Modification or removal of small levee systems owned and built by a private landowner may be easier to accomplish, although impacts to adjacent lands must still be investigated.

7 CONSTRUCTION CONSIDERATIONS

General construction considerations for most habitat restoration projects are included in the *Construction* Appendix. This section focuses on considerations that are unique to floodplain and CMZ restoration projects.

Projects that remove or modify levees or bank armoring typically involve the use of large machinery including large excavators and off-road dump trucks. Care should, therefore, be taken to limit impacts on existing vegetation and soils to the extent possible. It will be necessary to clearly designate entry and exit points and access roads. Construction equipment should be routed through less sensitive areas where feasible. The number of roads and the number of trips by large equipment should be minimized. Finding a nearby spoils disposal site will reduce impacts from vehicle traffic as well as reduce costs.

If site soils cannot support equipment and vehicle traffic, it will be necessary to ballast work areas. Special equipment for operating on soft ground may also be required to reduce soil compaction. If this equipment is not appropriate or available, ripping (de-compacting) of the construction access areas following construction may be necessary to decrease soil compaction.

The footprint of an old levee will also need to be ripped prior to vegetative establishment.

For levee removal or modification projects, entry and exit points and haul roads are often on the levee itself. Removing the levee in stages may allow for portions of the levee to remain in place for flood protection or to provide construction access during most of the project duration.

Clearing and grubbing (clearing roots and stumps) should be minimized to the extent possible. In some cases, vegetation can instead be trimmed to the ground level and covered with a geotextile during construction. Mature, desirable vegetation should be left in place or salvaged and replanted where possible during construction. Working outside of the tree drip line is essential to protection of tree roots. Because removal of mature vegetation may be necessary in some areas, consider saving islands of vegetation to serve as a natural seed bank and to provide habitat while the system recovers from construction disturbance. Trees that are removed during construction can be used as floodplain roughness elements and as habitat features. Fertile topsoil that is removed can be stockpiled for later use. Soil piles should be kept small to minimize composting which will reduce the available seed bank.

8 COST ESTIMATION

The following elements will need to be considered for cost estimation:

Feasibility studies. These including hydrologic, hydraulic, geomorphic, biologic, and specific habitat studies. Costs will vary depending upon the size and scope of the project.

Project design. This includes preliminary designs, final designs, and specifications. Regulatory processes and permits including NEPA/SEPA, ESA, USACE, state, county and city permits.

Land acquisition and protection. Costs vary widely depending upon current land use and local land prices. The proponent should work with qualified real estate professionals who can determine appropriate land values. Inquiries should be made to the county assessor about changes in tax rates if the area is being converted to a different land use.

Levee removal, augmentation, breaching, and/or construction. Levee construction/deconstruction will require mobilization and demobilization of equipment, pollution control, clearing and grubbing, bulk excavation, recontouring, hauling, and disposal of material. Additional material for levee construction and bank protection may be necessary, which will add to overall project cost. For levee setbacks, a temporary storage area may be required for the spoil material. Mobilization and demobilization costs will typically be a percentage of the total contract cost (generally 12 to 18%).

Excavation, hauling and disposal. Cost is based on the volume of material to be moved and the length of the haul route. The volume of a levee is readily calculated from survey data, which allows for a relatively accurate estimate of removal costs because excavation costs per cubic yard and hauling distances will be a fixed value. Hauling cost depends on haul distance, but general estimates can be made based on rental rates for dump trucks for small projects. For larger projects, contact a local quarry for trucking rates. The cost for material disposal will vary greatly depending upon the condition of the material. For clean, uncontaminated material, disposal costs may be low, or free. Contaminated soil will significantly increase cost.

Bank stabilization and other structures. Costs will vary depending on the stabilization approach and materials used.

Vegetative plantings. The cost for reestablishment of vegetation will vary depending upon availability of material and the labor involved in the actual planting. Advanced planning can significantly reduce costs by insuring that specific species are available in the quantities required. Native plant nurseries are becoming more common, and they will often propagate site-specific plants for future revegetation efforts if notified well in advance. See the *Riparian Restoration and Management* technique for more information about vegetative plantings.

Construction management. Construction management and inspection is a critical component of a project. Construction management includes inspection of construction methods and materials to ensure quality and to ensure adherence to specifications. Project progress is monitored and documented to ensure the project proceeds on schedule. Expenditures, invoices, and change orders are documented and tracked to ensure budgets are met.

Resource protection. This includes use of BMPs to protect water quality and habitat. It includes erosion control measures, dust control, spill prevention, and fish rescue. The contractor may be responsible for all or only a portion of these activities. Agency representatives can frequently assist with fish rescue and this may reduce costs.

De-watering. Isolation of the work area from flowing water, either through de-watering or use of sediment barriers, will frequently be required to reduce water quality impacts and to facilitate construction. Costs depend on how this is conducted and what materials and equipment are necessary. Construction of temporary cofferdams and pumping are typically required.

Contingency. Contingency costs can be as much as 30% of estimated construction costs when the project is within conceptual development. Contingency cost can be reduced once a detailed design is prepared and once potential uncertainties are better understood.

9 MONITORING

Project effectiveness monitoring is recommended to evaluate if objectives are being achieved and if adaptive management of the project is necessary. It is critical to monitor according to the objectives of the specific project. Monitoring programs that are not based on the project objectives, or that assume different or additional objectives, may fail to accurately evaluate project effectiveness (refer to Chapter 4 for information on defining project objectives). This section describes considerations for project monitoring with the understanding that certain monitoring elements may not be appropriate and additional elements that are not presented here may be required.

The purpose of monitoring is to determine if the goals and objectives of the project have been met, suggest changes if needed, as well as to learn more about habitat restoration projects in general. Monitoring of floodplains after the modification or removal of levees is commonly accomplished with the aid of aerial photography, digital terrain models (DTMs), satellite imagery, LiDAR, etc. Because the reconnection of streams to their floodplains can be extensive, aerial photos are useful for evaluation of the entire project area. Flow paths, deposition and erosion areas, and changes in vegetation can easily be identified on appropriately scaled aerial photos and LiDAR hillshade relief maps. Aerial photos can be taken during various seasons to allow for evaluation of flood extent, ephemeral habitat, and plant communities. For smaller projects, ground photo points may be sufficient to evaluate general trends.

The Salmon Recovery Funding Board (SRFB) Reach-Scale Effectiveness Monitoring Program[10] reports that projects that restore constrained channels are significantly increasing floodprone width in the first three years following project implementation. However, monitoring data are limited and monitoring of more projects over longer periods is needed. Recommendations for monitoring elements in the report include tracking topographic changes over time, hydraulic modeling to predict habitat availability for given flows, quantifying the amount of available floodplain habitat, making fish density estimates, and estimating fish survival during floods.

Specific monitoring items to consider include:

- Water level recorders for river and tidal areas. Water level recorders in the floodplain can be used to determine when a floodplain becomes activated. The gage can be calibrated to other gages within the basin.
- Piezometers can be installed in the floodplain to monitor shallow groundwater levels and hydraulic gradients.
- Vegetation type and abundance can be monitored with vegetation transects. Special attention should be given to shifts in vegetative communities and the introduction or eradication of invasive species.
- Topographic surveys can be used to determine if natural topography is developing on the floodplain (if previously leveled) and the extent of side channel development. For smaller projects (e.g., 10 acres or less), standard ground survey approaches (e.g. total station or survey-grade GPS) are appropriate for developing detailed topographic maps. LiDAR should be considered for larger projects.
- Structural components, such as bank protection or levee integrity, should be evaluated using standard engineering protocols. Specifically, an “as-built” survey should be completed after construction of all project components and a record drawing should be prepared.
- Bank erosion rates can be measured using survey data, bank pins, or repeat photos from established points.
- Floodplain inundation pre- and post-project can be monitored using water level recorders, photography, site visits, and modeling.
- Habitat availability, creation, and quality can be measured using standard habitat survey techniques.

Refer to *Monitoring* Appendix for more detailed discussion and monitoring resources.

10 MAINTENANCE

Operations and maintenance will be required for most projects. Full levee removal, accompanied with appropriate restoration of the floodplain, should require little or no maintenance beyond the establishment of native vegetation. For levee setbacks and removal of bank armoring, maintenance may be required to ensure property is not affected by erosion or flooding. For levee modification projects, levee maintenance is often the responsibility of the owner (e.g. diking district or county), so it will be necessary to coordinate with this entity with respect to long-term maintenance.

An operations and maintenance plan should include specific instructions to insure that the project is functioning properly. Requirements to consider include:

- Prompt repair or replacement of damaged components.
- Removal of obstructions from inlet and outlet facilities.
- Periodic survey of fill elevations.
- Evaluation of the levee surface for cracks in the soil.
- Evaluation of eroding areas, including main channel, side channels, floodplain surface, levee surfaces, and breach areas.
- Evaluation of vegetation condition, distribution, composition, and abundance.

A potential issue with existing or setback levees is the vegetation management standards required by the US Army Corps of Engineers (USACE) for levees enrolled in the federal Rehabilitation and Inspection Program (RIP) under Public Law 84-99. Under PL 84-99, the USACE is authorized to provide emergency assistance and cost-share to construct levee repairs following a disaster event. Eligibility for this cost-sharing program requires that levee sponsors comply with the USACE's RIP, which, as a national standard, requires the removal of vegetation greater than two (2) inches in diameter from levees to prevent vegetation related damages, allow for inspections, and allow for access during flood fighting efforts. If a levee is not included under PL84-99, the federal vegetation standards do not apply; and so incorporated vegetation into the levee prism is solely a matter of design goals, objectives, and performance of the levee for flood protection.

Except for levee owners such as King County, who have levees in the RIP and have worked with the USACE to apply a regional variance to the national vegetation standard, local governments in the Puget Sound region are caught between conflicting federal mandates. That is, a maintenance requirement to remove vegetation to maintain eligibility under the USACE's PL 84-99 funding assistance program versus a requirement to protect riparian vegetation conditions that have been identified as critical habitat for federally listed species in the Puget Sound Salmon Recovery Plan. In other words, to comply with one federal mandate, local governments must risk violating the Endangered Species and Clean Water Acts. This is also the case in Clark County, and other counties as well, and is something to be considered when projects involve existing or new flood protection levees.

11 EXAMPLES

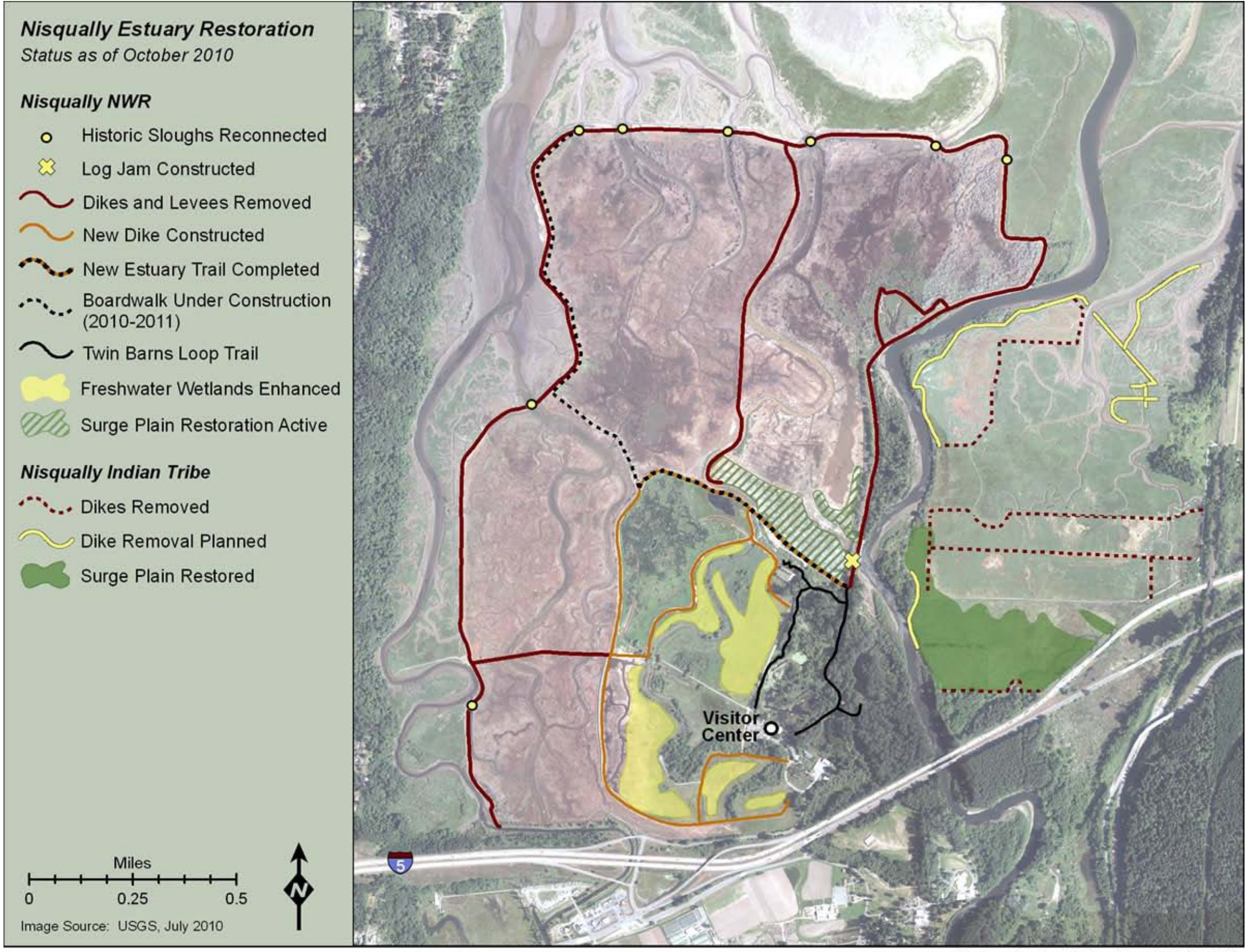
Numerous floodplain restoration projects have been completed in Washington State. Information on projects funded through the SRFB can be found at the SRFB Habitat Work Schedule website (http://hws.ekosystem.us). A few case studies of floodplain restoration in Washington State are presented below.

11.1 Nisqually Delta Restoration Project

The Nisqually Delta Restoration Project is a collaborative effort between multiple public, tribal, and private partners to restore floodplain and off-channel habitat in the Nisqually River Delta. The following information is excerpted from the Nisqually Delta Restoration website (www.nisquallydeltarestoration.org):

> *After a century of levees preventing tidal flow, the Brown Farm Dike was removed to inundate 308 ha of the Nisqually National Wildlife Refuge (Refuge) on 11 November 2009. Along with 57 ha wetlands restored by the Nisqually Indian Tribe, the Nisqually Delta represents the largest tidal marsh restoration project in the Pacific Northwest to assist in recovery of Puget Sound salmon and wildlife populations. Over the past decade, the Refuge and close partners, including the Tribe and Ducks Unlimited, have restored more than 35 km of the historic tidal slough systems and re-connected historic floodplains to Puget Sound, increasing potential salt marsh habitat in the southern reach of Puget Sound by 50%. Estuarine restoration of this magnitude and the potential contribution to restoration science is unprecedented in Puget Sound. Because of the mosaic of estuarine habitats, this large-scale restoration is expected to result in a considerable increase in regional ecological functions and services, representing one of the most significant advances to date towards the recovery of Puget Sound. The US Geological Survey is the lead science agency providing science support to document habitat development and ecosystem function with large-scale restoration.*

Figure 1. Restoration plan map for the Nisqually Delta Restoration Project. Plan map is from www.nisquallydeltarestoration.org.



Cartography by: J.Cutler, Nisqually Indian Tribe

11.2 Elk River Estuary

The following information is from Simenstad and Thom.[11] The Elk River estuary drains the southwest corner of Grays Harbor. The enhancement site is a 16 ha salt marsh that was leveed and used as pastureland for over 50 years. Over the period it was leveed, the site was colonized extensively by facultative freshwater wetland plants including the exotic species *Phalaris arundinacae* (reed canary grass). In June 1987, a 10 meter gap was excavated in the levee for tidal inundation as part of wetland mitigation plan. The diked habitat in the Elk River estuary subsided considerably, although the precise extent of subsidence has not been measured.

Local estuarine processes adjusted to the presence of the levee by accreting on the Grays Harbor side of the levee and subsided on the landward side of the levee. Consequently, an unusual gradient in tidal elevation developed from low marsh to high marsh (on the Grays Harbor side of the levee) to low marsh (on the landward side of the levee). The narrow dike breach combined with the elevation change between the higher, former "foreshore marsh" and the lower, new "back marsh" appears to be responsible for rapid erosion of a tidal channel at the point of the levee breach. Limited channel capacity also creates a backwater effect during an ebb tide, thus inhibiting the drainage of the tidal waters from the restored marsh area.

Monitoring habitat changes following the levee breach is limited to annual surveys of percent coverage of primary emergent wetland plants at five established points across the leveed site. Observations indicate a rapid decline in dominance of the predominantly freshwater plant assemblages to recruitment and increased dominance of facultative and obligate estuarine species of wetland plants such as *Salicornia virginica* (pickelweed), *Atriplex patula* (saltweed), and *Carex lyngbyei* (Lyngby's sedge).

11.3 Puyallup River Levee Setbacks

Approximately 90 miles of levees have been built in the Puyallup River system since the early 1990s. The levees were built primarily to control inundation of agricultural fields, however, the flood protection provided by the levees allowed for the development and human occupation of the floodplain. Flood protection was compromised over time as maintenance lapsed and sections of the levees were damaged or destroyed by floods (FEMA[12]). In recent years, levees have been removed and new setback levees have been constructed in order to enhance aquatic habitat and to manage flood risks.

<u>Ford Setback Levee</u>
In 1996, a flood on the Puyallup damaged several homes along the river a few miles upstream from the city of Orting, damaged or destroyed several hundred feet of a levee, and threatened an important local roadway (Orville Road). That event triggered efforts by the U.S. Army Corps of Engineers (USACE), in close cooperation with Pierce County, the Washington Department of Fish and Wildlife (WDFW), and the Puyallup Tribe of Indians to develop a plan to address the flood damages and lessen the risk of future damages along the river. The focus was the reach upstream from the city of Orting. The plan proposed creating a system of new setback levees (built several hundred feet from the river's edge) and bank protection measures.

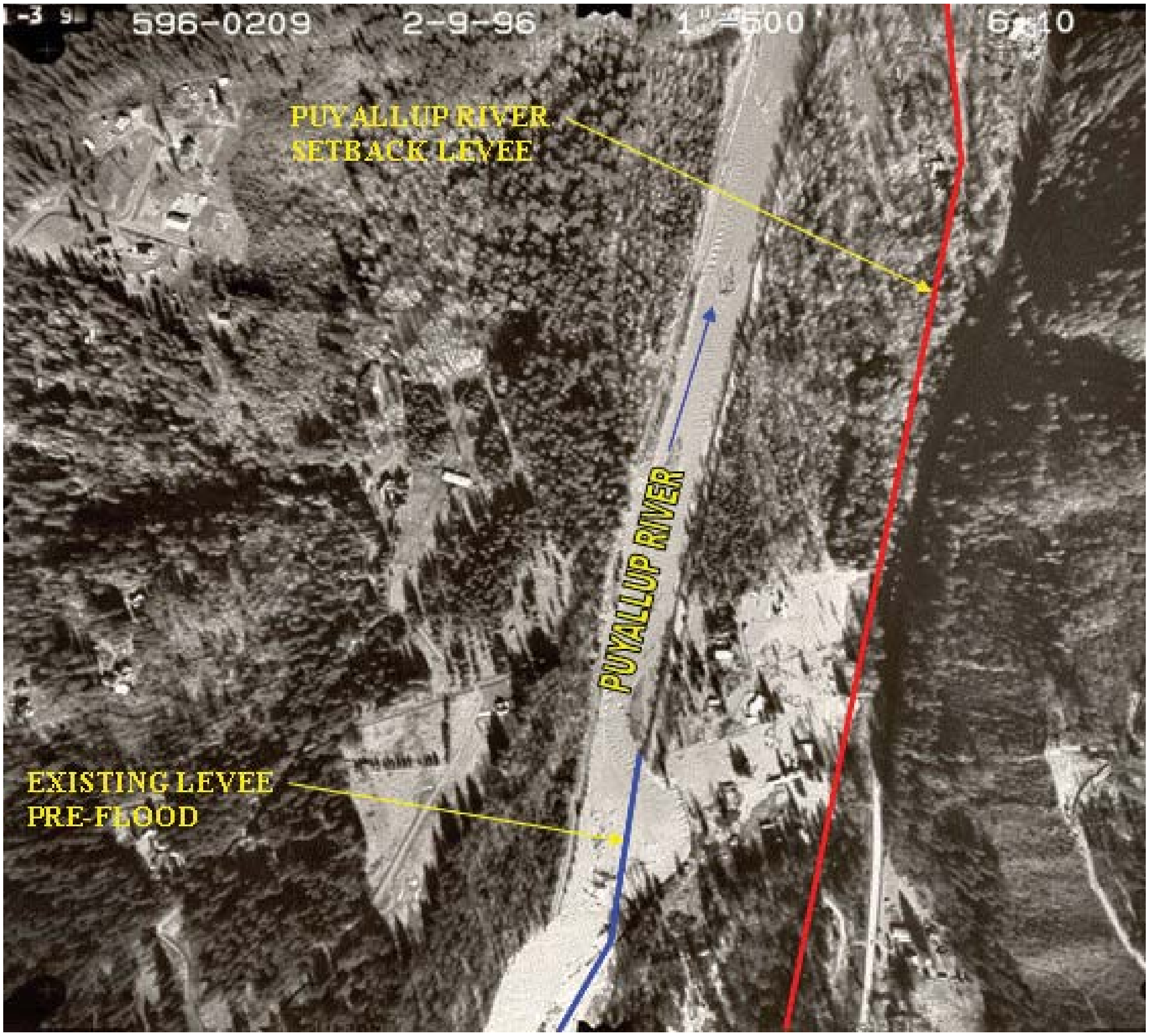
In 1997, ten thousand feet of new setback levee were constructed; 1,000 feet of existing levee were repaired and 2,600 feet of the riverbank were "hardened" against erosion (see Figure 2). The reconnection of the Puyallup River with about 125 acres of its natural floodplain had two positive consequences. First, it allowed the river more room to spread out and dissipate energy during flood events. During the floods 2003 and 2006, the levees greatly mitigated the flood impact to the area protected by the project. Secondly, it restored salmon access to approximately 2,000 feet of the channel of a tributary to the Puyallup, and within a few days of completion of the work, chum salmon were seen entering the small stream for the first time in many years. The restoration of the salmon habitat was a particularly welcomed outcome of the project for the Puyallup Indian Tribe which retains ancestral fishing rights to the Puyallup River system.

<u>Soldier's Home Setback Levee</u>
This project is located on the Puyallup River between RM 21.5 and 22.4. The project was completed in 2006 by Pierce County Surface Water Management. Objectives were to improve wildlife habitat and increase flood protection. The project re-connected approximately 67 acres of floodplain, allowing for natural channel migration and floodplain inundation. At its maximum, the river corridor width was increased from 250 to 1,150 feet. The new setback levee provides flood protection to adjacent properties.

Planning is underway for additional levee setbacks within the Puyallup River system with the following goals: 1) increase floodplain connectivity and flood storage,

2) reestablish short- and long-term geomorphic processes and function, and 3) maximize aquatic habitat diversity and use[13]

Figure 2. Location of Puyallup River Levee Setback. Plan map is from FEMA.Error! Bookmark not defined.



11.4 Other Projects

Lower Tolt River Floodplain Restoration: King County has implemented floodplain restoration work along the lower Tolt River near John MacDonald Park in Carnation, Washington. Work has included removing an old degraded levee and rebuilding a set-back levee to protect the park from erosion (www.kingcounty.gov/environment/animalsAndPlants/restoration-projects/tolt-restoration.aspx).

Qwuloolt Estuary Restoration/Ebey Slough (Snohomish River Estuary): The Tulalip Tribe has been involved in tidal estuary restoration work along Ebey Slough and within the Qwuloolt Estuary area since 1994. Tidal wetland, floodplain, and stream habitat has already been restored, and planning is underway for restoration of more than 400 acres of estuary. The project will construct a setback levee, remove tide gates, plant native vegetation, and reintroduce tidal inundation to fallow farmland (www.tulalip.nsn.us/qwuloolt/rp.html).

Skokomish Estuary Restoration: The Skokomish Tribe has implemented estuary restoration work in the Skokomish Estuary since 2007. Phase 1, completed in 2007, was the main shore and included removal of dikes to allow for tidal flooding of the area. Recolonization of salt marsh vegetation has taken well to the restored area over the succeeding three years. Phase 2, completed in 2010, included restoring Nalley Island to its historic state as a natural estuary. Work included building a temporary bridge for construction crews to remove interior dikes and soils (http://archive.habitatconference.org/2010/2010/11/skokomish-estuary-restoration-project).

Lockwood Creek (tributary to the EF Lewis River) in Clark County, Washington: Levee removal with some floodplain excavation to improve fish habitat. Project sponsor is the Clark Conservation District. The project was funded by the SRFB and implemented in 2000.

Spencer Island Wetland Restoration in Snohomish County: In the late 1990s, a cross levee was built and an existing levee was breached to re-create a tidally-influenced, freshwater wetland on 400 acres in the Snohomish River Estuary. The project was sponsored by Snohomish County Parks.

Deepwater Slough Section 1135 Restoration Project near Conway, Washington:[14] This project included a levee breach, levee removal, new dike construction and dike augmentation by the U.S. Army Corps of Engineers. Project construction was initiated in 1999.

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TECHNIQUE 3

SIDE CHANNEL AND OFF CHANNEL HABITAT

Side Channel and Off Channel Habitat

1 DESCRIPTION OF TECHNIQUE

This technique includes the creation, reconnection, and enhancement of side channels and off-channel habitats that are connected and associated with mainstem river channels. The side channel technique is often used in conjunction with other techniques in this guideline such as *Beaver Reintroduction*, *Floodplain and CMZ Restoration*, *Dedicating Land and Water to Stream Habitat Preservation and Restoration*, and *Riparian Restoration and Management*. Restoration of fish passage is frequently conducted as part of side channel restoration; however, fish passage is discussed thoroughly in *Fishway Guidelines for Washington State*[1] and *Design of Road Culverts for Fish Passage*[2] guidelines. The side-channel technique does not include artificial spawning channels, which generally include water supply structures, structures to supply upwelling water, and/or fish holding or segregation devices. Bell (1990)[3] includes a description and criteria for spawning channels.

The Side Channel and Off Channel Habitat technique may be the main emphasis of a stream habitat restoration project, or it may be a component of a broader set of techniques implemented in concert. Prior to embarking on designs for specific techniques, the restoration practitioner should have already completed a site, reach, and watershed assessment to identify causes of observed or perceived problems, to determine constraints to addressing these problems, and to frame the project in the broader context of a watershed restoration strategy (Chapter 4). Because restoration practice is most effective when it addresses root causes of problems rather than observed symptoms, a robust assessment that looks at potential causes at site-, reach- and watershed-scales will contribute to a more effective restoration strategy. In addition, design should only proceed when project goals, specific objectives, and design criteria (Chapter 5) have been clearly defined and a restoration strategy has been developed to meet these objectives. A site- or reach-scale technique may ultimately provide little value if it is not consistent with overall watershed priorities or integrated with other techniques as part of a restoration project.

The types of side channel restoration discussed in this guide include the following:

1. Creation – the creation of new side-channel habitats.
2. Reconnection –the hydrologic reconnection of existing side-channel habitat that has been disconnected through human actions such as levee construction, channel filling, or channel incision.
3. Enhancement – the enhancement of aquatic habitat within an existing side channel.

The focus of this technique is on restoration or creation of self-sustaining habitats that work within and support natural processes, including flooding, channel migration, and large wood recruitment. This should always be the goal in order to achieve true ecosystem restoration. In some cases, however, where site constraints or habitat conditions limit opportunity for process restoration, side-channel projects may still provide important benefits. Side-channel projects for these situations are also included in this technique.

Numerous types of side-channel and off-channel habitats exist, each with unique attributes depending on the biophysical setting and the processes that create and maintain them. Side channels and off channels are variously categorized and may include habitat types such as sloughs, oxbow lakes, wall-based channels, floodplain depressions, or chute cutoffs. The primary distinction is that their separation from the main channel and may have only seasonal or high water connections. This technique uses the term “side channel” as a general descriptor of all side-channel and off-channel habitat types. Table 1 provides descriptions of different side channel types. Side-channel habitat types can be characterized by their dominant source of water, their degree of connectedness to the mainstem channel, and the characteristic flow type, all of which may vary seasonally and between years. Different flow conditions may transform one side-channel type to another, and side-channel types may also evolve over time to other types. The categories in Table 1 describe the conditions found in each particular side-channel type for the majority of any one year.

In unaltered alluvial river systems, side-channel habitat is constantly created and abandoned as the river migrates laterally, avulses, or cuts off meander bends. In such systems, formation of side-channel habitat is usually associated with former stream channels abandoned through channel migration processes, or the landward side of gravel bars expanding during high flow events within the active-channel area. Side channels often follow a succession from an active side channel to a backwatered channel that may be only intermittently connected to the main flow during floods, and finally to a pond (oxbow lake) or wet depression on the floodplain. This evolution may occur over decades. As long as the stream is creating new side channels, all stages of side channel can development providing habitat for the successional of their contained plant and animal communities.

The type of side channel has direct bearing on the approach to a restoration project and its potential benefits to fisheries. General categories of side channels are used in these guidelines for convenience. Restoration projects may include several side-channel types. For example, a spring-fed channel might be constructed as a tributary to a mainstem side channel and the spring-fed channel may include connections to floodplain ponds or wall-based channels. The design of any side channel project should consider incorporating attributes of multiple side channel types.

Restrictions and constraints such as levees, dikes, bank protection, and channelization, often isolate side-channel habitats from the main stem and prevent or limit the channel from migrating in a manner that can create new side channels. As a result, this valuable habitat is frequently lost or becomes inaccessible to the fish and wildlife that use it. These represent lost opportunities that limit production of salmon on many large rivers systems in the Pacific Northwest. Typically, the most desirable restoration is to remove such constraints. The intent of some of the techniques within this section is to create habitat lost where constraints cannot be removed or to create new side channel habitat where natural processes require years to decades to create such habitat.

Table 1. Overview of side channel types. The source of flow and degree of connectivity may change depending on streamflow conditions.

Side Channel Type	Description	Primary source of flow	Degree of connectivity
Mainstem (flow-through) side channels	Mainstem side channels, also referred to as flow-through side channels, include active, secondary channels that are separated from the main channel by a stable island. Mainstem side channels can be active year-round, seasonally, or only during flood flows. Mainstem side channels are subject to the natural dynamics of the mainstem channel, including flooding, channel shifting, bed scour, and woody debris jam formation.	Main river channel. Lotic conditions with flowing water through the channel.	Well connected to river channel processes including scour, deposition, and wood transport. May convey flow year-round or only be active during high seasonal flows.
Backwater channels	Backwater channels are subject to backwater inundation from the main channel and are typically located in low elevation areas within the floodplain. Backwater channels are typically connected with the main channel only at their downstream end. The location of backwater channels determines whether or not they are scoured by high flows.	Main river channel. Backwatered from a downstream hydraulic control in the main channel. Groundwater flow may also contribute. Lentic conditions; although lotic conditions may occur during high flows.	Well connected to the river for fish passage and nutrient exchange, but not typically subject to scour and deposition except during floods. Typically has standing water for a large portion of the year. May dry up during low water conditions.
Groundwater (percolation) channels	Known as percolation (perc) channels, groundwater channels, or spring-fed channels. These are floodplain channels unconnected to the main channel at their upstream end and fed primarily by hyporheic flow, although other sources of groundwater may also be present. These channels are frequently constructed to support salmon spawning, particularly for chum, which seek out the groundwater upwelling conditions in these channels. Depending on location, groundwater channels may be scoured by high flows.	Sourced by hyporheic flow during most of the year. May dry when the water table drops below the channel invert elevation. Lotic conditions.	Generally connected for fish passage via the downstream end. Depending on elevation and degree of separation from the river, may be inundated by river flow during floods and thus subjected to scour and deposition during these periods.
Wall-based channels	Wall-based channels are found along the toe of higher terraces or valley walls. They are typically groundwater-fed but may also receive spring flow and surface flow from an adjacent terrace or valley wall. Wall-based channels are typically not scoured by main channel flows except during large floods.	Groundwater from adjacent terrace, hillslope tributary flow, or hyporheic flow. Lotic conditions.	Mostly protected from active river flows due to higher elevation and lateral separation from the channel. May or may not be connected for fish passage; depends on flow rate and channel conditions (e.g. gradient).
Floodplain ponds	Floodplain ponds are natural or constructed ponds in or above the floodplain such as abandoned gravel pits, mill ponds, river oxbows, and wetlands. They may be supplied by groundwater or surface water from streams, springs, or the mainstem, though they are frequently not connected to the mainstem river. Frequency of inundation by the mainstem depends on elevation and degree of connectivity. Floodplain ponds may be at different successional stages and may range from permanent to seasonally inundated.	All sources are possible, including river, groundwater, hyporheic, or tributary. Lentic conditions.	Mostly protected from active river flows. May or may not be connected for fish passage; depends on flow rate and potential obstructions such as beaver dams. Some ponds may only be connected during floods from dispersed floodplain flow.

2 PHYSICAL AND BIOLOGICAL EFFECTS

Side channels provide critical habitat for juvenile and adult salmonids, amphibians, and diverse other wildlife. The presence of side channels, especially a series of side channels in various stages of succession, increases the diversity of aquatic habitat available within a stream corridor. Also, during flood events, side channels offer aquatic species refuge from adverse mainstem conditions. In particular, groundwater-fed channels provide important unique benefits to juvenile and adult fish, as they provide a more stable environment for incubation and rearing than does a channel that relies solely on surface flow. Flow conditions and water temperatures are more consistent and predictable in channels fed by groundwater. Groundwater-fed channels are frequently warmer and clearer than the main channel in the winter and provide better prey (i.e. invertebrate) production, feeding opportunities, growth, and flood refuge. Groundwater channels are also less subject to the dynamic processes in the main channel, including sediment deposition and scour, and therefore may provide more stable spawning, egg incubation, and rearing habitats than main channel areas. In the case of amphibian, lentic side-channel habitat may be the only reproductive habitat in the system if alternative lentic habitat is unavailable.

Side channels provide valuable juvenile rearing habitat for multiple species.[4,5,6,7] Coho salmon, in particular, make widespread use of off-channel habitats, often gaining access to small stream and pond environments. Juvenile coho are known to actively migrate from mainstem locations to side channel habitats for protection from winter high flows and summer low flows (to avoid stranding risk). Although residence times vary, coho generally migrate back to mainstem habitats in the spring. Of the trout species, coastal cutthroat are most likely to be found in off-channel environments.[8] Steelhead make only limited use of off-channel areas; however, in some areas, parr and pre-smolt steelhead make significant use of groundwater channels for rearing and overwintering.[9,10] Although juvenile Chinook are not typically associated with off-channel habitat, interior stocks of Chinook make some use of off-channel ponds and side channels; typically for juvenile rearing and overwintering.[11]

Monitoring of smolt production from side channels in British Columbia detected no difference in production from restored side channel habitats compared to natural side channels.[12] Because of this, Blackwell and coworkers suggested that the major benefits of coho production at off channel restoration projects comes as a result of an increase in the quantity of available habitat rather than from an increase in quality of habitat. The results of a study to evaluate constructed side channels in the Northern Puget Sound region of Washington found that whereas total salmonid densities were not significantly different between channel types, coho densities were higher in constructed channels and trout densities were higher in reference channels during the winter.[13] A literature review of the effect of side-channel restoration on coho production[14] found that coho salmon parr biomass was greater in constructed stream-type side channels than constructed pond-type habitat. However, average parr weight was greater in pond-type habitats, suggesting that growth of parr in stream-type channels may be limited by their densities.

Side-channels also provide important salmonid spawning habitat. Chinook, steelhead, coho, chum, sockeye, and cutthroat will all utilize side-channels to varying degrees. Spawners of many species of salmon and trout select redd locations associated with groundwater (hyporheic) flow.[15] Chum salmon, in particular, prefer to spawn in groundwater-fed channels or seepage (i.e.

upwelling) areas.[16] Coho spawn in groundwater channels to some extent,[17] but most coho spawning occurs in relatively small surface-fed streams.[18] In the Cedar River, Washington, spawning by sockeye salmon has been documented in side channels and floodplain ponds.[19]

Understanding the species-specific life-stage uses of side channel habitats by salmonids is an important component of developing project objectives and design criteria. A complete review of this information is beyond the scope of this document. For additional information, please see the resources listed under Additional Reading at the end of this technique.

Besides benefits to salmon, side-channel wetlands and ponds have been found to provide critical habitats for a variety of amphibians, reptiles, birds, mammals, and mollusks species.[20],[21] In the case of stillwater-breeding amphibians, side-channels are critical since they can neither breed in main channel habitat and main channels are far less favorable for foraging. Side channels also provide important sources of primary productivity, nutrient sequestration, and organic mater input to the stream system.

3 APPLICATION OF TECHNIQUE

The type and scale of side channel projects depends on channel type (refer to Chapter 2 and *Fluvial Geomorphology* Appendix) site conditions, the objectives of the project, and available resources.

Ideally, side channels should be created where they will be sustained through natural processes. This includes allowing for natural channel dynamics including avulsions and channel migration, which may eventually overtake the project site. Though this occurrence is frequently viewed as a failure, if new side-channel habitat is formed as a consequence, the habitat is self-sustaining and habitat objectives may nevertheless be achieved. In many situations, however, active channel shifting may not be tolerable, but side channel projects may nevertheless provide important habitat benefits. Examples include areas where infrastructure or landowner constraints limit the ability for channel shifting, or where severe channel instability is endangering other sensitive species.

Side channel projects can be applied to a wide range of conditions, from relatively well-functioning to fairly degraded stream systems. In systems where natural processes are generally intact, side channel projects may focus on reconnection or enhancement of existing habitat. In a more degraded context, such as a leveed reach, projects might focus on creation of habitat that has been completely lost and that will no longer be formed through natural process.

A key to successful side-channel creation or restoration is site selection. An inventory of potential projects is valuable in order to optimize site selection. Such inventories should be conducted as part of watershed restoration planning or other efforts that may affect the connectivity or function of side channel habitats. Potential sites can be initially identified using aerial photos, LiDAR data, or topographic maps and then confirmed by field inspection. Topographic and vegetative features at the site, reach, and valley scales can give an indication of where potential side-channel projects would be appropriate. The indicators to use depends on the objectives of the project. For example, a project targeting chum spawning may seek out areas with potential hyporheic flow; whereas a coho rearing project may seek out areas to create backwater channels that are protected from winter high-flow events. Table 2 includes a number of indicators for locating side channel projects. In order to successfully site and plan a side channel project, these indicators must be paired with a thorough understanding of fluvial geomorphology, aquatic biology, riparian ecology, hydrology, and hydraulics. These are discussed further in Section 5.1.

For most projects, fish utilization in the reach will need to be considered, and for many projects fish use will be the primary restoration objective. Fish use of a specific project may depend on its physical location relative to the spawning distribution of the target species. If the site, for example, is located far above spawning areas, then juvenile use of the area may be limited. If the primary objective is spawning habitat, then the location of the project in relation to the current or potential spawning distribution will need to be considered. For spawning channels, fish supplementation is sometimes used to establish a spawning population. This has been done with chum salmon in the Lower Columbia region.

Table 2. Indicators of potential locations for side-channel projects. See Figure 1 for a visual depiction of some of the more common features that may support side channel restoration.

Valley-scale features

- Natural floodplain or valley constrictions may indicate hyporheic upwelling and downwelling that could support the development of groundwater-fed channels.
- Areas along the hillslope toe or along the toe of high terraces may indicate locations for potential restoration of wall-based channels.
- Alluvial fans often force hyporheic upwelling at their downstream ends. Relatively stable areas near the fan, such as along the lateral margin of the fan, may provide good locations for creation of groundwater-fed channels.

Reach-scale features

- Floodplain depressions such as meander scars and abandoned oxbows may indicate opportunities for side-channel creation or restoration. These paleo-channel areas also frequently have coarse subsurface material that may convey hyporheic flow and could support the creation of groundwater-fed channels.
- Relic channels at the downstream ends of meander bends are frequently fed by hyporheic flow that flows across the bend and may present good opportunities for groundwater-fed channels.
- Degraded (incised) channels may have historical side channels that are perched and could benefit from re-connection with the mainstem through excavation.

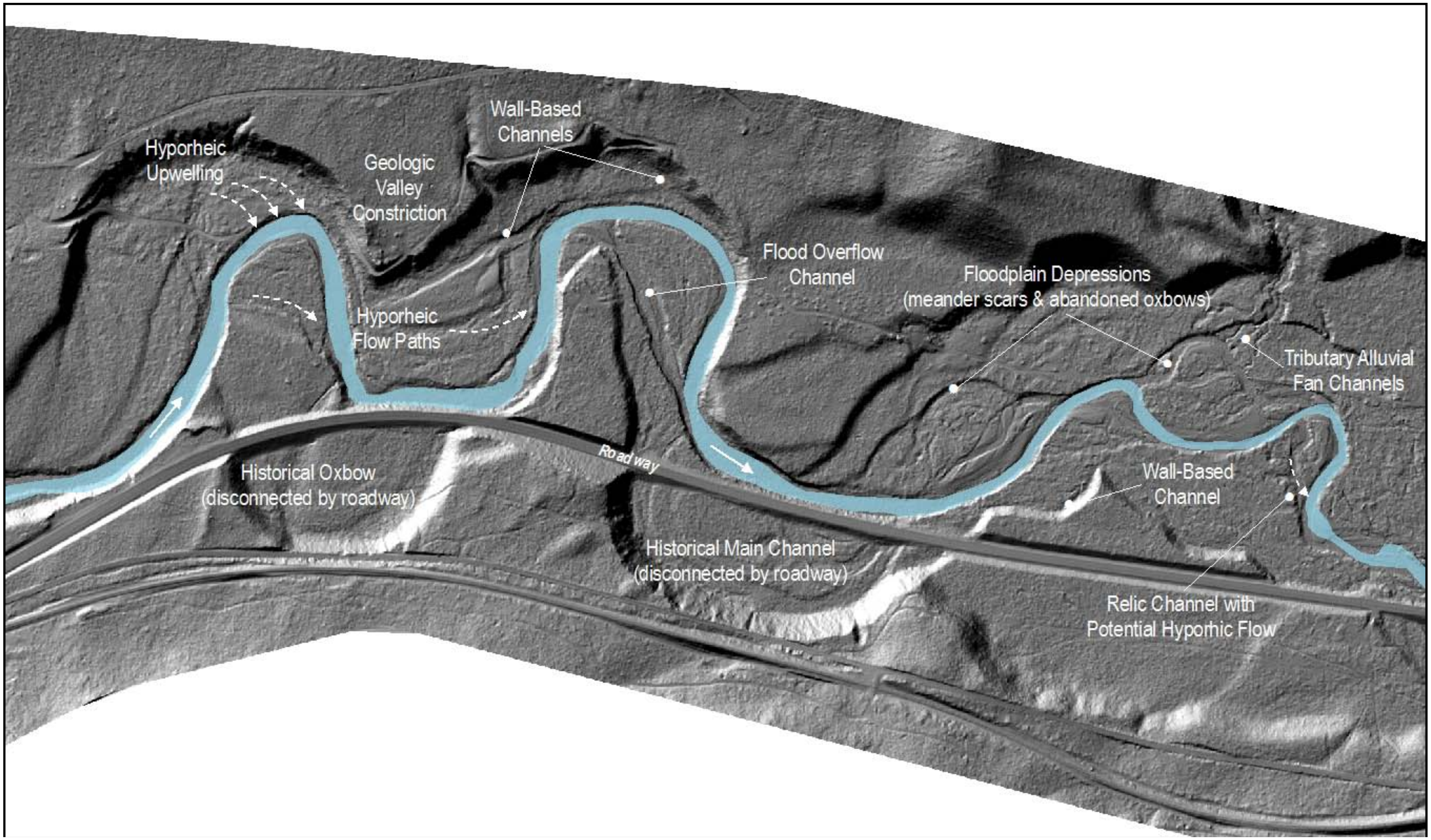
Vegetation indicators

- Wetland species may indicate channel depressions or shallow groundwater/hyporheic flow that could support groundwater-fed channels.
- Early successional species may reveal abandoned channel scars that can be used for side channel locations.

Human features

- Abandoned gravel pits may provide good side-channel enhancement opportunities.
- Levees or armoring that confines streams may indicate good places to create new side-channel features where they would not be created on their own.
- Levees, railroads, or roadways that sever connections with historical channels may present reconnection or enhancement opportunities. Simply restoring fish passage may be highly beneficial in some circumstances.

Figure 1. Hillshaded relief map showing geomorphic features that may indicate the potential for side channel projects.



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4 RISK AND UNCERTAINTY

Project risk is a function of the probability that the project will result in undesirable outcomes; whereas uncertainty refers to the limits of our knowledge about how a project will perform in the future (Refer to RiverRAT Appendix 3.5 for a thorough discussion of accounting for uncertainty and risk in stream habitat restoration design and management). Project risk and uncertainty should be considered as integral parts of project design. This is crucial if nearby or downstream properties exist, if public use of the waterway occurs, or if sensitive species are present that could be impacted by the project.

4.1 Risk to Habitat

Risks of disturbance to existing habitat associated with this technique are generally low, primarily because the majority of work is done outside the active channel and is not directly affected by the hydraulics of the mainstem. Short term risk to adjacent and downstream habitat exists from increased turbidity during excavation of the connection to the main channel and following reintroduction of flow to the side channel (this risk is higher with creation of new channels than with reconnection of existing channels). Also, wildlife associated with vegetation and soil that is removed during construction will be displaced. If an excavated side channel lowers the local groundwater level, potential exists that the water level in nearby wetlands and ponds will be lowered and the extent and type of riparian vegetation will change. Some risk of avulsion into the side channel may exist during a large flood event.

If the hydraulics of the channel are not assessed and designed appropriately, fish can become stranded in isolated pools within the channel. Water quality within the pools may become unsuitable for aquatic life or the pools may dry up, killing any animals stranded there. Risk of this occurrence is highest where flow through the side channel is intermittent, highly variable, or inaccurately estimated, and where side-channel elevations were not properly designed or constructed. Design elements that manage these risks are discussed in Section 5 *Methods and Design.*

Risk of the bed and banks of an overflow side channel adjusting during the first few years following construction exists until the channel form has stabilized to accommodate high flows. Higher flows may cause bed and bank scour that destroys incubating eggs of fish or amphibians, or their fry or larvae. Habitat features installed in the channel (e.g., wood and spawning beds), as well as fish and wildlife, may be redistributed or forced out of the side channel by high velocities, although new habitat may be created by these events as well. Over time, leafy material from trees and fine and coarse sediment may accumulate in the side channel, possibly limiting productivity or fish passage and/or causing the channel to flood less frequently and gradually succeed to a depressional wetland.

Side-channel restoration may be detrimental to some species. Predation of juveniles may increase in sites with established populations of predators. It may allow non-native invasive species opportunity to disperse. Oregon chub, which is endemic to the Willamette Valley, prefers off-channel habitat but is threatened by predation by non-native spiny-rayed fishes.[22] Access of fish to side channels may also negatively affect native amphibians.[23]

4.2 Risk of Channel Change

Some risk exists that creation or changes to a side channel could cause an avulsion. An avulsion is a significant and abrupt change of channel location into a new alignment resulting in a new channel across the floodplain (see Figure 2-17 from *Integrated Streambank Protection Guidelines*).[24] An avulsion is caused by concentration of overland flow that scours or headcuts a new or enlarged channel. Avulsion risk is increased by sediment deposition in the mainstem, which may increase flow into the side channel. If the flow capacity of a side channel were greatly increased, it might convey enough water to significantly enlarge the channel and eventually "capture" the entire mainstem into the side channel alignment. Risks of avulsion include potential loss to property and infrastructure and habitat. On the other hand, side-channel habitat is created by the natural process of avulsion and channel change – where a mainstem channel avulses into side-channel habitat, the abandoned mainstem channel typically becomes side-channel habitat.

Constructing, enlarging, or reconnecting a side channel can potentially increase the risk of channel avulsion. Managing risk of avulsion starts with understanding the factors that might cause it to occur. A channel site that is associated with a mainstem channel that is aggrading, a channel with levees that elevate flood flows to an elevation above the adjacent floodplain, or a channel susceptible to channel-spanning log jams is vulnerable to an avulsion. The fact that a channel exists parallel to the mainstem is a sign of avulsion potential or historic avulsion processes. See Section 5.4 *Managing Risk of Channel Change* for a discussion on how to address avulsion risk. A risk of the mainstem shifting away from a side-channel project may also exist, leaving it disconnected from the mainstem or of shifting towards the project and overtaking it. Design elements that manage these risks are discussed in section 5.4 *Managing Risk of Channel Change*. Some projects might be considered transient with a high probability and expectation of being affected or overtaken by migration of the mainstem channel. Management of risk should also include the level and cost of construction. For example, side channel restoration work at Gorley Springs on the Grays River in Washington was done in the 1980s with the expectation that aggradation of the main channel would cause an avulsion within a decade or so that would jeopardize the project. The channel was built to not exacerbate that risk and at a cost that could still realize a benefit in a short project life.

4.3 Risk to Infrastructure, Property, and Public safety

Reconnecting and creating side channels poses little threat to infrastructure, property or public safety unless the channel increases the likelihood of an avulsion, discussed previously. Public safety and the safety of wildlife are concerns at constructed floodplain ponds, particularly in the case of abandoned gravel mining pits. If the banks are too steep, it is difficult for anybody or animal that falls into the pond to climb out. Shallow beaches, sloping banks to at least 2:1, and adding large wood reduce the risk.

4.4 Uncertainty of Technique

The certainty of habitat gain varies among project types and objectives. Roni and colleagues[25] evaluated the variability and probability of success of common stream restoration techniques based on existing literature. Success was defined and evaluated as high, moderate, or low. They found that projects involving reconnection of existing off-channel habitats had a high probability of success; and the variability of success among projects was low.

Projects that involved creating off-channel habitat had a moderate probability of success, but a high variability of success. High variability appears to be at least partially due to the wide variety of off-channel projects constructed and reported.

The amount, type and longevity of habitat provided by the side channel depends greatly on the magnitude and frequency of flow and sediment delivered to the channel. If flows are lower than predicted, less habitat may be provided than anticipated, habitat may become isolated from the main channel, habitat may be unsuitable (shallow depth, poor water quality), or the habitat may not be accessible to fish and wildlife when needed. Habitat longevity also depends on the regular use by spawners to regularly clean gravel and flush out fines. Side channels subjected to overflow from the main channel may accumulate coarse and/or fine sediment that reduces the quality of spawning habitat. Appropriate site assessment, as described in the following sections, is necessary to minimize uncertainty of project outcome. Side channels that rely on groundwater as their primary source of water tend to be more stable and are longer lasting than overflow channels. However, changes in land use should be kept in mind as they may alter groundwater dynamics.

5 METHODS AND DESIGN

5.1 Data and Assessment Requirements

Data collection and assessment requirements will depend on the intent and the scale of the project, the nature of the channel, and the modifications to be implemented. Data collection and assessment must allow for careful consideration and analysis of the full range of potential effects. Table 3 contains a list of potential data and assessment needs for various types of side channel restoration projects.

Table 3: Potential data and assessment needs for side channel restoration projects. Specific data and assessment needs will vary depending on project type, scale, and site conditions.

All side channel projects
▪ Current species use of the site and habitat requirements for target species. ▪ Current aquatic and riparian habitat features and restoration opportunities. ▪ Topography, cross-sections, and longitudinal profile of project area including main channel, floodplain, and proposed side channel alignment. ▪ Sources and paths of overbank flow or additional surface flow during heavy runoff events. ▪ Characterization of floodplain roughness, including vegetation, large wood, and topographic features. ▪ Vertical and lateral stability of mainstem; observe characteristics that may indicate rapid lateral movement or channel degrading or aggrading. Also look for evidence of a channel that has already degraded and left potential side channels perched. ▪ Photo-documentation of site from permanent benchmarks that will not be disturbed by the project. ▪ Elevation control points (multiple) for follow-up surveys and monitoring. ▪ Flow and stage measurements, including high and low water stage at connection points between the main channel and proposed side channel. Establishing a rating curve for the main channel and active side channels may help with design. Static water levels may help to identify groundwater levels across the site. ▪ High-water marks to calibrate hydraulic calculations. ▪ Extent of wetlands and other sensitive habitats. ▪ Vegetation patterns, conditions, and need for restoration. Types and location of invasive species. ▪ Inundation analysis to determine flood frequency and risk of side-channel areas. ▪ Assessment of avulsion risk. ▪ Water quality of flow in mainstem and proposed side channels. ▪ Assessment of potential stranding risk in side channel.

▪ Large wood dynamics and the potential impacts of wood jams on side-channel connectivity and stability ▪ Site constraints and project limits (e.g., existing infrastructure, preservation of floodplain conditions, property limits).
Groundwater-fed channels
▪ Static groundwater levels throughout the year. ▪ Estimate of potential groundwater flow rate and volume based on pump tests or calculated transmissivity. Focus on time of year of species use. ▪ Assessment of groundwater quality. ▪ Topographic, geologic, and direct observations of evidence of hyporheic upwelling and downwelling in and near the project reach. ▪ Quality of bed material for use as project spawning material.
Backwater channels and floodplain ponds
▪ Pond elevation relative to the access channel to determine the type and magnitude of channel modifications necessary to ensure fish passage. ▪ Pond layout and bathymetry. ▪ Profile and characteristics of outlet channel. ▪ Current fish utilization including likely predators.
Reconnection of existing side channels to mainstem
▪ Assessment of existing habitat for fish and other wildlife within the side channel, including spawning gravel. ▪ Current fish utilization including likely predators. ▪ Potential water quality impacts to mainstem habitats.

5.2 Water Supply Considerations

The supply of water to side channels may include surface water from the main channel, hyporheic flow, groundwater flow from upslope areas (i.e. springs), or tributary flow. Many projects will include a combination of these sources. A channel may have an overflow source from the river during high flow seasons, a groundwater source during low flow seasons, and be supplemented with flow from a wall-based source. The sources of water affect sediment conditions, nutrients, organic matter availability, water temperature, flow, stability, and the diversity and longevity of physical features within the side channel. The amount of flow can be a controlling factor for adult usage, juvenile recruitment, and the objectives of the project. Besides surface flow, the amount of inter-gravel flow may also be important, such as for egg-to-fry survival in spawning channels.[26] For most applications, the most productive side channels are those with year-round fish access to allow rearing fish to benefit from optimal conditions whether in the main channel or side channel. However, side-channel habitats that are only available intermittently or seasonally can still provide important habitat benefits, and in some cases, may be preferable than year-round active side channels. An example would be the creation of a side-channel for late fall salmon spawning habitat that is designed to go dry during the summer in order to preserve instream flow and temperature conditions in the main channel during the warm summer months.

One of the major concerns with intermittent side channels is fish stranding, which may occur if the side channel loses surface connectivity with the mainstem but fish remain within the channel in isolated pools. This condition increases the risk of fish mortality through temperature impacts, predation, water quality, and potential eventual desiccation. Fish stranding risk can be reduced by 1) ensuring that target fish species will have exited the site by the time the surface connection is lost with the mainstem or 2) designing for year-round side channel connectivity with the mainstem. The impact of flow diversion on the mainstem will need to be considered as part of project planning and design. Diverting flows from the mainstem to the side channel can have potential impacts on fish passage, stream temperature, and habitat availability.

Flow in constructed groundwater-fed (percolation) channels is achieved by excavating a channel in the floodplain to a depth that intercepts groundwater. A hydraulic gradient is created when a channel is excavated below the static water level. The hydraulic gradient and permeability of floodplain soils control the amount of flow. Static water levels, and therefore flow rates, will typically vary throughout the year. Water source may also change throughout the year. As water levels change from high water levels in the winter and spring to lower levels in the summer and fall, the dominant source of flow may change from hyporheic to non-hyporheic groundwater sources. Success of a groundwater-fed channel is more likely if it is associated with hyporheic, river-sourced flow due to water that is generally saturated with oxygen and nearly saturated with total gases. Geologic, geomorphic, hydraulic, and biological indicators exist that can indicate presence, general rate, and direction of hyporheic flow. Stanford and Ward[27] and Edwards[28] describe hyporheic indicators at multiple scales. Information on assessing groundwater flow potential is included in Section 5.7 Special Considerations for Groundwater Channels.

If adequate groundwater flow cannot be achieved through excavation alone, then the installation of groundwater infiltration galleries may be appropriate. Infiltration galleries typically consist of buried perforated pipe that collects and concentrates groundwater flow and supplies it to the channel. The diameter and length of the pipe, as well as the location and burial depth of the pipe, are determined through field investigations. Field investigation usually entails digging a pilot trench to below the static groundwater level and conducting a pump test to determine the flow rate that is obtained per foot of trench. Pump tests are conducted by pumping the water level to a variety of depths below the static groundwater level and measuring the range of flow rates for a range of hydraulic gradients. These data can be used to help determine the amount of infiltration gallery pipe that is needed to provide a given flow for a given hydraulic gradient of the proposed channel. Conducting this assessment requires knowledge of groundwater flow properties and experience with interpreting the results of this test.

5.3 Channel Entrance and Fish Passage

5.3.1 Upstream entrances at flow-through side channels

The amount of flow delivered to a flow-through side channel is frequently governed by the configuration of the upstream channel inlet where it connects to the mainstem. The location and alignment of natural side channel entrances depend on channel type. Entrances into side channels associated with braided channels are random and unpredictable. Natural side channel entrances associated with avulsions or laterally migrating channels are usually located near the outside of the downstream channel bend. They may also follow the toe of a terrace.

When designing side channel entrances, the connection can be self-maintained in some situations by designing a constriction at the inlet that maintains a scoured thalweg and therefore a reliable connection with the mainstem. However, a constriction is only effective if the hydraulic profile of the side channel can create a head loss through the junction adequate to transport the sediment that is delivered to it. The goal of a constriction is to mimic natural side channels where debris accumulates at the inlet and meters flow into the side channel. The constriction of the debris maintains low flow water supply by scouring a thalweg, and it controls high flow by restricting flood flow into the channel. In a constructed channel, the constriction might be created with rigid structures; large boulders or logs have been used in some projects. Controlling flow at the channel entrance also helps to reduce the risk of channel widening and eventual capturing of the mainstem through avulsion through the side channel. Avulsions should only be prevented if they are not a response to natural channel processes or if an avulsion cannot be tolerated due to risk to property, safety, or habitat.

Despite well-designed inlet configurations that are designed to be self-maintaining, sediment deposition at the inlet will always be a risk. A few techniques exist that can be used to reduce the risk of inlet sedimentation that may lead to blocking flow and/or fish passage into the side channel. The first is to ensure that the inlet is not located within an expected deposition zone, such as at a point bar or within a riffle. Second, locating the inlet just upstream of a hydraulic control on the mainstem will increase the likelihood that flow will be backwatered into the channel. Third, a log jam or other structure can be used to maintain scour at the inlet. In aggrading reaches, it may be impossible to keep the inlet open without continual maintenance. Hydraulic conditions of the junction will certainly change over time with channel evolution and with sediment and debris accumulations. These changes should be anticipated to the point that risks to side-channel habitat and success of the project are evaluated

Formal intakes have been constructed to enhance flow to side channels. Lister and Finnigan[29] provide siting and design detail for more formal control structures including slide gates mounted on culverts or concrete structures, settling ponds, and log curtain wall intakes. Surface water intakes should be located at the outside of bends, which are usually characterized by a deep thalweg channel and are less susceptible to sediment clogging or recruitment to the side channel. This location often works well at sites where a railroad or road fill exists that separates the side channel site from the mainstem.

Flow can also be controlled in a side channel with a simple culvert (i.e,, without a control gate). A culvert of an appropriate size will act as an orifice to meter flow to the side channel by creating increasing head differential as the mainstem water level rises and increasing flow passes through the culvert. Scour downstream of the culvert must be accommodated by the design of the culvert installation. Design of the control structure includes a trade-off between flow control and a risk associated with formal intakes and control culverts blocking upstream passage of fish. The potential for damage or plugging due to icing events should also be considered for culvert intakes.

5.3.2 *Single entrance channels*

Backwater channels, groundwater channels, wall-based channels, and floodplain ponds are typically designed to have a single connection point with the mainstem, at least during average flow conditions. These projects require that channel entrance conditions are designed to maximize attraction and access for fish. Peterson [4] stated that the point where the egress channel joins the stream is the most critical aspect of project design. Nickelson and colleagues[6] stressed that extreme care must be taken to insure that the channel remains open at all flow levels and recommended locating alcoves at springs and tributary junctions. Designing for groundwater or tributary flow into the side channel may increase the attraction for fish that can sense these inputs. If flow from a side channel exits into a low-velocity area or eddy with habitat cover, the water is not rapidly diluted and fish have a better opportunity to find it than if it is rapidly dispersed and diluted in rapid turbulent flow.

The entrances of alcoves, backwater channels, and floodplain ponds are frequently at risk of sedimentation due to the lower relative velocity compared to the main channel. Prior to embarking on these types of projects, the potential for sedimentation should be evaluated by identifying the amount of sediment supply in the system and the deposition patterns in the reach. Allowing for periodic scour of the side channel habitat (i.e., during floods) may help to flush out accumulated sediments. Because sediment deposition is difficult to predict or control, it may be useful to establish a long-term monitoring and maintenance plan that allows for the periodic removal of accumulated sediments as needed to maintain project objectives. As part of this plan, it may be necessary to maintain machinery access routes to channel entrance areas in order to perform future maintenance activities.

5.3.3 Fish passage considerations

Large wood and/or beaver dams can block fish passage into side channels under certain conditions. Before modifying a beaver dam to improve fish passage, evaluate whether it is in reality a barrier. Beavers that use side channels often like to maintain a deep access to the mainstem. It may be just a few feet wide but backwatered by the mainstem even at low flows. Juvenile and adult salmonids often pass through beaver dams with drops of three feet or more that otherwise appear to be barriers. Multiple paths often exist within beaver dams for fish to move through. Fishways for juvenile and adult salmonids have been built into beaver dams to improve passage. They are described in the *Fishway Guidelines for Washington State*[1].

Road culverts or small dams can also block passage. If a channel is perched above the low water level of the mainstem, a drop may exist that blocks access. These situations may necessitate the removal of the obstruction or modifying the channel to step it up over the barrier. These techniques are described in the *Fishway Guidelines for Washington State*[1] and *Design of Road Culverts for Fish Passage*[2] guidelines.

5.4 Managing Risk of Channel Change

Various channel changes may put constructed project elements at risk of failure. These changes include mainstem avulsions into side channel locations, lateral erosion into side channels, mainstem bed degradation (incision) that severs hydraulic connectivity, and side channels filling with sediment. When considering these modes of failure, it is important to recognize that channel changes are frequently part of important natural processes that create and maintain habitat, including side channels, over time. Measures should be avoided that prevent these natural processes from occurring. In some cases, however, it will nevertheless be necessary to reduce the potential for channel change where infrastructure or property is at risk, where sensitive habitat is at risk, or where project construction would otherwise increase the risk of channel change beyond natural conditions. If post-construction sedimentation or channel migration risks indicate a need for a high level of maintenance, the project feasibility should be evaluated.

Increasing the capacity of a side channel or removal of floodplain vegetation may increase the risk of an avulsion. Avulsion risk is increased if the mainstem channel is aggrading or if the radius of curvature of a meander bend is sufficiently small to indicate an eminent neck cut-off. Erodible soils and lack of floodplain roughness will also increase avulsion risk. If a likelihood of increasing risk of avulsion due to the project exists, measures should be considered to manage the risk. Methods to control avulsion risk include the separation of the constructed channel from the river channel by lateral distance, control of flow to the side channel, increasing hydraulic roughness along potential avulsion pathways, and placement of grade control within the channel bed (placement of grade control should be considered with caution because it can limit natural channel adjustment processes; ideally grade control techniques should have a limited design life). Constrictions made of boulders and/or wood within a constructed side channel can control how much flow it can pass and therefore the risk of avulsion. Constructed spillways in areas where floodwaters will first enter the channel can help lessen the risk of headcuts forming at those places. Roughness elements, such as large wood placements and planted woody vegetation, can be placed within the constructed channel and within potential avulsion pathways throughout the floodplain to reduce the potential for avulsion. Grade control using boulders or large wood can also be used to reduce headcut risk within the constructed channel. See the *Instream Structures* technique and the *Integrated Streambank Protection Guidelines*[24] techniques on floodplain roughness, floodplain drop structures, flow spreaders, and buffer management for ideas that can supplement side channel construction to manage avulsion risk.

Other risks of channel change include lateral erosion of the mainstem into the side channel or a shift in the main channel away from the side channel, thus disconnecting it. Even a slight shift in the channel thalweg can impair side channel connectivity. Large wood placements can be used to manage the location of the thalweg as well as the migration of the mainstem channel. Placements that limit channel migration should only be considered a temporary solution to protect the new side channel until a time when channel migration processes can be tolerated.

Degradation (i.e. incision) of the main channel may also impair side channel connectivity, especially at low flows. If a side channel is perched because the mainstem channel has degraded, the solution may be to raise the mainstem channel back to its previous elevation or to further excavate the side channel. Refer to the *Channel Modifications* and *Instream Structures* techniques for information on these approaches.

Avulsion and erosion risk is increased if the main channel and the side channel overtop their banks at different times. This asynchronous floodplain activation increases the risk of high velocity overland flow between the main channel and the side channel, which can cause scour and headcutting that may result in undesirable erosion and potential channel avulsion. Hydraulics analysis, modeling, and examination of floodplain inundation dynamics can be used to help achieve synchronous floodplain activation. The use of floodplain roughness, as described earlier, will also help reduce the risk of erosion and avulsion.

Some side-channel projects, typically in the case of groundwater-fed channels, have used the excavation spoils to construct a berm parallel to the side channel to protect it from mainstem flood flows. Berms (aka levees), however, can restrict natural processes and can have confining and constricting hydraulic effects on the mainstem; these implications should be well understood

5.5 Water Quality

Anticipating water quality conditions within restored side channel habitats is important. For mainstem flow-through side channels, the water quality in the side channel will typically not be considerably different than the mainstem. Exceptions include instances where the project may contribute to thermal loading of the side channel or the mainstem, or where sources of pollutants enter the side channel downstream of the inlet. Water quality tends to be more of an issue in backwater or side channel reconnection projects in agricultural or industrial areas, where previously isolated areas may contain pollutants from upslope land use activities. Water quality of groundwater channels is also important, particularly dissolved oxygen. This is discussed in greater detail in Section 5.7.

Nutrients may be an important component of side channel projects. Salmon carcasses often play a large role in nutrient levels in side channels because carcasses are more readily retained than in mainstem habitats. Carcasses can produce a high level of biomass and nutrients that are retained on the site because they are not washed away during high water events. Salmon carcasses are an important source of nutrients to the food chain supporting stream-rearing species such as coho, cutthroat and steelhead[30] and distributed through the hyporheic zone to benefit other ecological functions in the floodplain. Samuelson[31] showed that coho and Chinook grew faster in abandoned floodplain gravel pit ponds in the Wynoochee River than in the river and fish grew faster in ponds that had been fertilized with salmon carcasses. Average lengths of juvenile coho and Chinook in the river were 30.4 and 41.3 mm, respectively. In contrast, they were 46.4 and 56.6 mm in the unfertilized pond and 49.6 and 66.5 mm in the fertilized pond. The size of Chinook salmon increased with fertilization; that of coho did not.

5.6 Habitat Considerations

The primary objective of most side-channel reconnection or creation projects is to provide habitat for salmonid spawning and/or rearing and to stimulate other functions of these habitats, including primary productivity. The proportion of the site used to meet a particular life history requirement can vary and may depend on flow in the channel, channel gradient, amount of backwater and design of the channel. Some sites are designed solely to function as spawning sites, whereas other sites may incorporate juvenile rearing and adult holding habitat. In general, greater benefits are achieved if diverse habitats are created that support multiple species and life stages. Diversity might include water depths and velocities, bed complexity, habitat features, and substrate. As a criterion for diversity, constructed channels could be designed to mimic comparable naturally occurring side channels in the region. Though most side-channel projects have targeted salmonids, they also provide benefits to many other fish and wildlife species. The number of species and age classes benefited theoretically increases with the diversity of habitats built into the design. A variety of habitat features can be included in side channels. These habitat features are described within other habitat restoration techniques in this guideline.

Installed habitat features may not function the same way in side channels as when they are built in mainstem channels. This is particularly the case in channels that do not receive scouring flows from the mainstem. Flow in these channels may not be adequate to scour under habitat structures, sort bed material, and transport large wood that will form log jams. Such features and functions may have to be constructed where flood processes are not anticipated to contribute to their development.

5.6.1 Cover

Habitat cover features should be located throughout the channel to provide juvenile and adult fish with cover from predators and refuge from high velocities. Cover is vital to the survival of overwintering juvenile fish. Without adequate cover, predators such as diving ducks can literally eliminate the entire complement of wintering fish, eliminating much of the fish habitat value for which the project was intended. Once predators find easy prey, they will typically remain until the food base is gone. Generally, the more complex and submerged the cover, the better protection fish will have from aquatic, terrestrial, and avian predators.

Intermittent deep pools can be provided with cover to add diversity and juvenile rearing and adult holding. Cover can be provided by log structures to support the toe of the channel and to provide rearing/refuge habitat. Boulders can also be used when the geomorphic context (e.g. channel type) is appropriate. Refuge alcoves are ponds excavated into the bank of a channel as refuge and rearing habitat. They are commonly excavated deeper than the channel and loaded with large wood.

If new large wood will not be replenished into a site, constructed wood structures might be anchored in place in portions of a side channel that is backwatered. Otherwise, the backwater effect floats the wood out of the channel, either into the mainstem or up onto the floodplain, and it is not naturally replaced. Refer to the *Large Wood and Log Jams* technique for more information.

5.6.2 Spawning substrate

If side channels are intended as spawning habitat, the spawning substrate may either be the native soil, cleaned native soil, or imported higher quality spawning gravel. Many channels have provided successful spawning habitat using existing substrate. An evaluation of the presence and quantity of potential spawning gravel can be conducted using excavation of test pits. It may be economically viable to screen gravel from the overburden for use as spawning bed material. Portable screens are available that can be brought to the site. To be economical, careful screening of a good sample is needed to be sure a high proportion of the desired size in the mix is present. Otherwise, the screening operation will extend the duration of the project since so much material will have to be sorted. The economics of processing substrate compared to importing it depends on the source and location of imported material.

If the channel sub-base material is sandy or clayey, a gravel filter may be required to support imported spawning gravel. Geotextile blankets have also been used, but are not recommended. The presence of a geotextile increases monitoring and maintenance requirements. Furthermore, the geotextile blanket will likely limit hyporheic flow and would create a physical barrier to movement into and out of the substrate for fish and wildlife species that spend any part of their life cycle in the substrate. Exposed geotextile decays and can become a hazard to spawning fish as their jaws and gills entangle in fragments of partially decayed fabric.

Appropriately sized gravel is critical to the success of a groundwater-fed spawning channel. Recommendations of spawning gravel sizes are summarized in literature reviews[32]. Rounded rock provides ideal spawning habitat for many salmonids. Angular or crushed gravels should never be imported to use as spawning substrate; they do not provide appropriate interstitial spaces for eggs and water flow, cannot be built into redds, and cause abrasion of the spawning adults. Substrate should not be homogenous. Variety in substrate features may be important for different life stages of salmonids as well as for invertebrates and other assemblages. See the *Salmonid Spawning Gravel Cleaning and Placement* technique in this guideline for additional information on spawning gravel mixes.

5.7 Special Considerations for Groundwater-fed Channels

Most of the following considerations for groundwater-fed channels are focused on channels designed for salmon spawning (e.g., chum spawning channels). However, many of these considerations also apply to groundwater channels designed to support other species and life stages such as juvenile rearing for salmon and steelhead.

5.7.1 Assessment of Flow Potential

For groundwater channels, the quantity of groundwater flow is important, so it is desirable to make pre-project estimates of the flow potential. Flows in groundwater channels have commonly varied from 2.8 to 7.1 cfs, with average velocities of 0.2 to 0.5 fps[33,34]. If channel flow is low (0.5 to 3.0 cfs), the optimum design might be to pond water to create rearing habitat. If flows are greater than about 3.0 cfs, pond and/or spawning habitat may be effective. Lower flows might be effective in small channel projects built with special equipment or by hand.

The amount of water that will flow as surface water in a groundwater channel is dependent on the groundwater level, hydraulic gradient, porosity of the substrate, and the area of contributing flow. Characterizing all of these to some degree will be necessary to identify groundwater flow potential for a constructed channel. As a first step, characterize the general groundwater levels, gradient, and flow direction at the site. This will give an initial indication of the potential for sufficient groundwater flow. A number of separate groundwater level measurements will be necessary throughout the site. Ideally, these would be obtained via test pits or through the installation and monitoring of groundwater wells (e.g., piezometers). Where it can be assumed that no confining layers are present, surface water within floodplain depressions may serve as a good indicator of groundwater levels. However, the observer should be careful to make sure that the water is not a local condition unrelated to groundwater, such as a vernal pool or recently collected precipitation. Profiles of groundwater levels throughout the site, including the mainstem, will indicate the direction and gradient of groundwater flow. This will change by season, so it will be necessary to monitor during the season and during flow conditions that will be the target flow condition for the groundwater channel. If the objective is to have year-round groundwater flow, monitoring during the dry season and when low flow exists in the mainstem may be important since water supply is most limited at those times.

Piezometers are frequently used to measure seasonal groundwater levels at a site and to characterize groundwater and surface water interactions. Piezometers are typically made using 1.5 inch to 3 inch PVC pipe buried to below the lowest seasonal static water level and extending a couple of feet above the ground. They include a perforated section at the bottom and are sometimes wrapped with filter fabric to reduce entry of fine material. They should be capped at the top but ventilated somewhere above the ground. Water levels in the wells can be recorded using water level data loggers, or by periodic manual measurements. Multiple piezometers at a site can help to determine the gradient and direction of groundwater flow. Installing them both parallel and perpendicular to the valley slope will help to gain an understanding of the groundwater profile relative to its source(s). This is useful for siting constructed groundwater-fed channels and for determining their potential effectiveness and seasonal duration.

Groundwater flow tests are also recommended in order to assess the flow rate that could be expected in a groundwater channel. An aquifer test using pump or slug tests within groundwater wells, combined with groundwater flow modeling, can be utilized; however, such evaluations are frequently impractical given the scale of most groundwater channel projects. As an alternative, a pump-test can be conducted within excavated test pits or trenches in order to identify potential groundwater flow rates. Because groundwater flow conditions may vary throughout a project site, a number of test pits may be appropriate. The number and spacing of test pits will depend on the size of the project area and the expected variability of conditions. In general, more certainty is gained with additional test pits. Pump tests simplify the description of the groundwater by making the assumption that the aquifer has no impermeable boundaries. Pump tests should be conducted during the target season when fish use of the groundwater channel is expected, or if year-round flow is desired, during the low flow season when river and groundwater levels are near their lowest.

Pump tests should be conducted by a qualified engineer or hydrologist that is familiar with how to conduct the test and how to interpret the results. The typical procedure includes excavation of a test pit to below the static water level using a backhoe. A pump is then operated at a high pumping rate to pump the water out of the pit. The pumping rate is then decreased to allow the pit to partially refill with groundwater. The pumping rate is adjusted until groundwater inflow and pump outflow reach equilibrium. It is important to maintain pumping at this rate for sufficient time to ensure that the groundwater within the zone of influence of the pit has reached a new static water level; this may take several hours. The groundwater inflow to the pit can then be calculated by measuring the flow rate being pumped out of the pit; using a stopwatch and a large container of known volume is typically used to obtain this value. The groundwater inflow rate can then be compared to pit dimensions in order to estimate the amount of flow per contributing area. More reliable results can be obtained by using this same general procedure but over a larger area, preferably a long and narrow linear trench that mimics a portion of the proposed groundwater channel. When interpreting pump test results, it is important to take into consideration the amount of water level drawdown used in the test and how this compares to the drawdown that is expected to result from the constructed channel.

Besides conducting pump tests, excavated test pits can also be useful for characterizing soil conditions, measuring groundwater temperature, and evaluating water quality. Soil conditions and elevations of soil strata in the test pits should be recorded. It also may be helpful to collect soil samples and compare gradations with those of other successful constructed groundwater channels. WDFW staff involved with past groundwater channel construction can be contacted for this information. It is also important to note that factors other than substrate gradation, such as hydraulic gradient and the area of contributing flow, will affect flow conditions.

Test pits may also be useful for evaluating the risk of penetrating confining layers that may cause loss of flow from a groundwater channel. This can occur when groundwater is perched on a relatively impermeable stratum of silt or clay that acts as a seal to contain the flow and keeps the level of groundwater relatively high. During channel and pond excavation for several previous projects, this seal was broken and flow was lost to deeper aquifers. Though assessment of this risk may be difficult, test pits may indicate where water is located above confining layers or loss of water may be directly observed. Piezometer data may also help identify this risk; potential indicators include 1) very consistent groundwater levels regardless of changes in river levels, 2) unexpectedly high groundwater levels compared to river levels, and 3) unusual groundwater gradients or directions of flow.

5.7.2 Assessment of Water Quality

Test pits can be used to evaluate groundwater quality. Water samples can be taken and evaluated for dissolved oxygen, total gases, and any other parameters that might affect fish health and egg incubation. Water chemistry tests should be performed if suspicious conditions are observed such as large amounts of iron precipitate, H_2S odor, evidence of petroleum products, or an unexplained absence of fish. Since salmonids do not always avoid low dissolved oxygen or high total gas environments[3], it is important to evaluate these parameters so a fish hazard is not created. Piper and colleagues[35] and Senn and colleagues[36] provide water quality standards for salmonid aquaculture that have been used for assessment of groundwater channel quality. Lister and Finnigan[29] recommend monitoring water quality monthly for at least one annual cycle. They recommend monitoring temperature, dissolved oxygen, and chemical constituents such as iron and hydrogen sulfide.

Water quality may vary with geologic conditions, over time, and as a project is developed. WDFW experienced at least one situation in which the initial test pit had water with no dissolved oxygen but after a pilot channel flowed for five months had a dissolved oxygen level of 5.6 ppm.[37] Total gases have been observed to vary with seasons as water source naturally changes between hyporheic and groundwater sources, but these changes have not been enough to be a problem. Ultimately, water quality has not been a driving issue in any of over forty groundwater channels constructed by WDFW in the last 25 years. However, in context of climate change, this will be an area in which vigilance will be important.

5.7.3 Channel slope and bank considerations

Groundwater channels should be excavated to a depth that maximizes the hydraulic gradient (in order to maximize flow rates) while minimizing mainstem backwater impacts and achieving species-based gradient targets. Channels constructed at too low of a slope may cause backwater pooling from the mainstem that impairs spawning conditions by decreasing velocity, increasing depth, and causing sediment deposition. Lister and Finnigan[29] recommend avoiding the temptation to maximize the channel length to gain the most habitat. Such a strategy may result in less than optimal slope and an increased risk of sediment deposition within the channel. They recommend that adequate slope or even slightly excessive slope be provided.

Constructing pools within the groundwater channel may be appropriate. Because fish naturally move far upstream, pools can be excavated at the upstream extent of channels and enhanced with habitat cover features (e.g. large wood) in order to give them protection. The intent is that fish will move back downstream when they are ready to spawn. Pools can also be excavated at other locations within or adjacent to the channel to serve as adult holding areas and to add diversity to the channel. To prevent loss of flow or high temperatures during low flow seasons, deep pools can be created that provide refuge and year-round rearing; however, this must be weighed against the potential for stranding risk if the pools go dry. Deep pools do not appreciably create additional surface flow unless they connect to more porous layers of substrate. In some cases, it may be appropriate to control water depth in pools through the use of drop structures. Use of these structures is covered in the *Instream Structures* technique. The structures create aeration that acts as cover and fish can use the pool to help pass the structure. Pools with large wood cover are useful in capturing and retaining spawned out carcasses, which keeps nutrients within the project area and provides forage for scavengers.

5.7.4 Spawning gravel considerations

Various strategies have been used to enhance the spawning substrate of groundwater channels. If the channel is protected from floodwater intrusion, no natural sorting of fines and gravel may occur. It should be noted, however, that in areas with active spawning, the spawning activity itself can annually clean the gravel by suspending and flushing out accumulated debris and fines, thus maintaining percolation inflow and flow through the gravel. Nevertheless, more active management of gravels may be necessary in some situations. The following methods have been used to enhance spawning substrate: 1) placing spawning gravel over filter blankets or layers of filter gravel, 2) mechanically and/or hydraulically cleaning channel bed substrate, and 3) over-excavating and replacing with imported gravel. Replacement has been the most commonly effective and efficient strategy but the preferred strategy at any site depends on local conditions such as gravel availability and access. Screening and washing material excavated from the channel is complicated due to the need for excavating, processing, and then replacing material. Impacts on riparian areas are also high. Gravel screening is typically only economical for large projects or where multiple nearby projects can be addressed. A common strategy is to screen large and small material out of pit run gravel supplied near the restoration site.

The required depth of spawning gravel depends on what is beneath it. If the natural base is unsuitable for spawning, eighteen inches or more of spawning substrate can be placed so it can be redistributed by spawning fish without exposing underlying material. If the natural bed is marginal or better spawning habitat, less imported material may be needed. Imported material is usually only needed for riffle and pool tail-out sections.

Lister and Finnigan[29] report the current custom in British Columbia is to use native in-situ bed material: "Comparison of chum salmon survival in channels with substrates of either native gravel, or artificially graded gravel, with smaller size fractions (<10 mm diameter) removed, has indicated that graded gravel offers no advantages in terms of egg-to-fry survival or density of fry production."[51]

5.8 Special Considerations for Floodplain Ponds and Gravel Pits

Floodplain ponds are stagnant or very slow moving open bodies of water or wetlands located within floodplains. They are frequently hydrologically disconnected from surface flow in the main river channel but may be connected during certain flow conditions (e.g. floods). They occur in a variety of forms; they may be natural, constructed, or enhanced as habitat. Water sources are typically groundwater or seasonal inundation from the main river. An abandoned gravel mining pit (see Figure 2) is a type of floodplain pond that is frequently enhanced for habitat enhancement in the Pacific Northwest.

Figure 2. Abandoned gravel pits and pond site near Satsop River.

5.8.1 Pond bathymetry and complexity

The depth, size, and complexity of ponds will affect the quality of aquatic habitat. Henning et al. [38] found that heterogeneity in habitat exists across the floodplain and salmon use varied among floodplain aquatic habitats such as in oxbows and ponds. On the Olympic Peninsula, Peterson[39] found greater survival of coho in deeper ponds (78%) compared to shallow ponds (28%). In contrast, Swales and Levings[40] suggest that shoreline perimeter and shallow areas are key to coho survival. Whereas shallow areas (<0.75 m) may be important for benthic insect food production, the availability of deeper areas (up to 3.5 m) may be necessary to maximize smolt survival.[39, 41] Lister and Finnigan [29] summarize that "off-channel ponds that have both shallow areas or shoals for food production and deep areas for overwinter security are most likely to produce good numbers of large, viable smolts". Shallow areas along pond margins may be conducive to spawning, especially along the upstream edge of the pond where there may be upwelling. Spawning in floodplain gravel pits, however, has been observed in water up to fifteen feet deep.

Habitat can be enhanced in floodplain ponds by modifying the water depth, increasing the water level to add area, excavating next to a pond to add shallow areas, or adding habitat complexity such as woody debris. Shallow water can be provided along the upstream edge of ponds to increase spawning potential. Constructing a series of ponds may maximize spawning habitat. If adequate gradient exists throughout the site and between each pair of ponds, upwelling at the upstream side of each pond can create additional spawning area.

Constructing a series of ponds can add habitat capacity, diversity, and can also help to manage the risk of avulsion by increasing hydraulic roughness and breaking up continual flow paths. Substantial risk of dewatering surface water connections between the ponds and as a consequence, stranding fish, exists if the ponds are too close together or the ground is too porous. Such a project should be done either in stages with a design that adapts to the hydrology or with a good understanding of groundwater hydrology to minimize the risk.

5.8.2 Fish passage

An efficient way to enhance habitat in floodplain ponds is to create or improve fish access between the pond and the main channel. A simple and common enhancement of isolated floodplain ponds or gravel pits is to construct a channel from the river to the pond to provide access for adult and juvenile fish. Access may provide spawning opportunity for adults, rearing habitat for juveniles, and may prevent fish stranding. Bates[42] describes options for fishways for juvenile and adult passage. Fishways for juvenile passage require precise flow control; too much flow in a fishway will block juvenile fish. Fishways within systems with spring-fed hydrology are practical for juvenile fish because flow is relatively constant and little or no bed material transport exists that might affect fishway operation. Any fishway, however, requires continued inspection and maintenance effort.

5.8.3 Managing predation

Predation is more likely a significant factor in floodplain ponds than other side channels. Zarnowitz and Raedeke[43] attributed 43 percent of the mortality to coho in an over-wintering pond to bird and mammal predators. To minimize bird and mammal predation, they suggest a pond size less than 2.5 ac with steep sides that drop to greater than two feet in depth, that two feet should also be the minimum pond depth, and that 75 percent of the pond area should have depths in the four to eight-foot range. Ponds in Washington coastal rivers were constructed with minimum depth of three feet to limit access by herons but with a five-foot wide beach around the perimeter that slopes up to a foot of depth.[44] The beaches were planted with plugs of slough sedge (*Carex obnupta*) on eighteen-inch centers. The slough sedge spreads rapidly and has been observed to provide substantial cover for juvenile coho. Other aquatic plants common to floodplain ponds and that can be imported from other ponds in the vicinity include small-fruited bulrush (*Scirpus microcarpus*), and hardstem bulrush (*Scirpus acutus*). These plants also provide food and cover for small mammals and waterfowl. Another type of predation to consider is non-native piscivorous fish. These species can have implications for overall salmonid utilization and survival in these habitat types. Henning and colleagues[45] found piscivorous largemouth bass and brown bullhead inhabiting permanent ponds coincided with low salmonid use. Caution should be taken when restoring ponds and gravel pits that have year around inundation, especially in river systems with non-native fish.

5.8.4 Water quality

Water quality of floodplain ponds may be different than other side channel habitats. Because of their size, surface exposure, and common lack of mature riparian vegetation, surface heating can be a concern. Warm surface water may reduce the rearing habitat available as fish are forced into deeper water and away from food production associated with the shallow edges of the pond. Warm water may also be more conducive to colonization of warm-water predators. A combination of warming and depth may create supersaturated gas conditions. High gas levels should be estimated based on expected heating, mixing, and pond depths. Water quality problems will be less if significant groundwater inflows to the pond.

Odors of hydrogen sulfide have been apparent in the winter at several floodplain pond sites,[44] implying stratification during summer months and anoxic conditions in the bottom of the pond. This could be due to lower quantity of inflow or no inflow into the bottom of the pond. This condition may be exacerbated by heating of the pond surface and excess pond depth.

5.8.5 Restoration of abandoned gravel mining pits

Abandoned gravel mining pits are common features in floodplains of many Washington stream valleys. Providing fish passage and restoring abandoned gravel mining pits can provide important aquatic habitat, though risks associated with their restoration also exist. The considerations above apply to natural or constructed ponds as well as to gravel pits. Several additional considerations are included below that are unique to gravel pit restoration:

- Gravel mining operations within the floodplain could be reclaimed either as part of the gravel mining operation or subsequent to it.
- Shaping the pond to optimize production is easiest if the gravel pit is shallow. Some pits are excavated only down to the groundwater level.
- Lowering the water level of a floodplain pit, which can occur if pits are hydrologically reconnected to the main channel, can add to the risk of avulsion because in the absence of high water in the pit, flood flows overtopping the pit may be able to headcut through the pit wall. This can lead to pit capture by the mainstem, which may significantly impair instream aquatic habitat conditions.
- Commercial gravel pit operations typically result in the loss of all riparian functions around the pits. Any restoration plan should include an aggressive program of revegetation of the shoreline of the pit. The revegetation could be started whenever a potential restoration site is identified and before work is accomplished.
- Creating a bench around the pit at or near the water level is useful to establish a perennial wet area for establishment of shrubs such as willows that are fast growing, provide cover, and have strong root binding qualities.
- Although gravel pits can be reclaimed as habitat, the practice of floodplain gravel mining may have risks that exceed these benefits at least in some cases. Bates[42], Norman and colleagues[46], and Kondolf [47] describe consequences and risks of floodplain pits including avulsion, entrapment of fish, colonization by warm-water species, and hydraulic effects on the floodplain.

6 PERMITTING

Permitting requirements for side channel restoration and creation projects will be very site- and project-specific. Channel and floodplain modification invariably involves physical disturbance, excavation and removal of material, haul in and placement of fill, and other conditions, so the full suite of regulatory permit approvals will typically be necessary. The work can disrupt habitat and water quality at the site and downstream. In some cases, it may be possible to conduct much of the restoration work outside of the active channel and therefore work can be conducted during periods that fall outside the US Army Corps of Engineers in-water work window.

Side channel restoration work can potentially be disruptive to wildlife. Special concern should be given to the potential for impacting threatened or listed species of birds. A general discussion of permitting requirements is included in the *Typical Permits Required For Work In And Around Water* Appendix of this document.

7 CONSTRUCTION CONSIDERATIONS

Side channel habitat is usually constructed out of the active flowing river channel and therefore may require less attention to factors that complicate construction in sites with moving water. Excavation, however, is often done in saturated conditions, and may require pumping and dewatering to facilitate construction. Planning construction during seasons of low groundwater levels may be easiest. If a channel is to be constructed in a surface water channel or in a spring-fed channel, a thorough plan for project sequencing and care of the water must be developed. Isolation and dewatering might include temporary closure berms to isolate work areas; treatment of turbid water may require filtering or settling basins before discharge to the main channel, or may be accomplished by pumping water onto the floodplain for natural filtering. Further discussion of these elements is provided in the *Construction* Appendix.

Timing considerations are less of an issue in the establishment of side channel habitat because the projects are usually conducted outside of the active channel. Nevertheless, construction should be conducted when potential impacts to species (e.g. migrating or spawning fish) can be minimized, and may be easier when groundwater levels are lower.

It may be possible to sequence the project to minimize impacts. For instance, excavation of a new side channel can sometimes be performed from within the new channel alignment, as opposed to from the sides of the new channel, in order to reduce impacts to existing riparian vegetation. For spawning channels, clean gravels should be placed last to ensure they do not become affected by fines during construction. If compaction of soils is undesirable, low bearing pressure equipment can be used.

Pockets of fine sand are often encountered during construction. This is typically the result of sediment sorting and filling of old channels as the floodplain developed. I t may be difficult to mechanically excavate the fine, saturated material, but if left in place, it may impair spawning gravel quality. A number of alternatives can be considered for addressing this issue: 1) if the channel realignment is flexible, investigate the lateral extent of the fine material to see if the alignment can be moved to avoid the sand; 2) the material can be dredged or pumped out; 3) a pool can be left for rearing habitat; or 4) it might be left in place and protected with a layer of larger rock.

Construction may require substantial excavation and hauling of spoils. Leaving the spoils on or near the site will reduce costs; however, careful consideration should be given to their effect on the constructed channel as well as the hydraulics of the floodplain. Topsoil and duff should be separated from gravel materials and clayey materials and stockpiled. Topsoil and duff can be spread back over the final project as part of riparian site restoration. Gravel might be sorted and/or screened for use as spawning material. Large wood, trees, and rootwads that are removed should also be stockpiled for use as habitat features.

Floodplain ponds were constructed in the 1980s by Washington Department of Fish and Wildlife to restore habitat lost by the mudflow associated with the eruption of Mt. St. Helens. Among other techniques, a series of ponds, or beaded ponds, were excavated by blasting.[37] Blasting technique was used at sites that had no access for equipment. Explosives precluded precise control of dimensions or geometry of the ponds. They initially had steep walls and depths of eight to ten feet that subsequently sloughed. Pond depths of just several feet ultimately resulted as fine sediment filled the deep ponds. This type of project has obvious safety and potential implications to wetland functions that must be addressed.

8 COST ESTIMATION

Cost is highly variable in side channel restoration projects. Primary factors that may control project cost include the size of the project, land acquisition, volume of excavated material, location of the spoils disposal area, quantity of spawning gravel needed (if any), large wood quantities and sizes, site access, and dewatering and sediment control measures. The experience of the construction crew and the design team will also affect project costs. Some side channel projects may require additional analysis and design costs to evaluate groundwater flow conditions (e.g. pump tests and piezometers).

9 MONITORING

Project effectiveness monitoring is recommended in order to evaluate whether objectives are achieved and if adaptive management of the project is necessary. It is critical to monitor relative to the objectives of the specific project. Monitoring programs that are not based on the project objectives, or that assume different or additional objectives, may fail to accurately evaluate project effectiveness. This section describes general considerations for project monitoring, with the understanding that certain monitoring elements may not be appropriate and additional elements that are not presented here may be required.

Physical habitat and biological monitoring can be used to gage the effectiveness of side channel restoration projects. Where project objectives specify biological outcomes, such as productivity or utilization, biological metrics will be necessary to measure effectiveness. Biological monitoring may include annual spawner counts or redd surveys as a direct measure of salmonid spawning utilization. Trapping and counting of adult and juvenile fish entering and leaving a site may be used to evaluate the total productivity, including rearing use, of a channel. Ideally, objectives will also specify a timeframe over which results are anticipated.

Monitoring will be typically necessary prior to and for many years following project construction, and again after several generations of fish have used the site.

Smolt production is another potential monitoring element but may not accurately evaluate project effectiveness. Some sites have had large parr density but low smolt outmigration the following spring. These parr may have relocated to other habitats in the summer either due to competition or due to a life-history strategy such as re-locating to larger downstream channels for additional rearing.[48] It will be important to look at both parr and smolt production, especially if high in the area of spawning distribution. Parr and smolt evaluations are typically performed as part of a larger monitoring program and will require experienced personnel and a significant commitment of time and resources. Biological monitoring for non-fish wildlife will depend on the local fauna. A local habitat biologist should be consulted to determine the appropriate and feasible species to monitor.

Besides biological monitoring, the monitoring of physical conditions is important to document the effectiveness of implemented physical measures at achieving biological objectives. Periodic flow measurements can be used to determine whether the flow in the side channel is constant or diminishes over time. Analysis of sediment in the gravel bed can be used to evaluate its quality over time. An evaluation of headcut-prevention measures should be performed after large floods that overtop the channel. Effects of the project on groundwater and implications to wetlands can be monitored. Piezometers installed for the initial site assessment can be maintained and monitored for several years to see how the project affects or interacts with groundwater levels and flows.

For a comprehensive review of habitat monitoring protocols, see *Inventory and Monitoring of Salmon Habitat in the Pacific Northwest – Directory and Synthesis of Protocols for Management/Research and Volunteers in Washington, Oregon, Idaho, Montana, and British Columbia*.[49]

The Salmon Recovery Funding Board (SRFB) Reach-Scale Effectiveness Monitoring Program[50] evaluates a subset of SRFB-funded projects in order to determine project effectiveness. A few “off-channel” restoration projects were evaluated according to several metrics, including 1) juvenile fish density by species, 2) mean thalweg residual pool vertical profile area, 3) mean residual depth, 4) mean canopy density along the banks, and 5) proportion of the reach with three-layer riparian vegetation. Although no significant results were found with respect to habitat or fish response metrics, some observations were made with respect to the maintenance of a connection with the main river. Projects designed to be connected only at high water had a lower chance of remaining connected and supporting fish habitat compared to projects designed to be connected at a greater range of flows. The report concludes that adequate velocity must be maintained in the off-channel habitats in order to prevent sediment aggradation that leads to channel disconnection.

10 MAINTENANCE

Maintenance may be necessary to ensure that connectivity is maintained with the main river channel. This is especially true for projects within depositional environments and in systems with high sediment loads. It is almost inevitable that fine sediment and organic material will gradually accumulate in the side channel. Natural succession and maintenance of side channel habitat occurs during floods through scour or channel migration, and spawning fish also clean and sort substrates. If natural flood and associated erosion conditions are not present at a site, maintenance operations may be needed to remove sediment, clean fishways, or replace wood, among other actions. Periodic cleaning of gravel and/or supplementation with new gravel may be required to maintain full habitat potential.

11 EXAMPLES/CASE STUDIES

11.1 Effects of Side Channel Projects on Salmonid Smolt Production

Numerous habitat enhancement programs in British Columbia and Washington State have developed off-channel spawning and rearing habitat, primarily to benefit salmon.[51] Projects have included restoration and modifications to river floodplain swales, abandoned side channels, floodplain channels along steep terrace bluffs, and access to floodplain ponds, all in order to increase salmonid spawning and rearing habitat. Many of these projects rely on providing a mechanism for the introduction of additional ground and/or surface water to provide the desired fisheries benefit. Between 1986 and 2001, 92 off-channel sites in four watersheds in Washington State have been restored or enhanced. Smolt production is summarized by watershed in Table 5.

Table 5. Project smolt production by watershed.

Watershed	No of Project Sites	Area of habitat (sq. m.)	Estimated mean annual smolt production	Potential project contribution to total basin smolt production
Skagit	22	507,000	182,000	18%
Stillaguamish	25	382,000	68,000	24%
Hoh	19	74,000	16,000	20%
Quillayute	27	118,000	118,000	10%

Estimates of the coho utilization and productivity of these sites are based on smolt outmigration trapping results at selected sites. The mean smolt production densities quantified at monitored sites are applied to the area of total restored habitat in each watershed, to estimate the potential coho smolt production of all restored sites. (Note: the Stillaguamish estimate does not include the production potential of four large, relatively open water sites, since this habitat is not likely being used at densities assumed at other, smaller-scale sites).

The project contribution is the ratio of the estimated mean annual smolt production to the total basin smolt production, which is estimated each year on the major coho producing rivers in Washington (D. Seiler, WDFW, Fish Management Program, unpublished data). An additional value is the contribution these sites make to the presmolt population. These are juveniles that either emigrate prior to smolting that do final rearing in downstream areas or juveniles that are recruited into the project from upstream spawning, rear temporarily and then leave before smoltification. In both cases, these fish benefit from the habitat, likely have higher survival and develop better condition, but have not been accounted for in the data because trapping only occurred during normal migration periods.

11.2 Case study – Nolan Channel

Nolan Channel is typical of a groundwater channel located within the floodplain of the Hoh River. The area selected for construction was actually a low swale within the flood plain, which seemed secure from active flooding. This was determined by observing recent high water marks relative to the proposed surrounding ground of the swale. Vertical survey control was established at the upper, middle and lower ends of the adjacent river reach. Pumps tests were performed in the proposed channel area to verify substrate, groundwater elevation and percolation potential relative to the river.

Tributary to:	Hoh River in Jefferson County, Washington State
Channel Length:	2400 ft
Groundwater fed length:	1600 ft
Total Excavation:	22,000 cubic yards
Pump Test Data:	
Drawdown Index:	1.0
Apparent Velocity	0.04 fpm
Project Construction Cost:	$160,000 (2001 Dollars) Cost per cubic yard: $7.30
Drop in river water surface:	8 feet (0.0029 ft/ft slope)
Drop in channel water surface:	2.5 feet (0.0010 ft/ft slope)
Design species:	Coho Salmon (juvenile and adult) Trout (juvenile and adult)
Project Features:	50 % pool/riffle channel design Refuge Bays Pool Cover Structures Shallow Wetland Habitat Large Rearing Pool at upper channel Channel Log Controls

11.3 Case study – Clackamas River Side Channel, OR

The Clackamas River drains a 900 mi^2 watershed on the western slope of the Cascade Range in northwest Oregon. It flows 83 mi from the headwaters to its confluence with the Willamette River and is a river of regional importance as habitat for salmon and steelhead. One hundred years ago, side channels along the Clackamas River provided optimum habitat to young salmon and steelhead to occupy and access groundwater-fed side channels.

The Oregon Wildlife Heritage Foundation (OWHF) received a grant from Portland General Electric (PGE), to create three new side channels off the Clackamas River to restore valuable rearing, forage, and refuge habitat for juvenile salmon and steelhead native to the Willamette River Basin. The new channels utilize large woody debris to emulate old growth forest stream conditions, control flooding, and provide habitat for spawning and rearing fish.

The project included 4,400 feet of side channel habitat, making this one of the largest off-channel rearing habitat efforts in the Pacific Northwest. Design of new channels included:

- A created upper channel that brings water in from the Clackamas and releases it further downstream (see Figure 3). Constructed with a series of pools and riffles, large engineered log jams are strategically placed to provide flow into the 1,650 ft channel.
- A created groundwater-fed lower channel that is 2,600 ft long (see Figure 4). Shallow groundwater, besides inter-gravel flow, provides cool water in the summer months.

- A third channel at the outlet portion of a larger existing side channel to the Clackamas. It was plugged with sediment at the bottom end and running through a County Park. The lower 200 ft was opened to allow young fish to enter, forage, seek refuge and return to the river.
- Over 450 large trees were utilized throughout the project in log jam complexes and in-channel habitat features.
- The project is the result of a unique collaboration between Portland General Electric (major funding), the Oregon Wildlife Heritage Foundation (funding and project management), Metro Regional Parks and Greenspaces (property easements and long-term site management) and the Oregon Department of Fish and Wildlife (permitting coordination and long term species monitoring). It was completed during the summer of 2004.

Figure 3. Upper side channel that is connected to the Clackamas River at its upstream and downstream ends (Inter-Fluve, Inc.).

Figure 4. Lower side channel that is a groundwater-fed channel connected to the river only at the downstream end. A constructed infiltration gallery was used to increase the flow to this channel (Inter-Fluve, Inc.).

11.4 Case study – Salmon Creek Greenway Project, Vancouver, WA

The Salmon Creek Greenway Project was conducted by Clark Public Utilities to enhance juvenile salmon rearing conditions in lower Salmon Creek. The project involved the construction of an approximately 0.5-acre (~600 lineal feet) backwater habitat area connected to mainstem Salmon Creek. The project is located within Salmon Creek Greenway Park, a popular public park within a heavily suburbanized part of the Vancouver metropolitan area. Habitat within lower Salmon Creek is affected by numerous upstream watershed land uses including residential development, transportation corridors, agriculture, timber harvest, and mining. Portions of lower Salmon Creek adjacent to the project area have been subjected to streambank armoring, channelization, confinement from bridges, and past gravel mining. Much of the riparian and floodplain area has been cleared and paved to support recreational uses in the park.

This project was designed to provide critical off-channel habitat for juvenile salmonid rearing that will not be otherwise created on its own due to impairments to stream geomorphic processes (e.g. confinement and bank armoring). The backwater habitat was designed to be inundated year-round in order to provide both winter flood refuge as well as summertime habitat diversity (see Figure 5). Large wood was added to the backwater area in order to provide habitat cover and complexity. Riparian restoration work has included planting native woody vegetation throughout the riparian area. The project was constructed in the summer of 2010 and received an above-bankfull flow event during the first winter following construction (see Figure 6).

Figure 5. Salmon Creek backwater channel entrance (Clark County, WA, Inter-Fluve, Inc.).

Figure 6. Salmon Creek backwater channel during flood (Clark County, WA, Inter-Fluve, Inc.)

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TECHNIQUE 4

CHANNEL MODIFICATIONS

Channel Modifications

1 DESCRIPTION OF TECHNIQUE

Channel modification includes practices that significantly alter channel planform, profile, and cross-section geometry as a means to restore aquatic habitat. This technique covers modifications that range from complete reconstruction of a channel to smaller-scale alterations that induce incremental changes to channel form. Depending on the specifics of the project, this technique may include elements of other techniques presented in the SHRG, including *Instream Structures*, *Large Wood and Log Jams*, and *Floodplain and Channel Migration Zone Restoration*.

The Channel Modifications technique may be the main emphasis of a stream habitat restoration project, or it may be a component of a broader set of techniques implemented in concert. Prior to embarking on designs for specific techniques, the restoration practitioner should have already completed a site, reach, and watershed assessment to identify causes of observed or perceived problems, to determine constraints to addressing these problems, and to frame the project in the broader context of a watershed restoration strategy (Chapter 4). Because restoration practice is most effective when it addresses root causes of problems rather than observed symptoms, a robust assessment that looks at potential causes at site-, reach- and watershed-scales will contribute to a more effective restoration strategy. In addition, design should only proceed when project goals, specific objectives, and design criteria (Chapter 5) have been clearly defined and a restoration strategy has been developed to meet these objectives. A site- or reach-scale technique may ultimately provide little value if it is not consistent with overall watershed priorities or integrated with other techniques as part of a restoration project.

Depending on project objectives and the geomorphic context of the reach, modification of the channel may be an appropriate technique to accelerate recovery of a stable, sustainable natural channel and floodplain. This can be accomplished through alteration of:

- Channel form, which consists of channel:
    - planform (the shape/pattern of a channel in map view; planform is defined by sinuosity and meander characteristics),
    - cross-section (the shape, width, and depth of a channel from bank to bank and across the floodplain), and
    - longitudinal profile (the elevation, slope, and shape/pattern along the channel bed)
- Location of the channel

Planform, cross-section, and profile are integrated and mutually-adjusting features. Thus, altering one will affect the others, and alteration of any of these typically results in a change in the hydraulic and sediment transport characteristics of the channel.

When properly applied, channel modification can result in a cost-effective, comprehensive habitat improvement strategy, preferable to the periodic and chronic-fix approach that treats problems symptom by symptom. However, a thorough understanding of the complexities of channel modification techniques, and of the stream channel in question, is necessary for a successful and sustainable project. Because all channel modification techniques result in changes to channel process, a thorough understanding of fluvial geomorphology is essential to developing channel modification projects. Refer to the *Fluvial Geomorphology* Appendix and to SHRG Chapter 2, *Stream Processes and Habitat*, for further discussion of channel planform, cross-section, profile, and channel stability and equilibrium.

Dedicating Land and Water to Stream Habitat Restoration, Rehabilitation, and Preservation is a complementary technique that protects the investment and increases the extent of restoration as well as its long-term sustainability. See also the *Riparian Restoration and Management* technique for discussion of related riparian areas, and the *Integrated Streambank Protection Guidelines*[1] (ISPG) for details on streambank components of channel modification. While streambank stabilization should not be considered a form of restoration, the incorporation of deformable constructed streambanks can be an essential component of restoration. Long term solutions using channel modification as a tool will be sustainable only if natural rates of lateral adjustment and channel migration are accommodated. The ISPG[1] details these considerations and concepts.

2 PHYSICAL AND BIOLOGICAL EFFECTS

Channel modification alters the amount and pattern of energy within the channel, which affects the following:

- Sediment transport – including the size distribution and volume of sediment mobilized, transported, or deposited.
- Hydraulics – including velocity, shear stress, turbulence, water surface elevations, and other hydraulic variables.
- Large wood – including recruitment, transport and retention of large wood.

Due to the impact on multiple fundamental channel processes, the potential for inadvertent consequences is high. Careful physical analysis and design are required. Furthermore, effects on the attributes listed above can propagate upstream or downstream of the modified channel reach, or into tributaries, and may affect channel stability, habitat features, and floodplain interactions within and beyond the project area.

Channel modification projects provide numerous potential physical and biological benefits. Projects often provide immediate benefits by directly creating habitat features. However, channel modifications should ensure that diverse habitat is created and sustained over the long-term by ensuring that the channel is allowed to adjust to inputs, but still retains characteristic features and forms over time (i.e. dynamic equilibrium). Components of this “process-based” approach may include restoring natural rates of floodplain inundation, channel migration, sediment transport/deposition, and large wood recruitment. Restoring these inputs and processes will not only improve long-term habitat conditions but will also increase resiliency to future natural or anthropogenic disturbances.

Potential physical and biological benefits of channel modification include the following:

- Improved stability and sorting of gravels for salmonid spawning
- Restoration of floodplain inundation
- Greater diversity in channel bedforms and substrate textures
- Greater diversity in channel hydraulics and velocities
- Improved nutrient cycling and exchange within the channel and between the channel, floodplain, and hyporheic zones
- Greater potential for fish to find refuge during high and low flows
- Moderation of water temperature extremes due to improved hyporheic exchange, floodplain storage and groundwater connectivity
- Improved riparian zone function (e.g. large wood, shading) and stream-riparian interactions
- Improved habitat quality and diversity for riparian-dependent terrestrial fauna (e.g. migratory birds, amphibians)
- Moderation of streambank erosion to bring it into line with natural rates, thus restoring channel stability
- Achievement of sediment equilibrium

Channel modification projects may also result in inadvertent, potentially negative physical and biological effects. This is particularly true when finished projects do not meet restoration objectives, were not constructed as specified in planning, or were designed with inadequate knowledge of watershed processes, disturbance regimes or altered watershed conditions. Failure to achieve objectives is frequently related to the imposition of rigid channel forms in river systems that are naturally dynamic and subject to adjustment. Constraining dynamic processes will either lead to simplified and degraded habitat or to severe and unpredictable channel response (e.g. significant erosion, deposition, or project abandonment). Many well-intentioned channel modification projects have resulted in unexpected bank erosion in adjacent reaches, aggradation or degradation of the channel bed, or other impacts to habitat and processes due to changes in channel slope, bed elevation, and sediment transport capacity. Furthermore, the dynamic nature of hydraulic forces, and the uncertainties inherent in design and analysis may result in inadvertent impacts from channel modification, even when properly designed.

Some potential negative physical and biological effects include undesirable or unintended:

- Incision or aggradation within the project reach or in upstream, downstream or tributary reaches
- Bank erosion due to changes in hydraulic forces or bank stability
- Mid-channel bar formation and widening
- Channel avulsion (sudden shift in channel location across the intervening floodplain)
- Flanking of in-stream structures
- Increased sediment delivered to downstream reaches due to post-project channel adjustments
- Decreased sediment delivered to downstream reaches due to reduction of bank erosion rates to below natural levels
- Altered patterns of flooding
- Creation of fish-stranding hazards

- Shifts in composition and distribution of riparian plant, fish, and wildlife species, including establishment of non-native species

Short-term risks associated with construction may also exist. These risks are increased if at-risk species are present. Construction related risks can be minimized by taking proper precautions and by anticipating potential outcomes. Some of the potential risks during or shortly following construction include:

- Mortality, physiological stress or displacement of aquatic macroinvertebrates, amphibians, and fish due to in-stream activity, increased turbidity, deposition of fine-sediment, and channel abandonment
- Increased sediment input to downstream reaches during construction or during channel re-watering, affecting pools and spawning gravels
- Increased sediment input to downstream reaches during the wet season following construction, affecting spawning gravels
- Disturbance or displacement of wildlife due to construction activity and loss of riparian vegetation
- Temporary loss or imbalance of nutrients and food supply

Short-term impacts associated with construction, and how to reduce those impacts, are discussed in greater detail in the *Construction* Appendix. These impacts must be weighed against long-term benefits in the context of species and habitat resiliency.

3 APPLICATION OF TECHNIQUE

Channel modification is typically applied in areas where channel equilibrium processes or forms have been disrupted and hence the channel no longer able to provide the quantity, quality, or diversity of desired habitats. Before selecting channel modification as a technique, it is therefore necessary to understand how equilibrium processes have been affected, and at what scales. Disruptions to channel equilibrium typically fall into two categories:

1. *Reach-scale:* Reach-scale impacts result from physical modification of the channel or immediately adjacent areas. Examples include road crossings, channelization (straightening, dredging, widening, bank or bed armoring, and levee construction), removal of large wood, removal of bank vegetation, or other actions that artificially confine a channel, alter its slope or hydraulic roughness, or alter the resistance of the bank to erosion.
2. *Watershed-scale:* Watershed-scale impacts result from cumulative upstream perturbations that may occur throughout the contributing watershed, including upland areas. Habitat degradation often occurs as a result of land use practices on a watershed scale that affect the rate, timing, distribution, and type of sediment, water, and large wood delivered to the stream. Such changes can alter the stability of the channel bed and banks, and can induce sudden or progressive change in the channel type or form. These changes alter the distribution, abundance, quality, and accessibility of habitat within the stream corridor.

If reach-scale impacts are the cause of degradation, removing the source of degradation and allowing natural recovery to take place (i.e. passive restoration) may be a cost-effective, low-risk solution. In other cases, however, channel modification techniques may be appropriate; these include: 1) when the time required for passive restoration is unacceptable; for instance, when ESA-listed species are significantly impacted by degraded habitat and their populations are not able to withstand a long period for habitat recovery, 2) where degradation of channel form and process is so severe that natural recovery is unlikely without taking a more active restoration approach, or 3) where the reach-scale source of impairment cannot be fully removed, and where channel modification techniques can restore habitat form and process to the extent practical within existing constraints.

Where watershed-scale disturbance is the root cause of degraded conditions, these causes should be addressed first. Otherwise, chronic, watershed scale disturbance, such as accelerated sediment input or altered hydrology, are likely to perpetuate the unstable, degraded conditions, hampering natural recovery and putting channel modification projects at risk. If watershed conditions are in flux, channel modification is unlikely to be sustainable over the long term. If land use has been corrected, however, channel modification can be used to accelerate recovery. The effectiveness of channel modification techniques will depend on the degree to which the watershed impacts have been remedied or stabilized. In some cases, greater benefits may be obtained by addressing land-use-related disturbances and then allowing for natural recovery, without even attempting restoration at the reach-scale.

Where it is not possible to remedy watershed-scale impacts, some degree of channel modification may nevertheless be appropriate to improve habitat conditions. For instance, where watershed processes have been permanently changed but are now stable, channel modification may be used to create a new equilibrium condition or to promote more rapid natural adjustment to altered watershed conditions, provided the current hydrologic, sediment, wood recruitment, and disturbance regimes can be accurately quantified and accommodated in the design. In these cases, an adaptive management plan may be necessary to ensure long-term habitat objectives are met.

Because channel modification typically involves substantial on-the-ground and in-channel disturbance, it should not be a first choice in restoration, but should instead be used only when restoration goals cannot be obtained using less invasive techniques (e.g. natural recovery, passive restoration, removal of barriers, etc.).

Generally, the goal of channel modification is to reconstruct a channel form that is self-sustaining. This implies that processes such as channel migration will occur, but at sustainable rates. A stable channel is not immobile, but rather one that maintains its form over time as it moves the sediment and water presented to it from upstream (i.e. is in equilibrium). In order to be self-sustaining, processes by which natural structural elements such as large wood are recruited should also be restored. If large wood recruitment and channel migration are not accommodated, what remains is a managed structural approach, which is unlikely to be self-maintaining over the long term. The managed structural approach may be appropriate in some settings, such as urban areas, but it does not represent long-term restoration.

It is critical to recognize that while an equilibrium channel is pleasant to look at and falls within expected parameters, habitat-forming mechanisms may not be present.[2] For instance, though a channel may be at equilibrium with respect to sediment load, other processes that create habitat may be absent, such as available riparian trees for large wood recruitment or instream large wood needed to create complex scour pools. Channel modification can provide an equilibrium condition that is conducive to maintaining habitat or promoting the development of habitat, but may be lacking in habitat at the onset. Other habitat enhancement techniques, such as log placements, should be considered in conjunction with channel modifications to provide target habitat and bed and bank stability in the short term. Long-term habitat sustainability can only be addressed by restoring and maintaining habitat-forming processes such as large wood recruitment and channel migration, both of which result in dynamic channel boundaries and "messy" appearance at times.

It is also important to note that not all channels exist naturally in an equilibrium state. As discussed in SHRG Chapter 2, *Stream Processes and Habitat*, alluvial channels are "self-formed," that is, built from material transported and deposited by river flows, and thus take on a shape that allows sediment input and sediment output to be in equilibrium. However, if the time between channel-modifying disturbances is shorter than the disturbance recovery time, the type of equilibrium assumed in this paradigm may not apply. For example, morphological recovery from debris flows or large floods may take a long time. Sometimes, analysis of such channels may reveal a consistent size and frequency of disturbance. However, channel modification in such cases is highly risky, due to design uncertainty and the power of large, frequent disturbances to undo human efforts.

Some valley settings are known to be highly dynamic, making them poor or risky choices for channel modification. Examples include:

- Transitional areas, such as alluvial fans, where high stream power, decreasing sediment transport capacity, and convex topography cause frequent avulsions and rapid channel migration rates
- Areas with high sediment loads, such as glacial outwash valleys (which tend to be naturally braided channels)
- Confined channels with fine-textured, erodible valley side slopes (which have concentrated flow and high energy during peak runoff)

Channel modification methods can be used at multiple scales, from small projects conducted at the site- or reach-scale to multiple continuous reaches of a river. An example of a small-scale project is the removal of a structure (e.g. culvert) and the re-construction of the channel through the former structure location. An example of a large-scale modification is the removal or setback of levees through a long reach of river valley (refer to the *Floodplain and Channel Migration Zone Restoration* technique).

Channel modification projects may include changes to the profile (slope) of a channel and its bedforms, changes to the planform, cross-section, or all of these combined. The appropriate use and application of these modifications are discussed in the sections that follow. Although profile, planform, and cross-section modifications are discussed separately, it is important to recognize that changing one component usually results in changes to the others. For example, changes to channel planform often result in changes to channel profile because a channel cannot be lengthened or shortened without changing its slope.

3.1 Channel Profile Change

Channel profile refers to the slope, or gradient, of the channel bed and the variation of that slope through a reach. Channel slope will change as a result of any activity that changes the bed elevation at a point or changes the length of channel between two constant elevation points. Profile modification can be used to alter energy dissipation patterns, habitat complexity, riparian zone function, floodplain inundation frequency, and water quality. Example strategies for profile modification and potential effects of this technique are provided in Table 1.

Reach-scale channel profile alteration is often proposed specifically to address degraded habitat which has resulted from past river management, including 1) straightened, incising (eroding) channels, 2) widened, aggrading (depositional) channels, and 3) human-caused fish passage barriers.

Table 1. Types of profile modification strategies and potential effects of profile modification.

Example profile modification strategies	Potential attributes that are changed by profile modification
▪ Installation of large wood, drop structures or channel fill (e.g., roughened channel) to raise the bed ▪ Reconfiguration of a previously straightened or channelized stream to lengthen the channel, thereby increasing sinuosity and reducing the slope ▪ Installation of large wood, boulder clusters, or other roughness elements that promote predictable patterns of scour, deposition, and local energy dissipation ▪ Enhancement of hyporheic flow by steps in water surface elevation, either longitudinally (along the channel) or laterally, such as between a main channel and a side channel	▪ Total sediment transport energy for the reach, changing both the sizes and amounts of particles moved ▪ Velocity patterns (maximum velocities and velocity gradients near the bed or banks) ▪ Near-bank and near-bed erosive force (shear stress) ▪ Water access to floodplain and side channels at given discharge levels ▪ Bed sediment texture (particle sizes) ▪ Changes in the rate and volume of hyporheic flow

3.2 Channel Planform Change

Channel planform refers to the spatial pattern and location of a channel looking down on it from above. One common descriptor of planform is “sinuosity,” which is a ratio of channel length to valley length and describes the degree of meandering. Planform modification is often proposed to address the same reach-scale habitat degradation discussed under profile change, including straightened, incising channels and widened, aggrading channels. Disruptions to natural planform have a number of potential causes, including 1) floodplain disconnection through levees or fill, 2) increased erosion through LWD removal, riparian vegetation removal, armoring in adjacent reaches, channel encroachment structures, or aggradation from downstream flow constrictions, and 3) land management which alters sediment loads (e.g. heavy road density, heavy logging, disruption of streambank vegetation) or flow regime (e.g. dams).

Channel planform modification is a major undertaking, involving reconstruction of the channel bed, habitat features, channel banks and floodplain. It requires consideration of sediment transport, sediment mobilization, hydrologic regime, and disturbance patterns. Channel planform modification should be considered only where the existing planform is in disequilibrium and the watershed causes of that disequilibrium have been addressed, or are quantified and can be accounted for in the channel design. Example strategies for planform modification and potential effects of this technique are provided in Table 2.

Table 2. Types of planform modification strategies and potential effects of planform modification.

Example planform modification strategies	Potential attributes that are changed by planform modification
▪ Reconnection or reconstruction of historical meanders in a straightened (channelized) reach ▪ Relocation of the channel to a more stable, less degraded, or historical location. ▪ Removal or modification of levees, bank armoring, or infrastructure that artificially confines the channel (see the *Floodplain and CMZ Restoration* technique) ▪ Redirection of a channel to improve processes that promote or maintain habitat while accommodating infrastructure constraints ▪ Redirection of a channel away from a source of contamination or a physical hazard (such as an abandoned floodplain gravel mine)	▪ Change in bedform composition including pools, pool-tailouts, riffles, chutes, bars, etc. ▪ Diversity of bed sediment texture (sizes), due to variation in deposition patterns (sorting) through the meander sequence (e.g. pool, pool tail-out, riffle, etc.) ▪ Changes in the rate and volume of hyporheic flow ▪ Establishment of a channel migration process, at an appropriate rate, due to differential erosion at outer bends, which results in gravel recruitment, large wood recruitment, and diversity of edge habitat (undercut banks, etc.) ▪ An increase in the proportion of the stream's energy which is dissipated by friction (as the water is made to turn around bends) rather than erosion

3.3 Channel Cross-Section Change

Changing a channel's cross-section involves altering its width, depth, or shape across the channel, and can include modification of channel banks and bars. Cross-section modifications are most commonly applied to the main channel, but also include modifications of floodplain elevations or features.

Example strategies for cross-section modification and potential effects of this technique are provided in Table 3. More information on restoration of incised channels is provided in Section 3.3.1, below.

Table 3. Types of cross-section modification strategies and potential effects of cross-section modification.

Example cross-section modification strategies	Potential attributes that are changed by cross-section modification
▪ Installation of in-channel structures, such as large wood, boulder clusters, drop structures, porous weirs, groins or barbs (refer to ISPG[1]) that obstruct, constrict, or redirect flow. ▪ Reshaping or relocating the bank. ▪ Construction of an inset floodplain or floodplain bench along an incised channel, and reestablishing meanders or other appropriate planform features at the new, lower elevation to accelerate the natural recovery process[3] ▪ Excavation of depositional material from aggrading channels ▪ Removal of levees (for further discussion of levee removal, see the *Floodplain and CMZ Restoration* technique)	▪ Flood stage (elevation) and the ability of the channel to convey flood water ▪ Water velocity ▪ The amount of water surface area subjected to solar heating ▪ Volume and particle sizes of sediment transport for a given discharge ▪ Large wood retention and interaction of wood with the water ▪ Habitat complexity and hydraulic diversity, including substrate type, velocity, depth, and bank margin cover ▪ Establishment of natural channel migration rates

3.3.1 Incised Channels

A special case of channel cross-section modification is restoration of incised channels. The dynamics and causes of channel incision are detailed in the *Fluvial Geomorphology* Appendix. Three general approaches to rehabilitation of incised channels[4,5] exist:

1. Allow natural process to establish a new equilibrium condition, which typically involves initial incision, channel widening and enlargement, and eventual stabilization of banks and deposition of floodplain within the incised and enlarged channel.[6]
2. Excavate and construct a new floodplain at the incised channel elevation or higher, which is a proactive acceleration of the natural progression of incised channels listed previously. This could encompass the entire floodplain or only selected portions of the floodplain, such as excavating material on the inside of meander bends or constructing inset floodplain benches adjacent to the channel.
3. Raise the channel elevation to reestablish reconnection with the floodplain by raising the channel bed or moving the channel to a new or former location on the old floodplain surface. Restoring the historical channel grade typically involves installation of drop structures, grade control, or channel fill to restore the elevation of the channel bed. In some cases, creation of a different, but more stable, stream type within the incised channel may be appropriate, but this should be done with caution to ensure the new channel type can be supported by contemporary stream processes.

The first two approaches are appropriate when the cause of incision is systemic and not likely to be restored, such as in developed or developing watersheds that have a permanent change in sediment transport character, or where structures have encroached on and narrowed or eliminated the old floodplain. The third approach is appropriate when reach alterations are the primary cause of incision, and sediment supply and hydrologic regimes are not otherwise significantly altered. A fourth approach, stabilizing the channel in-place using artificial, hardened structures is often considered, but may offer little in terms of habitat value or long-term stability.

Restoring incised channels can aid in reconnecting the incised channel to its floodplain. Incised channels that are reconnected to an active floodplain become more stable because water depths and velocities in the channel are reduced relative to those in an incised channel. If flood flows spread out over the floodplain during relatively frequent floods (i.e. one- to five-year return-interval events), channel erosion may be minimized.

Incised channel restoration involves detailed analysis of sediment transport and consideration of sediment supply. Refer to the *Sediment Transport* Appendix for more information on analysis of sediment transport. For further information on problems and solutions specific to incised channels, refer to the Additional Reading.

4 RISK AND UNCERTAINTY

Project risk is a function of the probability that the project will result in undesirable outcomes, whereas uncertainty refers to the limits of our knowledge about how a project will perform in the future (Refer to *RiverRAT* Appendix 3.5 for a thorough discussion of accounting for uncertainty and risk in stream habitat restoration design and management). Project risk and uncertainty should be considered as an integral component of design. This is especially important if nearby or downstream properties exist, if the public uses the waterway, or if sensitive species are present that could be impacted by project failure.

4.1 Risk to Habitat

Generally, the goals of channel modification projects are to restore long-term aquatic and terrestrial habitat. However, channel modification may result in significant short-term adverse impacts to species and habitat due to construction disturbance. In some cases, months to years may be required for recolonization and full recovery of some habitat components. Aquatic species that colonize the bed and banks of newly constructed channels are particularly at risk until vegetation becomes established and bed material is redistributed to a stable configuration during high flow events. A risk also exists that a poorly designed channel modification project, or one that includes significant rigid structures, may fail in critical areas and have a negative effect on habitat or channel maintaining processes rather than a positive one. A contingency plan should be in place to deal with unexpected consequences. For further discussion of the potential impacts to habitat, refer to the previous section on *Physical and Biological Effects*.

4.2 Risk to Infrastructure, Property, and Public Safety

Because channel modifications often constitute comprehensive channel reconfigurations, inherent risks exist to infrastructure, property, and public safety. The level of risk depends on specific site conditions as well as the complexities of design and implementation. In some cases, habitat objectives may be at odds with property protection or safety objectives. For instance, channel modifications that increase flooding or LWD recruitment, although beneficial for habitat, may nevertheless pose risks that are unacceptable to the local community. These constraints need to be explicitly considered in design and solutions should be identified that address risks while still meeting habitat objectives to the extent possible.

The following questions should be answered as part of project assessment and design:

- What are the potential impacts to upstream, downstream and adjacent habitat, infrastructure, and public safely if the project succeeds, or if it fails? What is the probability of those impacts occurring? What factors influence that risk (e. g. valley setting, large wood input, or dependence on man-made structural elements such as grade control)? What can be done to minimize the risk?
- Are land-use activities or natural disturbance events likely to have future impacts to the project site? If so, how will they impact the project's success?

Refer to the *Public Safety* Appendix for additional information regarding risk to public safety.

4.3 Reliability/Uncertainty in Technique

In general, channel modification projects have a high degree of uncertainty with respect to achieving intended objectives and preventing unintended consequences. For any given project, the degree of uncertainty will be a function of the scale and complexity of the project. Because channel modification techniques have the potential to significantly alter hydraulic variables (e.g. shear stress, velocity, and turbulence) and sediment transport (e.g. scour and fill), an inherent risk of a project not meeting its intended objectives or of causing unintended consequences exists. Risk and uncertainty can be reduced or eliminated by applying a comprehensive analysis and design process that addresses all aspects of stream channel design.

At a minimum, the design will need to consider many different components of the stream system, including sediment transport, habitat suitability, bed substrate, bank material, vegetation, hydraulics, and hydrology. In addition, design should be conducted by an interdisciplinary team consisting of specialists in geomorphology, hydrology, engineering, riparian ecology, and habitat biology. For further discussion of how to evaluate and address risk and uncertainty in channel modification project elements, refer to *RiverRAT* Appendix 3.5 – Uncertainty and Risk.

5 METHODS AND DESIGN

5.1 Data and Assessment Requirements

Channel modification projects will generally require the greatest amount of data, analysis, and assessment compared to other stream restoration techniques. This is because channel modification projects involve fundamental changes to, or even reconstruction of, stream channels. As discussed previously, a comprehensive design and assessment approach must be taken to decrease uncertainty and ensure project success. A comprehensive design and assessment approach will consider multiple stream and watershed processes at multiple time and spatial scales.

Data and assessment needs will be highly dependent upon the availability of existing information, the intent of the project, the nature of the channel, and the modifications to be implemented. Because the character and behavior of the stream is highly influenced by the character and condition of the watershed and because any alteration of channel can have far-reaching impacts, it is essential that data collection and assessment for channel modification be comprehensive and allow for careful consideration and analysis of impacts and effects. In some instances, such as where low complexity and low risk exist, design may utilize a subset of the recommended data and assessment techniques described in this section; however, for most projects, comprehensive data collection and assessment using multiple disciplines will be necessary.

Channel modification design should include reach assessment at a minimum, and watershed assessment in most cases. The scale of the survey should match the scale of problems being addressed, and should make sure to correctly identify and measure the root causes of those problems (refer to Chapter 4 for discussion appropriate strategies to address varying root causes). For instance, restoring a channel that has been over-widened due to grazing, but that is located in an otherwise pristine watershed, may only require a reach-scale analysis. In comparison, restoring a channel that has been over-widened due to elevated sediment supply from upstream forestry activities will require a watershed-scale analysis to make sure future trends in sediment supply are well understood before attempting restoration. Elements of reach- and watershed-scale analyses are presented in Table 4. For further discussion of assessment, refer to SHRG Chapter 3, *Stream Habitat Assessment*.

Table 4. Reach- and watershed-scale data collection and analysis components.

Reach-scale data collection and analysis components
• Topography of project area and adjacent reaches, including floodplain and terraces
• Survey of planform, profile, and cross-sections of existing reach, upstream and downstream reaches, and reference reach (if available) with permanent benchmarks located outside of the construction area
• Sediment characterization of streambed (surface and subsurface) and bank materials of existing reach, upstream and downstream reaches, and reference reach (if available)
• Geomorphic assessment including identification of channel type, channel form, morphological trends, large wood dynamics, and the influence of riparian vegetation (see Section *5.1.1 Fluvial Geomorphology*).
• Evaluation of sediment transport volumes and size distribution (see Section 5.1.4, *Sediment Transport Capacity*). Any channel modifications must be able to accommodate the sediment load without unanticipated adjustments.
• Hydraulic conditions (see Section 5.1.3, *Hydraulics*), including velocity and shear stress of existing channel, flood and overbank flow profiles and floodplain flow patterns (especially channel exit and re-entry areas)
• Mapping of soil materials and vegetation, paying particular attention to soil water regime (ability to support re-vegetation) and soil stability (resistance to mass failure and erosion)
• Evaluation and documentation of the distribution and condition of existing aquatic and riparian habitat. Describe major plant, fish, and wildlife species and communities that may be positively or negatively affected by the project.
• Evaluate bank erosion rates, streambank stability (resistance to mass failure and erosion) and streambed (vertical) stability. Identify active channel incision or aggradation, and the causes of these conditions.
Watershed-scale data collection and analysis components
• Sediment budget for the watershed (identification of sediment sources and routing patterns and quantification on a decadal time scale to assess whether current conditions and proposed design reflect the long-term patterns)
• Watershed hydrology (see Section 5.1.2, *Hydrology*). This includes channel forming discharge, low flows, flood discharges, and design discharges.
• Large wood recruitment, transport and retention
• Riparian function (shade, temperature)
• Point and non-point sources of water quality degradation that may affect project success
• Groundwater/surface water/hyporheic interactions in terms of volume and timing
• Disturbance patterns (frequency and recovery rates from large disturbances such as flood or fire)
• Watershed land-use and the impacts on sediment, flow, water quality, and large woody debris
• Trends in watershed land management and response to management

Specific considerations for data collection and assessment are included below within their respective disciplines.

5.1.1 Fluvial Geomorphology

Channel modification design will need to ensure the project fits within the geomorphic context of the stream system and its watershed. Due to the scale of most channel modification projects, a comprehensive fluvial geomorphic assessment will be required. Refer to Chapter 2, *Stream Processes and Habitat* for additional information regarding geomorphic processes as they relate to stream restoration and to the *Fluvial Geomorphology* Appendix for additional information on performing a geomorphic assessment and for a discussion of potential data sources. Key questions and considerations that relate directly to channel modification projects are included below.

- How has the stream or watershed been altered from historical conditions? How has the flow regime of the stream, its sediment and wood supply, and its disturbance regime (frequency, magnitude, and extent of flooding, fire, mass wasting, and other events) been affected by these changes? What impacts has this had on riparian vegetation, stream habitat, and channel profile, cross-section, and planform?

- Is the channel in a natural setting or has it been moved to an unnatural location (e.g., is it perched or has it been lengthened or shortened making it susceptible to aggradation or incision)?
- What are the extents of the floodplain and channel migration zone? How have these changed from historical conditions and will the project affect these processes? What role do flooding and channel migration play in habitat formation and availability?
- What are the equilibrium conditions of the channel? Is there a source of bed material to replenish that transported out of the reach during high flow events? Consider the site’s location relative to any upstream reservoir, pond, wetland, or sediment detention basin.
- How will the proposed cross-section, configuration, and slope affect the stability of the channel?
- How will the proposed modifications respond to recruitment of large wood? Will instream large wood need to be actively managed?
- What is the role of riparian vegetation with respect to bank stability, shading, large wood recruitment, and beaver activity?
- How deformable (i.e. erodible) are the bank boundaries in the existing and proposed conditions? Will interim stability be needed on streambanks following construction?
- Will the project be self-sustaining? If the proposed design will not create a naturally self-sustaining channel, is there a self-sustaining design alternative? If not, is there staff and funding to support permanent monitoring and maintenance of the project?

5.1.2 Hydrology

Hydrologic analysis will be required for most channel modification projects in order to identify seasonal and inter-annual patterns in low and high flows at the projects site. The extent and frequency of floodplain inundation is particularly relevant for channel modification projects, since inundation is typically altered as a result of the project. Groundwater dynamics and the relationship with surface water may also be important, particularly as it relates to low flow conditions.

Three components of surface flow that may be useful for the design of channel modifications: low flow, channel-forming flow, and flood flow. Identifying low flow volumes will primarily be necessary to ensure that habitat conditions, such as fish passage, stream temperature, or cover, are suitable during low flow periods. Channel-forming flow is typically used to determine channel dimensions. Flood flows are useful for examining floodplain inundation patterns and for evaluating risk to property or infrastructure. The *Hydrology* Appendix includes further details on these flows, and how to determine appropriate values for a given project.

Besides surface flows, hydrologic considerations for habitat design may include hyporheic and groundwater flows and their interaction with surface water. Groundwater and hyporheic flow conditions may have an important impact on the availability and suitability of habitat that is created as part of channel modification projects. Sub-surface flow conditions can be characterized through measurement and/or modeling. In some cases, simply identifying the variation in groundwater stage throughout the year will be enough to inform project design. In other cases, it may be necessary to quantify sub-surface flow volumes or directions. For instance, chum salmon specifically orient towards upwelling areas, where groundwater is expressed in the channel, for spawning. Basic groundwater/hyphoreic information can be obtained through installation and monitoring of shallow groundwater wells (e.g. piezometers) or through pump tests. The importance of subsurface flows, subsurface flow processes, and techniques for measuring them are included in SHRG Chapter 2, *Stream Processes and Habitat*, and the *Hydrology* Appendix.

5.1.3 Hydraulics

Hydraulics analysis is essential to successful design of channel modification projects, as factors such as velocity, shear stress, turbulence, and flow vectors determine sediment transport rates, scour depths, bank erosion, structure stability, depositional areas, gravel sorting, and fish passage. The new channel may also alter the depth and extent of flooding. Such changes will need to be evaluated, especially where there is risk to property, infrastructure, or habitat. The *Hydraulics* Appendix provides detailed descriptions of analyses and methods for measuring and determining hydraulic variables in the design process.

Mathematical or numerical hydraulic models provide a valuable tool for determining channel geometry. These models can be used to determine the dimensions of a channel and to determine inundation periods for floodplain overflow, refuge flooding, and other areas of off-channel inundation. Hydraulic models and their application are discussed in the *Hydraulics A*ppendix.

5.1.4 Sediment Transport Capacity

Sediment transport refers to the erosion, transport, and deposition of bed and bank material that may range from boulders and gravel to sand, silt and clay. Channel modifications typically alter the existing patterns of sediment transport through the reach. Sediment within a stream can enhance and provide habitat (e.g. spawning gravels) or degrade habitat (e.g. fine-grained sediment within spawning gravel), and therefore characterization and design of sediment transport is an integral component of channel modification design. To a large extent, the size and shape of the channel will determine the size of material that will be eroded, transported, or deposited within the channel. These processes influence the viability and quality of habitat, particularly spawning habitat and aquatic food production (e.g. benthic invertebrates rely on coarse substrate for production).

Channel modifications require consideration of existing bed substrate and sediment supply. In alluvial channels, equilibrium conditions relate to the supply of material from upstream and the ability of the channel to transport that material. To ensure that the constructed channel does not significantly incise or aggrade, the channel must be capable of transporting the size and volume of material that is delivered from upstream. Where supply is limited, the bed material may need to be of sufficient size to withstand mobilization. Many channel modification projects are aimed at improving spawning habitat for salmonids. In these cases, the size of material required for spawning needs to be considered as part of design along with requirements maintain channel equilibrium. If these two objectives are in conflict, then the design may need to be revised or objectives revisited.

Refer to the *Sediment Transport* Appendix for additional information on techniques for evaluating and analyzing sediment transport.

5.2 General Approaches to channel modification design

Three general approaches exist to channel modification designs: Analog, Empirical, and Analytical.[7] Chapter 5 provides detailed explanations of these approaches. Channel modification design may use any of the approaches described above, or a combination of the three. Project objectives, site conditions, availability of an appropriate reference reach, and data availability may dictate what approaches are applied. Using more than one approach to determine the same design parameter helps to verify its validity (where results are similar) and alert the designer to potential errors (where results differ). For complex channel modification projects, or where considerable uncertainty exists, using analytical methods will be necessary; but these should also be checked against anolog and empirical methods where relevant information is available.

Careful analysis of the watershed should accompany any channel modification work to determine if significant alteration of the watershed hydrology has occurred. If urbanization, timber harvest, grazing, agriculture or other human activities have affected the watershed, the hydrology, sediment, and large wood regimes may be significantly and permanently altered. Natural changes such as fire should also be considered. Selection and design of channel modification treatments based on historical conditions should be considered only where changing watershed conditions can be accounted for, or where the watershed has already been restored to historic conditions. In any case, future anticipated conditions are a critical element of any channel modification design.

5.3 Design Methodology

Channel modification design will require the integration of designs for a number of different but interrelated project elements, for which specific design criteria can be developed. Refer to Chapter 5 for more information on the general design process and for developing design criteria.

A detailed discussion of channel modification design methodologies is beyond the scope of this document because of the relative complexity and variability in channel modification projects. A qualified geomorphologist should be consulted to help evaluate the necessity and applicability of major channel modification work and to assist in design. Additionally, qualified professional engineers should be consulted to evaluate the potential risks to safety, property, and infrastructure associated with channel modification projects. Habitat biologists will also be needed to determine species requirements and habitat restoration objectives. Finally, plant biologists are essential to assure that recovery and stabilization of disturbed areas is successful. For further information regarding contemporary approaches and limits of knowledge of channel modification design methods, refer to the documents listed in Section 12, Additional Reading.

Though each channel modification project consists of the integration of a unique set of project components that require unique sequences of design actions and supporting decisions, the following conceptual example is provided to illustrate a channel modification design process that could be applicable to each of the three basic methodologies listed in the previous section. The steps listed assume that watershed assessment, physical and geomorphic reach survey and biological resource assessments have already been completed, and that project objectives, site constraints and risk/cost/benefit analysis have defined the need for, and scope of, the channel modification project.

Conceptual Example: Steps in Channel Modification Design

1. Determine design discharge for each design element (low flow, channel-forming flow or flood flow)
2. Determine channel cross-sectional area
3. Determine average channel width
4. Determine average channel depth
5. Determine planform geometry
6. Compute reach slope
7. Check water and sediment conveyance
8. Iterate through steps 2-7 to ensure water and sediment conveyance meet design criteria
9. Develop (deformable) bank designs
10. Add habitat features consistent with geomorphic function
11. Develop revegetation and riparian designs

The method followed in this example uses channel width as a starting design parameter. That is, a selected value of width is verified (or not) by computations occurring at a later step. If the width is not verified, it is adjusted and the design steps repeated until concurrence is reached. Using average channel width as a starting parameter has the advantage that regional relationships for width tend to have less scatter than relationships for slope, if an empirical approach is used, and width tends to be easily and consistently measured and adjusted if an analog approach is followed. Slope is computed as a subsequent step in the process, where it is used to check for water and sediment transport capacity.

Some practitioners advocate the use of slope, rather than width, as an initial design parameter. Design may start with a narrow range of allowable slopes, which then determine cross-section design, progress to planform characteristics, and ultimately lead to confirmation (or rejection) of design slope. Designing from slope as a first parameter has the advantage of direct ties, through physical models and equations, to water discharge and sediment transport. This is often highly desirable, especially if the analytic approach is used.

The method described in the example presumes that the size distribution of the sediment in transport, and the streambed surface, are known (from measurement at the project site and at the site analog). If actual sediment size in transport is unknown, or if the project involves gravel supplementation, measures must be taken to design the streambed sediment gradation as part of the process rather than treat it as given (see Bed Material Considerations, below).

The design of channels is necessarily an iterative process, to an even greater degree than suggested by the simplified example given above. Whether width, slope, or other physical variables are selected as initial design parameters, the process always involves iterative adjustment of design until physical (hydraulic and sediment transport) process criteria are met. Furthermore, site constraints, stakeholder interests, and other objectives complicate the design process. For example, site constraints may limit planform options to a narrow range of possible slopes. Cross-section characteristics must be designed to achieve the desired hydraulic conditions within the range of acceptable slopes. However, cross-section character influences planform design, as a strong relationship exists between cross-section character and planform in most equilibrium alluvial channels. Once a preliminary channel design is achieved, it must be checked to evaluate sediment transport and ensure equilibrium, which may invoke further iterations. The addition of habitat elements to a design template may affect the roughness or capacity, leading to additional design iteration. Small changes to various design components are necessary in a backwards and forwards process to achieve the desired end-product for a particular project. No single linear series of design tasks exist that can be followed to arrive at a final design.

The following sections provide further considerations for design of specific channel modification elements. Design of each of these elements is commonly guided by design criteria that define specific design objectives. For further discussion of design criteria, refer to Chapter 5; for examples of design criteria and how they are applied to design, refer to *RiverRAT*, Appendix 2 – Design of Stream Channels and Streambanks.

5.3.1 Cross-Section Considerations

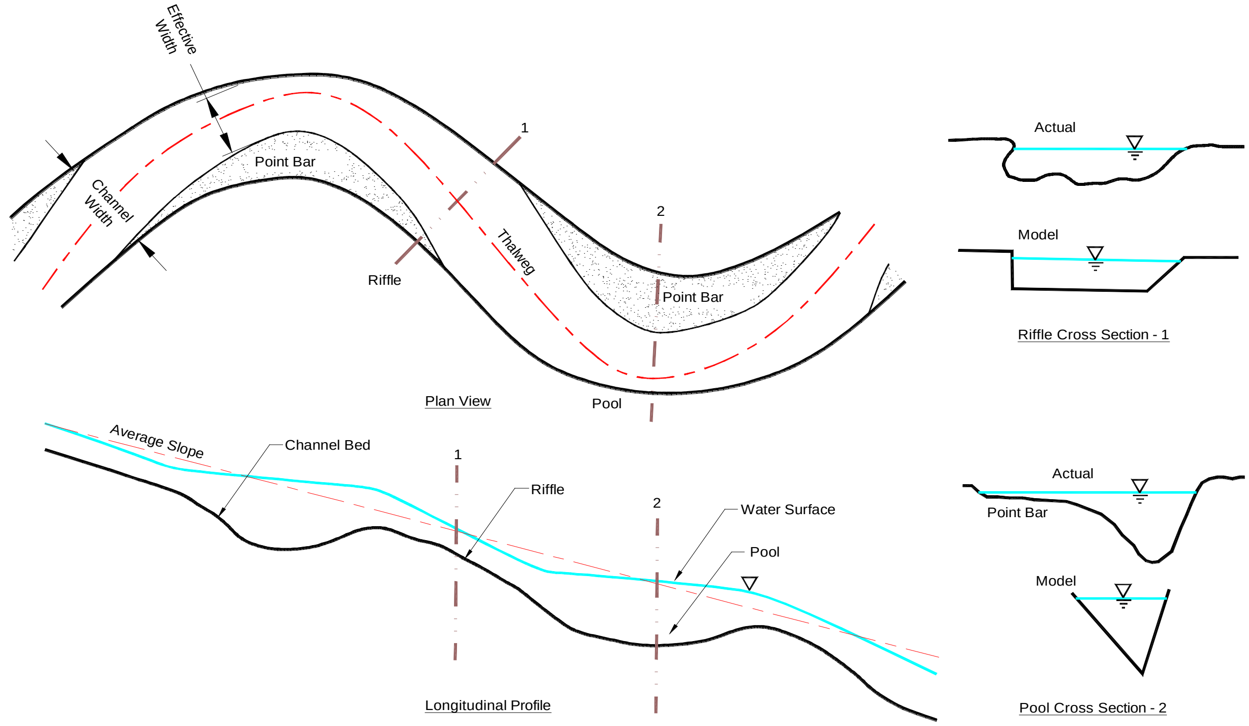
The primary design considerations for cross-section modification design are:

- Sizing the cross-section to convey the dominant discharge and sediment supply. If the channel is oversized, deposition will likely occur. If it is undersized, scour will likely occur (possibly causing bank erosion and/or channel incision) unless the bed and bank material are immobile at flows to which they are subjected. Either scenario may impact the profile, sediment supply, and floodplain connectivity of the project, or that of upstream and downstream reaches.
- Shaping the cross-section to provide habitat and hydraulic complexity
- Geomorphic stability (self-maintenance of channel shape over time)
- Geotechnical stability (resistance of banks to mass failure).

The size and shape of the cross-section are typically designed simultaneously, as the shape affects the ability of the channel to convey flows and sediment. Cross-section design will also be dependent upon channel slope and roughness as they, along with channel cross-section, are factors in flow conveyance (refer to the Manning's Equation discussion in the *Hydraulics* Appendix). Cross-section design is often conducted using hydraulic models (refer to *Hydraulics* Appendix); although simpler hydraulic calculations and methods may be appropriate in smaller streams, and field analogs may be appropriate in some cases.

Cross-section design using hydraulic models usually begins with relatively simplistic and angular channel templates for various channel features, including pools, riffles, and runs. Once the template channel dimensions and slope are established to convey the dominant discharge (or other selected design discharge) and to maintain sediment equilibrium, the cross-section can be modified to include a thalweg (point of maximum depth), with asymmetry across the section. Cross-section shape and thalweg position are varied along the channel to create appropriately placed habitat elements (pools, pool tailouts, riffles, chutes, or steps) for the stream type considered. This variation in cross-section generates streambed topography and forces an interaction of cross-section with planform design (i.e. meandering of the thalweg). The thalweg of a meandering channel lies near the center of the channel along relatively straight sections and moves to the outside of the channel bends where a pool typically forms—hence, the cross-section of pools and riffles is different (see Figure 1, below). A thalweg is necessary to ensure adequate water depth during low flow. Cross-section asymmetry will affect the roughness of the channel and will have to be accommodated in calculations for channel dimensions. Habitat complexity is improved if cross-sectional dimensions are specified as a range rather than a single value.

Figure 1: Channel cross-section in relation to position on longitudinal pool-riffle sequence in an alluvial stream channel. Note how thalweg (deepest point) shifts to outside of bends at pools and remains centered in riffles, and how slope is greater at riffles than at pools. During peak flows, riffle and pool water surface slopes tend to equalize, approaching the average reach slope. Hydraulic and sediment transport models typically use idealized cross-sections and average slopes, as shown.



Channels come in various shapes that are related to the channel type and boundary conditions that characterize the reach. Determination of an appropriate shape may be based on an analog, empirical, or analytical design framework. Self-sustaining channels in nature tend to exhibit consistent relationships between width and depth, cross-sectional area and watershed area, width and pool spacing or meander length, etc. (see discussion of Hydraulic Geometry and Stream Classification in the *Fluvial Geomorphology* Appendix).

5.3.2 Channel Profile and Bedform Considerations

The slope of the bed is typically varied through a reach. It is steepest through riffles or over drops, and shallow or inverse through pools (see Figure 1). The location, spacing, and shaping of these stream channel bedforms (e.g. pools, pool-tailouts, riffles, chutes, etc) is a critically important component of design, and it involves not only profile considerations, but also planform and cross-section considerations. If the stream cannot support the configuration of constructed features, significant erosion, deposition, and re-adjustment may occur, often to the detriment of habitat.

When selecting a channel slope, the designer should consider the topography, the slope of the upstream and downstream channel, and the effects of channel slope on design discharge and sediment transport. Slope helps determine stream discharge, stream power, shear stress, and sediment transport. If the slope of the modified channel reach is much greater than that of the upstream reach, incoming bed material will be too small to be retained within the modified reach and the modified channel (and upstream channel) will likely incise. If the slope of the channel is much lower than that of the upstream reach, sediment deposition is likely to occur until a stable transition slope develops. This evolution may be accompanied by rapid channel migration (avulsion) and associated bank erosion and flooding. In severe cases, formation of a depositional landform (such as a channel perched above its former floodplain) may ensue. Deposition can temporarily starve downstream reaches of sediment, inducing bed coarsening or incision.

Profile design is often conducted using hydraulic models (refer to *Hydraulics* Appendix), although simpler hydraulic calculations and methods may be appropriate in smaller streams and field analogs or empirical ranges may be appropriate in some cases. For example, where channels are being relocated, the elevation and location of the historical channel may be used to inform designs. Historical channel location may be indicated by the depth of buried alluvial material within the soil profile. It is important to acknowledge, however, that contemporary processes may not justify designs that mimic historical channel location or form.

Several considerations are included below for channel profile and bedform modification design:

- Steeper channels have greater energy and capacity to transport sediment for a given discharge and channel dimension. Conversely, flatter profiles (more sinuous channels) reduce sediment transport capacity. Proper channel profile is needed for equilibrium sediment transport processes.
- Steps, which cause abrupt drop in elevation, dissipate energy locally and thus break up the channel profile. This has the effect of 1) making less energy available overall to transport sediment through the reach, 2) creating a localized scour and associated deposition area, and 3) reducing the longitudinal extent of high-velocity zones.
- Variations of the profile through a reach, in the form of steps (drops), riffles (steep sections) and pools (deep, flat sections) promote habitat variability and hydraulic complexity.
- Raising or lowering streambed elevation will alter the frequency and extent of floodplain inundation.
- Channel profile influences the passage of fish and other aquatic organisms through the channel and into adjacent floodplain habitats.
- Modifying the elevation of the channel requires slope alteration at either the upstream or downstream end of the modified reach, or both.

5.3.3 Channel Planform Considerations

Channel planform is the shape of the stream in plan view and is described by its sinuosity, wavelength, amplitude, belt width, and radius of curvature. The primary design considerations when modifying or designing the channel planform are:

- Channel length and channel slope are directly related
- Slope may be constrained by sediment transport characteristics
- Site constraints on meander amplitude and wavelength may exist due to valley width or location of infrastructure

- Radius of curvature determines lateral migration tendencies (see below)
- Topography may complicate design options or construction timing. Relocation of the channel away from the valley topographic low point results in a perched condition, which creates instability and fish stranding problems. Designs where a new channel alignment crosses an old channel require careful construction sequencing and use of constructed plugs to prevent avulsion during peak flows.

When using an analog approach, and given an identical valley slope as the reference reach, reference reaches can be used to select both mean and extreme values for various planform parameters, thereby allowing a designer to incorporate variability in design. When using an empirical approach, planform characteristics are typically defined by their relationship to channel width or other cross-section values, and may provide a range of acceptable values for each planform characteristic. Even where an analytical approach is followed, empirical ranges for planform characteristics can be used to confirm reasonableness of designs.

When designing channels in watersheds that have altered hydrologic and sediment regimes, or where lateral constraints preclude other approaches to planform design, the most important characteristics to consider are sinuosity and radius of curvature. Often, sinuosity is already established in the design process as a function of channel slope (note that steeper channels tend to be less sinuous than low-gradient reaches). Site constraints may dictate the limit of wavelength and amplitude. However, radius of curvature (R_c) can be varied considerably in most situations and can provide valuable opportunity for variability in planform. The ratio of R_c:W (radius of curvature to channel width) has been studied extensively and found to correspond to susceptibility to erosion, both in nature and in controlled laboratory experiments. This ratio, therefore, can be used to define limits for planform characteristics. Meandering alluvial channels tend to have an R_c:W ratio of between 2 and 3.[8] Channels within this range have been shown to minimize energy losses due to flow curvature. Not surprisingly, this maximizes the energy available for erosion, and thus also corresponds to the greatest lateral migration rates and pool scour depths in otherwise stable channels.[9] Thus, while this ratio is common in equilibrium alluvial channels and mature meander bends, it may not be appropriate for design of a newly constructed channel in large or steep (high energy) streams, or where lateral stability has been compromised by impacts to riparian vegetation. In such instances, larger R_c:W ratios (3 to 4) may reduce erosion potential initially. Although empirical relationships can help define the range of potential design parameters, each site is different, which limits the utility of empirical relationships in many situations. Site specific factors, such as channel type, substrate, valley setting, equilibrium condition, vegetation conditions, and large wood dynamics, will all need to be considered in determining the appropriate planform configuration.

In some cases, sine-generated curves have been used to design planform, but these typically result in a very regular, smooth-curved layout. A sine-generated curve minimizes opportunity for variability. Furthermore, such regular and perfect planform is rare in nature except in extremely homogenous materials with uniform flows.

Design of planform requires careful consideration when the new planform crosses the old channel location. In some cases, it may be appropriate to fill the old channel, and in other cases, it may be desirable to leave at least some portions of the old channel unfilled. For instance, crossings may provide opportunities to create off channel rearing habitat for fish. Where a previous channel connects with the new channel, leaving a portion of the old channel open (upstream of the crossing) can provide low velocity off-channel habitat. However, channel plugs in the old channel may be necessary in some situations to reduce headcut and avulsion risk during high flows. It may be best to break up lengths of old channel into segments, forming a string of ponds, to reduce avulsion risk. The material used for plugs (e.g. porous alluvium versus compacted fill) will need to be considered with respect to its impact on subsurface flow and stability. It is recommended that plugs be designed by engineers with experience in design and construction of small earthen dams, and should be designed similarly to dam overflow channels. Channel plugs are usually designed to match the floodplain elevation at their crest, and may require armoring on their downstream side to prevent headcutting during overbank flow events. Creating a shallow slope on the downstream end of the plug and heavily mulching and/or vegetating it may also help to reduce headcut risk. Likewise, potential headcutting at places where floodplain water enters an old channel from the side must be carefully considered to avoid a channel avulsion.

5.3.4 Control of Streambed Elevation

Control of streambed elevation (often referred to as “grade control”) is usually unnecessary for channel modification projects that are designed to function within the existing geomorphic context of the stream and watershed. In some cases, preventing vertical erosion may actually interfere with natural sediment scour and channel adjustment processes that are important for creating and maintaining stream habitats. Nevertheless, control of streambed elevation is sometimes necessary in order to:

- Provide a grade transition from a reconstructed reach to an upstream or downstream reach to compensate for channel bed elevation discrepancies between the two
- Prevent incised areas downstream from inducing headcutting upstream through the reconstructed reach
- Prevent channel incision when the size or volume of sediment transported into the reach is too small to provide stability to the new channel (e.g. downstream of an impoundment or other sediment trap)

Methods commonly used to control streambed elevation include drop structures buried large wood or large rocks, or placement of coarse streambed material (e.g. roughened channel). Refer to the *Instream Structures* technique for additional information on this restoration strategy.

5.3.5 Bed Material Considerations

In natural systems, substrate character (size, gradation, porosity, and depth) can vary substantially through a reach and has a strong influence on channel stability, equilibrium channel processes, and aquatic habitat. Streambed stability is dependent primarily on the size, gradation, depth, and supply of the bed material. Habitat value (e.g., for salmonid spawning) is also dependent on these attributes, and is also dependent on the porosity of the bed substrate. A primary decision for channel modification projects will be whether or not bed material is placed in the channel as part of the project. In many situations, modifications can be implemented within existing substrate and alluvium, as long as channels can be designed to establish equilibrium between the streambed and the sediment in transport. However, there are some cases where artificial placement of gravels or other bed material may be appropriate, and may be necessary as part of a long-term maintenance program. These cases include the following:

- Reaches with very low sediment input from upstream. This occurs as a result of upstream sediment traps (e.g. dams and lakes) or widespread upstream channel armoring, and
- Where appropriately sized bed material is initially unavailable. This occurs in situations where stream channels are relocated and adequate bed material is not available at the new channel site but is nevertheless necessary to provide initial channel stability or spawning gravel until natural recruitment can provide a long-term supply.
- To augment spawning gravels, in particular, where natural recruitment of spawning gravels is constrained. Supplementation of gravels is discussed in detail in the *Salmonid Spawning Gravel Cleaning and Placement* technique.

These conditions will require careful analysis of existing bed substrate and sediment mobilization and transport both in the project area and in adjacent upstream and downstream reaches.

Overall, consideration of bed material and the potential need to supplement should address the following questions:

- Is there an adequate sediment supply (from upstream and within the banks) to replenish any material that is eroded from the reconstructed channel?
- Will the sediment supply from upstream provide the necessary gradation of material to provide desired habitat functions in the project reach? If not, then what does the geomorphic setting suggest is sustainable? For example, a high-energy reach with low sediment supply is expected to form a coarse surface layer, and imported gravel may not persist unless hydraulically shielded or placed in off-channel habitat. Likewise, clean gravel is not expected to persist in a gravel-to-sand transition zone.
- Is the reconstructed reach designed to ultimately accommodate channel migration? What size gradation of sediment is recruited when this happens, and is this different from what it was historically?
- Is there alluvial material in the new channel location that can provide immediate stability to the bed and banks of the new channel after construction? If not, it may be appropriate to install bed and bank toe substrate within the newly constructed channel.
-

Bed material supplementation will require a determination of the size, gradation, and volume of bed material to be added. Design of imported bed substrate materials is one of the most complex and challenging aspects of channel modification design. This is in part due to the high degree of complexity of sediment transport processes in natural systems, the difficulty in measuring and documenting these processes, and the fact that most studies resulting in equations to describe these processes are founded on limited ranges of applicable variables such as channel slope, substrate size and gradation, and other hydraulic variables. Obtaining and properly dispersing the desired sediment mixture is equally challenging. The sections below include considerations for determining bed material composition and volume. The *Design of Road Culverts for Fish Passage* guidelines[10] provides further discussion and resources for design of bed substrate gradations.

Size of substrate. The design criterion for bed mobility for channel restoration is usually related to a dominant discharge (Refer to the *Hydrology* Appendix for discussion of dominant discharge). In naturally functioning stream systems, bed substrate designs commonly use a target of the D_{84} particle size mobile during dominant discharge flows.[10] Thus, at bankfull conditions, nominally 84% of the bed substrate material would consist of a size that could mobilize, and 16% would be immobile. It should be noted, however, that the particle size and equations used for bed material design may vary significantly depending on channel characteristics including slope, channel type, and mode of sediment transport. Experience with hydraulics and sediment transport analysis, and knowledge of stream geomorphic processes, is critical for designing bed substrate for channel modification projects.

Typically, a channel bed consisting of a range of size classes will form a coarse but mobile surface layer or “pavement” after exposure to high flows. Refer to the *Sediment Transport* Appendix for a more in-depth discussion of surface (pavement) layer dynamics. Riffles will require coarser surface substrate than non-riffle portions of the channel, and should be constructed to be less mobile during most flows. How much material actually mobilizes will be a function of scour depth, bed substrate size, surface (pavement) coarsening and the particular hydraulic conditions at a given site and discharge. This allows for gravel sorting processes that are essential for maintenance of spawning gravels, certain macroinvertebrate habitat, and hyporheic flow.

Substrate gradation. Gradation refers to the range of particle sizes and their proportions in the bed material mixture. In situations where the upstream or downstream reach is used as an analog for design, the substrate gradation from various components of the analog reach can be used as the basis for design. However, in many instances appropriate analogs are not available, in which case detailed hydraulic and sediment transport analyses are necessary to determine substrate gradations.Other methods for determining substrate mobility are presented in the *Hydraulics* Appendix, the *Sediment Transport* Appendix, the *Design of Road Culverts for Fish Passage* guidance, and the *Salmonid Spawning Gravel Cleaning and Placement* technique. A well-graded mix that includes fines is critical to ensure that porosity is reduced to prevent subsurface flow during low flows. Conversely, too many fines will reduce porosity to a degree that limits incubation value of salmonid eggs within gravels. “Spawning” sized material is not appropriate in all situations and should not be forced into a design. The value of adding it may be short lived if it transports out of the new channel in the first storm. Unless it can remain naturally stable in the system, it should only be used to supplement other more stable material.

The degree to which the gradation is designed to be mobile or immobile (forming an armor layer) will depend on site-specific channel character, underlying and adjacent materials, sediment input from upstream and the degree of acceptable risk. For example, in urban watersheds that have limited or no supply of gravels in historically alluvial systems, the bed substrate may have to be immobile to prevent channel incision. Protection of the channel will have to be balanced with the need for mobile spawning gravels.

Volume of substrate. The volume of substrate required is a function of the length and width of the channel as well as the necessary depth to satisfy hydraulic requirements. Where imported bed substrate is expected to be mobile, it should be installed to a minimum depth related to the estimated depth of scour through the channel. Calculation of scour depth is discussed in the *Hydraulics* Appendix. The lower end of scour depth can be estimated by measuring pool depths in a reference reach. It is important to note, however, that scour depths that occur during high flow events are greater than those observed at lower flows. The depth of scour is dependent upon site-specific hydraulic conditions and the size of bed material and will vary through the reach. Using the maximum depth of scour for the reach is recommended for selecting a substrate depth. For loosely mixed material, it may be appropriate to increase the depth of installed material greater than what is calculated in order to account for the early transport of fine material and eventual sorting, which leads to more densely packed bed material.

5.3.6 Bank Reconstruction

A stream channel is defined at its lateral margins by its streambanks. Streambank character is a significant element of boundary conditions that determines channel dynamics and channel character. Most channel modification activities will require reconstruction of channel banks on one or both sides of the channel. Even modification projects that affect only the channel profile should consider the impacts of the activities on the channel banks. Any change in the physical character of a channel typically results in changes to the hydraulic conditions within the channel, and thereby may affect the stability of existing channel banks. The best conceived channel modifications could fail due to poorly designed or constructed streambanks.

Ultimately, some rate of streambank erosion is part of a naturally functioning system. The challenge to designers is to prevent “excessive” erosion, especially during the vulnerable period following channel modification. Elements of streambank stability and design are described more fully in the ISPG,[1] but to briefly summarize, bank stability is a function of:

- Geotechnical factors (soil strength, which is affected by bank height, bank slope and augmentation by roots)
- Surface protection (by vegetation, or by resistant soils or rock)
- Near-bank hydraulic forces (including reentry of floodplain water)

Where streambank stability is dominated by influence of vegetation, as in meadow systems, streambank reestablishment requires re-growth of healthy riparian vegetation. Sometimes, re-introduction of flow to the reconstructed channel is delayed or done in stages, allowing peak flows to be shunted away in order to protect the new vegetation as it is being established. Another alternative is to control initial erosion using biodegradable fabrics. Although a risk of fabric washout or undermining during peak flows exists, this may be preferable to the complexity of staged flow re-introduction in many projects.

Sometimes bioengineered approaches are used to accelerate recovery of vegetative stabilization. This may include design of “deformable” streambanks, which lock the channel in place only for a planned time interval. The use of fabric encapsulated soil lifts is commonly used to provide interim stability while still allowing for the growth of planted streambank vegetation. Eventually, once the fabric decomposes, the root strength of planted vegetation provides long-term bank stability. In other cases, hydraulic structures, such as large wood, are used to provide interim stability for a longer time period, which may be necessary in order to allow for mature riparian forest vegetation to reestablish. This may be part of a strategy to regenerate a mature vegetative buffer zone that ultimately serves to accommodate channel migration. In other cases, social concerns may preclude channel migration, and bank protection may therefore need to be non-deformable. When the choice to create non-deformable banks is made in such situations, it becomes crucial to state upfront the implications that this choice has on long term sustainability of habitat, and on future commitments to maintain the channel, artificially. The design and reconstruction of streambanks for channel modification often requires an equal effort in design, construction, and expense to the channel modifications themselves.

In particular, consideration should be given to:

- Deformable vs. non-deformable banks that will accommodate natural rates of lateral adjustment and channel migration
- Use of biodegradable materials in channel bank construction
- Proper planting techniques, maintenance and water availability for successful revegetation
- Risk to adjacent property and infrastructure

5.3.7 Riparian Revegetation

Riparian vegetation provides streambank stability, nutrient exchange, shade, and a source for wood recruitment. Revegetation should be an integral part of most channel modification projects, particularly where bank reconstruction is involved. Revegetation is frequently not given due consideration. The long-term stability of a channel, particularly a modified channel, may be highly dependent upon stabilizing riparian vegetation on the channel banks. Process-based restoration presupposes some width of riparian buffer, in which vegetation-dependent riparian functions are allowed to dominate. In particular, stable streambanks are not immobile, and where healthy riparian plant communities exist, natural rates of bank erosion serve useful ecological and physical functions.

The use of vegetation in reconstructed channel banks is detailed in the *Riparian Restoration and Management* technique and in the ISPG.[1] Note that irrigation, weed control, and herbivory protection is often necessary for one or more years to establish vegetation, particularly in eastern Washington projects.

5.3.8 Habitat Considerations

Most reconstructed or modified channels should incorporate habitat elements. Although proper channel design fundamentally hinges on physical and geomorphic processes, every opportunity should be taken to enhance habitat complexity. Valuable habitat is best achieved in new channels by incorporating large roughness elements, such as boulders or wood. Large wood supports fish use and production, and is a critical component of stream physical processes, including off-channel development, pool scour, hyporheic flow, gravel sorting, and floodplain connectivity.

Creation of habitat in channels is discussed at length in other techniques within this document, and any of these other techniques can be incorporated into channel modification designs. It should be noted, however, that large roughness elements and habitat features can substantially affect the hydraulics of the stream by affecting velocity, shear, and sediment transport and by increasing water surface elevations. The design process should consider the degree of habitat and roughness that is appropriate and should ensure that these elements do not affect the performance of the channel in detrimental ways.

6 PERMITTING

Permitting channel modification projects will be very site- and project-specific. Channel modification invariably involves physical disturbance of the channel, which disrupts habitat and water quality at the site and downstream at least in the short term. A comprehensive discussion of permitting requirements is included in *Typical Permits Required for Work In and Around Water* Appendix. Because most channel modification projects involve the movement, redistribution, or installation of material within the channel, permitting for these projects is typically comprehensive and the permitting process rigorous, particularly if conducted in streams containing organisms affected by the Endangered Species Act.

Many channel modification projects may qualify for a streamlined process for fish habitat enhancement. Smaller projects conducted as part of grander coordinated watershed restoration efforts may be facilitated by an expedited permit application. Both of these alternatives are part of the general Joint Aquatic Resources Permits Application (JARPA) permit process. Refer to the *Typical Permits Required for Work In and Around Water* Appendix for details about this streamlined permit process. Note that the availability of streamlined permitting processes should not be taken as an excuse to avoid full involvement of all the necessary disciplines (biology, geomorphology, hydrology, engineering, riparian ecology, etc.) in the design process, or the necessity for careful peer review.

7 CONSTRUCTION CONSIDERATIONS

Construction of channel modification projects requires careful sequencing of work phases. Construction steps may include the following (not necessarily in this order):

- Installing erosion and sediment control;
- Providing access for and stockpiling imported materials, waste materials, and transitional redistributed materials;
- Constructing a diversion channel to carry streamflow around the construction zone;
- Diverting stream flow during construction;
- Rescuing fishes from areas to be dewatered;
- Dewatering construction areas;
- Constructing the channel bed and streambanks, and installing habitat features;
- Redirecting flow into the modified channel; and
- Decommissioning diversion channels.

Further discussion of these components can be found in the *Construction* Appendix.

Construction of channel modification projects will generally require dewatering of the channel either by diverting all flow or by isolating parts of the channel during construction. Dewatering is essential to facilitate construction and to control sediment inputs to the stream. Fish and amphibian trapping and relocation may be required to remove them from the project construction area. The lower end of an existing channel might be left open and connected so there is in-stream habitat until the new channel is established with vegetation.

Construction contracting for channel modifications requires careful attention to the specialty nature of the work at hand, and is discussed in detail in the *Construction* Appendix. Most channel modification projects are very specialized projects that may require specific equipment and innovative approaches. Selection of a contractor should include consideration of previous experience in stream restoration work, as well as availability of specialized equipment.

Because channel modification and habitat work often requires the direct supervision by experienced habitat construction specialists, a contractor may be unable or unwilling to provide lump sum bids on many project elements. Contracts should, therefore, make allowance for time and materials delivery on certain project elements, such as installation of boulders or wood, creation of bedforms, or other intricate project components. This also allows for small design changes without requiring a work change order.

With channel modification, perhaps more so than with other types of restoration work, the risk to natural resources, aquatic populations and infrastructure necessitates diligent construction inspection and quality control by project designers. Unforeseen circumstances in the field are common, and require prompt, knowledgeable design and implementation decisions. Waiting until late in the project before initiating inspections for design compliance, BMP implementation or fulfillment of material specifications is not an option with channel modification projects.

Channel modification often requires complete dewatering. Consequently, the work should be timed to occur during low-water periods. Critical periods in salmonid life cycles, such as spawning or migration, should also be avoided. Additionally, critical periods for other species dependent upon the channel system, including amphibians and birds should be avoided. In-stream work windows vary among fish species and streams. Contact The Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows. Further discussion of construction timing and dewatering can also be found in the *Construction* Appendix.

8 COST ESTIMATION

Channel modification project costs are site and design specific and vary according to the size of the channel. The costs of reconstruction and relocation projects range considerably depending on the size of the channel, complexity of modification techniques and site constraints. Design costs for channel modification are commonly 10 to 20% of construction costs. Key cost items will include dewatering systems, acquisition of imported materials, location of spoils sites, heavy equipment operation and rental, construction supervision and revegetation. Dewatering may be a significant cost for many channel modification projects because it requires, in most cases, complete dewatering of the entire channel or at least half of the channel. The need to import materials for any component of the modification will greatly increase implementation costs. If an entirely new channel is being constructed, or an historical channel is being reconstructed, all of the work can be done in the dry, thus dewatering is not necessary until the water is turned out of the old channel reach and into the new one. However, high groundwater levels may sometimes necessitate dewatering even in such cases.

Many channel modification projects will require reconstruction of channel banks. Costs associated with bank reconstruction can be significant and will also need to be taken into account. Bank reconstruction may represent 50% or more of construction costs for a reconstructed channel. Refer to the ISPG[1] for further discussion of bank protection construction costs.

9 MONITORING

Project effectiveness monitoring is recommended in order to evaluate if objectives are being achieved and if adaptive management of the project is necessary. It is critical to monitor according to the objectives of the specific project. Monitoring programs that are not based on the project objectives, or that assume different or additional objectives, may fail to accurately evaluate project effectiveness. This section describes considerations for project monitoring, with the understanding that certain monitoring elements may not be appropriate and additional elements that are not presented here may be required.

The Salmon Recovery Funding Board (SRFB) Reach-Scale Effectiveness Monitoring Program[11] evaluates a subset of SRFB-funded projects in order to determine project effectiveness. Monitoring components for instream habitat projects include habitat metrics (i.e. pool area, pool depth, large wood volume) and fish metrics (i.e. salmonid rearing density). Monitoring was not conducted for any large-scale channel modification projects and results are only preliminary. The report recommends monitoring of more projects for additional years. Recommendations for monitoring elements in the report include incorporating additional metrics (i.e. velocity), focusing on structure-specific effects, and increasing the sample size.

Monitoring of channel modification projects should be initiated prior to construction, with baseline-conditions surveys of the physical channel, its banks, and its habitat value. This will allow comparison of modified conditions to pre-project conditions. Additionally, monitoring should include detailed as-built surveying and photo documentation of the project area and upstream and downstream reaches to allow for evaluation of performance relative to design. Refer to the *Monitoring* Appendix for further discussion of monitoring considerations and practices.

Monitoring is a topic that often receives insufficient emphasis in watershed restoration. As the restoration field evolves, careful, well-planned monitoring is the only way that practitioners will learn what works, what does not work, and what are the benefits and impacts of particular procedures. Although a diversity of professional opinion may always exist, reported monitoring results (preferably quantitative) from actual projects will help inform the scientific facets of these opinions. To be of value, monitoring should be designed to directly measure project outcomes relative to stated project objectives, and should occur on time and spatial scales that reflect specific objectives and are appropriate to riverine evolutionary processes. Tracking projects for only a few years will ultimately not settle questions about long-term benefits, recovery from disturbance, or process sustainability. Finally, the importance of reporting project monitoring results, both negative and positive, so that others may benefit from the experience, cannot be overstated.

Channel modifications are presumably conducted to restore both reach-scale physical process and habitat objectives. Therefore, monitoring of channel modification projects will typically include monitoring of geomorphic parameters as well as habitat parameters.

9.1 Geomorphic monitoring

Geomorphic monitoring should include the following, at a minimum:

- As-built construction drawings
- Survey of planform, cross-sections, thalweg and bank profiles, with permanent benchmarks
- Bed substrate sampling
- Vegetation survey for type, abundance, and distribution
- Large wood survey (if appropriate)
- Monumented photo points

Aerial photos are an excellent way to monitor large restoration projects. Changes in planform, vegetation, channel complexity, and the spatial extent of sediment deposits can be easily identified. A good review of geomorphic monitoring planning and implementation is provided in Montgomery and MacDonald (2002).[12]

9.2 Habitat/Fish/Wildlife monitoring

Fish and wildlife populations are determined by numerous biological and abiotic factors besides physical habitat.[13] An increase or decrease in fish and wildlife populations following a stream channel restoration project therefore may be completely unrelated to geomorphic changes brought about through restoration. This is especially true of anadromous fish populations, which may be controlled in part by fishing pressure, passage barriers, rearing habitat, or ocean conditions.[14] Fish populations may be subject to natural fluctuations, and an increase in a fish population may lag years behind improvements in habitat as the aquatic invertebrates and terrestrial food sources develop in response to improvements in bank and channel structure.[13] However, habitat and fish monitoring may include the following:

- Snorkel surveys of fish population and use of habitat
- Habitat assessments for fish and wildlife
- Spawning surveys and redd counts
- Juvenile screw traps
- Migratory box traps
- Macroinvertebrate surveys
- Riparian vegetation surveys
- Bird surveys (point counts, nest counts, etc.)

10 MAINTENANCE

Operations and maintenance requirements will be determined largely by project objectives and by regulatory agency requirements. These requirements should be carefully integrated with a monitoring plan, such that monitoring results will determine the need for various operations and maintenance. In theory, channel modification projects should not require any maintenance, as the objectives should be to create self-sustaining channel systems. An exception to this would be projects designed with rigid banks in settings that would otherwise allow for natural channel migration.

Various project elements associated with channel modification projects, such as bank reconstruction and habitat features, may require periodic inspection and maintenance or repair. For example, a reconstructed channel may rely on vegetation to stabilize soils on the streambanks and irrigation may be necessary to establish plants rapidly. Modified channels may be especially vulnerable to damage during the first years of operation, particularly if they are subjected to high flows before vegetative components are able to provide support. However, the design must allow some deformity to occur in order to create and sustain adequate fish habitat. For this reason, moderate erosion along banks should be expected, and some degree of maintenance and repair should be anticipated especially during the first three years of the new project.

11 CASE STUDIES

Numerous channel modification projects have been completed in Washington State. Information on projects funded through the SRFB can be found at the SRFB Habitat Work Schedule website (http://hws.ekosystem.us). Case studies of two channel modification projects in Washington State are presented below.

Salmon Creek Restoration Project

The Salmon Creek Restoration Project, in Jefferson County, WA, was conducted by the Jefferson County Conservation District (JCCD) and other partners to accomplish the following objectives: 1) restore an approximately 0.5 mile reach of Salmon Creek (from river mile 0.25 to river mile 0.75) to a self-sustaining configuration to prevent the need for periodic dredging, and 2) enhance fish habitat throughout the reach, with a particular focus on endangered summer chum salmon.

Salmon Creek is a tributary of Discovery Bay. The reach is an important spawning ground for endangered summer chum salmon. It also provides spawning and rearing habitat for non-listed runs of winter steelhead, coho salmon, sea-run and resident cutthroat trout, sculpin, lamprey, and other fish species. The lower reach of Salmon Creek was channelized for agriculture in the late 1880s/early 1900s and the adjacent property was used as pasture for cattle. Stream habitat throughout the site was degraded. Levees isolated the stream from its floodplain. Riparian vegetation along the channel was sparse. In addition, the channelized reach was subject to sediment aggradation, high water temperatures, lack of channel complexity and in-stream cover, and excessive levels of fines in the gravel.

Sediment aggradation occurred as a result of several factors. The site is located in a natural deposition zone downstream of a grade break as the stream transitions from hillslope to valley bottom. There is also elevated supply due to extensive upstream timber harvest. Annual pulses of sediment were also contributed from a large landslide associated with an upstream tributary which was rerouted in the past and fell over an approximately 25-foot high bluff (stabilized in 2000 prior to the Salmon Creek restoration project). Aggradation was also related to stream relocation that created a condition where the channel was perched above the surrounding ground. Relatively frequent high flow events would overtop the right bank levee and leave the channel.

The competence of the remaining flow to carry sediment substantially decreased, and the sediment dropped out. Lastly, a fish weir was located at approximately river mile 0.3. The fish weir severely constricted the channel and backwatered the upstream reach, encouraging upstream sediment deposition. The reach was maintained in its impaired configuration by levees and periodic dredging.

The project entailed constructing an approximately 3,500 foot long channel with a more natural configuration. Figure 2 shows the existing channel and the channel modification design in plan view. The designed channel lies closer to the topographic low point in the valley, and achieves better connection with its floodplain. The new channel crosses the old channel once. A floodplain had to be excavated along the upper 300 feet of new channel where it transitions into the existing channel to avoid creating incised conditions. Only the main channel was excavated in the rest of the project site. Figure 3 is a detailed plan and profile view of a typical mid-reach segment, including cross-section designs and large wood structures. Figure 4 shows one of these structures under construction. Finally, Figure 5 is an aerial view of the project under construction. The new channel was excavated and wood and streambed materials were added in the summer of 2003. The project then sat for a year to allow bank and riparian vegetation to somewhat establish and stabilize the soil. Water was diverted into the new channel in June 2004.

Since completion of construction in 2003, and diversion of water into the new channel in 2004, several physical and biological parameters have been measured repeatedly in the new channel section of Salmon Creek by the JCCD and its partners. These parameters include channel cross-section measurements, intragravel dissolved oxygen sampling, macroinvertebrate sampling, summer chum return sampling, and site photography. Repeat cross-section measurements from July of 2004 to August of 2008 show a channel whose thalweg has migrated laterally at a rate of about 1 ft per year and deepened toward the outside of a bend (Figure 6). The pool scour at this location suggests that the problem of persistent aggradation in the former channel has been corrected during the monitoring period, and that pool habitat is being naturally created. Both dissolved oxygen and macroinvertebrate monitoring suggest that these parameters started lower than control reach levels immediately following restoration, steadily increased over time, and in 2008 had achieved levels consistent with the control reach (Figures 7 and 8). Summer Chum returns to Salmon Creek following restoration and a supplementation program have met or exceeded the 8-year mean recovery goal between 2004 and 2010 (Figure 9). Photographs at several locations on the new channel show stable banks with maturing riparian vegetation, intact log jams, and maturing conifers on the floodplain (Figure 10).

Figure 2: Channel modification example: Salmon Creek, Jefferson County, Washington. Plan view, showing reach delineation, locations of pools, and large wood complexes.

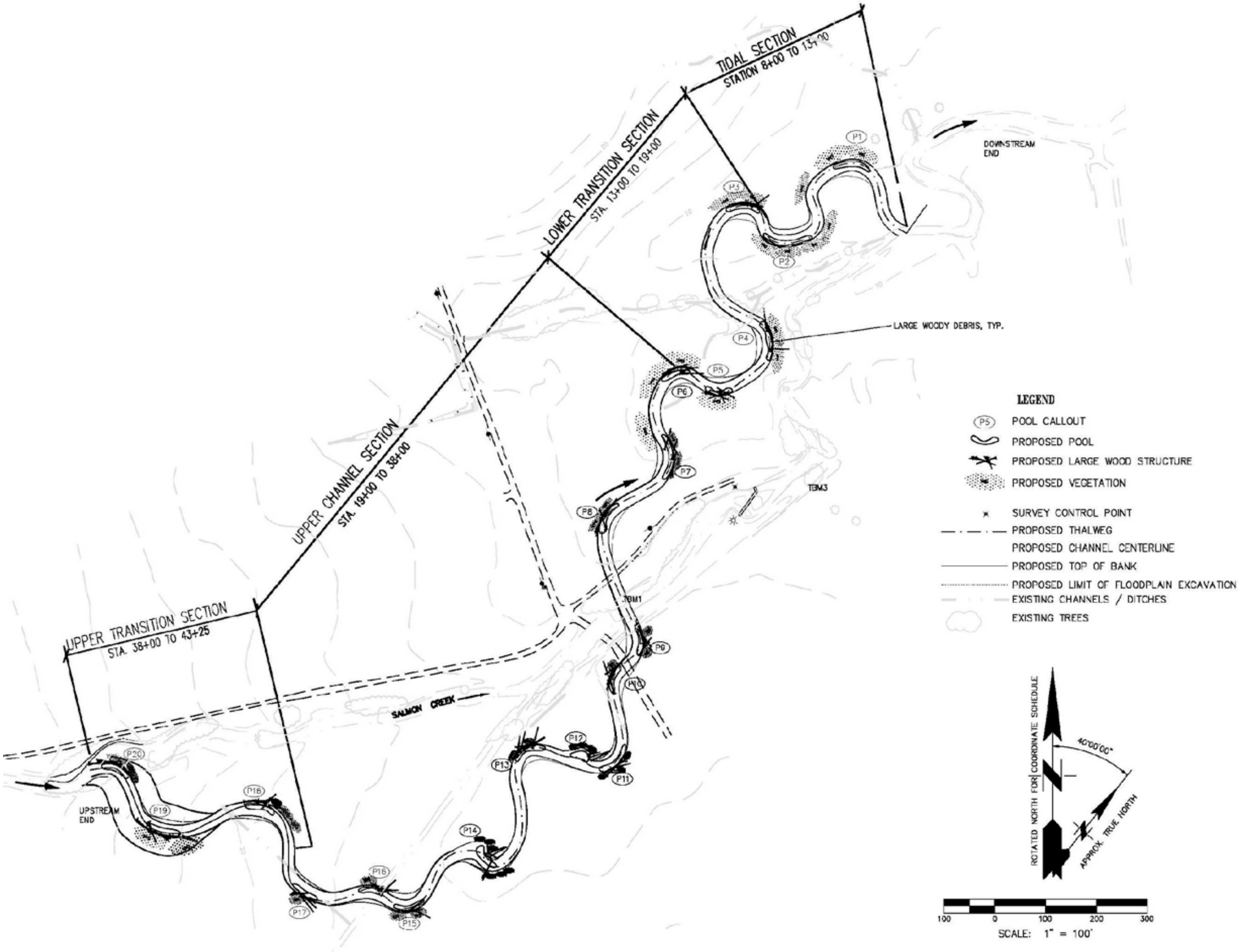


Figure 3: Channel modification example: Salmon Creek, Jefferson County, Washington. Plan view and longitudinal profile of transition section at upstream end of project. Connection with existing channel required a short section of constructed floodplain.

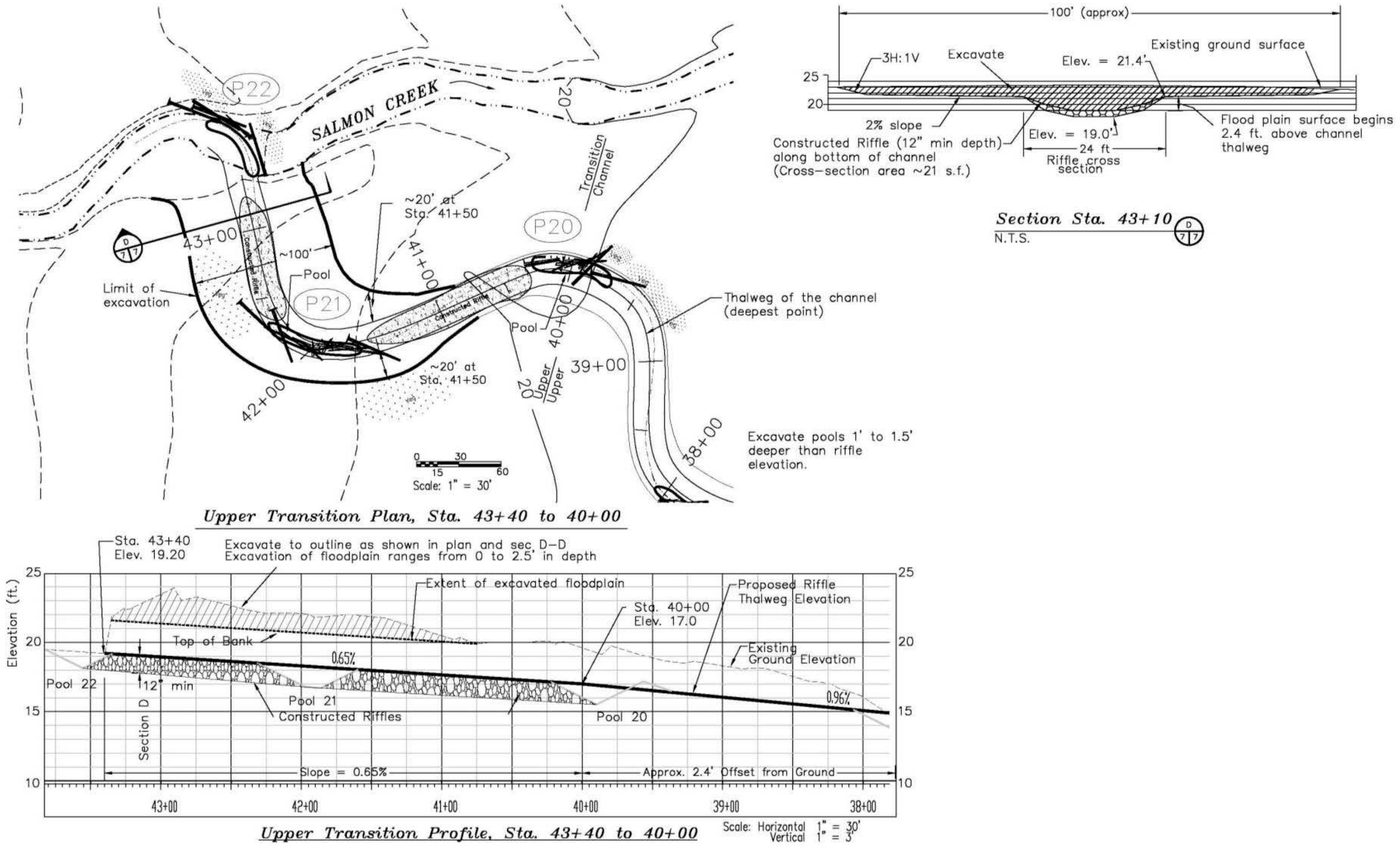


Figure 4. Construction of a large wood complex.

Figure 5. Aerial view of Salmon Creek project under construction. Photo provided courtesy of the Jefferson County Conservation District.

Figure 6. Repeat cross-section surveys in the re-constructed channel of Salmon Creek (From JCCD).

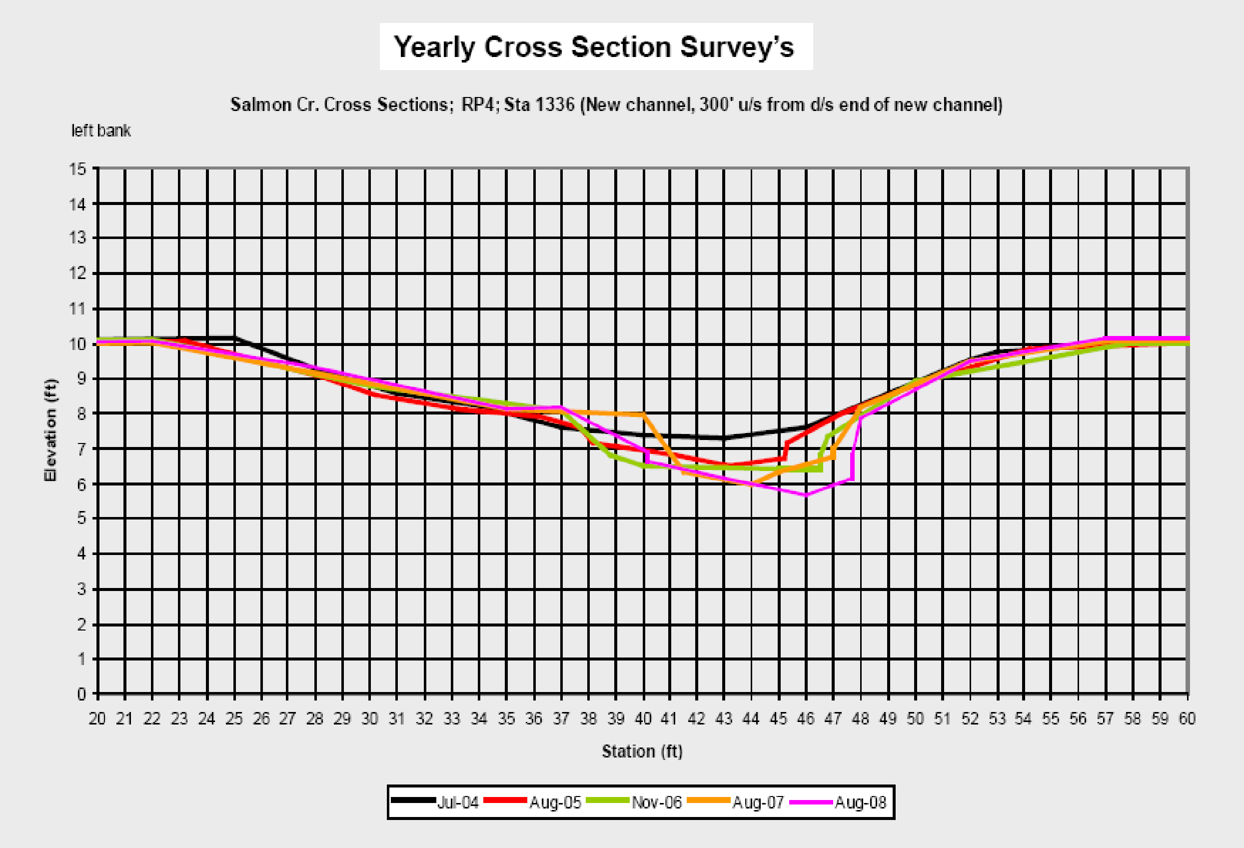


Figure 7. Intragravel dissolved oxygen levels in Salmon Creek before and after project completion (From JCCD).

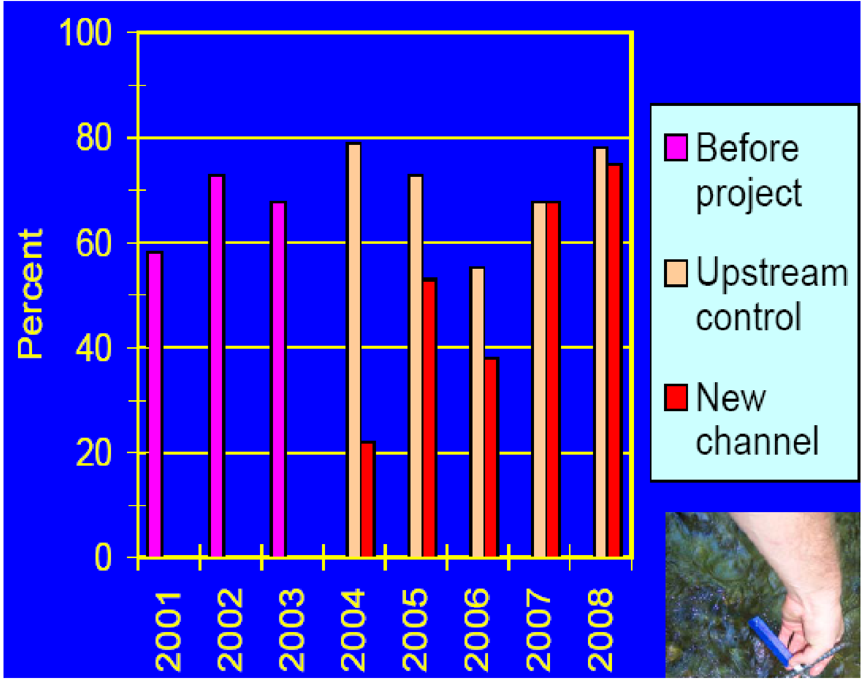


Figure 8. Results of Macroinvertibrate sampling in Salmon Creek before and after project completion (From JCCD)..

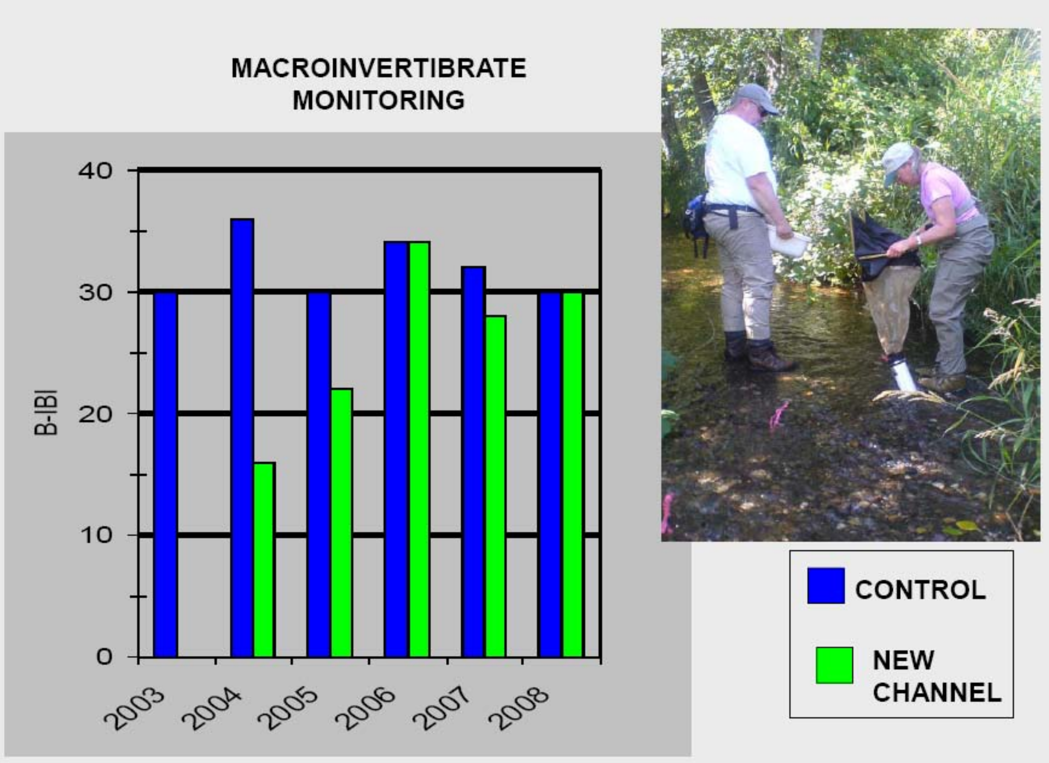


Figure 9. Results of return chum counts in Salmon Creek before and after restoration, and in Snow Creek, an adjacent watershed. Figure courtesy of the Jefferson County Conservation District.

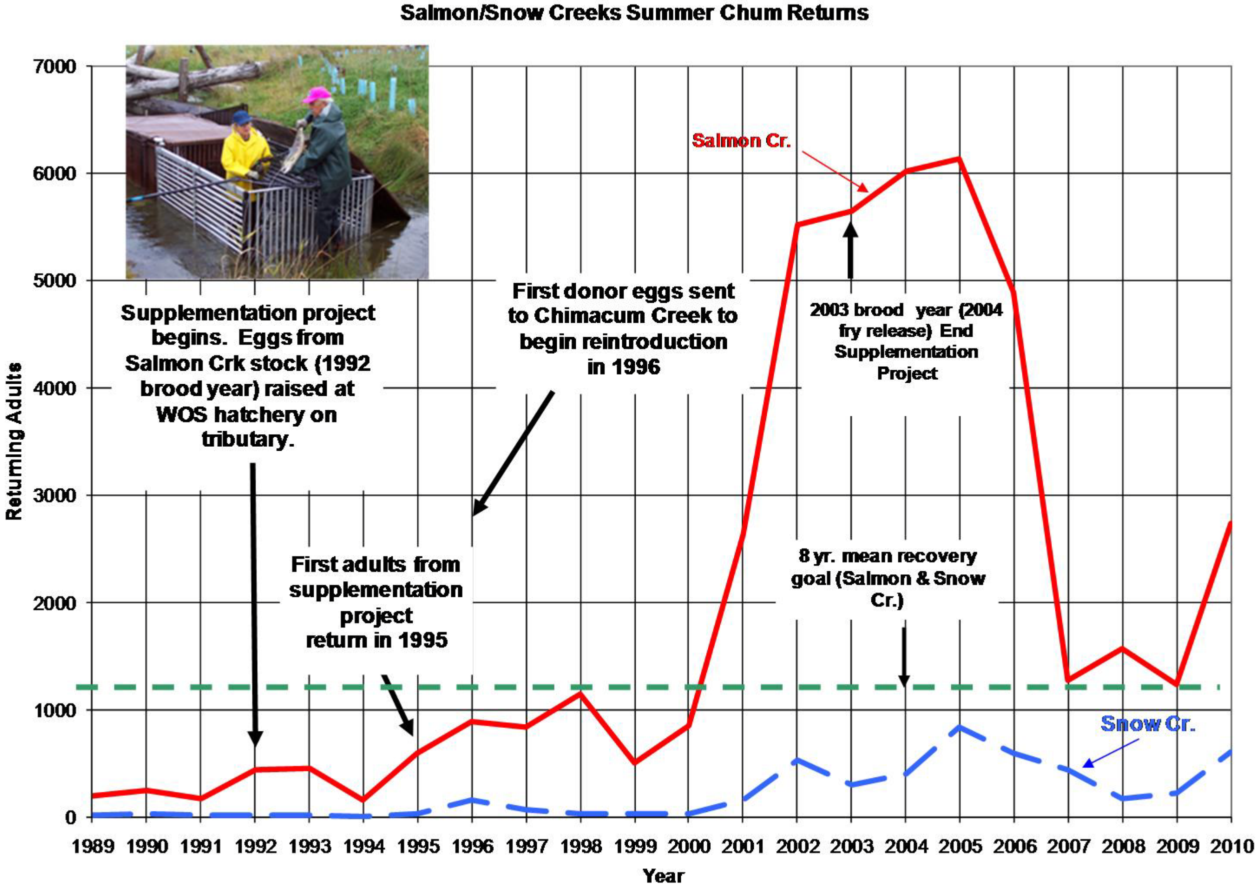


Figure 10. Photographs taken at several locations along Salmon Creek 6 years after construction was completed (From JCCD).

Hemlock Dam Removal and Stream Channel Reconstruction

Following the removal of Hemlock Dam on Trout Creek, WA, a new channel was constructed through the former reservoir. Reservoir sediments were removed and the new channel was constructed to best fit the assumed historical channel alignment, for which data were limited. The project was completed in the summer 2009.

Hemlock Dam was originally constructed in 1935-1936 to provide hydroelectric power to the USFS Wind River Ranger District and other facilities, and was later modified to provide irrigation water to the Wind River Nursery. The nursery was closed in 1997 and the dam no longer provided irrigation water or hydroelectric power. The 26-foot high dam and associated reservoir affected adult and juvenile passage of ESA-listed summer run steelhead. The dam and reservoir also interrupted sediment transport, altered natural channel dynamics, and contributed to elevated summer stream temperatures. This project included dam removal and approximately 2,000 feet of channel reconstruction within the former reservoir area (see Figure 11).

The design channel dimensions were obtained using information from adjacent reaches, from existing empirical information, and from hydraulic modeling. The frequency and type of habitat units were obtained from habitat surveys conducted in nearby reaches of Trout Creek, with adjustments based on project reach gradient and planform. Limited historical records and geomorphic features were used to develop planform geometry and design gradient. The channel was constructed using large woody debris and boulders integrated into the banks (see Figure 12). Log jams were constructed in locations where natural wood accumulations would occur and where jams could maintain pool scour and provide complex habitat cover. Floodplain wood was placed throughout the floodplain in conjunction with extensive replanting in order to provide stability and hydraulic roughness to the newly exposed surfaces. No cabling or artificial means of anchoring was used for the placed woody debris. Wood was ballasted through interlocking jam construction, integration of boulders and alluvium into jams, and integration of buried pilings and horizontal logs.

Figure 11. Hemlock Dam and reservoir before removal of dam and construction of new channel (left photo); stream channel reconstruction design (middle); and following construction (right photo) (Inter-Fluve, Inc.).

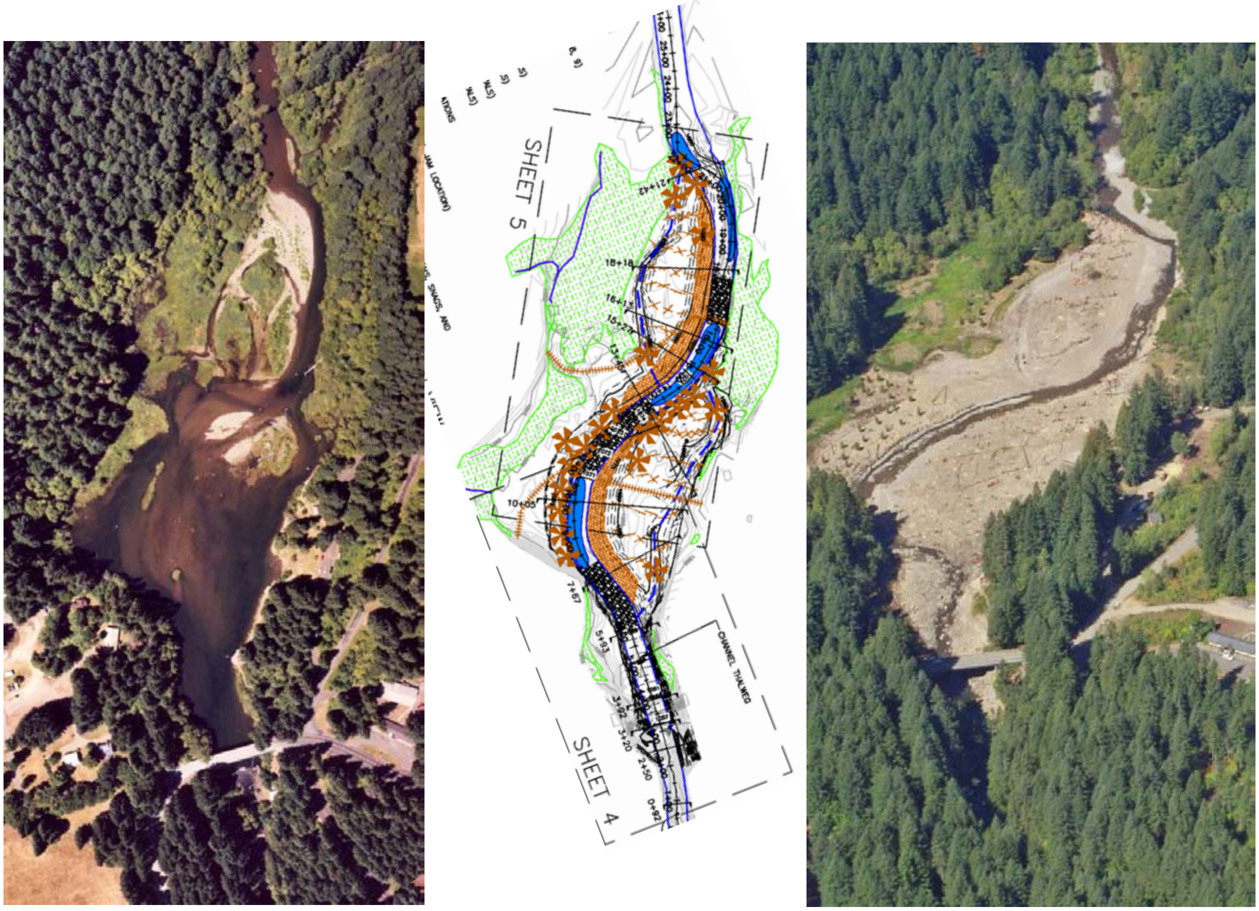


Figure 12. Reconstructed channel segments in the former reservoir of Hemlock Dam; Trout Creek, WA (Inter-Fluve, Inc.).

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TECHNIQUE 5

RIPARIAN VEGETATION AND MANAGEMENT

Riparian Restoration and Management

1 DESCRIPTION OF TECHNIQUE

Riparian zones are defined as the land adjacent to streams, rivers, ponds, lakes, and those wetlands whose soils and vegetation are influenced by ponded or channelized water.[1] They are the transition areas between aquatic and upland habitats with elements of both ecosystems. Riparian zones include both the active floodplain and the adjacent plant communities that directly influence the stream system by providing shade, fine or large woody material, nutrients, organic and inorganic debris, terrestrial insects, and habitat for riparian-associated wildlife. As such, riparian zones provide a rich and vital resource for fish and wildlife. Approximately 85% of terrestrial vertebrate species in Washington use riparian habitat for all or part of their life cycle.[2] Since the arrival of immigrants in the early 1800s, 50% to 90% of riparian habitat in Washington has been either lost or extensively modified[1]. This technique describes methods and factors that influence the restoration and recovery of native riparian plant communities.

Urban development, agriculture, livestock grazing, logging, mining, recreation, and weed invasion impact riparian plant communities by removing or altering vegetation, modifying soil conditions, and disrupting natural disturbance cycles (e.g., fire, floods). The health and composition of the riparian zone is also impacted by channel incision and diverting or impounding water for irrigation, hydroelectric power generation, domestic and industrial water consumption, and similar uses that alter the depth of the water table and patterns of floodplain inundation. Techniques to restore riparian zones and reestablish native plant communities may be passive or active. Passive restoration involves halting those activities that degrade the riparian ecosystem (e.g., fencing livestock from the area) in order to foster its natural recovery.[3] Active restoration involves direct manipulation of the landscape, such as grading and planting, in order to accelerate its recovery. Where altered stream flow regimes or channel changes have isolated the stream from its floodplain or created unstable channel conditions, successful restoration of bank and floodplain vegetation may require channel modification, levee modification or removal, water management modification, or land use changes (refer to the *Channel Modifications* and *Floodplain and Channel Migration Zone Restoration* techiques and Chapter 4.7 *Flow Regime*). Regardless of the specific technique employed, restoration efforts are likely to fail unless the cause of riparian degradation is identified and addressed. Due to the relatively long growth and establishment periods for many plant species, both active and passive approaches to riparian restoration require years or decades for benefits to be fully realized.

Large-scale riparian restoration projects may require acquiring and procuring large amounts of plant materials. It may be necessary to order large quantities of plants early in the summer for fall planting. Local genetic stock of native plants will be best suited to site conditions.[4] Some of the required plant materials may be cut from adjacent healthy donor sites near the project area, or salvaged from construction sites. In either case, source material should be carefully researched to ensure it was legally collected, donor sites were not adversely affected, and material is disease-free and adapted to local site conditions. More information on the potential impacts of this technique is provided in the *Risk and Uncertainty* section. Plant materials can also be obtained from nursery suppliers.

Riparian restoration is most effective when riparian areas can be protected from deleterious land use activities for the long term through land purchase, formal conservation easements, or similar agreements (see *Dedicating Land and Water* technique). Other complementary techniques to consider when restoring riparian zones include removal of floodplain fill, levee removal and modification (see *Floodplain and Channel Migration Zone Restoration* technique), filling in or disabling drainage ditches, and reconnecting, restoring, or creating side channels and other floodplain features (see *Side Channel and Off-channel Habitat* technique).

2 PHYSICAL AND BIOLOGICAL EFFECTS

Riparian/floodplain habitats may consist of side channels, off-channel ponds and wetlands, perennial or intermittent streams and springs, and periodically flooded grasslands and forests.[5] These habitats offer feeding, reproduction, and refuge habitat for invertebrates, fish, amphibians, reptiles, birds, and mammals. In addition, these habitats significantly influence instream habitat. Depending on the type, extent, and density of vegetation, riparian areas may provide the following critical functions to streams:

- Provide shade, which helps to moderate stream temperature, providing relatively cool water in summer and warm water in winter. Stream temperature, in turn, influences the dissolved oxygen content of the water. Shade also reduces evaporation.
- Improve water quality. Riparian vegetation retains sediment and pollutants from overland flow and during flood events, and increases the uptake, storage and release of nutrients into and out of the aquatic environment.
- Retain water during storm events and release it slowly over time, providing longer-term base flow contributions.
- Stabilize stream banks and control erosion and sedimentation.
- Provide a source of large and small wood, which can act as sediment storage areas, provide cover and refuge habitat for fish and other aquatic organisms, and create or improve the quality of pools, riffles, backwater, and off-channel habitat.
- Provide near-bank cover.
- Provide roughness to the stream.
- Provide leaves, twigs, and insects which are important food, nutrient, and refuge sources for fish and other aquatic life.
- Provide leaf litter to streams and rivers to feed “shredder invertebrates” which provide prey base for fish populations.
- Block farm chemical residues from seeping into surface waters.
- Create diverse habitat with summer and winter thermal cover for long term native wildlife population survival.

Riparian areas that are accessible to floodwater help reduce the depth of instream flow during high-flow events, thereby lowering the sediment carrying capacity of the stream (and, in turn, bed and bank erosion) and encourage the capture of floating wood. Vegetated floodplains reduce flood flow velocities so as to limit scour and encourage sediment deposition on the floodplain. Riparian vegetation can also cause the loss of water through transpiration, especially in the summer.

Although some benefits of riparian zone restoration are seasonal in nature, they may be crucial to the survival of species dependant on that habitat during critical periods. See Knutson and Naef[2] and Kauffman et al.[6] for more information on the fish and wildlife benefits associated with riparian zones.

3 APPLICATION OF TECHNIQUE

Riparian restoration may be used as a stand-alone technique or in conjunction with other stream restoration and enhancement efforts. However, it can only be applied where short- and long-term land use, management activities, and site conditions are compatible with establishing and growing the desired riparian vegetation. Riparian restoration and management may be undertaken on sites ranging from narrow stream fringes characterized by sharp transitions to upland habitat to wide riparian corridors with gradual transitions to adjacent uplands. Riparian restoration can be implemented on small sites with limited budgets. However, the benefits to fish, wildlife, water quality, and the physical condition of the stream are much greater when applied on long continuous lengths of stream and across entire floodplain widths, as opposed to applying it on isolated patches. However, even when planted in narrow or small patches, riparian habitat will provide cover and forage for wildlife, provide shade and nesting sites during summer months and provide a source for expanding riparian plant species into the future. Restoring many small patches may eventually result in long continuous lengths restored.

Using passive land or water management changes to improve riparian condition will be most successful where land uses have degraded but not entirely eliminated desired vegetation and soil structure. Sites affected by severe land uses such that they are characterized by sparse or weedy vegetation and disturbed soils may require active restoration including weed control, site preparation, supplemental planting, plant maintenance, or silvicultural treatments. If the stream channel is unstable (e.g. it is actively aggrading, incising, or segments are in hydrologic transition due to recent land use changes), the cause of the instability should be addressed before active riparian restoration. Otherwise, new plantings will likely be lost to bank erosion or water table changes. However, passive approaches to riparian restoration may still be appropriate. A strategically placed fence can sometimes fix several land use issues by allowing natural regeneration of already established native riparian species along a shoreline.

Since a well-established riparian corridor can buffer a stream from adjacent land uses and promote channel stability, a riparian corridor should be incorporated into all stream restoration work. This includes constructing or modifying channels (see *Channel Modifications* technique); installing or removing bank protection (see *Bank Protection Installation, Modification, and Removal* technique); reconnecting, restoring, or creating side channels and other floodplain habitats (see *Side Channel and Off Channel Habitat* technique); and adding large wood to the stream or floodplain (see *Large Wood and Log Jams* technique).

4 RISK AND UNCERTAINTY

4.1 Risk to Habitat

Riparian restoration presents limited risk to existing habitat because restoration is generally implemented where there is little or no natural habitat value. Riparian areas are by definition prone to disturbance from floods, so they have dynamic vegetation and are populated to some degree by disturbance-adapted plants. However, in some instances, potential risks to existing habitat include:

- Disturbing existing habitat during weed control due to herbicide drift or large scale removal of existing vegetation in preparation to planting
- Disturbing adjacent habitat to gain access to project areas
- Loss of existing habitat where plant material is harvested for transplant
- Introducing disease or pests by plants that are imported to the site

Where possible, consider and avoid these and other risks to habitat through careful planning. Efforts to restore or replace damaged habitats should be implemented where such disturbances are unavoidable or could potentially occur during the course of project implementation.

4.2 Risk to Infrastructure and Property

When undertaken on a large scale, riparian restoration and management may pose an increased risk of flooding or damage to infrastructure and other property located in the floodplain. Such risk can occur when the restored vegetation increases the hydraulic roughness of the streambank and floodplain, thereby raising floodwater elevations and possibly increasing channel sinuosity[3]. While riparian restoration is generally beneficial, it is important to understand, acknowledge, and minimize the potential risks. Educate all landowners adjacent to large riparian restoration projects to help alleviate concerns. Take the important opportunity to explain how a floodplain works and the role of riparian zones in stabilizing shorelines during flood events.

4.3 Risk to Public Safety

Because large riparian planting projects that restore woody vegetation across the floodplain can increase the risk of flooding, public safety may be at risk. Logs and branches will recruit into a river or stream as a result of restoration work; again, educate the landowner and public. This risk may be minor if the affected area is used only seasonally or occasionally, such as a park, or it may be substantial if any infrastructure is affected.

4.4 Uncertainty of Technique

Riparian vegetation can rapidly reestablish under proper land use and site conditions. However, failure to identify the numerous biological and physical site factors that affect riparian plant communities can hamper the success of recovery efforts. Biological factors that limit establishment or recovery of native plants include weed invasion; small and large mammal browsing; beaver harvest; trampling or rubbing by livestock, deer or elk; plant disease or pest infestations; and plant competition. Physical factors that can limit plant growth include drought; low water table; excessive or unanticipated inundation regimes; sediment and related flood flow deposition; scour and erosion; and overly compacted, saline, shallow, or disturbed soils. Vandalism, mowing, off-trail motorized biking and unmanaged camping may also be a problem in some areas. Only some of these physical and biological factors can be controlled. Careful analysis of the project site is recommended to understand issues that could hamper restoration success.

A risk also exists that the desired plant community will not recover and mature to the desired state and provide the anticipated benefits within the desired time frame. Even under optimal conditions, native vegetation can take years to establish and may take decades to mature or cycle through the several successional stages that will ultimately provide all of the desired benefits. Using supplemental techniques that provide certain benefits within a shorter time frame can reduce this risk. For example, if riparian restoration is undertaken to provide a long-term source of wood to the stream and floodplain, then placing large wood directly in the stream or floodplain will provide immediate, short-term benefits while riparian vegetation matures.

5 METHODS AND DESIGN

Passive riparian restoration may include halting or modifying land use and water management practices that degrade the riparian plant community or prevent it from recovering. Active restoration measures may range from supplemental planting to extensive site preparation and short- and long-term maintenance. Major preparatory work such as channel modification, levee modification or removal, and restoration of stream hydrology may also be required to restore conditions that make recovery possible. This work may be needed to address channel stability, floodplain connectivity, or water availability (e.g. water table too low or too variable to support the establishment and growth of riparian vegetation).

Riparian restoration requires a thorough understanding of the role that natural disturbance plays in affecting plant colonization and succession patterns such that diverse and productive riparian ecosystems are maintained. In addition, one must consider site-specific conditions such as soil type and exposure to drought, floods, sediment deposition, wind, and sun.

Planning and carrying out a restoration activity must include the activities listed below. Notice that planting, which many people think of as the culmination of a project, is actually in the middle. Many projects fail due to lack of proper follow-up after planting, as well as a lack of careful planning and design. Even on a very small project, each of these steps must be considered to ensure no important piece of the puzzle is missed

- Planning
- Site assessment
- Design
- Site preparation, including weed control
- Planting
- Establishment/maintenance
- Monitoring
- Adaptive management

5.1 Data Collection and Assessment

Successful planting requires sufficient planning, site evaluation, monitoring, and maintenance to ensure that long-term goals are met. The list of steps below is the recommended sequence for most riparian revegetation plans. Each step in the sequence is discussed in more detail in this technique. If any step is left out or not completed due to budget constraints, the success of the project may be compromised.

- Conduct a site evaluation
- Identify site constraints
- Identify needed changes in land management
- Develop design criteria
- Select plant species
- Select plant material types
- Determine planting density and layout
- Schedule timing of plantings
- Consider site preparation requirements
- Determine planting techniques using current horticultural best practices
- Define procedures to monitor and maintain project

5.1.1 Site Evaluation

Riparian areas are often characterized by diverse site conditions caused by flowing water that sorts sediments and creates floodplain soils that are stratified both vertically and horizontally. Varied floodplain topography creates a gradient of depth and duration of flooding. Every plant has an optimal position along this hydraulic gradient. The hydraulic gradient and hyporheic flow, coupled with variations in soil structure, vegetation, and topography create a complex and dynamic network of habitats throughout the floodplain.[7] Thus, site evaluations are essential to ensure plants are matched to the existing site conditions at the time of planting.

The person conducting the site evaluation should examine the project area and a vegetative community reference site, preferably in the same or a nearby watershed with similar site conditions, similar flood history and hydrology. At a minimum, the following information should be collected:

- *Plant Distribution/Colonization* – Note the distribution of dominant woody and herbaceous species (including weeds) relative to river stage, hydrology and shade, and which plants are colonizing freshly deposited soils. Find good sources for local cutting collection and/or plant harvest or salvage. Often this must be done at a reference area because the restoration site does not have any plants or it has introduced or invasive plants.
- *Shade* – Observe and note how canopy cover will affect light availability for new plants.
- *Lower Limit of Perennial Vegetation* – Determine the lowest bank elevation that will support perennial vegetation. This is most accurately determined on gradually sloping banks, where an easily observed continuum exists, ranging from the unvegetated channel to annual plants to perennial plants. If possible, note how this elevation relates to river discharge. See Riparian/Wetland Project Information Series No. 16, March 2001 (Revised), *Riparian Planting Zones in the Intermountain West*, at http://www.plant-materials.nrcs.usda.gov/pubs/idpmcarwproj16.pdf

- *Depth to Groundwater* – Ideally, this is determined using test pits or monitoring wells. In the absence of such tools, it can be estimated using the elevation of late-summer base flow, although this is not always accurate at the furthest area from the water surface.
- *Soils* – Describe existing soils on different bank and channel features such as bars and overbank-deposition areas. Note the soil texture (e.g., sandy, rocky, clayey, organic). Note whether soils are well drained (gravelly or sandy) or poorly drained (clayey or organic), how moist the soil is, and whether it is friable or highly compacted by livestock or heavy-equipment operation. Look for cut banks that identify soil profile by depth. Note whether shallow soils or till are present. Additional information such as soil pH, salinity and nutrient status can be helpful but is not often collected. This information can be determined by sending a sample to a soil lab.
- *Human/Wildlife Use of the Site* – Note whether there is existing or a potential for human and animal foot traffic, recreational river use, grazing, deer and elk browsing, beaver activity, or other potential impacts to vegetation and soil.
- *Hydrology* – Check to see if portions of the site periodically flood. If so, attempt to determine how often and for how long. Look for physical indicators of high flow, such as sediment deposition, wood, and trash. Assess possible surface connections with side channels or depressional wetlands.
- *Geographic Characteristics* – Determine the elevation, slope and aspect of the site. Plant species harvested for revegetation projects that come from high elevations may not grow well at low elevations. Some species are more adapted to steep slope conditions and provide greater resistance to slope erosion than others. South-facing slopes are typically much drier than north-facing slopes.

5.1.2 Site Constraints

Early in the planning process, identify potential factors that may limit successful revegetation. While most site constraints are biological or physical in nature, they may also be related to project budget and management or to the scheduling of construction activities. Often, early recognition of site constraints can lead to creative solutions that may increase plant survival, simplify construction, and save money.

Below are some possible site constraints, many of which are specifically related to natural riparian processes:

- Weed and grass competition for water, nutrients, sun, and space.
- Direct sun exposure.
- Over compacted soils.
- Overly drained soils.
- Poorly drained soils.
- Deep summer water table.
- Shallow soils/bedrock.
- High amounts of sediment deposition.
- Large flood events expected soon after planting.
- Potential ice flows/damage.

- Poor native species availability.
- Soil compaction due to heavy foot traffic (human or animal).
- Nearby seed source of aggressive weeds.
- Construction sequencing conflicts.
- Livestock, deer and elk grazing/trampling/browsing.
- Heavy beaver damage.
- Tide-influenced hydrology.
- Limited site access.
- Herbicide drift from adjacent agriculture.
- Incompatible mowing and pruning activities (common at golf courses and near power lines).
- Rodent problems (common in high grass or weeds).
- Extended inundation.
- High soil salinity (common in arid areas that are irrigated).
- Dam-influenced or otherwise modified hydrology.
- Reduced riparian/stream interaction.
- Insufficient maintenance budget.

It is also crucial to consider landowner needs and zoning requirements. Some riparian treatments may be appropriate in one setting and not in another. For example, the allowable height or species of vegetation may be limited due to the proximity of utilities, safety concerns, or because the vegetation will block views.

When planning to install structures such as fences, offsite watering facilities, irrigation systems, and other features in the riparian zone, consider the potential effects of high water events and flood flows. These effects include deposition of sediments and debris as well as scour. It is best to locate these structures outside the flood prone area whenever possible. High water zones should be clearly marked on all planning maps.

5.2 Changes in Land Use or Water Management

It may be necessary to change land use or water management to foster natural recovery of riparian vegetation or to complement revegetation efforts. Incompatible land use activities may include livestock grazing, timber harvest, mining, agriculture, mowing, road building, earth moving, filling, construction of buildings or other facilities, recreation, or any activity in the watershed that modifies the natural hydrology of the site. Stopping or modifying these activities to reduce adverse effects on riparian function may require purchasing or leasing the land (see *Dedicating Land and Water* technique), water rights, regulation of development, or a legally binding commitment by the landowner (e.g., a conservation easement). Restoring riparian habitats through changing land use and water management requires a long-term commitment to be effective. This commitment should also extend to maintenance and repair work whenever applicable.

In situations where changing land use and water management are used as a stand-alone treatment, consider the likelihood and time period for natural regeneration of desirable vegetation and the potential for weed invasion. This is particularly important if the land use change involves grazing removal. Eliminating livestock can result in weed proliferation if not adequately anticipated with an approved weed control plan in place. As described in Briggs,[8] factors that affect the natural distribution and propagation of riparian plant species include:

- Spatial and temporal variation in the seed bank.
- Variation in scour and deposition.
- Characteristics vital to species' germination and growth.
- Inundation depth, frequency, extent, and duration.

Factors influencing seed availability include the composition of the buried seed bank, proximity and abundance of desirable and undesirable species to the site, abundance and characteristics of seeds produced by the species, and dominant seed dispersal mechanisms (e.g., animals, wind, water). Sites that flood receive seed in the water, whether of desirable or undesirable species. Also, many seeds will not germinate in well-mulched soil because they require light to germinate. Consequently, a build-up of non-native weeds may prevent native seeds from sprouting and becoming established. Vegetative propagation (sprouting from stems, lateral roots, or trunk bases) is also a common form of regeneration for many riparian plant species and could be important in the recovery process.

Other factors listed above, such as scour, deposition, elevation, drainage area, geology, and flow regime affect the distribution of water-borne seeds, dispersion and the ability of seeds and plants to germinate and establish. Characteristics vital to species' germination and growth include water availability, soil condition, physical and biological constraints, and flow regime. Inundation patters are also important for riparian plants. Many plant species are adapted to and depend on flooding for propagation. Although they won't germinate in standing water because their roots need oxygen, seeds will germinate on the bare soils that follow the retreat of flood waters. Flood disturbance can revitalize riparian ecosystems by producing sites that lack competition from other plants and have high moisture availability. Such sites are ideal for establishing colonizing vegetation such as red alder, black cottonwood, and willow species.

5.3 Recommended Minimum Width of Riparian Habitat Areas

The width of the corridor to be restored or enhanced will be site specific, dictated by budget constraints, land ownerships, infrastructure, valley width, and similar variables. But whenever possible, riparian zones should be wide enough to protect and preserve fish and wildlife habitat and to connect riparian habitat to other adjacent habitats including upland forests. Table 1 lists recommended minimum widths for riparian habitat associated with streams.

Table 1. Recommended riparian habitat area widths (Source: Knutson and Naef)[2].

Stream Type	**Recommended Riparian Habitat Area Width (feet)**
Types 1 and 2 streams ("Shorelines of the State" and channels with widths greater than 20 feet)	250
Type 3 streams or other perennial or fish bearing streams that are five to 20 feet wide	200
Type 3 streams or other perennial or fish bearing streams that are less than five feet wide	150
Type 4 and 5 streams or intermittent streams with low mass wasting* potential	150
Type 4 and 5 streams or intermittent streams with high mass wasting potential	225

These widths are measured on each side of the stream, starting at the ordinary high water line. However, if the stream reach is located in a broad, alluvial valley and able to migrate across the valley, these width measurements begin at the edge of the channel migration zone (the area within which a stream has or may migrate laterally under its current geomorphic regime-it is commonly defined by historic meander limits or meander belt width[9]).

The following are important additions to the recommended Riparian Habitat Area widths.

- If the 100-year floodplain exceeds these widths, the Riparian Habitat Area width should extend to the outer edge of the 100-year floodplain.
- Larger widths may be required where priority species occur (refer to Appendices C and D of Knutson and Naef[2] for specific recommendations; see also Morrison[10]).
- Add 100 feet to the riparian habitat area's outer edge on the windward side of riparian areas where existing trees are susceptible to blowdown.
- Extend the Riparian Habitat Area widths at least to the outer edge of unstable slopes along Type 4 and 5 waters in soils of high mass wasting potential.

The widths recommended in Table 1 are intended to maintain fully functional riparian ecosystems and to provide sufficient habitat to meet the needs of fish and wildlife. Riparian habitat functions that were considered in making these recommendations include control of stream temperature, provision of large wood and other organic material to the stream system, regulation of stream flow, filtration of sediments and pollutants, erosion control, microclimate maintenance, and wildlife habitat. Other widths may be sufficient to maintain a subset of these functions.

5.4 Planting

If modifying land use or management alone is not sufficient to recover the riparian zone, the parties will need to develop and implement a planting plan. The following recommendations are based on a combination of current horticultural best practices; the limitations of installing projects with little time, money, and skilled labor; site limitations such as fish windows, floodwaters, poor access, and surrounding weed populations; and other difficulties. Many exceptions exist to these general recommendations; each site is different and no one rule fits every situation. Each project needs to be carefully planned and implemented so that the techniques used are the best ones for that particular project and site.

5.4.1 Design Criteria

Revegetation planning should generally begin with developing design criteria. Design criteria are specific guidelines that quantify desired performance attributes to meet project objectives. A general revegetation guideline or objective might be “to provide habitat” or “to provide erosion control,” whereas a design criterion might be “to provide overhanging shrub cover along 50 percent of bank within three years.” Design criteria for vegetation should specify requirements for habitat needs, size of material, species diversity and erosion control. While specific design criteria are not always necessary, developing objectives is the most important part of developing a plan. Developing clear objectives will help keep the project on track by limiting actions to those that will help meet the objectives. Refer to Chapter 5.1.3, *Design Criteria for Project Elements* for further information.

5.4.2 Plant-Species Selection

Plant species selection must be tailored to site conditions. The soil, light, and moisture requirements of individual plant species must match those occurring at the site at the time of planting. It does no good to plant for future conditions if plants will not survive until those conditions come about. For example, planting shade-dependent species on a sunny site that will one day be forested will fail. In an unpublished 2001 study[11] conducted by WDFW on 10 channelized stream restoration projects in western Washington, the most common cause of plant mortality was poor plant species selection and distribution. Other controllable causes of plant mortality observed in the study included inadequate site preparation and/or maintenance (watering and weed control), inadequate protection from animal damage, poor plant stock quality, and improper planting techniques and timing. When planting in riparian zones, it is important to accurately assess available moisture and inundation patterns (Chris Hoag, Idaho NRCS, personal communication).

To maximize benefits to native fish and wildlife species, use only native plant species. Native plants are adapted to local climates and disturbance regimes (e.g., fire, flood, landslides), compete well for survival on native soils, are adapted to local insect and disease infestations, and provide food and habitat for native wildlife. Make sure the species you are considering are local to your area, not just native to the state. Check the UW Burke Herbarium website for species distribution information: http://biology.burke.washington.edu/herbarium/imagecollection.php. The reference site provides a guide for the project area’s planting design; however, the role of succession must be taken into consideration. For instance, a nearby site with conditions similar to the project area might be dominated by a relatively mature stand of western red cedar trees and an understory of salmonberry. Planting those same plants at a denuded site with full sun and wind exposure will likely result in high plant mortality, unless the plants have access to lots of moisture. Western red cedar, western hemlock, salmonberry, Indian plum, low Oregon grape, and salal establish best in shady conditions. Colonizing species, such as Douglas fir and red alder, will be better adapted to the extreme temperature and moisture variability of bare exposed soil. Sometimes the best reference site is one that has been disturbed and is in a state of recovery.

Historic plant communities at the site are also helpful when developing planting plans. Again, consider the role of plant succession. Also, if the watershed has been significantly hydrologically modified (i.e. heavily urbanized, downstream of a reservoir, or drained), the historic plant community may no longer be able to survive. In these areas, one might have to use other native vegetation.

Table 2 (shown at the end of this technique due to the size of the table) lists native woody species one might consider using on riparian restoration projects. This list is not exhaustive, but it does provide helpful information to consider while selecting plants. Consult plant guides, local references[12,13] or colleagues for further information on specific plants. Many native plant nurseries exist in the state of Washington. As with any purchase, when choosing plant material, assess the quality of the plants: Cheaper is not necessarily better. Staff at native plant specialty nurseries may be able to help you select plants.

It is important to understand year-round water inundation patterns at the project site in order to plant species in suitable locations. In the Pacific Northwest, many herbaceous species (sedges, rushes, bulrushes, and more) are able to grow in permanently saturated soils. Woody species need oxygenated soils for at least part of the growing season, as a general rule, and so are found on streambanks, the edges of wetlands, or in areas where the water draws down for part of the growing season. The growing season starts around mid to late February on the west side of the state and early April on the east side, and extends through the end of September. The average growing season will vary by year, by site, and by species, so this is only a general estimate. Another factor is soil type. Plant roots are not usually able to grow in very dense soils, such as an unfractured hardpan layer or a thick clay lens. Do not assume your plants will have access to the water table if it lies below a layer such as this. Even if the plants' roots eventually reach the water, it will not happen quickly and your plants will not have access to that water until they are well-established.

Conifer species are often chosen for planting on riparian sites due to their ability to eventually contribute long lasting, large woody material to the stream or river. Recent research demonstrates that the presence of red alder (*Alnus rubra*) can contribute to the growth of conifers in nitrogen deficient sites in coastal Pacific Northwest forests. Also, alders contribute to the health of stream systems, improving habitat for salmon and other species.[14,15] It might be useful to interplant alders and conifers or to plant alders first and then come back and plant appropriate conifers later in the understory.

Plant species should be selected with an emphasis on the following:

- Suitability for anticipated climate, hydrology, elevation, soils and constraints of the planting site at the time of planting.
- Reasonable availability in desired quantity (either from nurseries or a local source).
- Probability of successful establishment (based on best available experience or

information).
- Desired growth form or shape and size (as specified in design criteria).
- Ability to achieve desired plant diversity (as specified in design criteria).
- Ability to provide desired fish and wildlife benefits, such as food and shelter habitat (as specified in design criteria).

Additional considerations include:

Diversity. Natural riparian plant communities have a variety of plant species and successional stages important for support of diverse fish and wildlife populations. A mix of deciduous and coniferous trees exists in naturally forested areas. Deciduous trees are more abundant in frequently or recently disturbed areas, whereas conifers are generally more abundant in vegetative communities that have more mature or advanced seral conditions. In naturally non-forested areas, the dominant vegetation may be shrubs, or grasses and forbs.[1] Planting a variety of species ensures the highest likelihood of project success. Monocultures are susceptible to total failure when exposed to disease or unfavorable site conditions. Consider planting a mix of fast- and slow-growing plants, deciduous and evergreen. The reference site can guide the selection.

Multiple canopy layers. Multiple canopy layers provide more habitat niches to support diverse wildlife populations. Mature, naturally forested areas support at least three of the following canopy layers: humus, grass/forb, short shrubs, tall shrubs, small trees, and large trees. Naturally non-forested riparian areas may support fewer layers.[2]

Genetics. Research on multiple species makes it clear that genetics does matter in long-term plant growth and reproduction, as well as short-term survival and should be taken into account in restoration planning and implementation (see *An Introduction to Restoration Genetics* at http://www.ser.org/content/genetics.asp and also *Protecting Plant Genetic Resources* at http://www.fs.fed.us/wildflowers/nativeplantmaterials/careaboutgenetics.shtml). However, obtaining information about the genetic background of the plants may not be easy. A nursery that collects their own propagules will know the genetic provenance (place where the seeds and cuttings were collected) of the plants they sell however; nurseries that buy propagules from seed collectors or other nurseries may not have that information. Further, one should not assume that local nurseries always carry local plants. It is always important to inquire about genetic provenance or seed source. Genetic seed zones (geographic areas where it is acceptable to move plant genetic material) are established by detailed research and are commonly used for conifers and a few broadleaf trees. You can find these genetic seed zones at: http://www.dnr.wa.gov/ResearchScience/Topics/ForestResearch/Pages/lm_tree_seed_zones.aspx Climate-based provisional seed zones for species without genetic data can be found at: http://www.fs.fed.us/wildflowers/nativeplantmaterials/rightmaterials.shtml. Contract growing with local genetics is an increasingly available option and may not cost more than regularly stocked plants, but will need to be ordered 18 to 24 months, or more, prior to planting.

Exposure tolerance to:

- *Sun, wind, low soil nutrients or pH extremes*. When choosing plants for a disturbed streambank or riparian zone, consider each plant's role in succession. Pioneer species such as red alder (*Alnus rubra*), black cottonwood (*Populus trichocarpa*), and willow (*Salix* spp.) are naturally tolerant of extreme, adverse conditions, such as low soil-nutrient levels, moisture stress, and full sun and wind exposure. Alternatively, some native conifers, such as western red cedar (*Thuja plicata*) and western hemlock (*Tsuga heterophylla*), form late-succession forests and establish best under shady, relatively protected conditions.[16] Planting such seedlings in direct-sun locations often fails. Success of late successional species may be substantially improved if planted after a nearby shrub or tree layer develops a canopy.
- *Grazing*. Planting species capable of stump sprouting or suckering from roots (identified in Table 2 [shown at the end of this technique due to size of the table] by a "†") will reduce long-term grazing impacts.
- *Flooding*. Certain species are better adapted than others to periodic inundation and sediment deposition. The degree of tolerance varies among species. For instance, willows can grow in frequently flooded areas (even within the active channel), whereas big leaf maple or western hemlock is most often found on flood prone surfaces above the 10-year return interval flood level.

The restored plant community may change over time as a result of disturbance, succession, and subtle variations in the topography, soil structure, and moisture regime. Some of the planted stock will likely flourish at the expense of others. Scour, deposition, and inundation will be detrimental to some species, but pave the way for colonization by others in the vicinity. It is important to analyze the causes of mortality before replanting a species that has failed on a site.

5.4.3 Plant Material Types

Plant-material types include cuttings, seed, container, and bare-root stock. They are further classified into herbaceous and woody plant categories. Base the selection of specific woody or herbaceous plant-material types on design objectives or design criteria, site conditions, and site constraints. Many projects use a combination of woody and herbaceous plant-materials.

5.4.3.1 Woody Plant Material

Woody plants, which include both shrubs and trees, are widely used in riparian restoration projects to provide bank stability, habitat and aesthetic appeal. Their roots are strong and mechanically reinforce soils by adding tensile strength.[17] Large riparian trees will eventually contribute large woody material to streams when they topple, and all woody plants provide shade and cover to streams. Undercut tree and shrub roots provide excellent fish habitat, especially the roots of mature cedar, hemlock, and spruce. Shrubs with their multiple, flexible stems dissipate stream energy and encourage sediment deposition rather than scour. Common woody plant materials are discussed below.

Live Stakes. Live stakes consist of harvested stems of certain shrub and tree species that have the ability to root very easily from cuttings. They are capable of developing both roots and shoots if planted in proper conditions. Cuttings are popular in bank-stabilization projects because they are inexpensive and easily installed. For the best chance of success, cuttings must be harvested during the dormant season and planted within days of collection. Expect up to 80 per cent mortality if the buds on the cuttings have begun to open; plant respiration initiated before root development will make the plant vulnerable to desiccation. Willow species (*Salix* spp.) are the most commonly used and successful cuttings. Other species used with success in Washington include black cottonwood (*Populus balsamifera trichocarpa*) and red-osier dogwood (*Cornus stolonifera*). Species that are less commonly used, but root well from cuttings and can be tried experimentally on your site, include salmonberry (*Rubus spectabilis*), elderberry (*Sambucus* spp.), Pacific ninebark (*Physocarpus capitatus*), mallow ninebark (*Physocarpus malvaceous*), black twinberry (*Lonicera involucrata*), Nootka rose (*Rosa nutkana*), golden current (*Ribes aureum*), wax current (*Ribes cereum*), mock orange (*Philadelphus lewisii*), spirea (*Spiraea* spp.)[7] and snowberry (*Symphoricarpos albus*).[18,19,20]

Not all of the species listed above are appropriate in live-stake applications due to their relatively small, flexible branches, but may be appropriate as components of fascines and brush layers. Whether installed as live stakes, fascines, or brush mattresses, cuttings provide excellent erosion control and bank stabilization. More detail on cuttings is provided later under *Planting Techniques*.

<u>Containers</u>. Container plants are nursery-grown plants available in different sizes and shapes of containers. They are distinguished from most other types of plant materials by well-developed soil/root mass. Because of this, planting can occur throughout much of the year if adequate water is available. Table 3 lists advantages and disadvantages of container plants:

Table 3. Advantages and disadvantages of using container plants for restoration projects.

Advantages	**Disadvantages**
Available all year.	More expensive to buy and install.
Can be installed almost year-round as long as the ground is not frozen.	Bulkier, and therefore more expensive, to transport and install, especially on sites with poor access.
Generally have higher survival than bare-root plants, unless they are root-bound.	If planted incorrectly, may not survive long-term.
Easier for inexperienced crews or volunteers to plant correctly.	
Summer installations must be irrigated and will have lower survival.	

The root systems of container plants are initially established within commercially available potting soils, which are actually soil-less media. These “soils” typically have characteristics much different than that of the planting site and root migration must be encouraged during planting into surrounding native soils. Avoid purchasing root-bound material. More detail on this is provided later in section *5.4.9. Planting Techniques*.

Conventional landscaping nurseries typically provide container plants in four-inch, one-, two-, or five-gallon containers. Some native plant nurseries offer a wider array of container sizes, some of which tend to be taller and narrower than conventional ones. The greater depth-to-width ratio of the tube provides the plant with better resistance to pullout caused by flowing water and better access to deep, moist soil than conventional nursery containers. These tall, narrow containers, however, may cause roots to grow out more than down.[21] These innovative containers include, but are not limited to, Cone-tainers™, 14-inch-deep Treepots™, PVC pipe four to six inches wide by one or more feet long, biodegradable burlap "socks," and biodegradable coir (coconut-husk fiber) containers. Better containers have ribs inside that reduce root circling.

<u>Bare-root</u>. Bare-root plants consist of rooted plants grown in a nursery field, harvested without soil, and sold packaged in bundles with their roots surrounded by damp material. Table 4 lists advantages and disadvantages of bare-root plants:

Table 4. Advantages and disadvantages of bare-root plants for restoration projects.

Advantages	Disadvantages
Less expensive to purchase and install than container plants. Because they cost less, you can afford to plant more, which might make up for higher mortality.	Short availability and planting window; generally late December to February or March.
Weigh much less; easier and less expensive to transport and store on site, especially sites with poor access.	Can have a very low survival rate if stored or planted incorrectly, which is commonplace.
Will not be rootbound (unless they started as plugs). Can see whole root system; can do corrective root pruning if needed. Roots are in direct contact with only the native soil, which encourages root migration out of the planting hole when proper planting techniques are used.	

The main limitation of bare-root plants is their narrow planting window in the dormant season. This increases the need for proper planning and may require a larger planting crew. Bare root plants must be dormant before they can be dug from the fields in which they are grown and must also be planted in a dormant condition. They cannot be planted in frozen or flooded ground and they must be planted before they break bud. Consequently, the planting window is dictated by the harvest window, site conditions, and resumption of spring growth. In western Washington, the planting window is generally December through February and in eastern Washington, it is November through March.

Bare-root plants require careful handling to prevent roots from being exposed to sun or wind for more than a few minutes. Plants should be covered and their roots kept moist at all times. Providing proper care and storage may limit the number of plants that can be delivered to a site. With proper storing, correct timing, and careful handling, survival rates can be 80 to 90%.

<u>Ball and Burlap</u>. Ball and burlap (B&B) plants are dug in the field and the rootballs with surrounding soil are wrapped in burlap and string or wire. They are generally large trees and shrubs, 6 feet or taller. The large size is beneficial in protecting them from animal browse and

over-shading by tall weeds. The disadvantages of B&B plants include extreme vulnerability to drought, poor ability to compete with weeds and higher cost. Additionally, their large size and bulk make handling difficult. They also require guy wires and staking for stability during the first several years after planting with periodic adjustments. These items must eventually be removed. In sum, B&B need a high level of care that is not practical or desirable on restoration sites. In addition, their survival rate can be poor due to large losses of their root system in the harvest process.

Salvaged. Sometimes shrubs and trees can be salvaged during the construction phase of a stream restoration project or another nearby construction project. Best success will be had with small plants moved while they are dormant. This can be done by hand or with equipment. If carefully coordinated, excavators or tree spades can cost-effectively transplant a large number of seedlings, saplings and, sometimes larger shrubs and trees. Frequently, this type of large equipment can provide an entire plug of mixed vegetation including the target shrub or tree and its associated herbaceous layer. However, using large equipment can cause unintended damage or compaction to surrounding areas that were not scheduled for clearing. Furthermore, larger material will experience more transplant shock and require more follow-up care. Salvaging is generally a cost-effective method to obtain plant materials when labor and equipment costs are low, such as when the work is done by volunteers. Many counties in the Puget Sound area have native plant salvage groups that can assist in this effort.

When salvaging plant material, keep in mind that salvaged plants are an assemblage of living stems, crown, and roots excavated as a single unit. In addition, the soil bound by the roots is considered a component of the salvaged plant.[8] Consequently, successful salvage requires excavating enough of the soil root mass to support the above-ground foliage. However, if the soil is known to be contaminated with seeds or root pieces of invasive plant species, it is best to leave that soil behind and protect the delicate roots of the salvaged plant with wet burlap, damp leaves, etc. On smaller plants (under 6' tall), much of the root mass can be retained using shovels or a backhoe. On larger shrubs or trees, excavators and tree spades may be required; however, some trees may have root masses too extensive to allow successful salvage and transplant.

The larger the plant being transplanted, the lower survival rate it will have. The root systems on large plants are more likely to get damaged during transplantation, and the damaged root system may not be capable of supporting the relatively large, above-ground portion of the plant during the first growing season after transplant. To reduce the shock of transplanting, dormant plant materials are preferred, but if conditions require non-dormant salvage, plants must be frequently irrigated to maintain soil moisture until late fall.[8] Pruning branches on salvaged material will stimulate branch growth and suppress root growth – contrary to the goal.[22] Willow clump plantings can be planted with the root systems and collar much deeper than the soil surface (as deep as 3-4 feet below the surface). This allows the roots to be placed in the saturated zone rather than above it.

In western Washington, most small native trees, shrubs, forbs, and graminoids are easily salvaged.[10] The exceptions, which are relatively few, include: low and tall Oregon grape

(*Mahonia nervosa* and *M. aquifolium*), huckleberry (*Vaccinium* spp.), salal (*Gaultheria shallon*), kinnikinnik (*Arctostaphylos uva-ursi*), and madrone (*Arbutus menziesii*).

In eastern Washington, plants salvaged by the Walla Walla County Conservation District include (Mike Denny, personal communication):

Alnus rhombifolia - white alder
Cornus sericea - red osier dogwood
Pseudotsuga menziesii - Douglas-fir
Ribes aureum - golden current
Rhus trilobata - smooth sumac
Rosa nutkana - Nootka rose
Rosa woodsi - Wood's rose
Salix amygdaloides - peach leaf willow
Salix exigua - coyote willow
Sambucus cerulea - blue elderberry
Symphoricarpos albus - snowberry

Seed. Seeds are commonly used for revegetation projects, and can be less expensive than using plants. However, growing woody plants from seed can be difficult, and is often less successful than efforts using other types of woody plant materials. Whenever possible, seeding woody plants should be combined with materials such as cuttings, bare root, or container plants. Cottonwood and willow rely on moisture regimes associated with high flows to spread, and therefore may be appropriate for seeding as floodwaters recede, depending on site-specific conditions.[23]

5.4.3.2 Herbaceous Plant Material

Herbaceous plants are non-woody species including rushes, sedges, grasses, ferns, and forbs. They generally have fine-textured roots that grow six to 24 inches deep, depending on species, soil type and site hydrology. In contrast to woody plants, most herbaceous plants form dense cover over the soil surface. Their fine root mats and dense cover provide excellent shallow soil reinforcement and protection from surface soil erosion. Unlike some woody species, the flexible stems of herbaceous plants bend under flood flows, providing high-flood conveyance.

Seed. Seed is relatively inexpensive, and, if planted properly, can quickly establish itself as a short- or long-lasting ground cover. In reconstructed streambanks, seed is generally spread by hand or with a mechanical seeding device, and then covered with a temporary erosion-control fabric to protect the seed from washing out during flood events. Erosion control fabric is expensive to apply to large areas, but is necessary where overbank flows are anticipated to occur immediately after floodplain reconstruction. Erosion control fabrics with fine openings or fabrics not held tightly against the soil surface will prevent emerging leaves and stems from penetrating the fabric. Many erosion control efforts fail in this manner and the lack of visible vegetation is often initially blamed on poor germination until inspection under the fabric reveals seedlings that died in their efforts to penetrate the fabric. Larger riparian and floodplain restoration projects in less frequently flooded areas may use less expensive material, such as certified seed-free straw or cellulose fiber mulch. Mulch can be used to protect newly-sown seed from moisture loss, wind displacement, and competition from weeds. Seed is also available in pre-seeded erosion-control mats. These mats may be useful on steep slopes where it would otherwise be difficult to place seed. However, pre-seeded mats are relatively expensive, and their use often results in spotty vegetative cover. Seed can also be applied using hydroseeding methods, however, hydroseeding is not recommended for streambanks or floodplains subject to frequent flooding because it offers little protection against flowing water. Some suggestions for selecting the most suitable mix of seed are discussed later in this technique under *Planting Techniques*. In all cases, weigh the need to protect a seeded surface with fabric against the risk of losing all placed seed and significant soil erosion if the floodplain is inundated prior to establishment of vegetation.

In situations where only native material of appropriate genetic origin is allowed in replanting programs, such as National Park Service or Forest Service lands, but plants are not available, then sterile seeds can be used. Sterile grasses, such as ReGreen, Quickguard, or Pioneer, are becoming increasingly available.

Container. Nursery-grown herbaceous species are widely available in various containers, from plugs to four-inch pots to one gallon pots. Very small plugs are vulnerable to desiccation from poor soil contact or lack of water. Natural Resources Conservation Service (NRCS) research in eastern Washington[24] reveals that the best plug results were obtained using 24-cubic inch plugs. This size plant will have a good root system and above-ground biomass; enabling rapid establishment that helps it compete with weeds and not drown during flood events. Where local genetics are desired and local seed is available, nurseries might be able to produce contract-grown herbaceous plants relatively quickly.

Bare-root. Emergent wetland herbaceous plants, such as sedges and rushes, are available as bare-root rhizomes, tubers, etc. They are easy to install and less expensive than container plants. Unlike woody bare-root stock, herbaceous bare-root plants may be planted in the fall, winter, or spring, depending on water level and other site conditions. Fall plantings, however, do not thrive if submerged all winter and spring plantings may require supplemental irrigation the first summer if planted in sites with summer drawdown periods. Unlike woody plants, dormancy is not a requirement for herbaceous bare root plant survival.

Salvaged. Salvaged sod, if available without weeds, is an outstanding type of herbaceous plant material. It has a dense soil/root mass that is relatively resistant to erosion, it establishes quickly, and it uses materials that may otherwise be discarded. Salvaging and transplanting sod requires an excavator or other specialized, heavy equipment. Sod should be salvaged when the underlying soil is moist, to prevent break up during handling.

Pre-vegetated Mat. Pre-vegetated coir mats resemble conventional turf sod and have advantages similar to salvaged sod. Well-grown mats have dense root systems that quickly penetrate the soil if installed correctly. Poorly-grown mats are a waste of money; be sure to specify a density and inspect the mats before purchase. Coconut mat provides temporary erosion control until the vegetation gets established. Available from some native plant nurseries, these products may be a low-risk (but expensive) means to quickly establish herbaceous cover.

5.4.4 Plant Density and Layout

Planting densities for streambanks and floodplains are determined on a “plant per linear foot” basis if planting on a narrow strip along the water's edge, or on a "feet on center" basis if planted on larger or wider areas. Table 5 provides general density recommendations for various plant materials. These recommendations are a starting point for planning and may need to be adjusted depending upon project budget, erosion-control requirements, probability of survival, role of vegetation in establishing hydraulic roughness, mature size, and anticipated time to maturity.

Table 5. Recommended densities for plant materials.

Plant Material Type	Recommended Planting Density
Cuttings	1 to 2 ft on-center or used in soil bioengineering
Herbaceous	1 to 2 ft on-center
Shrubs	3 to 5 ft on-center
Trees	5 to 20 ft on-center
Seed mix	Varies

A small increase in planting density can substantially increase the number of plants per acre. For example, decreasing plant spacing from five feet on-center to three feet on-center increases the number of plants per acre from approximately 1,792 to 4,840. Bare-root plants are sometimes planted more densely because they are more affordable. Dense plantings are more effective for weed suppression and soil erosion control, as well as helping meet performance standards more quickly. A worksheet and an online density calculator can be found at: www.soundnativeplants.com/PDF/Calculating%20plant%20quantities.pdf. Table 6 provides planting-density conversions.

Table 6. Planting density equivalencies.

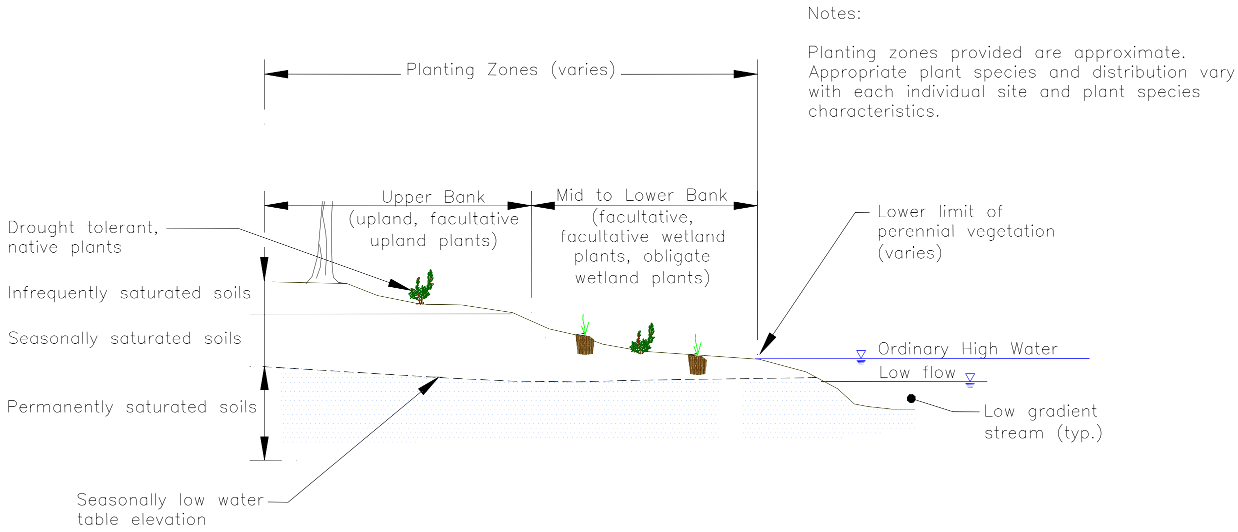
Feet on center	Square feet per plant	Plants per acre
1	1.0	43,560
2	4.0	10,890
3	9.0	4,840
4	16.0	2,722
5	25.0	1,742
10	100.0	435
15	225.0	193
20	400.0	109
25	625.0	70

After determining plant densities, the layout of plants across a site must be decided. The simplest approach is to distribute plants uniformly across appropriate hydrologic planting zones, evenly distributing different species at a specified spacing. This will result in uniform coverage and easier installation, maintenance, and monitoring (especially several years later after vegetation gets thicker). Hydrologic planting zones are described by mapping the frequency of inundation on the planting surface. Typical zones are:

- Summer low water level to limit of perennial vegetation
- Limit of perennial vegetation to 2-year return flood elevation
- 2-to-10-year return flood elevation
- 10-to-25-year return flood elevation
- Above 25-year return flood elevation.

Plants have specific inundation preferences. Creating flood inundation maps for larger projects helps determine appropriate placement (Figure. 1**)**.

Figure 1. Hydrology-based planting zones.



Notes:

Planting zones provided are approximate. Appropriate plant species and distribution vary with each individual site and plant species characteristics.

Planting by hydraulic zone alone does not necessarily optimize fish and wildlife habitat and aesthetics. The planting layout should also be based on the size and type of material, the individual plant species habits, erosion control, and the habitat needs of fish and wildlife. For example, low-growing shrubs or herbaceous plantings might be distributed uniformly across a streambank, whereas tall shrubs and trees are clustered near pools to provide fish cover. When planting a number of species in the same area, group similar plants together in clusters rather than interspersing all species equally. Plants that tend to form thickets, such as salmonberry (*Rubus spectabilis*) or hardhack (*Spirea douglasii*) can be planted closer to each other. Plants that tend to grow as solitary individuals, such as many tree species, can be planted further apart.

When planting, consider future maintenance requirements. New plants often need supplemental water during the first (and sometimes through the second or third) summer following planting.

Control of grasses and weeds surrounding new plants need to occur for three or more years to minimize competition until the installed plants are well established. Plants installed with a mower's width between them probably are not close enough to shade out weeds. Mowing also reduces vegetative spread of desirable plants, the opposite of most objectives. Heavy mulch between plants will suppress weeds and conserve moisture, which potentially reduces the frequency of maintenance. However, mulch is not generally recommended in areas subject to frequent flooding. Cluster planting may also offer an acceptable compromise for landowners unwilling to sacrifice their view in order to revegetate the riparian zone.
See 5.4.7 *Weed Control* for more information.

5.4.5 Timing of Plantings

Each plant material type has an optimal planting window, summarized in Table 7. In riparian areas, timing of flood flows or wet site conditions might prevent or limit site access during otherwise acceptable planting periods. Suitable planting periods for each plant material type must be considered and adequately incorporated into project implementation and construction planning. In the Pacific Northwest, the best time to plant is in the fall after the rains have begun. This allows plants a good chance to get established while soil moisture is plentiful and temperatures are still warm enough for root growth. It also allows plants the most time to get established before they have to endure the summer drought conditions of the Pacific Northwest. Winter is the next best time to install plants, with earlier in the season being better. Conifers are able to photosynthesize throughout most of the winter and do not become dormant like deciduous plants in wintertime.[25] Spring plantings often fail to establish adequate roots to enable them to survive their first summer drought. Irrigation can make the difference between survival and failure of a spring planting. Summer installation is not recommended even with irrigation except in extenuating circumstances.

Table 7. Recommended planting windows.

Type of Plant Material	**Recommended Planting Window**	
	Eastern Washington	**Western Washington**
Seeding	Fall when moist; spring when moist and maybe follow-up irrigation	Spring/fall is best; summer seedings need frequent irrigation
Dormant cuttings	Fall is best; winter if ground is not frozen[26]	Fall is best; winter is good, spring is suitable only on sites with copious moisture
Containers	Fall is best; spring plantings will require regular irrigation through the following summer and fall	Fall is best; winter is good; spring is suitable only on sites with copious moisture; summer is suitable only with frequent irrigation
Bare-root plants	Late winter/early spring only	Late fall through winter
Salvaged trees/shrubs	Dormant season (November to March) is best, irrigate at least first summer after planting	Dormant season (November to February) is best; irrigate at least first summer after planting
Salvaged sod	All year where the ground is not frozen and soils remain sufficiently moist; irrigate when insufficiently moist	All year where the ground is not frozen and soils remain sufficiently moist; irrigate spring/summer transplants

The Washington State Department of Transportation (WSDOT) has a standard specification for the timing of seeding and planting projects (Table 8). After tracking many years of planting projects, WSDOT has shortened the seeding and planting windows in the last 5 years due to poor survival of material installed before and after the current windows.

WSDOT allows plant material to be installed outside these windows only if an irrigation system is operational before planting.

Table 8. WSDOT standard specification for seeding and planting activities.

Activity	**East of the Cascades**	**West of the Cascades**
Seeding	October 1 through November 15	March 1 to May 15, September 1 to October 1*
Planting	October 1 through March 1	October 1 through March 1
2010 Standard Specifications at http://www.wsdot.wa.gov/publications/manuals/fulltext/M41-10/Division8.pdf		

*Up to Nov 1 for lower Puget Sound Basin in areas close to water, where temperatures are mildest.

5.4.6 Site Preparation

The site must be prepared before installing plant materials. Because of the natural fluvial processes that occur in streambank and riparian areas, some site-preparation strategies used in upland forests, grasslands, and landscaped areas may be inappropriate. For example, weed mats, woody mulch, and similar techniques used to control competing vegetation in uplands, may be washed away if used in flooded areas such as streambanks. There is often a trade-off in both cost and effort between aggressive site preparation and required site maintenance. For example, required maintenance at a site dominated by dense thickets of weeds may be lower if aggressive site preparation techniques are used. As a result, the magnitude, longevity, and periodicity of available funds should be considered when selecting site preparation techniques.

When developing a planting plan, consider the site preparation, short- and long- term maintenance, and the equipment required. If a site will require aggressive site preparation or frequent mowing to control the growth of undesirable vegetation, and funding is limited, it may be more cost effective to plant dense clusters of vegetation, using aggressive site preparation techniques within each cluster, rather than uniformly distributing vegetation throughout the site. This will reduce the preparation and planting area and allow the use of a mower or tractor between clusters rather than throughout the entire site. These planted areas can then be expanded as more funding becomes available.

5.4.6.1 Soil Modification

A site with intact topsoil may have adequate levels of soil organic matter and nutrients. In this case, the soil will not need to be amended unless a soil laboratory test reveals deficiencies. An excess of soil organic matter or nutrients is not useful and may be detrimental.

In sites where topsoil has been altered or removed, the soil may need to be modified using amendments, mulch and fertilizer. Each contributes different benefits to the plants. A soil amendment is any bulk substance mixed into the soil that benefits plant growth (e.g. compost).

Compost mixed into the soil will increase soil organic matter, increase water holding capacity, and provide slow-release nutrients. Physically incorporating amendments into the rooting zone increases their retention under flood flows and may encourage deeper rooting than if placed on the soil surface. A common specification is three inches of compost tilled into the top 8 to 12 inches of disturbed soil (not intact topsoil).[27] Avoid incorporating compost, topsoil, or any other bulk material into individual planting holes; it will make it difficult for the plant roots to emerge from the hole. Compost is also an excellent medium for seed germination, so if used on the soil surface, it must be covered with mulch. Any time soils are exposed to the light, there is a potential for seed germination. This could be desirable if the seed bank is native or undesirable if the seed bank is an invasive species that will compete with installed plants. If the seed bank is undesirable or if weed seeds will blow or wash-in, cover the soil surface to prevent germination.

In contrast to soil amendments, mulch is a material laid over the soil surface. Mulch provides many benefits on a restoration site including providing a source of long-term organic matter and nutrients, conserving water, moderating soil temperatures, and reducing seed germination by excluding or reducing light to the soil surface and by reducing access to the soil for a deposited seed. The latter can help reduce weed growth. The most commonly available mulches are ground bark, wood chips, and straw. Bark is a waste product of the forestry industry and comes in different grinds. A medium grind is best as too many fine particles can repel water and a too coarse grind can allow light to the soil surface. Bark decomposes more slowly than wood chips so provides more weed control but less organic matter and nutrients. Wood chips can be a mix of wood and leaves or needles (arborist chips) or be all woody material. Arborist chips decompose more quickly and so provide faster nutrients and organic matter to the soil but provide shorter-term weed control and moisture retention. Straight wood chips last longer, provide more weed control and less nutrients and organic matter. Hog fuel is very coarsely ground wood, with stick pieces still intact. It may lack aesthetic properties to some but is perfectly good mulch. Straw is not recommended in most instances as it almost always has seeds in it. The Washington State Department of Agriculture has a program that certifies straw to be free of noxious weed seeds, but not free of other seeds. For more information see their website at http://www.nwcb.wa.gov/.

Fertilizer is a concentrated form of soil nutrients that does not contribute bulk. Soil fertilizer that used in uplands may not be appropriate in riparian zones for several reasons. Many riparian species naturally thrive in soils low in organic matter, characterized by high sand and gravel/cobble content and may already be adapted to low-nutrient sites or obtain their nutrients in association with stream flow. In addition, surface applications of fertilizer may be washed away by flood flows and contribute excess nutrients to the aquatic system before riparian plants can utilize them. Weeds may also be more competitive on fertilized sites than on typical alluvial sites that are dominated by low-nutrient, sandy and gravelly soils.

Research has been done on sites prone to drought with a product referred to as “water crystals.” Water crystals are synthetic polymers added to the rooting zone that sometimes improve moisture retention and thereby allow plants to better withstand drought. Sometimes, however, this product appears to remove water from the rooting zone and make it less available to plants and reducing plant survival. This product should be tested in small-scale field trials to determine if it will work at the project site.[28,22]

5.4.6.2 Topsoil Salvage

In some cases, it may be possible to salvage topsoil during excavation. Choose stockpile areas that will not damage existing resources. After excavation, the salvaged topsoil can be reapplied to the new surface before planting. The advantage of salvaging topsoil is that it contains valuable organic matter and soil micro-organisms. It may also have native seeds or root fragments that will help establish desirable vegetation on your site. A drawback is that it may include non-native seeds or roots that will quickly establish weeds on the site.

Topsoil organic matter will decompose and soil organisms will die over time and therefore topsoil should be reapplied to the site within a growing season. Storing the soil in rows, as opposed to piles, and keeping it cool and shaded will increase organism survival. The process of salvaging and reapplying topsoil damages its structure. To partially compensate for this effect, incorporate compost into reapplied topsoil. Do not use more than 10% compost by volume, [22] a soil test will provide initial organic matter levels. Also topsoil should not be excavated or moved when topsoil is wet (if topsoil is too wet to till, it is too wet to move). It is also important to minimize handling wet topsoil and avoid compaction by traffic.

5.4.6.3 Decompacting Soil

Sites with compacted soils need to be decompacted to improve conditions for seed germination, plant rooting and growth, macro and micro-organism survival and reproduction, and soil drainage. All methods aim to change or construct different physical properties that may influence seed germination and seedling establishment and survival. Sites that will be seeded will benefit from a finer seedbed whereas planting sites can and should be left very rough. Extremely compacted sites, such as old roadbeds or house sites, need ripping. Ripping is generally done with large construction equipment with very sturdy tines that can reach a depth of 18”. Tilling is done with smaller equipment that can reach a depth of 10 to 12”; landscape contractors typically have this type of equipment. Keep in mind that flood-prone soils that are excessively scarified may be more susceptible to erosion. Also, remember that any time soil is exposed to light, seeds will germinate. Site preparation techniques to control undesired vegetation are discussed below under *Weed Control*.

5.4.7 Weed Control

A good working definition of a weed is any plant that could interfere with project objectives. This is not limited to listed noxious or nuisance weeds; common pasture grasses are serious competitors for water and nutrients and have out-competed newly installed desirable species on many riparian projects. Seeded erosion control grasses can also out-compete installed woody plants and cause mortality. Weed control and monitoring will be an essential component of any riparian restoration project, particularly during the early plant establishment phase. Lack of weed control is a major cause of project failure.

Riparian areas dominated by invasive non-native plants are often targets for restoration because weeds often affect the structure and development of native plant communities. Since restoring the optimal native plant community at these sites may be difficult or impossible given the competition from weeds, a native substitute community capable of surviving and suppressing weed growth in the long term may be the best option. The only effective long-term method of weed control is to create conditions unfavorable for weed propagation, establishment, and survival or else eradicate or minimize the seed source. Reduction of seed source is not likely in situations with populations of undesirable species upstream. Unfavorable site conditions may include shading of sun-loving weed species, covering of bare soil so weed seeds cannot germinate, or periodic flooding of flood intolerant species. Densely planted willow, cottonwood, and alder can reduce weed growth to a level where beneficial plants can compete, even though weeds may not be eliminated. Closely planted conifers create a deeper shade that may in time suppress weeds as canopy closure reduces light penetration to the understory and reduces the number and extent of sun loving species.

Removing weeds over a large area may temporarily decrease bank and floodplain stability due to reduced vegetative cover. For instance, tilling removes all vegetative cover and exposes bare soil to erosion. This reduced cover may also reduce the quantity or quality of wildlife habitat until native vegetation is established. The short-term impact of weed removal on soil stability and fish and wildlife depends on the technique used. Nevertheless, suppression or successful eradication of weeds often provides significant long-term benefits. Also, soil disturbance may expose buried weed seeds to light and trigger germination, so plan how this will be controlled. It may be better to kill the weeds, leave them in place, and plant through the dead material.

The method of weed control should be carefully selected, its benefits weighed against potential negative impacts. For instance, removing reed canary grass from a stream channel may increase channel conveyance of water, sediment, and woody material and allow a diverse channel bedform and plant community to develop. However, if dredging is used to remove reed canary grass from the channel, the physical and biological effects include direct destruction of instream habitat and aquatic life within the area of application and destabilization of the upstream channel. It may also alter the cross-section and profile of the stream, causing channel incision or aggradation, and isolating the stream from its floodplain, which in turn impacts plants and wildlife within the floodplain. These effects may extend up- and downstream of the dredged area.

Before implementing weed control, a thorough understanding of the following considerations is important:

- Biology of the targeted species;
- Short- and long-term effectiveness and limitations of control efforts;
- Risk to non-target species and the ecosystem as a whole; and
- Long- and short-term availability of funds and work crews.

While the only long-term methods of weed control are to eliminate its seed source and to create conditions unfavorable for weed propagation, establishment, and survival; several techniques can be used to temporarily control and manage weeds including:

- Manual and mechanical control: pulling weeds by hand or with tools such as a Root Talon or Weed Wrench, girdling, mulching, mowing, surface soil removal, dredging, singeing with hand held torches, and flooding.

- Controlled grazing with cattle, sheep, goats, or geese: controlled grazing consists of short duration (i.e., less than 1 week), high intensity grazing during vulnerable life history stages of the target species.
- Mulch and/or weed barrier fabric.
- Prescribed fire.
- Flooding.
- Biological control.
- Controlled herbicide applications at appropriate times of year.[29]

Some of these techniques will be required to prepare the site before planting, while others will be required as part of a short- and long-term maintenance plan. Often, there is a trade-off between pre-project site preparation and post-project maintenance. For instance, on upper floodplain sites that have a low probability of flooding (and subsequent soil erosion), weeds throughout the site can be killed with herbicide before planting. Following this up with the application of a biodegradable weed barrier such as cardboard covered with a thick layer of mulch immediately after planting can suppress weed growth and retain soil moisture, minimizing, but not eliminating, the need for long-term maintenance. This technique works best when applied to a whole area or site. Weed roots do not necessarily stay directly underneath the plant; they can roam far and wide searching for water and nutrients. So controlling weeds in a 3’ diameter circle may reduce shading of installed plants but will do little to reduce root competition.

A wide variety of weed barrier fabrics are commercially available and they all have their pros and cons. They may reduce weed growth if properly installed but must be removed later unless they are bio- or photo-degradable. They can reduce water and gas transfer to the soil and will prevent vegetative propagation of the installed plants. The tighter the weave, the fewer weeds will grow but the more water and gas will be restricted. A looser weave will allow more water and gas to pass through but also more weed growth. Mulches such as wood chips are a better choice in areas that do not flood. Also, bio- and photo-degradable fabrics do not appear to degrade as fast in our shady and cool westside or cold and dry eastside sites as the manufacturers claim they will.

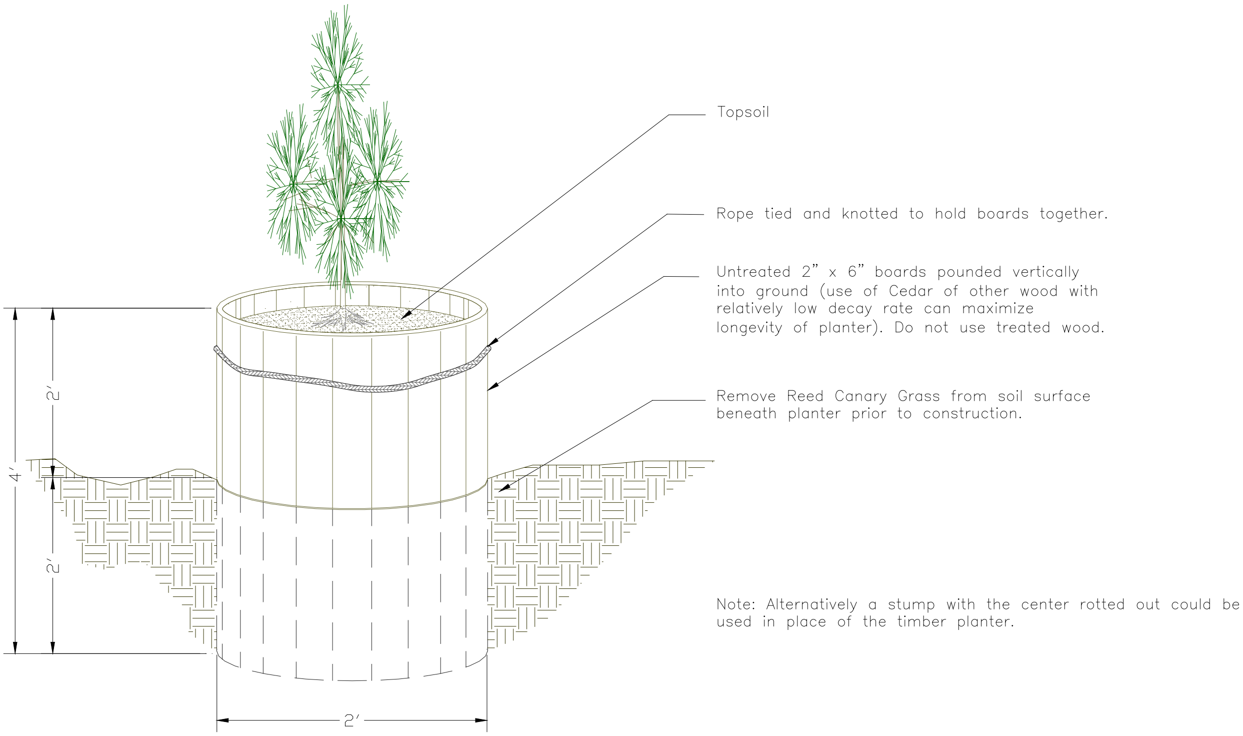
In areas with large deer or elk populations, controlling entire weed populations may open up the plantings to grazing. In these areas, it may be better to control weeds in a circle around desired plants and leave tall weeds between them. Or install other browse protection such as plant guards or fences. In a case like this, weigh the pros and cons of browse damage against weed competition.

When considering herbicide use, research the latest best management practices. New research is regularly published on the best techniques for getting maximum effectiveness for the least amount of chemical used, including timing, concentration, and application method. Consult the state or county weed control board, conservation district, or Washington State University Extension office for specific information and recommendations. The Nature Conservancy has a comprehensive weed control techniques manual.[29] The local NRCS office may also have current information on controlling invasive weed species. No matter what the weed or strategy employed, weed removal efforts will likely be short-term if not combined with revegetation efforts to crowd, shade out, or otherwise suppress the weeds.

Care is needed to prevent weed control activities from damaging or destroying installed plants or desirable volunteer vegetation. Small plants are especially vulnerable to damage from string trimmers (“weed whackers”) and mowers because their thin bark does not yet protect the cambium layer from damage. Landscape contractors jokingly call it “mower blight” or “weed whacker blight” but the reality is that young plants are frequently killed by improper weed control efforts. Plants can be protected from this kind of damage by solid sleeves. Also, if spot spraying around desirable vegetation, construct a shield (flattened cardboard boxes will do in a pinch) and work in teams to protect non-target plants from over-spray.

One experimental method for reed canary grass control is creation of artificial hummocks or planting mounds in the riparian zone using heavy equipment. Various versions of this concept have been employed in western Washington. One version, used by the Skagit Fisheries Enhancement Group and the Jefferson County Conservation District, consists of creating mounds of earth 2 to 5 feet tall of various size and shape throughout the riparian zone and planting them with native vegetation. Another version used by King County included installing untreated wooden planks vertically into the ground to form a round planter 2 to 3 feet above the surrounding soil (Figure 2). The planter was then filled with soil and planted with Sitka spruce, which was abundant on natural hummocks in the adjacent wetland. These hummocks or mounds create relatively dry microhabitats that may offer vegetation planted on them a competitive advantage over the surrounding stands of reed canary grass. Preliminary monitoring data for the earthen mounds found that plant survival was higher and reed canary grass was less dense on the mounds versus off the mounds.[11] A variation of this approach would be to use the heavy equipment to scalp a large portion of a reed canary grass monoculture to remove much of the rhizomes and stems while also creating the hummocks. Further study is necessary to determine the long-term effectiveness of these techniques and the hydrologic and hydraulic impact of the mounds.

Figure 2. Example of artificial planting hummock.



5.4.8 Irrigation

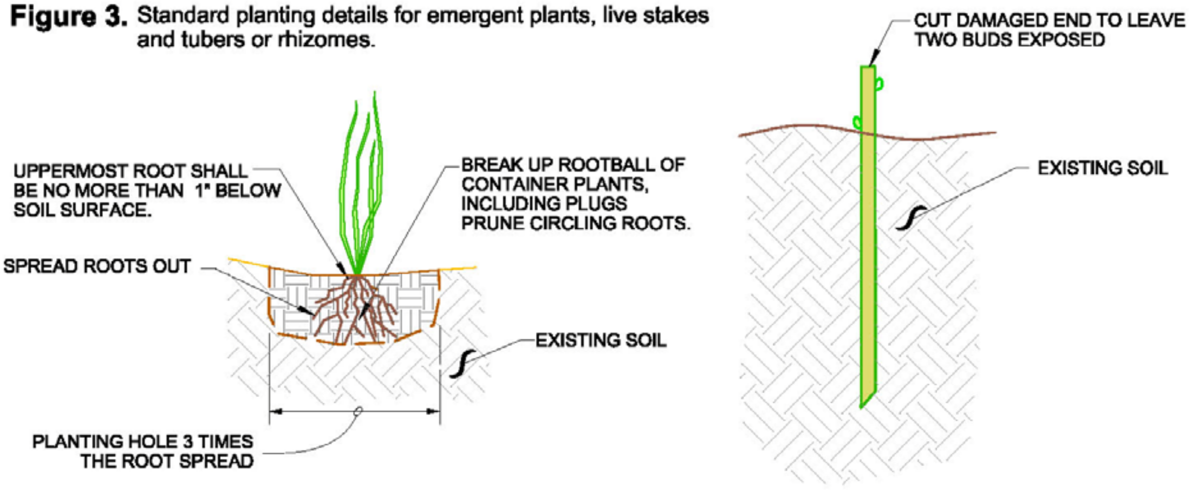
Seeds and plants must be watered in when they are planted. Watering at planting will help eliminate air pockets and will ensure that the soil around the root system is at or near capacity. Plants that are not rooted in moist soils will need to be watered regularly throughout their first dry season until the fall rains are consistent. Good site preparation, such as aggressive weed removal and mulching, can reduce the need for irrigation as more of the site water is available for the desirable plants. A variety of irrigation methods are available, from the use of a water truck and hose to the installation (and later removal) of PVC pipes and overhead sprinklers or drip tubing. Constructed irrigation systems should be operational prior to plant installation. The on-line paper “Irrigation Systems for Restoration & Mitigation Sites” at http://www.soundnativeplants.com/PDF/irrigationpaper.pdf provides some details to help determine the best system for each project.

5.4.9 Planting Techniques

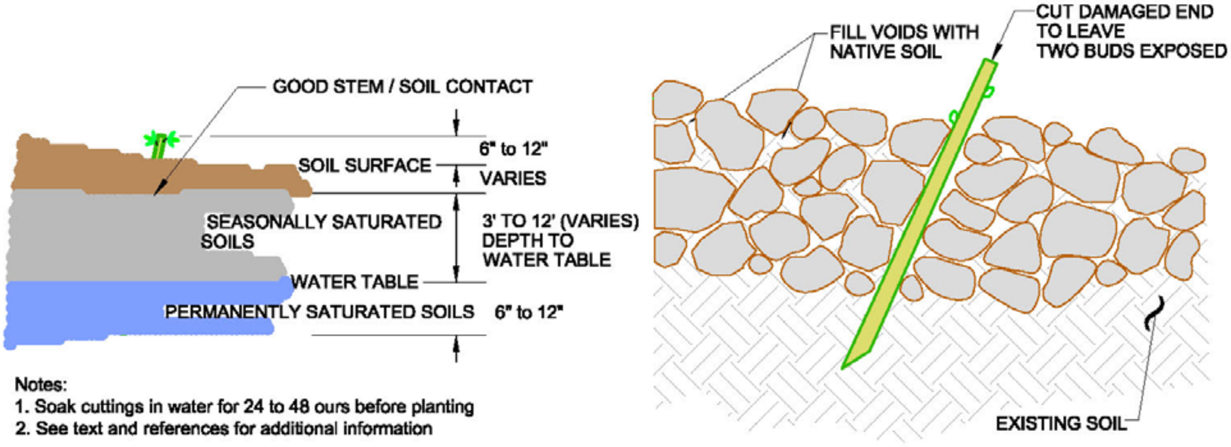
Proper selection, storage and planting of vegetation are critical to the success of stream revegetation projects. All plants used on site should have a healthy, vigorous appearance, and be free of dead material, insects, and disease in the roots and tops. Previous to planting, store plants in locations where they are protected from sun, wind, cold, heat, browse, and physical abuse. Planting technique in streambank settings will vary depending on the type of plant material. Diagrams that illustrate best management planting practices for a variety of plant materials can be downloaded from http://www.wsdot.wa.gov/publications/fulltext/Standards/english/PDF/h10.10-00_e.pdf. Figure 3 shows standard planting details for live stakes, emergent plants and tubers or rhizomes. Figure

4 shows standard planting details for ground cover and shrub, tree plantings. These planting details, or standard plans, can be included in contract plans to specify correct planting techniques or can be used as teaching tools for volunteers or new crews. Perfect planting techniques will not ensure survival if good site preparation has not been performed.

Figure 3. Standard planting details for emergent plants, live stakes and tubers or rhizomes.

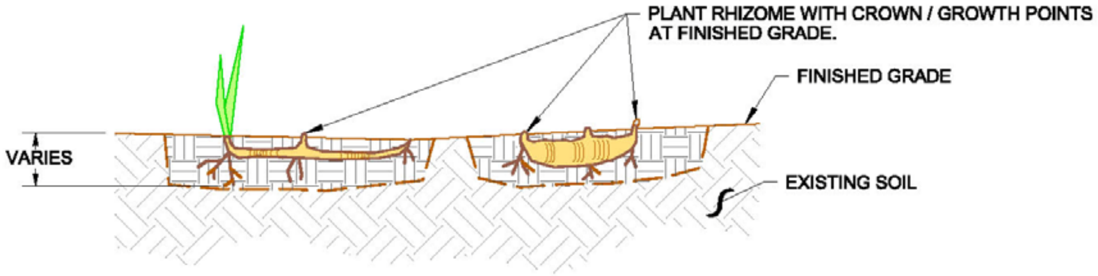


EMERGENT PLANTING DETAIL TYPICAL LIVE STAKE INSTALLATION



Notes:
1. Soak cuttings in water for 24 to 48 ours before planting
2. See text and references for additional information

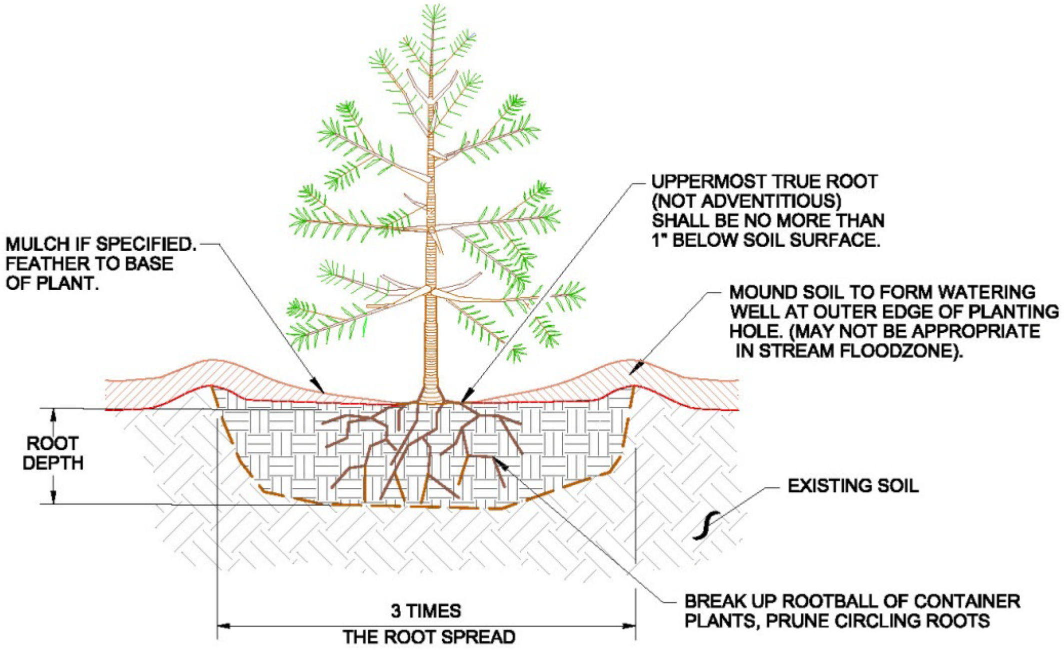
LIVE CUTTINGS PLANTED INTO STREAMBANK LIVE STAKE INSTALLATION IN RIPRAP



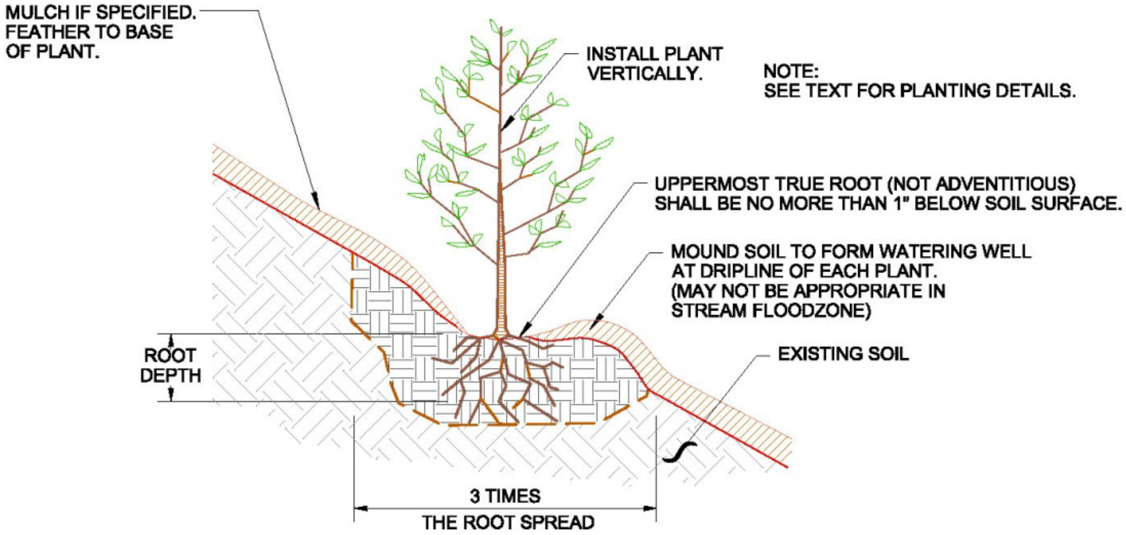
TUBER OR RHIZOME PLANTING DETAIL

DRAWN BY: FERN LIDDELL, WSDOT

Figure 4. Standard planting details for ground cover, shrubs and trees.



SHRUB, TREE AND GROUND COVER PLANTING DETAIL



NOTE:
SEE TEXT FOR PLANTING DETAILS.

SLOPE PLANTING DETAIL
(INCLUDES ALL PLANTS ON SLOPES)

DRAWN BY: FERN LIDDELL, WSDOT

5.4.9.1 Seeding

Careful selection of seed mixes and following proper seeding methods are key for a successful planting project.

Developing Seed Mixes

Seed mixes are combinations of grass, forb and occasionally woody plant seeds. Depending on the project, they may be used to provide either short or long term cover. Some suggestions for developing seed mixes include:

- Select approximately five species that are biologically suited to your site.
- Select at least one proven, quick-establishing species.
- Use locally collected seed as much as possible
- Avoid hard-to-find species.
- Select certified weed-free seed inspected by the Washington State Department of Agriculture.
- Have your local NRCS office or a seed supplier help determine seed rate, and purchase seed in pounds of Pure Live Seed (also referred to as "PLS lbs.").
- Experiment with different species, and monitor results.
- Do not use commercially-purchased wildflower mixes. These mixes will have non-native species, or at least non-local genetics. The mixes also frequently include species not listed on the package (http://www.washington.edu/news/archive/id/7637)

Seeds should be delivered to the site in the original, unopened bags showing a certified net weight, date of germination tests, supplier's name, certified guarantee of analysis including the composition, purity and germination percentages, and percent weed seed. Seed should not contain more than 1% weed seed with 0% undesirable species. No noxious weeds should be specified and listed on the label. For areas east of the Cascades, the seed mix should specify no sweet clover.

Avoid an erosion control mix on a site with installed woody plants because the woody plants may not be able to complete with the vigorous grasses. It's important to select at least one proven, quick-establishing species. This may justify use of short-lived, non-native cover crops, such as annual rye or winter wheat. Or a sterile hybrid such as Regreen® or a native, dry-site species, such as slender wheat grass or Canada wildrye, that provides good short-term erosion protection but will eventually be replaced by a species more tolerant of moist soils. Short-lived species are particularly appropriate when vegetation established by seed is expected to provide only short-term erosion control until native herbaceous and woody plants get established. Short-lived species will provide less long-term competition. Using annual cover species on surfaces that are prone to drought may result in poor establishment of perennial species, as annuals may consume soil moisture early in the establishment period, stressing slower establishing perennials and reducing their ability to compete.

Primary Seeding Methods

There are three primary seeding methods: drilling, broadcasting, and hydroseeding (see Table 9). The most appropriate method for a particular site will depend on size, terrain, accessibility, soil characteristics, and time of seeding. The preferred and most effective method is drill seeding. However, if the site is on uneven ground containing obstacles or debris, or is inaccessible to large equipment, broadcast seeding is preferable. Hydroseeding is a less effective method because the seed to soil contact is not as good. It should, therefore, be limited to steep, inaccessible areas. Prior to seeding an area, consider risks from wind displacement or rising water levels that can displace and wash away seed/seedlings, mulch, and binders, particularly when using hydroseed.

Table 9. Advantages and disadvantages of various seeding methods.

Drill Seeding	**Advantages**	**Disadvantages**
	Seed to soil contact is high, maximizing germination.	Creates rows that can persist for years in eastern Washington, which may be visually unacceptable.
	Most successful on slopes 3:1 or flatter.	Unless specially modified drills are used, all seeds will be planted at the same depth resulting in the smallest seeds being planted too deep.
	Seed depths and seeding rates can be closely controlled.	Seeds drilled in rows may suffer from high inter-seedling competition.
	Proven high revegetation rate.	Cannot be used on rocky soils or steep slopes.
Broadcast seeding	Can be used on slopes that are steep, rocky, or inaccessible to equipment.	Germination and establishment tends to be lower than with drill seeding.
	The variable planting depths that result from broadcast seeding allows better establishment of small seeds.	Requires double or triple the seeding rate of drill seeding; seeding rate calibration is less precise. Seed to soil contact can be poor without some kind of packing or dragging.
	Vegetation not in rows.	
Hydroseeding	Can be used on slopes that are steep, rocky, remote, or inaccessible.	Results less satisfactory due to poor seed/soil contact; fewer seeds germinate.
	Vegetation not in rows.	Requires water.

Drill seeding:

- Seed to a depth of 0.25 to 0.5 inches. Exact depth depends on the size of the seed (based on grass species). Larger seeds should be planted 0.75 inch deep.
- Seed along the contour to avoid erosion from water flowing down drill furrows.

Broadcast seeding:

- Before seeding, rake soil to eliminate crusting.
- After seeding, cover the seed by harrowing, chaining, or raking.
- Do not seed on windy days.

Hydroseeding:

- Use the two-pass method to improve soil-seed contact, where the seed and a small amount of mulch are sprayed first with a tracer dye, then the remaining mulch is sprayed over that.

- Do not add fertilizer to the mix.
- Spraying hydroseed slurry on steep, impermeable slopes may wash seeds off the slope.
- Hydroseeding often results in sheets of mulch and seed, which can be damaged or lost if overbank flooding events occur before seeds germinate and take root.

More seed is not necessarily better. Instead, focus on getting good seed-to-soil contact by gently compacting seeded streambank areas with an excavator bucket or a contractor's compacter. Imprints left in the soil by tracked equipment during construction can help to collect seed and rainwater and provide a moist microclimate for seed germination. Also, use surface irregularities such as depressions, rocks, logs, etc. to create favorable microsites for seeds to germinate and establish.

To maximize survival, seed should be planted according to the planting windows in section *5.4.5 Timing of Planting*. Or consult your local NRCS or Cooperative Extension office. To provide erosion control during the winter months, seed must sprout and root well prior to the start of the winter dormant season. Straw mulch can increase the likelihood and rate of seed germination. Newly germinated seeds offer little erosion control benefit. Where the potential for natural recruitment of native vegetation is high, lightly seeding the area may be more effective than heavily seeding. This will limit competition for the native vegetation.

Erosion-control fabrics can be used along with or in place of straw mulch to prevent straw and seed from washing downstream. It is recommended that only fabric comprised entirely of decomposable material be used. Fabrics that use a plastic netting or mesh can easily get blown or washed into the adjacent stream or watercourse and act as gillnets for fish. Or if it stays on site, can get tangled up in mower blades. It may also be harmful to wildlife that ingest or become entangled in it. Bio- or photo- degradable materials tend to last longer in the cool cloudy environment of western Washington or the cold arid environment of the eastern Washington than manufacturers report. Clear plastic can be used over the seeded area in the fall to prevent erosion of seed and mulch from rains and enhance establishment due to the "greenhouse effect." The plastic must be removed once growth is underway to prevent overheating and smothering of the seedlings.

5.4.9.2 Harvesting, and Installing Cuttings

The most common type of plant material used on streambanks is live cuttings. Many on-line and published planting guidelines are available. Additional recommendations related to collection, storage and installation are provided below:

- Collect cuttings from healthy vigorous stock; those collected from stressed plants root poorly. Examine donor plants carefully and avoid those with canker, insect exit holes or frass, or mechanical damage. Collect cuttings from male and female plants, if applicable. One to two year-old wood is generally better than older wood, and cuttings taken from the center and bottom of the plant will frequently root better than those taken from the outside edges. Excellent cutting material frequently sprouts a year or two later from shrubs pruned along roadsides, from areas heavily browsed, and in other disturbance locations. Collecting dormant cuttings will improve survival.

- Collect cuttings in a manner that will not permanently damage the donor population or the surrounding area. Use the size and health of the local plants, the density of the species in the area, and the environmental conditions of the site to determine how much of a plant to collect. For example, in a lush site in western Washington, it might be acceptable to harvest half of a clump of willow, whereas on a relatively arid site in eastern Washington, only 1/20 of an individual plant should be collected.[8] Only salvage sites can be stripped of plant material.

- Harvest cuttings with a sharp tool. Cutting the bottom with an angled cut and the top with a straight cut will identify the top from bottom and may aid rooting. Cut right next to but not into a node. Stubs will die back to the nearest node and the dead wood can be an entry point for insects or disease.

- Cuttings should be at least one-half inch in diameter, relatively straight, 18 to 48 inches long, and include two or more nodes (buds). At least one node must be planted underground to grow roots and at least one must be planted above ground for the leaves to emerge. Investigate soil conditions before collecting or specifying length of cuttings to a supplier. Shorter cuttings are preferable if the donor site has a subsurface soil layer that is hard to penetrate; longer cuttings would need to be trimmed after installation. Longer cuttings may be necessary depending upon planting site conditions (e.g., deep water table; erosive forces) and application (e.g., brush layers and fascines versus live stakes). Generally, cuttings should be long enough to extend into the moist soils in the vicinity of the lowest seasonal water table with no less than 3/4 of the total length of the cutting in the ground.[30] It may be necessary to experiment with a variety of cutting diameters because the literature is not consistent and varies depending upon species under consideration.[8] Cutting diameters less than one half inch may be necessary for species with relatively small diameter stems (e.g. *Symphoricarpos* spp.).

- Cuttings should be kept moist, cool, and shaded until planting. Even on a cold day, exposure to direct sunlight will stress them. Cuttings will be most successful if harvested and planted in the same day. If this is not possible, cuttings can be soaked in water and left in the shade on site. Once cuttings start to grow roots (after around two weeks) they must be planted as rooted plants, not live stakes. Soaking the cuttings for 1-2 weeks prior to planting is recommended to improve survival of cuttings in eastern Washington. If cuttings cannot be installed within days of collection, consider refrigerated storage up to several months. The cuttings must be damp but not too wet or they will mold even in refrigerated conditions. Stored cuttings should be soaked before installation.

- Best survival occurs with dormant planting. Anecdotal reports suggest that successful establishment is sometimes possible from cuttings planted in early summer and early fall if leaves and branches are stripped from the plants and cuttings extend into moist soil or are irrigated, but the success rate is rarely more than 40%.

- Roots need oxygen to grow. Cuttings will root first and easiest into the capillary fringe (damp zone) above the water table, though at least some species will root into moving or standing water as well. Cuttings will not root into a compacted hardpan, or through an unfractured one to get to the water below (Chris Hoag, personal communication, March 2011).

- If the site is not irrigated, the bottom of the cutting must reach a depth where the soil is permanently damp. One quarter or less of the cutting should extend above ground, especially in arid areas. If more than one half of the cutting extends above the ground, there will likely be too much shoot growth for the new roots to support. Also, the part of the plant above ground is vulnerable to desiccation in dry windy conditions. When cuttings are planted in weedy conditions, determine the length of the cutting based on the plants need for sunlight and exposure versus the risk of drying out due to imbalanced root to shoot ratio and exposure to wind and sun.
- Cuttings planted in very loose soil (i.e. uncompacted sandy loam), can be tamped in using a “dead blow hammer” (i.e., a hammer with a head filled with shot or sand).[31] In all other situations, use rebar, an iron bar, or a willow-planting tool to create a pilot hole for the cutting. The diameter of the pilot hole should be slightly smaller than the cutting to ensure good stem-to-soil contact. The live stem must fit tightly in the planting hole, leaving no air space. If the cutting is forced in, it may be damaged and survival will be reduced.
- Consider planting dense willow “rows” (3 per lineal ft) in an excavator-made trench, rather than “hand” planting individual cuttings. Cuttings should be 5-10 ft in height; the trench should be at least half the length of the cuttings; and reach the water table. Such willow rows are inexpensive, do not require irrigation, resist pullout during flood events, and create floodplain roughness.

Refer to the *Construction Considerations* section of this technique for more information on specialized planting tools and techniques.

5.4.9.3 Inspecting Container Plant Materials.

New plants need to be inspected to make sure that they meet specifications and are acceptable for the project. Poorly rooted, rootbound, sickly, or otherwise unacceptable plants are unlikely to survive long-term in the rigorous conditions of a restoration project. Well written specifications provide standards to enforce through inspection. The following website provides a link to standard specifications for plants ***http://www.wsdot.wa.gov/Design/Roadside/***.

Container plants should be inspected top to bottom. Examine leaves for color, insect and disease damage, and size. It is common for leaves to harbor opportunistic fungal and bacterial infections in the fall and plants should not be rejected for this reason. The same infections would be reason for rejection in the spring or summer, however. Take a sample of the largest and smallest plants out of their pots and examine the rootballs. Perfectly ready plants have rootballs that hold together when removed from the container but do not have circling roots. Rootbound plants, especially any species that does not thicket or propagate vegetatively, should be rejected; they will not do well long-term on your site even if they survive short-term. Planted rootbound trees that will eventually grow large are likely to become hazard trees if in an area frequented by humans. Healthy roots are plump, firm, moist, and in the growing season have pale root tips. Plants with dry, withered, shriveled, slimy, or smelly roots, or brown root tips in the growing season, are not healthy and should be rejected. The size and health of the roots is critical for survival its first summer.

5.4.9.4 Installing Container Plant Materials.

The success of planting techniques for container plants depends in large part upon the specific container size and dimension. For example, narrow “tubeling” containers can be planted through erosion-control fabric with minimal fabric cutting, but larger containers require cutting fabric strands and this can potentially weaken the fabric. On particularly erosive sites, consult the fabric manufacturer for guidance on what size and density of holes is acceptable without compromising fabric strength and integrity. Also, cutting holes like this makes it difficult to spread out plant roots and is not optimal.

Planting holes can be either hand dug with shovels or machine dug by mechanical equipment including augers, excavators, and backhoes. The planting hole should be two to three times the diameter of the container and exactly as deep. The rootball should have plenty of loose soil around it for roots to grow into and should rest on solid soil so that it will not later subside as the soil settles. Loosen and uncoil or slice circling or twisted roots, then vigorously break up the rootball to encourage root growth outside of the potting soil. It is important that the rootball is broken up in order that the roots are not confined and can grow outwards into the site soil. On small projects with plenty of labor, soil can be removed from the rootball and installed as a bare-root. This is also the time to do corrective root pruning on trees that will grow large because circling roots can girdle the tree as it grows in diameter. Also, when planting from tall containers, break up and spread out the roots to allow them to grow outward in their normal pattern.

All plants need to have the top true root (not adventitious root) planted just underneath the soil surface, and have native backfill material gently firmed around the roots. Examine the rootball carefully to locate the top true root; sometimes rootballs come buried too low in the container and small adventitious roots will grow into that extra soil on top. A trough or low soil berm around the planting hole may be used to retain water. However, care should be taken to keep the trunk base of upland species dry. Supplemental water is recommended in any situation where the plants will not have access to moist soil their entire first summer and is most critical for spring installed plants. If using mulch, avoid letting the mulch come in contact with the stem of upland species.

Mechanized planting machines might facilitate large-scale revegetation efforts and those occurring in rocky soil. Refer to the *Construction Considerations* section for more information.

5.4.9.5 Inspecting Bare-Root Materials.

Bare-root plants are typically shipped in tied bundles that are packed in moist material inside plastic bags within cardboard boxes. Upon receipt, open the boxes and inspect a sample of the bundles. Look at the plants on the interior of the bundle. Roots should be damp and plump, not dry, withered, shriveled, or slimy. If tugging gently on a root separates the skin from the core, the root is dead. Branches should be whole, not broken without leaves or open buds. A very small amount of fuzzy gray mold is acceptable as it is incidental and will disappear when planted. For short-term storage (up to a week), open the bags slightly to allow a small amount of air exchange. Make sure roots are well covered by damp but not wet material, and place in a cool, shaded location out of the wind. Nurseries will ship plants in batches according to your installation schedule, so longer term storage should only be necessary in case of project delay. For storage longer than a week, refrigerate the boxes or unpack them and "heel" them in, by placing the bundles of plants in shallow trenches with the roots covered with moist but not wet material. Work the moist material in between and inside the root masses so that the roots are completely surrounded by moist material. The tops of the plants are exposed, not buried. The "heeled" in plants must be in the shade and out of the wind. Roots must be kept moist and protected from sun and wind at all times.

5.4.9.6 Planting Bare-Root Materials.

Bare-root plants must be planted during the winter through early spring (western Washington) to mid-spring (eastern Washington) dormant season. The planting season may extend later if irrigation is available, but survival will be low if the buds have begun to open, even with irrigation. When planting, ensure that all roots are directed downward so that none bend up towards the surface, and make sure that the soil is gently firmed around the roots so that there are no air pockets. The best planting technique is to dig a hole with a shovel that is twice as wide as the root mass and just as deep. Create a small mound of soil in the bottom of the hole and place the plant on top with the roots arrayed evenly around the hole. Then fill the hole in while holding the plant upright. Firm the soil gently around the roots to eliminate air holes while watering. It is common but much less effective to use a planting bar, hoedad, or mattock to create a slit in the soil that the roots are placed into; the slit is then closed using the tool. Roots must be cut to the length of the tool to prevent bending the roots at the bottom of the slit. Bending the roots, or "J-rooting" will kill the plant. This technique forces the roots into a two-dimensional plane and does not create loosened soil for the roots to grow into. Shovel planting is slower but produces a better plant. Using an auger with a small diameter bit may be used if care is taken to obtain a hole depth appropriate to the planting material and to use the bit to loosen the soil surrounding the hole.

If circumstances dictate, create a trough or low soil berm around the planting hole to encourage retention of water. However, keep the trunk base of upland species dry. Depending on site conditions, irrigation is recommended during the first, and sometimes additional, growing season after planting. Avoid letting any mulch contact the stem of upland species. As with larger container plants, installing bare-root plants through erosion-control fabric requires that fabric strands be cut, thereby weakening the fabric. On particularly erosive sites, the advantages of bare-root stock over cuttings should be weighed against the potential for compromising fabric strength and integrity. Consult the fabric manufacturer for guidance on hole size and density.

5.4.9.7 Planting Salvaged Materials.

Plants salvaged by hand are replanted with hand tools and plants salvaged by machinery are replanted by machinery, frequently the same machinery that dug them up. While storage and/or transport of salvaged material are possible, the increased handling, especially for woody materials, tends to increase cost and reduce survival rates. The following salvage sequence is recommended:

1. Prepare the planting site (including digging holes if needed).

2. Salvage plants, by excavating as much of the root mass as possible and directly transferring the salvaged plant to the planting site with the soil and root mass intact.

3. Install the salvaged plants in moist soil immediately. Use the best management practice planting techniques described above in the sections on container or bare-root planting.

Minimizing transport of salvaged materials is key to their success and survival. Make sure the roots stay damp; they will dry out quickly if exposed. If the plants must be stored before replanting, they should be planted into containers (potted up) or handled as ball-and-burlap (B&B) plants. To B&B a plant, transfer the plant from the ground with the soil around its roots still intact onto a piece of burlap placed alongside the plant. Tie the burlap around the root ball with twine, keeping the soil intact. Whether potted or B&B, the plants will need a nursery level of care in the growing season, with irrigation, pest and disease control, browse protection, etc. Following planting, irrigation is advised.

Dormant-season salvage is best, November through February (western Washington) or through March (eastern Washington), although this is often not possible in eastern Washington due to frozen ground. Salvage can take place earlier or later if irrigation is available and the risk of somewhat lower survival is acceptable. Salvaging plants is most successful if plants are collected from moist soil conditions and planted on wet, cloudy days so that roots are less likely to dry out and soil is retained around the roots.

6 PERMITTING

Construction activities in wetlands associated with placement of fill (e.g., creation of hummocks in a reed canary grass stand) or instream work are subject to federal, state, and local permitting. Permits include Section 404 of the Clean Water Act, Washington State Hydraulic Project Approval, and potentially Endangered Species Act (ESA) and Shoreline Management Act approval. Developing alternative water sources may require a water right from Department of Ecology as well as ESA consultation if there are listed fish in the stream from which water is drawn. Herbicide application may also require the use of licensed applicators and ESA consultation if there are listed species that could be affected. The type of herbicide employed around water and the timing and method of application is also restricted. Contact the Washington Department of Ecology or the Washington Department of Agriculture for information regarding herbicide use in and around open bodies of water. Refer to the *Typical Permits Required for Work In and Around Water A*ppendix for more information regarding each of these and other permits that may apply.

7 CONSTRUCTION CONSIDERATIONS

Access routes, project timing, and type of equipment used should be selected to limit the impacts of heavy equipment on streambanks, floodplains, wet soils and stream channels. The risk of exposing equipment to flood events should also be minimized. See the *Construction A*ppendix for more details

7.1 Equipment

The project's scope and site conditions determine the types of tools required for installing riparian vegetation. Where soils are fine-textured, moist, and not overly compacted, plants can be installed with hand tools. Sometimes, however, it is more effective to use some type of mechanized planters to create planting holes, especially if long cuttings are being installed or if soil is coarse-textured or compacted. Conventional earthwork equipment, such as bobcats, backhoes, augers, excavators, and tree spades can be used to install riparian vegetation. Additionally, restoration practitioners have developed planting devices specifically for woody plantings. Some examples include the stinger, which is used for interplanting riprap; the ripper, used to plant cemented floodplain soils; and the water-jet stinger[32,33] which uses pressurized water to create a deep hole for planting long willows in fine textured soils. With the exception of the stinger, all of these devices were developed exclusively for planting cuttings. A variation of the stinger was developed that is capable of planting three-inch-diameter rooted-plant plugs. These tools are described briefly below.

7.1.1 Hand Auger

Hand augers are appropriate for planting containerized material along unarmored streambanks. Different sized bits can be used for different sized containers, from plugs to gallon-sized material. Small diameter bits can also be used to help plant cuttings in compacted soils where planting bars are difficult to use.

One person utilizing an auger can dig holes for several people installing plant material. Dig the holes only as deep as necessary for the type of material being used. Digging with an auger can cause the sides of the hole to become glazed, hampering root growth. To remedy this, lift the auger a few inches from the bottom of the hole and rotate the auger in a circle so the bit will loosen the soil around the planting hole.

7.1.2 Stinger Method

The stinger method makes it easier to plant cuttings in compacted streambank soils and riprapped banks. As an attachment to a backhoe or excavator, the stinger can push three to four inch-diameter cuttings into the soil to depths of up to approximately seven feet.[30,34] The Janicki stinger was developed in 1995 for the Washington Department of Fish and Wildlife to attach to the bucket of an excavator. It consists of a solid steel rod, approximately three to four inches in diameter that creates a pilot hole through coarse or rocky layers of streambank or riprap and stops when it reaches the softer, native soil underneath (subsoil). The finer subsoil serves as a rooting zone for installed willow or cottonwood pole cuttings. Cuttings are inserted into the pilot holes by hand and pushed down to the required depth with the heel of the bucket. Cuttings must be footed in moist subsoil and there must be a continuous tight fit between the cutting and the soil. The cutting should make its own hole through the native subsoil. No more than one-half of each cutting should protrude above the soil; six inches is recommended. This system has been used across western Washington with great success and eases planting in difficult conditions such as floodplains where water tables are as much as six feet beneath the ground surface or in streambanks with riprap layers up to five feet thick. The Janicki stinger can plant 40 to 50 cuttings per hour on average. Because the Janicki stinger can push the cuttings in only as far as the riprap surface, cutting survival may be low in thick layers of riprap, unless soil has been incorporated into the riprap matrix. For more detail, refer to http://www.plant-materials.nrcs.usda.gov/pubs/idpmctn8088.pdf.

A planting device similar in purpose to the Janicki stinger is the "expandable stinger," which consists of a pair of eight-foot-long, elongated probes that open and close, with an internal plant receptacle. This device was developed and patented by Dan Culley of Dayton Tractor in Dayton, Washington and is now available from Northwest Revegetation and Ecological Restoration (erniek@nwrer.com). Like the Janicki stinger, the expandable stinger also attaches to an excavator bucket. The cutting is placed inside the probe's plant receptacle with the tips closed to hold the cutting in place and the excavator drives the probe into the ground. Once the probe has reached the proper depth in the soil or riprap, the operator opens the probe (it operates hydraulically from the cab of the excavator), and the cutting is released. The probe is then removed from the hole; the probes are closed; a new cutting is inserted, and the process is repeated. The advantages of the expandable stinger over the Janicki stinger include:

- The cutting is protected at all times rather than being pounded into place, leading to higher survival rates.
- Smaller-diameter cuttings can be used. The probe can accommodate 1/2-inch- to four-inch diameter cuttings that are up to four feet in length. Larger cuttings may be held in the tip of the probe and driven into the soil.
- The "shear wall," a compacted wall in the planting hole created when planting tools are inserted into the soil, is minimized or eliminated. The probe tip of the expandable stinger has longitudinal ribs that break up the compacted soil around the walls of the planting hole as the probe is removed and allows the now-loosened soil to fill the hole. Without this feature, shear walls can be created, hampering the proper dispersal of roots and often resulting in poor or unsuccessful growth.

The expandable stinger is capable of planting in streambanks, floodplains and through riprap up to four feet thick. It has been used to plant 30 to 250 cuttings per hour, depending upon site conditions. This tool is especially useful in rocky substrates and can increase survival rates in these conditions.

A variation on the expandable stinger, also available from Northwest Revegetation and Ecological Restoration, is capable of planting three-inch-diameter rooted-plant plugs into unarmored streambanks at a rate of up to three hundred per hour.

7.1.3 Ripper Method

The ripper was also developed to facilitate revegetation efforts in cemented floodplain soils with deep water tables. It consists of a five-foot-long shank pulled behind a D-8 Caterpillar bulldozer or equivalent. The shank creates a narrow trench in the soil. Up to four workers drop cuttings into the trench from a platform on the tool bar of the ripper as it moves along. The ground may collapse under its own weight back onto the cuttings. More often, however, to ensure good soil contact with the cuttings, the operator must ride over soil mounded up to one side of the trench with the outside of the bulldozer track. The minimum width between trenches is the width of the bulldozer track, approximately four to five feet. Trenches are normally placed perpendicular to the stream or at a downstream angle. Advantages of the ripper include that it loosens the soil around the cutting to promote good root development, and the trenches of relatively uncompacted material can help to draw water from the stream to recharge the aquifer. Disadvantages include that it can be used only on large-scale projects, and the ground is left in a roughened state that may not be acceptable if immediate aesthetics are of concern or if disturbed soils are at increased risk of erosion. The ripper has been used to plant an average of 1,000 cuttings (up to six inches in diameter) per hour into cemented floodplain soils.

7.1.4 Water Jet Stinger Method

Another method to create a deep, narrow hole for long willow or cottonwood pole cuttings is the water jet method.[35] Unlike the stinger, this method is designed for sites with fine-textured soils, a low rock or gravel content, and relatively deep water tables. This planting system consists of a gasoline powered water pump that forces water from the nearby stream through a long rod with a special nozzle. The nozzle creates a pressurized flow capable of creating a six-foot-deep hole in approximately 20 seconds (in good conditions). The length of rod depends on the length necessary to reach the summer water table, but typically ranges from 3 to 10 feet. If the willow cuttings are promptly placed in the scoured holes, the slurry of saturated sediments within the hole will form a tight fit between the cutting and the soil, which increases cutting survival. For more information, see http://www.plant-materials.nrcs.usda.gov/pubs/idpmctn1083.pdf.

7.1.5 Construction Sequencing

Construction sequencing for riparian restoration activities must consider vehicular access as well as material placements to ensure efficient progress. A comprehensive sequence of the re-vegetation of a floodplain surface dominated by weedy plants may involve:

- Conduct weed control activities as directed in the site preparation plan.
- Excavate planting holes for plants in zone A-1 as shown on the plans.
- Install plants in zone A-1 and prepare soil surface in zone A-2 for seeding.
- Seed zone A-2 using access road through zone B as shown on plans.
- De-compact zone B to ensure soil density of haul road meets specifications.
- Construct temporary irrigation using hand crews in zone B.
- Broadcast seed mix and place erosion control fabrics per specifications in zone B
- Plant stem cuttings using hand crews in zone B as shown on the plans.
- Create as-built plan to document construction conditions and to prepare for plant establishment, maintenance, and monitoring.
- Erect site access barriers.

Heavy equipment must have access areas where necessary, but compaction caused by access should be minimized. Similarly, once soils are de-compacted, or seed, plants, or erosion control fabrics are in place, access by heavy equipment should not be permitted, as damage will occur.

7.2 Contracting Considerations

Use of volunteer work crews can be well suited to riparian restoration projects. If well supervised and trained, volunteer work crews can be a cost-effective means to install fences or plants, and monitor recovery, changes in landuse, or response to flood events on a modest scale. Another advantage to volunteer crews is that they can be directed on-site without having to adhere rigidly to a bid design and contract. And they can respond more flexibly to on-site changes. However, on larger jobs the efficiency and expertise of a contracted work crew may be more cost effective and easier to manage than a volunteer crew.

Contracts with paid work crews should allow for some “fit-in-field” adjustment if possible. This applies especially to planting efforts so adaptive management can respond to unanticipated field conditions such as unexpected soil types, flows higher than expected, changes in plant material availability, or slower construction/installation rates. Revegetation efforts may benefit from installation in phases, or over several planting seasons so that plant species are installed in proper microsites. One of the problems with low-bid contracts is that the contractor will want to stick closely to the bid design and will charge for any changes, which will reduce opportunities to respond to changed field conditions or increase expense.

Consider contractor bonding, especially on jobs bid with survival specifications. Some jobs are bid so that it is up to the installation contractor to ensure a certain percentage of survival of planted vegetation a year from the planting date. While percent survival and duration is often negotiated, many contractors may not want to come back and replace materials that died or otherwise failed to meet vegetation specifications. Bonding of the contractor will give the project proponent a sum of money to repair deficiencies if necessary.

8 ESTIMATING COSTS

Revegetation efforts are sometimes given a low priority in aquatic restoration projects because they are perceived to be expensive or natural regeneration is inappropriately assumed to be sufficient. Given the potential benefits of native revegetation discussed above, the costs are actually relatively low compared to many stream restoration activities, especially those that require work within the channel. General planning level estimates for reestablishing native vegetation on unvegetated flood prone surfaces typically run $0.15 to $3 dollars a square foot. More detailed costs of individual components are provided below.

Planting costs depend on the scale of the effort, required site preparation, planting technique (machines vs. hired hand labor vs. volunteer hand labor) and long-term maintenance costs. Direct costs include site preparation, plant materials and installation, and long-term maintenance. Indirect costs may include establishment and administration of easements, negotiation of dam water management, and fencing where livestock exclusion is necessary. Additional costs will be incurred if significant channel and floodplain restoration is required to restore a functional riparian hydrologic regime, for instance, if the stream is incised or the floodplain has been filled or levied. In some cases, revegetation costs are cheaper in the long-term, if extra money is spent initially to purchase better plant materials, install browse protection or implement an irrigation plan because of reduced maintenance and replanting costs

The following are approximate costs for woody plant materials. These represent wholesale material costs only and depend on the quantity ordered.

- 3 feet long willow cuttings - $1.50
- 6 inch diameter willow post - $25
- 10 cubic inch shrub tubeling - $0.90 to $2
- 10 inch herbaceous plug - $0.90 to $1.25
- 1-gallon container - $3 to $5
- 1 to 2 foot tall bare-root shrub - $.50 - $1.00
- Locally salvaged willow clump - $25; (includes labor and equipment to dig, transport and store on site)

Costs for installation depend on equipment costs, site conditions and the scale of the job. Labor costs vary depending on the project location. Table 11 provides labor time estimates for various kinds of planting work. These times can vary widely based on soil texture and compaction, access, weather, and other site conditions, as well as the experience, motivation, fitness, and supervision of the crew.

Table 11. Estimated labor time for various types of plant material.

Activity	**Per Person Labor Required***
Dormant posts[26]	10 – 20 posts/hour
Live stakes	20 – 60 cuttings/hour
Bare-root trees & shrubs	20 – 45 plants/hour
Bare-root herbaceous	35 – 65 plants/hour
Dormant tubers/rhizomes	45 – 100 plants/hour
1 gallon (#1) containers	12 – 20 plants/hour
5 gallon (#5) containers	2 – 10 plants/hour
10 cubic inch plug	45 – 75 plants/hour
Spread mulch by hand	1 – 2 $yard^3$/hour
Blow compost** on	200 $yard^3$/8 hour day
Install weed mats	15 – 20 mats/hour
Install browse protection tubes	12 – 18 tubes/hour
Seeding[26]	
Broadcast	0.05 – 0.5 acres/hour
Hydroseeding	0.12 – 0.37 acres/hour

* The lower end of the range is what might be expected on a typically difficult site or with an inexperienced crew and the higher end is what might be expected on an easy site or with an experienced crew. Excellent planting techniques are assumed.

**Hose can reach up to 600 feet. Use only fine or medium compost.

Approximate installed costs in 2004 for fencing per linear foot were $0.90 for 3-5 strand barb wire fencing in rangeland applications; $1.25 for woven wire rangeland fence; $1.15 for 3-5 strand barb wire fencing in riparian areas; and $0.50 for electric fence on fiber posts.

Bio-degradable erosion control fabrics used to protect seedlings and reduce surficial erosion typically cost $2 and $3 a square yard and an additional $2 to $3 a square yard to install. Installation includes key trench construction, backfilling, and staking as per manufactures recommendations. Browse protection and mulch cards can add an additional $1 to $2 per tree installed. Temporary irrigation systems can cost as much as $6,000 per acre. In some areas this cost can be reduced somewhat if irrigation lines and sprinklers are rented or reused at another site, although contractors may charge full cost even if their system is reused.

Alternative water source development costs for livestock excluded from the stream vary significantly depending on method. Examples of approximate installed costs include:

- 2 ft deep fiber tanks - $1.10 per gallon;
- 750 gallon troughs - $800;
- Pipelines from spring to tank including 1” diameter pipe, backhoe-dug trench, valves, and fittings - $2.50 LF.
- Livestock nose pump (www.nosepump.com) - $325

9 MONITORING

Monitoring should be scheduled at least annually and perhaps as often as quarterly, depending on the project age, site conditions, and monitoring goals. At least one monitoring should occur during the growing season when identification of plant species is easiest. Quarterly monitoring might be required for newly installed projects (especially arid sites), sites with heavy weed competition or sites with other threats. The objectives of a monitoring plan should be clearly specified, consistent with project goals, and linked to project maintenance. For specific details on vegetation monitoring refer to the *Monitoring Considerations* Appendix and Elzinga et al.[36] and Winward.[37] The monitoring plan should indicate the methods used to evaluate plant establishment and growth relative to design criteria (see Chapter 5.1.3, *Design Criteria for Project Elements*). Often descriptive monitoring data is sufficient to evaluate project success, identify problem areas, compare effectiveness of different treatments and provide guidance for subsequent maintenance. Photo points are an inexpensive, simple, and useful technique for monitoring riparian zone recovery.[36,37] In situations where quantitative data is required, care should be taken to determine the minimum sample size necessary to draw statistically valid conclusions. Following are additional recommendations:

- A newly installed site must be visited regularly the first growing season to check plants, control weeds and assess need for irrigation.
- Write success criteria so that volunteer desirable native plants also count towards meeting the criteria.
- Use of reference sites to compare to the restored sites is helpful in understanding how your project site is progressing.
- If experimental techniques are used, a sufficient portion of a budget should be set aside for monitoring, and quantitative monitoring may be justified to document the advantages/disadvantages of the technique.
- On sites where herbicides are applied, the monitoring area should include adjacent areas within “drift range” of herbicide application.
- Use photo points and brief memos taken seasonally to monitor the effectiveness of landuse changes such as grazing strategy, complete cattle exclusion, or changes in

mowing frequency.

- All monitoring activities should identify threats to project success.

Determining the success of riparian restoration projects may require monitoring for longer than project budget and management scenarios allow.[6] For example, development of a woody canopy can require decades for full recovery. Such monitoring is typically beyond a project's scope. Five to ten years of monitoring is a realistic goal and long enough to determine if the restoration effort is likely to have the desired results. Refer to the *Monitoring Considerations* Appendix for more information on developing a monitoring plan.

10 ESTABLISHMENT AND MAINTENANCE

Long-term streambank stability and habitat restoration require the establishment and maintenance of plantings. Establishment times vary, but typically require at least three years. During this period, young trees and shrubs are susceptible to drought, competition, mowing, and browsing/trampling by livestock and wildlife. To improve survival, project areas should be inspected regularly to identify problems and modify management strategies. This is especially important the first summer when new plantings are the most vulnerable. It is also important to involve those responsible for on-site maintenance. There have been numerous examples of maintenance crews mowing down new plantings.

Management that may be required for establishment and maintenance of plantings include:

Supplemental water. Watering needs will depend on soil texture, weather, and planting depth. In general, plants should be watered for at least the first growing season, or until plants develop root systems capable of reaching a depth where the soils are permanently moist. Watering heavily and infrequently encourages deep root growth for drought tolerance. However, small rootballs hold a small amount of water, so irrigation of newly installed plants must be frequent. Irrigated sites must be inspected frequently to ensure the system is functioning.

Fences. Temporary or permanent fences may be needed to exclude livestock, wildlife and/or heavy human and pet traffic from newly planted areas. Exclusion fences for wildlife, such as deer, elk and moose, must be significantly taller and more robust than those used for livestock. It is important to inspect and maintain fences to make sure there are no breaches; even short-duration grazing can severely reduce plant survival and trample plants.[5] Chaney et al. (1993)[38] provides information on the benefits of fencing, rotational grazing, and livestock access limitations.

Ungulate Browse Protection. Foliar repellents (such as DeerAway™), bud caps, mesh tubing or stem screens are needed to protect highly palatable species such as dogwood and willow from large mammal browse damage. Foliar repellents work best in arid areas where they are not washed away by rain. The Walla Walla Conservation District reports the best success with Plant Skyyd™ mixed a half cup of vegetable oil to one gallon of product and applied in ambient air temperatures of ≥ 50° F. See http://www.fs.fed.us/t-d/pubs/htmlpubs/htm01242331/index.htm for a paper that compares deer repellents. In cases of heavy ungulate use, fencing may be the only option. All methods may be less effective in flood prone areas subject to inundation and hydraulic forces of flowing water. The Internet Center for Wildlife Damage Management can be found at http://icwdm.org/.

Small Mammal Browse Protection. Rodent girdling is a common problem in open pastures and meadows. Materials for protecting plants include aluminum foil, arbor guards, plastic-tube plant protectors and/or chicken wire. Aluminum foil is practical to use only on small sites with regular maintenance. Plastic-tube plant protectors not only protect plants from rodents but they also shield plants from direct sun and wind exposure, retain moisture, and protect plants from mowers. At sites with large rodents such as beaver and muskrats, chicken wire fencing may be needed to protect plants during establishment. All protectors must be removed before they girdle the plants and this should be included in the estimated cost of restoration. The threat from rodents can also be lessened by reducing cover near the new plants.

Plant replacement. Before replacing plants that die, it is important to determine why the plants failed to establish and determine if another species might be more appropriate. Also consider if naturally colonizing plants may be meeting monitoring objectives and therefore plant replacement is unnecessary.

Weed Control. Weed control should focus on controlling or eradicating species likely to degrade the site or violate state/county regulations. Three to five years of regular control efforts are commonly needed. Recommended references include section *5.4.7 Weed Control*, local or state weed control board, and an excellent reference by Tu et al.(2001).[29] Sites prepared before planting with thorough weed control and mulching may need less weed control. However, this may not prevent weed problems if a nearby site is donating large amounts of weed seed to the project site (i.e. upstream reed canarygrass). Care must also be taken to prevent transfer of weed material on equipment. For guidelines see: http://www.dpiw.tas.gov.au/inter.nsf/themenodes/slen-5nu68g?open. If mowing is the only weed control method, it must be done regularly enough to hamper weed growth. For fast growing species like grasses, mowing will need to take place regularly. Mowing reed canarygrass only once or twice a year can actually increase density of stems (http://www.invasive.org/gist/moredocs/phaaru01.pdf). It is also important to note that large scale weed control occasionally opens a planting area to ungulate browse if not done in conjunction with fencing or other control measures.

11 EXAMPLES

The following figures show some examples of riparian planting.

Figure 4. Contrast in plant communities where livestock are excluded (right side of fence line).

Figure 5. Natural recovery of vegetation at Asotin Creek in Asotin County, Washington, five years after fencing livestock from the stream.

Figure 6. Revegetation project on Harrison Creek in Skagit County, Washington. Site was dominated by reed canary grass. Strips of ground were disked prior to planting to facilitate establishment and maintenance. Tubes were used to protect plants from small mammals.

Figure 7 Revegetation project in O'Grady Park in King County, Washington. Site was dominated by reed canary grass. Plantings occurred in patches across the site. Each patch was heavily mulched and surrounded by deer fence.

Figure 8. Revegetation project in Palouse County, Washington

Figure 9. New growth emerging from live cutting (left); Bare-root Ponderosa pine protected by plastic tube (right).

(b)

12 REFERENCES

Eastern Washington riparian restoration
Browse through the publications to find information on riparian vegetation and stream restoration for the Great Basin and Intermountain West Regions.
http://www.id.nrcs.usda.gov/programs/tech_ref.html#TechNotes

Wetland and riparian restoration in general
The NRCS has put a collection of their resources on two separate national web pages. Make sure the publication you're reading is applicable to your situation.
http://plant-materials.nrcs.usda.gov/technical/publications/riparian-pubs.html
http://plant-materials.nrcs.usda.gov/technical/publications/wetland-pubs.html

Genetics
Why do we care about genetics? University of CA, Davis
http://www.grcp.ucdavis.edu/projects/FactSheetdex.htm

Protecting plants from animals

Wildlife Damage Research at the National Wildlife Research Center in Corvallis, OR.
http://www.aphis.usda.gov/wildlife_damage/nwrc/field/oregon/indexor.shtml

Weed Control

The Washington State Noxious Weed Control Board http://www.nwcb.wa.gov/

The Nature Conservancy http://www.invasive.org/gist/index.html

Reed Canarygrass Management Guide: Recommendations for Landowners and Restoration Professionals ftp://ftp-fc.sc.egov.usda.gov/WA/Tech/RCG_management_0509.pdf

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TECHNIQUE 6

INSTREAM STRUCTURES

Instream Structures

1 DESCRIPTION OF TECHNIQUE

For the purposes of these restoration guidelines, instream structures refer to features intentionally placed in the stream or floodplain for habitat restoration. These features are often variously referred to as drop structures, vanes, porous weirs, roughened channels/constructed riffles, or boulder placements. Large wood (LW) and log jams that are placed for habitat complexity are technically considered instream structures; however, due to the many types of LW projects, the unique conditions associated with LW projects, and the frequency of their use, LW is covered as a separate technique. This technique does, however, cover drop structures, vanes, and porous weirs that may incorporate LW, but it does not cover other types of LW placements that are in common use; see the *Large Wood and Log Jams* technique for information on these other types of LW projects.

> The Instream Structures technique may be the main emphasis of a stream habitat restoration project, or it may be a component of a broader set of techniques implemented in concert. Prior to embarking on designs for specific techniques, the restoration practitioner should have already completed a site, reach, and watershed assessment to identify causes of observed or perceived problems, to determine constraints to addressing these problems, and to frame the project in the broader context of a watershed restoration strategy (Chapter 4). Because restoration practice is most effective when it addresses the root causes of problems rather than observed symptoms, a robust assessment that looks at potential causes at site-, reach- and watershed-scales will contribute to a more effective restoration strategy. In addition, design should only proceed when project goals, specific measurable objectives, and design criteria (Chapter 5) have been clearly defined and a restoration strategy has been developed to meet these objectives. A site- or reach-scale technique may ultimately contribute little if it is not consistent with overall watershed priorities or integrated with other techniques as part of a restoration project.

Instream structures encompass a range of materials, functions, longevity, and scale. The structural techniques included in these guidelines are limited to those that are most commonly applied to habitat enhancement projects and that have the potential to provide benefits to fish and wildlife when used appropriately.

Most structures can be sorted into categories that serve to characterize their general influence on stream processes and habitat. These include structures that:

- Control or limit vertical erosion or incision through stabilization of channel profile or by controlling sediment supply or inducing aggradation.
- Control or limit lateral erosion by offering bank protection.
- Create or modify habitat by inducing local scour or promoting hydraulic diversity.
- Modify flow conditions to direct or converge flow to create desired habitat conditions or to protect property or infrastructure in a habitat-friendly manner.

Considering the spectrum of structures presented here, as well as possible structures that are not specifically included in these guidelines, the purpose of this technique guideline is to provide general guidance on factors to consider when adding any structural element to a stream.

2 PHYSICAL AND BIOLOGICAL EFFECTS

2.1 Physical Effects

Structures placed in a stream channel will affect physical processes in the immediate vicinity of the structure as well as in upstream and downstream locations. Any structure placed in a channel or floodplain has the potential to affect the following:

- Hydraulics. Structures that come into contact with flowing water obstruct streamflow and force it to run over, around, or under the structure. This alters the concentration or expansion of flow vectors, and thereby affects velocity, depth, and shear forces associated with velocity and depth. Refer to the *Hydraulics* Appendix for details on how to model and predict hydraulic effects of structures. Any effect on hydraulics has the potential to affect other channel processes and habitat conditions.
- Sediment transport. Sediment transport is a function of sediment characteristics and hydraulic forces. The effect of structures on hydraulics, therefore, may impact sediment transport in the vicinity of the structure or upstream of the structure. Refer to the *Sediment Transport* Appendix for a discussion on sediment transport considerations.
- Bed scour. Structures commonly cause flow acceleration, which can lead to local bed scour. Bed scour may be a habitat enhancement objective, or may be an unwanted consequence. Refer to the *Hydraulics* Appendix for additional guidance on bed scour.
- Erosion and deposition. Bed and bank erosion is a function of local hydraulics and of the composition of the channel bed and banks. Erosion and deposition resulting from structures can be predicted using methods and tools presented in the Hydraulics and Sediment Transport Appendices.
- Channel planform and profile. Structures designed to decrease erosion may prevent alterations to channel planform or profile. Conversely, any structure that affects hydraulics and sediment transport will create the potential for affecting the course of the channel in planform and in bed elevation. These effects may be difficult or impossible to predict.
- Wood recruitment and transport. Structures that affect erosion can also affect wood recruitment that occurs in association with bank erosion. Similarly, they may affect transport or retention of wood by catching wood.

2.2 Biological Effects

Structures are typically used in portions of streams that have been determined to have limited natural tendencies to foster the new development of, or the ability to maintain, existing natural habitat features. For example, structures are often placed to improve the habitat variability for fish in otherwise uniform flow conditions. They are also commonly used to reduce the frequency of scouring events along a channel boundary or increase the frequency of floodplain inundation to foster growth of planted riparian vegetation. Most structures can be categorized by their primary function with respect to how they influence the character and availability of habitat:

- Altering channel substrate conditions to favor a particular species of fish by causing aggradation, scour of existing substrates or by direct placement of substrates.
- Altering inundation frequency and duration of near bank and floodplain areas, thereby affecting plant growth and natural selection and availability and character of refuge.
- Improving vegetative growth along channel banks by limiting bank erosion or shear forces.
- Creating channel complexity and associated habitat complexity by splitting or converging flow into/out of separate channels or indirectly by recruiting and capturing floating woody debris.

The degree to which placed structures achieve these desired biological goals depends on the interactions among a number of parameters, including:

- Riparian vegetative community composition.
- Fish and wildlife community composition.
- Existing streambed and soil composition.
- Hydrologic and geomorphic processes.
- The length of time a structure is expected to perform a function.

Structures are frequently designed and placed as fixed, static elements with outcomes that may achieve an initial function but that become inappropriate or even harmful to habitat as conditions change. This is particularly problematic given the continual successional changes that biological communities experience. For example, late successional vegetative communities tend to result in an increase in channel stability. Will a rock structure placed for bank stability along a stream with early successional vegetation become an undesirable geologic feature once the vegetation recovers? Using structural placements out of context with biological community characteristics inevitably leads to failure or features that are useful only for short durations.

3 APPLICATION

3.1 Appropriate Use of Technique

Structures are placed in a stream or floodplain to improve habitat where it is deficient or for stabilization of the streambed or banks. Placed structures are often intended to serve as analogs to otherwise naturally occurring features. Structures are most appropriate in streams with significant human alteration where natural functions are impaired and are unable to create adequate habitats on their own. This includes urban streams, rural channels with significant human use or development of the floodplain, or streams with fundamental and on-going alterations to hydrology, LW, or sediment inputs. Other examples include stream reaches managed by flood control agencies to protect residents from flooding or where dams are used to regulate flow conditions for agriculture or water supply. Human management of these waterways often circumvents or critically alters natural processes that provide or maintain habitats. Structures in these locations may be necessary and appropriate, particularly where grade control is warranted to protect against channel incision, where lateral control is needed to protect important human infrastructure, or where instream habitat is lacking and is no longer being provided naturally.

Structures should be used with caution in dynamic, alluvial environments. Because many structures are designed to be relatively static, they are best used in areas that are naturally stable or where natural dynamics are constrained by human influence. Placing structures in settings that are highly dynamic may lead to failure of the structure, or conversely, may result in structures that are grossly overbuilt in order to prevent their failure. Alluvial environments by definition are constantly moving, therefore, the life span of a fixed or static feature is short unless it is designed to deform at the same rate as the surrounding environment. Placing fixed structures in a landscape in motion simply means the design life or effectiveness of the approach will be short lived. In areas where natural vegetative and channel successional processes dominate stream conditions, structural treatments should only be applied or considered as temporary measures.

The application and performance of any given structure type is highly dependent on the context in which it is placed. Structures placed outside of the proper geomorphic, hydrologic, and biological context will have a high risk of failure in accomplishing objectives. Take, for example, a pool feature in a steep step-pool stream, which is formed through different hydraulic mechanisms (i.e. flow over boulder steps) than a pool in a low-gradient alluvial stream (i.e. lateral scour at meander bends). Attempting to create pools in an alluvial stream using boulder drop structures would therefore be out of context with the geomorphic setting and would be prone to failure. Habitat structures placed within the proper context will support natural processes and habitat, whereas structures placed out of the proper context will risk failing to accomplish restoration objectives.

Though instream structure placements can be successful for certain goals or objectives [1], caution should be taken to avoid the tendency to: 1) focus on the symptoms of habitat degradation rather than the cause, 2) act without full understanding of the needs of affected fish and wildlife communities,[2] or 3) provide benefits for a specific target fish species at the expense of other fish and wildlife.[3] As a result, benefits may be temporary or limited because the treatment does not fully address the factors that limit ecosystem recovery. In addition, incorrectly designed or constructed structures are prone to failure, may become barriers to fish passage and can cause further ecosystem degradation.[4,5]

3.2 Structure Types and Functions

Structures can have numerous forms and functions but can generally be categorized within the following types: drop structures, porous weirs, roughened channel (constricted riffles) and boulder clusters. Table 1 summarizes the functions provided by the various types of instream structures.

Table 1: Functions provided by instream structure types.

Function	**Drop structures / porous weirs**	**Roughened channel / constructed riffles**	**Boulder clusters**
Restore step pool morphology to an altered channel	X		
Limit or stop channel incision	X	X	
Limit or stop bank erosion	X		
Create structural and hydraulic diversity in uniform channels	X	X	X
Change the sediment deposition/scour characteristics of a reach	X	X	X
Scour the channel bed, maintain pool features	X		X
When used in a series, provide fish passage over barrier drops	X	X	
When used in a series, elevate incised portions of channel	X	X	

Drop structures

Drop structures include weirs, vanes, sills, check dams, and log drops. Drop structures create a distinct drop in water surface elevation over the structure (see Figure 1 and Figure 2). They can be utilized to provide grade control, redirect the channel thalweg, control channel alignment in confined areas or in proximity to infrastructure, alter and maintain the width to depth ratio of the channel, protect an eroding or sensitive streambank, create and maintain a scour pool for fish habitat, concentrate low flow into a deeper, narrower channel to improve fish passage in otherwise flat-bottomed channels, backwater the upstream channel (to increase riffle water depth, provide fish passage over barrier drops, provide water to diversions, or other uses), and encourage sorting of sediment at the pool tailout.[6,7] Drop structures can be made of a variety of materials including boulders, gabions, concrete, steel, or wood. Drop structures may be full or partial channel spanning and may extend into one or both banks and into flood prone areas. They may be oriented in many potential directions relative to flow and the orientation may even change (e.g. zigzag) along their length. For most applications, orientations range from perpendicular to the channel to an upstream angled arch or “V”. Elevations along the weir crest relative to the channel bed vary considerably; some may parallel the bed topography, whereas others may have considerable deviations. Drop structure widths (i.e. upstream to downstream) are typically narrow; in the case of sheet pile weirs, they may be fractions of an inch thick. Boulder weirs, on the other hand, may span several grain diameters.

Figure 1. Rock weir. Cedar Creek, WA.

Figure 2. Log weirs. Hylebos Creek, WA.

Figure 3. Rock vane. Tucannon River, WA

Porous weirs

Porous weirs are low-profile structures typically comprised of boulders that span the width of the channel. Collectively, the boulders within a porous weir redirect flow by concentrating water between individual rocks. Porous weirs are typically arranged to form an upstream-pointing arch in plan view, with their lowest point located at the apex of the arch. Porous weirs may be utilized for many of the same functions as drop structures; however, they are not typically used to significantly raise the channel bed enough to steepen its profile. Although similar to drop structures in appearance, porous weirs are designed with spaces between boulders that allow water, sediment, fish, and other aquatic organisms to move through the structure. Conversely, drop structures are typically continuous, solid structures without gaps or openings. As a result, porous weirs are less likely than drop structures to present a passage barrier to fish and other aquatic species. The principal purpose of a drop structure is to control channel-bed grade, whereas porous weirs are used primarily for flow redirection and to increase channel complexity through scour and sorting of sediment.

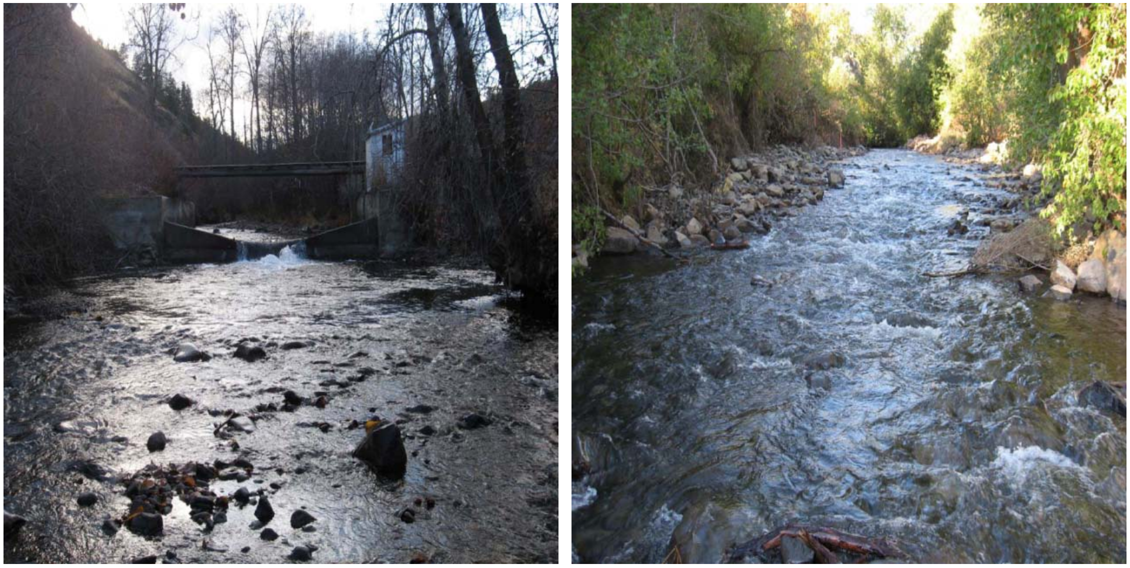
Figure 4. Porous boulder weir. Cedar River, WA.

Roughened channels or constructed riffle

Roughened channels or constructed riffle structures are typically designed to armor a reach of channel bed and/or to mimic natural riffle features in a stream (Figure 5). They are similar to drop structures in that they span the channel and can have a variety of orientations and elevations. They differ in that they typically span a longer distance along the channel and do not create an abrupt drop in water surface elevation. They are usually built with rocky materials that vary in size and thickness. These structures are generally constructed to provide grade control while retaining fish passage, maintaining characteristic pool-riffle sequences, and providing the ecological benefits (e.g. insect production) of natural riffles.

Figure 5. Fish barrier dam (left) replaced by roughened channel / constructed riffle (right). Johnson Creek, OR.

Figure 6. Diversion weir (left) replaced by roughened channel / constructed riffle (right). North Fork Ahtanum Creek, WA.



Boulder clusters

Boulder clusters are groups of boulders placed in the stream channel to provide hydraulic roughness, habitat diversity, and velocity refuge for aquatic biota. Boulder clusters can be placed directly on the streambed or partially buried within the bed to increase stability. They may be placed in various portions of the channel depending on habitat objectives and stability considerations. Boulder clusters are typically designed to provide velocity diversity under a variety of flow conditions in a reach of otherwise uniform velocity. They are not channel spanning and do not provide channel grade control. In some cases, they may be used to help divert flow, create localized pool scour, and trap and sort sediments.

Figure 7. Constructed boulder clusters in Hylebos Creek, King County, WA.

4 RISK AND UNCERTAINTY

4.1 Risk to Habitat

Placement of structures in a stream channel involves a significant degree of inherent risk due largely to the uncertainty of future events and the limits of our ability to model and predict the response of the channel to placed structures. Instream structures have the potential to adversely impact existing habitat by altering channel processes such as sediment transport, scour, and deposition. Depending upon the channel size, bedload movement, and particle size, it may take time for the channel to adjust to a new structure. In the adjustment period, spawning areas may scour or accrete, and any eggs or alevins in the bed could be impacted. Relative to other habitat-enhancement options, instream structures tend to provide uniform habitat features with little diversity, especially if placed in a series.

Because instream structures frequently create an abrupt change in water surface elevation that did not historically exist, a risk exists of creating a migration barrier to fish and other aquatic organisms. Although structures are sometimes placed to increase passage for a target species or age-class of fish, the impact on non-target species or age-classes should be evaluated. Where structures enable fish species to gain access to areas they do not currently inhabit, they could significantly alter predator, prey, and competition relationships among the existing resident fish species. These effects should be given careful consideration.

During construction, there are frequently short-term negative impacts to the stream environment in the form of increased turbidity, temporary loss of habitat as flow is diverted, and loss or disturbance of vegetative, invertebrate, and vertebrate life forms within the reach. Construction impacts will need to be minimized for the project area and for access and staging areas by implementing best management practices for sediment control, dewatering, and fish rescue. Follow-up reclamation and restoration measures may be needed. Consideration should also be given to the potential habitat impacts to source areas for boulders, logs, and other materials. This is particularly true of materials sourced from the project site or nearby riparian sources. Even materials derived from upland source areas can create local impacts as well as impacts that eventually manifest downstream.

4.2 Risk to Infrastructure and Property

Similar to risk to habitat, structure placement presents risks to infrastructure and property due to the uncertainty of future events and the limits of our ability to model and predict the response of the channel to placed structures. Risks are often amplified in locations heavily managed by human efforts. Given that structures are most suited to these locations, extra care and due diligence during the design process is warranted.

Instream structures have the potential to greatly increase channel scour or aggradation processes within the channel bed and along channel banks. Designs that place instream structures near or immediately upstream of piers, culverts, or other infrastructure need to be carefully considered, as resulting scour may undermine structure footings and aggraded sediments may reduce flood conveyance.

Property boundaries are often defined by channel banks or along a location mid-stream. Structures that alter these property boundary locations can affect property ownership, even if the ownership boundary is one of common understanding. Consider the situation in which two owners both own to the middle of a stream; what happens when the stream moves due to protection along only one side? In addition, structures that create significant upstream backwater can place upstream property and structures at increased risk of flooding and erosion. Weir structures that are constructed too high across the channel or that direct flow toward the channel banks rather than toward the center of the channel can result in significant bank erosion and potential loss of property. These risks can be significantly reduced by evaluating design scenarios through detailed water surface modeling (refer to *Hydraulics* Appendix).

Structures can also trap and retain floating debris and then catastrophically shed these materials in mass during high flow events. Floating debris is a major concern in areas of public infrastructure as it presents clear threats to downstream infrastructure. Accumulated materials can also reduce flood conveyance thereby affecting local flood elevations.

4.3 Risk to Public Safety

Many of the potential risks to public infrastructure mentioned above also pose risks to public safety. For instance, if a bridge pier is undermined, not only is the bridge at risk but so is the public that uses the bridge.

Most safety issues associated with instream structures have to do with stream-based recreation, including fishing, swimming, and boating. Recreational users frequently access or travel along streambanks by climbing over bank features. Placed structures can inadvertently create slipping or falling hazards to these users. Instream structures can create entrapment hazards for boaters and swimmers. This is especially true if placed materials have not settled well since installation and therefore create voids and gaps between them. Drop structures that create a significant change in water surface elevation, such as may occur during high flows, may create a flipping hazard to boats. Structures that trap woody debris may also provide entrapment and pinning hazards to boaters and swimmers. In some cases, the restoration objectives of instream structures may be compromised if recreationalists modify them to enhance conditions for swimming or boating.

Refer to the *Public Safety* Appendix for other considerations and further discussion regarding Public Safety.

4.4 Uncertainty of Technique

The uncertainty with accomplishing restoration objectives varies widely depending upon specific project conditions, including amount of available data, level of analysis detail, channel response characteristics, hydrologic variation, potential for disturbance events, and the level of knowledge of the biologic response. These conditions are very site specific and therefore adequate design investigations for every project must be conducted. Consideration of uncertainty during the design process is important. Uncertainty is determined during the analytical part of the design. The analysis should be used to determine that an outcome is clear and unequivocal or is more of a best guess based on professional judgment.

Use of uniform design guidance may increase uncertainty in some situations. Successful installation of a structure at one location on one stream does not assure the same success of a similar structure on another similar stream. Thus, relying solely on uniform design guidance that does not consider the specific conditions of the target stream will increase uncertainty in structure performance. There may be particular uncertainty in outcome of placing rigid instream structures in dynamic alluvial environments. This is because such features are out of context with the geomorphic setting of the stream and the effects on alluvial channel boundaries will be difficult to predict.

Instream structures can be designed and constructed with a high degree of certainty for intended function, structural integrity, and longevity. For example, vane structures installed in the 1950s (and earlier) to maintain navigation depth in the Columbia River are still operational today. If properly constructed and maintained, it is reasonable to expect that these structures will serve their intended function for many years to come. In Spain, diversion weirs dating back to the Roman Empire are still functional (albeit regularly maintained) today.

Uncertainty in any instream design or management endeavor stems from numerous sources. For a comprehensive discussion of uncertainty and risk as it relates to stream habitat projects, refer to RiverRAT Appendix 3.5 – Uncertainty and Risk.

5 METHODS AND DESIGN

5.1 Expertise Required for Design

Specialized expertise will be required depending on the processes being analyzed. For example, a project intended to affect sediment transport through a reach may require detailed analysis of flow durations, sediment supply, and the application of analytical methods only familiar to professionals with specialized training in these fields. Required expertise will also be a function of the risk imparted to property, infrastructure, public safety and the environment due to both the presence and potential failure of the structure. For example, if failure of a structure has the potential to compromise the integrity of a high-pressure sewer line, the designer will need to have experience not only with stream hydraulics and scour, but also with the physical qualities of the sewer line materials and their ability to withstand calculated forces.

Less expertise may be required in some cases, especially for small projects in remote areas where little is at risk if the structure fails. Project design in low-risk settings may be effectively conducted using an analog approach (see more on this approach in Chapter 5, *Designing and Implementing Stream Habitat Restoration Techniques*.) by individuals familiar with stream processes, fish habitat requirements, and an appreciation for the unpredictability of the natural environment.

Caution should be taken when selecting structure types and applying generalized design guidance provided by design manuals. This design guidance may not always be applicable to the project stream. Although generalized guidance may be helpful as part of design, it should be considered only one of multiple approaches used in combination to develop project designs.

Generalized guidance should not substitute for due diligence on behalf of the designer, especially in high risk settings.

Stream restoration designers need to be aware of regulations and requirements that govern the design and installation of structures, particularly as it relates to engineering. The State of Washington defines engineering activities as "*any professional service or creative work requiring engineering education, training, and experience and the application of special knowledge of the mathematical, physical, and engineering sciences to such professional services or creative work as consultation, investigation, evaluation, planning, design and supervision of construction for the purpose of assuring compliance with specifications and design, in connection with any public or private utilities, structures, buildings, machines, equipment, processes, works, or projects*". Instream structure placement in streams will generally require engineering expertise as well as expertise from other disciplines. Engineers, geologists, ecologists,hydrologists, landscape architects, fishery biologists, and other professionals typically involved with stream work all have accreditation organizations with their own professional standards and requirements of due diligence. The designer should also be aware that licensing requirements may apply.

5.2 Developing Design Criteria

Design criteria are specific, measurable attributes developed to meet and clarify project goals and objectives. They are established at the outset of a project and are used to guide the design process. Design criteria provide numeric limits of project performance and tolerance, and serve as a design target for performance of project elements. Once design criteria are established, site investigations and analysis can be performed in order to determine if and how the design criteria can be met at the site. Based on these analyses, the appropriate elements (i.e. structure types and configurations) are then developed into project designs and specifications.

It is fairly common now for an instream project to cost many hundreds of thousands of dollars and affect a wide variety of stakeholder groups. Landowners, fish enhancement groups, tribes, natural resource agencies, and others may be closely involved. Steering committees are frequently formed to develop the goals and objectives and to oversee design. Early involvement of these groups is essential for the success of the project. Input from stakeholders should be obtained at the outset of project planning. This input can be crafted into project objectives, upon which design criteria are based.

Design criteria are further discussed in Chapter 5. Additionally, RiverRAT Appendix 2 – Design of Stream Channels, provides detailed discussion and examples of design criteria for a variety of stream restoration project elements that may include structures.

Common categories of design criteria for instream structures are described in the following sub-sections.

5.2.1 Physical and Biological Response

Defining physical or biological response criteria will be an important component of most instream structure projects, especially where the goal is enhancement of physical habitat or biological conditions. Physical response criteria might define desired levels of bank erosion, scour, flow velocity, backwatering, or sediment deposition. Biological response criteria might define levels of rearing cover, spawning capacity, insect production, or fish passability.

If the intent of the project is to increase salmonid spawning utilization, then design criteria might define requirements for water depths, velocities, and substrate sizes during the spawning season. If the intent of the project is to enhance salmonid juvenile rearing, then design criteria might focus on temperature, velocity, cover, and food resources. Design criteria for bank erosion projects might include desired levels of bank stability, maximum toe scour, and maximum tolerable velocities along the eroding bank. Fish passage design criteria might include maximum drop/jump heights, plunge pool depths, rifle depths, and velocity at defined flow levels.

5.2.2 Design Discharge

Design discharges are relevant to many aspects of design, including structure stability and desired habitat effects at specific times throughout the year. Most structures are intended to remain stable up to some return-interval flow deemed appropriate according to project objectives for structure stability. In urban settings, this may be the 50-year flood or some other infrequent flood event based upon the life expectancy of the project. Discharge criteria may also be specified in order to satisfy fish and wildlife needs at certain times of the year. It may be appropriate to develop a suite of design discharges in order to satisfy multiple objectives for a single structural element. For example, the design criteria for a structure installed to provide fish passage through an upstream culvert might need to withstand a 100-year flow without failure to provide continuous passage and preserve the integrity of the culvert and roadway. However, a need may also exist to provide for fish passage during low flows and specific seasons. Timing and discharge requirements for aquatic species will vary depending on the target species and age class (e.g., fish passage requirements for adult chum salmon will differ greatly from that for juvenile coho salmon). However, designers should be encouraged to consider the needs and limitations of all fish and aquatic life whenever possible so as not to benefit one species at the expense of others.

Design criteria should also consider the future discharges that may be needed to create and maintain habitat conditions over time. Certain benefits associated with instream structures (such as cover or shelter from fast moving currents) are available to fish and wildlife immediately following installation. However, other benefits (such as maintenance of pool scour, stabilization of channel profile or planform) require hydraulic forces during high flow events before they are realized. To effectively evaluate and monitor for project effectiveness, design criteria should clearly specify the flow conditions (and their recurrence probabilities) that will be necessary to create and maintain habitats over the long-term.

In general, structures capable of redistributing sediment and wood should be designed to function for the range of flows that constitute effective discharge. The *Hydrology* Appendix provides discussion and guidance on how to determine various design flows, including channel-forming and effective discharge.

Any flow prediction is accompanied by uncertainty. Even long periods of record for gauged streams cannot predict future flow events perfectly; a fact that became clear during the flood season of 2007 throughout the State of Washington. Experienced designers sometimes forget the effects of big flows after a few years, and young designers may have never seen a large flood event. The uncertainty associated with developing design discharge is manageable for frequent events, but it may carry a larger risk for large rare events.

5.2.3 Design Life and Deformability

The design life for a structure refers to the expected life span of the structure, and will vary with the application and materials used. Some structures may be temporary features intended to fill a function until natural processes or conditions are restored. In contrast, mitigation projects may be required to last as long as the impacts for which the mitigation is required. Structures implemented in locations with public infrastructure may require extensive design life considerations due to potential effects on the infrastructure and/or the design life of the structure itself. Design life should not be confused with stability criteria, which typically define the maximum flow conditions under which structures are intended to remain stable, regardless of their age.

Most designers relate design life of an installed structure to the ability of that feature to perform its desired function over a designated period of time; for example, the length of time a particular structure will provide habitat for fish. If the surrounding hydraulic forces change over time due to growth of vegetation on the banks or a shift in the channel, the structure’s performance may change prior to the end of its design life. Potential channel adjustments like these need to be considered, especially for projects where modifying successional trends in channel shape and vegetative communities are part of the objectives.

Criteria for design life typically have to do with setting specific requirements for rates of material decay, with consideration of half-lives or other measures of functional use. For example, criteria for erosion control fabrics might include the length of time the fabric is necessary and the strength it must have at the end of this life span. Regardless of how criteria are developed, they need to consider the long-term fate of a feature based on material composition as well as the potential fate based on potential long-term channel and vegetative changes.

A particular challenge in establishing design criteria for an intended design life is the uncertainty associated with future flow events. A structure intended to remain stable for 10 years may be subjected to a 20-year, 50-year, or 100-year flow in any year following installation. Design criteria for design life, therefore, typically require both an intended design life and a stability criterion related to flow. For example, a structure may be expected to last 10 years, but only up to the 50-year flow; at higher flows or after 10 years, deformation of the structure would be expected.

Structures are typically designed and constructed to be relatively non-deformable, meaning that they persist as constructed for as long as the materials remain sound. Alternatively, they can be designed to eventually deform through undermining, entrainment of structural components, or degradation of components. Deformation generally occurs during high flow events that exceed a specific design flow.

Design criteria for deformability typically specify what the deformation will look like (e.g. movement of part or all of the structure) and what is an acceptable rate of deformation. For example, a constructed riffle may be designed to deform or move during a 5-year event because the lateral boundaries containing it are judged to be subject to deformation at that same time.

5.2.4 Design Constraints

Besides developing design criteria, it will also be necessary to identify design constraints. These can be thought of as a form of design criteria that place limits on the design. In some cases, design criteria may conflict with constraints; these conflicts will need to be resolved as part of the design process, which may entail modifying project objectives in consultation with stakeholders. Although it is important to explicitly define any potential constraints at the early stages of planning, designers should be cautious with making assumptions with respect to constraints. Cases may exist where something initially seems unfeasible (e.g. social acceptance of placing a structure in a stream) but later turns out to be possible.

Constraints may be associated with various stages and components of a project. Examples include the following: 1) where there may be risk to the public during construction activities, criteria may be necessary to determine when and how construction proceeds, and what safety measures will need to be taken; 2) there may be constraints associated with acquisition of materials that are impractical to obtain or transport; 3) constraints imposed by narrow in-water work windows or by low-flow thresholds needed for construction may delay construction or stretch the work efforts beyond one construction season; 4) inadequate access or material staging sites may limit construction scheduling or efficiency; 5) grant funding may direct a portion of the effort to be utilized by volunteer groups; 6) plants for re-vegetation efforts may need to be grown for several years prior to implementation to assure adequate supplies. These types of logistical constraints should be carefully considered and documented as criteria for the design team.

5.3 Data and Assessment Requirements

Data and assessment requirements include information derived from physical, biological and socio-cultural attributes of the project area. This information provides the design team with the foundation for decision making. The following data and assessment requirements are only a generalized list for consideration; other investigative needs may be required. More investigation is typically required for larger, more complex projects and projects located in high risk environments. However, in general, each of these areas should at least partially be investigated regardless of how big or small, simple or complicated a project might be.

Physical data and assessment requirements:

- Geomorphology: Determine project and reach-scale channel type, valley setting, sediment characteristics, large wood processes, air photo analysis of planform changes, trends in channel incision or aggradation, and effects of land-uses on channel processes.
- Hydrology: Compile primary descriptors of the flow regime, including the magnitude, frequency, duration, timing, and rate of change of stream flow including any information on flood history.
- Topography: Obtain topographic data from either a ground-based survey or photogrammetry. Survey data will typically include slope/profile, planform mapping, cross sections, property boundaries, and other human or natural features that might affect project design.

- Hydraulic analysis: Conduct hydraulic analysis using modeling or other accepted methods in order to characterize existing hydraulic conditions and to determine the hydraulic effects of proposed structures. The hydraulic analysis will incorporate topographic, hydrologic, and vegetative data. Verify or calibrate results using observed water surface data where available.
- Sediment transport analysis: Collect information on sediment volumes and grain size distributions. Use this information in conjunction with the hydraulic analysis to characterize existing conditions and to determine the effects of proposed conditions on bank erosion, bed scour, deposition, and spatial organization of bed sediments.
- Geotechnical analysis: For bank stability projects, gather information on soils and their susceptibility to erosion. Use this information in conjunction with the above investigations to characterize existing and proposed conditions.

Biological data and assessment requirements:

- Botanical characteristics: Compile information on existing vegetative community conditions relative to inundation frequency and wetland indicator status. Any invasive species found on-site as well as basin-wide need to be documented (e.g.. Japanese knotweed infestation).
- Fisheries characteristics: Compile information on existing fish communities (both native and invasive) and their life history requirements, including season of use.
- Wildlife characteristics: Compile information on existing wildlife communities (both native and invasive) and their life history requirements, including season of use.

Socio-cultural data and assessment requirements:

- Land ownership: All adjacent property owners must be identified as well as other landowners that may be affected by the project. Easements or other conditions/limitations of landownership that might affect the project should also be identified.
- Existing infrastructure: Human features including structures, utilities, earthwork, and land-management practices should be located and mapped. This includes houses, roadways, bridges, water and sewer lines, pipelines, dams, diversions, fences, ditches, or other miscellaneous infrastructure.
- Historical or archeological features: Obtain maps or otherwise identify features with historical or archeological significance. A professional archeologist is often required where native sites are involved and the State Historical Preservation Office may need to be notified for altering historic structures (e.g. a dam, bridge or historic building).
- Public safety: Identify recreational use types, including seasons and frequency.

Analysis will typically require collaboration across multiple disciplines and the use of findings from one area of investigation for the analysis of another. For example, the hydraulic analysis of existing conditions may require using information gathered from the geomorphic, hydrologic, topographic, and botanical investigations.

Further discussion on gathering data and selecting assessment procedures is provided in Chapter 5 and specific guidance on data and assessment is provided in respective Appendices on Geomorphology, Hydraulics, Sediment Transport, and Hydrology.

5.4 Design Components

Individual design components will vary depending on specific project conditions; however, all projects generally follow a similar design process. Refer to Chapter 5 for a discussion of the design process as it relates to specific project elements, as well as to integration of design elements.

For instream structure projects, design begins with development of a thorough understanding of existing conditions, which is obtained by completing the investigations mentioned above in Section 5.3. The existing conditions hydraulic model provides a basis to begin applying various alternatives into design trials. Following each trial, results are measured against the design criteria to determine the best fit. Typically, these trials are done within a hydraulic model that can predict water velocity and bed shear values as well as inundation patterns within the project boundaries. Each trial adjusts various configurations or placements of each structure until the design criteria are met.

This iterative design process creates a variety of feedback loops whereby physical parameters are adjusted that affect biological parameters. The increase in elevation of a weir, for example, might result in increasing the frequency of inundation of the floodplain, which would then impact the vegetative community, perhaps favoring one vegetation type over another. Another example would be adjusting the elevation of a structure in order to reduce bed shear stress values that would favor the deposition of spawning sized gravels. The permutations are many (as multiple variables are at play); however, recall that ultimately, the final project configuration should be determined based on how well the design criteria are satisfied.

Specific analytical considerations for structures placed in stream channels commonly include:

- Hydraulic effects of the structure: Paying particular attention to the change in flow direction and force over a wide range of flows and implications for channel response.
- Scour depth associated with the structure’s influence: Consider the depth to which the channel bed and substrate may be eroded over the range of anticipated flows, and the structure’s impact on local scour around and under the structure.
- Anticipated aggradation associated with the structure’s influence: Consider the extent to which the bed and substrate may be changed over the range of anticipated flows, and the structure’s impact on local aggradational influences that may be propagated upstream due to backwater caused by the structure(s).
- Drag forces on the structure: Determine the loading placed on elements of the structure due to its effect in obstructing flow over the range of discharges. This is particularly important for structures that extend into high velocity areas of the channel.
- Buoyancy forces: Calculating this is particularly important for wood that may be submerged as the effect of buoyancy may compromise structural integrity.
- Materials used for construction: Consider the composition and size of structural materials relative to native materials. Are the materials appropriate within the context of the

setting? Are they more or less deformable than the native, *in situ* materials, and what are the implications for channel response?

- Flood or inundation impacts of the structure: Determine the impact on water surface elevations over a range of flows, related inundation frequencies, and effects on shear and scour across the channel. What are the effects on regulatory flood elevations?
- Channel adjustment: Perform an analysis of possible avulsion routes that may result from the project during its life span. This is particularly important for streams that have aggraded or are prone to lateral migration.
- Safety: Consider public safety (including recreational users)-see the *Public Safety* Appendix for public safety considerations.
- Design life: Determine how long the structure is required to function. Always consider what is likely to happen to the structure after it has ceased to be functional.
- Failure mode: Consider the forces acting on the structure and potential channel adjustment processes that may result in failure. Consider potential upstream disturbances (e.g. floods and debris flows) that may lead to failure.

Structures placed as fixed objects within an alluvial channel tend to generate significant and uncertain channel response and may be prone to physical failure. Many of the reference materials that offer design guidance for structures focus only on the intended effects of the structures (e.g. bank stabilization or pool formation), but do not offer guidance on how to evaluate whether or not the structure will be maintained in the channel given site hydraulics and fluvial geomorphic processes. Unfortunately, much of the design guidance does not acknowledge that hydraulic modeling is very useful for determining effects of structures and is essential as part of a comprehensive approach when used with a set of design criteria to guide the outcome.

Following are general considerations for a suite of design elements. This information is intended to assist the design team in conducting an iterative design process.

5.4.1 Materials

Structures are typically constructed using rock or logs, although sheet pile, wood planks, concrete, and other artificial materials are sometimes used. In general, structures constructed in a stream dominated by large wood should be comprised primarily of wood, whereas those in a boulder dominated stream can be comprised of rock in order to blend with their surroundings and to provide habitat benefits similar to the native materials.

The selection of material should be based, in part, on the required durability and stability to meet design criteria, but will also need to consider construction logistics. Construction access to the site and availability of materials may influence structure design and material selection. What access routes and staging areas are available? Will these routes limit the type of equipment, and therefore, the type and volume of material that can be utilized? Will the cost or availability of materials limit the design?

Material longevity directly affects project design life (see Section 5.2.3) and is most easily calculated for materials that slowly but predictably degrade or rot with time. For rock, material decay is generally not an issue if. Rock should be sound, durable, dense, and free from cracks, seams and other defects that would tend to increase its deterioration from weathering, freeze-thaw, or other natural causes. In the case of wood, continuously saturated wood can last for centuries, whereas exposed wood may rot within several years. Erosion control fabrics and anchoring materials composed of metals or plastics have predictable rates of decay. In their material specifications, the manufacturer usually supplies information on service life or degradation rates of these types of materials.

The majority of instream structures are constructed using rock or wood. Information is provided below with respect to the selection of rock materials for instream structures. Refer to the Large Wood and Log Jams Technique for a discussion of wood material selection, sizing, and use.

5.4.1.1 Rock sizing

Instream structures frequently utilize rock as the primary component of the structure(s). This section discusses the selection of rock sizes and types for instream structure construction. The size, shape, and placement of rocks are chief factors governing its longevity. Individual rocks must remain relatively immobile up to the selected design flow, with the acknowledgment that some shifting and settling may occur. Forces acting on the rock include stabilizing gravitational forces and destabilizing forces related to the momentum of flow impinging on the rock and hydrodynamic lift forces from flows over the top of the rock.[8] Additional force may be exerted on the rock by wood, debris, or ice.

For some applications, angular rock may be preferred over rounded rock for its ability to lock tightly together to prevent movement during high flows, and the fact that it is also less likely to roll. Angular rock (as opposed to rounded river rock), is usually derived from quarries rather than from the streambed itself. Rounded rock, on the other hand, is preferred for habitat structures when it is available. The ability to shift in response to changing conditions means that the structure will tend toward more alluvial characteristics. A potential benefit of rounded rock is that it is less likely to create a fish passage barrier when appropriate sizes and placements are used. Rounded rock is also preferred because it is naturally occurring, and when the project has reached its expected life span, the constituent components can be incorporated into the natural background with fewer deleterious effects. Some sizing methods are based on rounded materials, others can be adjusted to compensate for shape. For example, the angle of repose for a material of 1 foot mean diameter decreases by approximately 5 degrees from very angular to very rounded. Rounded materials can be easily specified by referring to WSDOT Specifications 9-03.11 Streambed Aggregates, which specifies all size classes from small gravel to boulders. The diameter of rounded rock, if used, will have to be greater than the mean dimension of angular rock to provide the same resistance to entrainment. When specifying the dimensions of individual grains, as a general rule, the greatest dimension should be no greater than three times the least dimension.[9]

Riprap sizing methods can be used, with modifications, to size rock for drop structures and weirs. Riprap sizing is based on a blanket of stone placed roughly parallel to flow, and relies on interlocking for stability. As a result, the size of rock determined by standard riprap-sizing procedures will be too small for drop structures unless allowances have been made to account for impinging flow, such as those described in EM 1110-2-1601.[10] The NRCS[11] suggests using standard riprap sizing criteria at the design flow, but modifying it in the following manner:

$$D_{50\text{-weir}} = 2 \times D_{50\text{-riprap}}$$
$$D_{100\text{-weir}} = 2 \times D_{50\text{-weir}}$$
$$D_{\text{min-weir}} = 0.75 \times D_{50\text{-riprap}}$$

Incipient motion equations for coarse boulder movement can also be used for drop structure design, and in some cases may be more applicable than riprap sizing equations since they do not rely on inter-stone contact. Two such equations, developed independently by Isbash[12] and Costa,[13] are included below.

Isbash conducted hydraulic investigations concerning the phenomena that occur when constructing rock dams in running water. The minimum velocity necessary to remove loose stones lying in a channel on top of rock fill was documented to be:

$$V_{min} = 0.86 \{2\ g\ [(SG_s - SG_w)/SG_w]\}^{0.5}\ D^{0.5} \qquad \text{Isbash, 1936}$$

where:
V_{min} = minimum velocity
g = gravity = 32.2 ft/s^2 = 9.81 m/s^2
SG_s = specific gravity of stone, varies with the type of stone—generally ranges from 2.2 to 3.2
SG_w = specific gravity of water, generally assumed = 1.0
D = diameter of the stone (assuming a spherical shape)

Rearranged to solve for the minimum diameter of stone (D_{min}) necessary to withstand a given design velocity (V), Isbash's equation becomes:

$$\mathbf{D_{min} = V^2/\{1.479\ g\ [(SG_s - SG_w)/SG_w]\}}$$

Costa studied nine steep bedrock channels in the Colorado Front Range to test the accuracy of velocity and depth estimates for historical peak floods based on the size of boulders transported during the flood event. He developed the following equation by taking the arithmetic average of four commonly used methods for computing stream velocity.

$$V_{avg} = 9.571\ D^{0.487} \qquad \text{Costa, 1983}$$

where:
V_{avg} = average velocity (ft/s)
D = diameter of the stone (ft)

Rearranging to solve for D:

$$\mathbf{D_{min} = (V_{avg}/9.571)^{2.05}}$$

Note that D_{min} represents the maximum rock size likely to move for a given velocity and, therefore, a minimum rock size to be utilized within an instream structure subject to direct flow.

5.4.2 Height, configuration, and position in the channel

Structures that change the existing streambed elevation can restrict flow at that location. The percentage of flow restricted by a structure varies with the depth of flow. Low profile structures can redirect and restrict a relatively large percentage of low flows, but with increasing flows they restrict a decreasing proportion of flow once the structure is overtopped. The effect of structures on flow characteristics (i.e. resistance, velocity, shear, and turbulence) will likewise change as the depth of flow increases over the submerged structure.

Structures that protrude above the water surface are very effective at catching wood and other floating debris, since they “comb” the water surface. Material that racks up on the structure increases the size of the blockage to flow and the degree of backwater or hydraulic drop caused by the structure. This potential for racking of material must be incorporated into design.

Structures that vary in elevation in section or in profile can be very effective at concentrating flow at certain discharges. Upstream “V” configurations or angled configurations that change in elevation relative to profile are popular methods for concentrating flows. These effects are widely published: however, the effects are often limited to a narrow range of flow conditions. Flow conditions outside this effective range can produce very different hydraulic effects. Published design guidance often provides specifications for structure angles, shapes, and drop heights irrespective of stream type, flow characteristics, or bed and bank material composition. These uniform specifications should be used with caution as they do not necessarily incorporate knowledge of specific hydraulic effects of the structure in the project reach.

Generalized configuration information of instream structures can be found in several widely distributed references[14,15,16,17,18,19] and at the Natural Resources Conservation Service’s web site (http://www.ndcsmc.nrcs.usda.gov/technical/Stream/index.html - please note that certain of the techniques and structures found on this site may not be appropriate for use in Washington State). The numeric relationships and positioning information these references provide can prove a useful starting point for the modeler. However, despite the details presented on structure placement found in these resources, only detailed modeling of these features can verify effects at various flows.

Specific position of structures within the channel requires consideration of intended outcome and associated risk to habitat, safety, or infrastructure. Hydraulic modeling of structures can verify channel response since effects will vary with channel slope, substrate sizes, cross sectional area, and planform. Hydraulic modeling may be needed to evaluate probable response and function under the full range of anticipated flows. Because structures typically accelerate or redirect flow, careful evaluation of potential increases in shear and scour, particularly along streambanks, is a necessary design exercise. The need for sophisticated, multi-dimensional modeling should be weighed against the risk and costs; in a remote river, the minimal risks may not warrant the use of intensive modeling. The opposite is true in heavily used urban corridors.

5.4.3 *Structure Spacing Considerations*

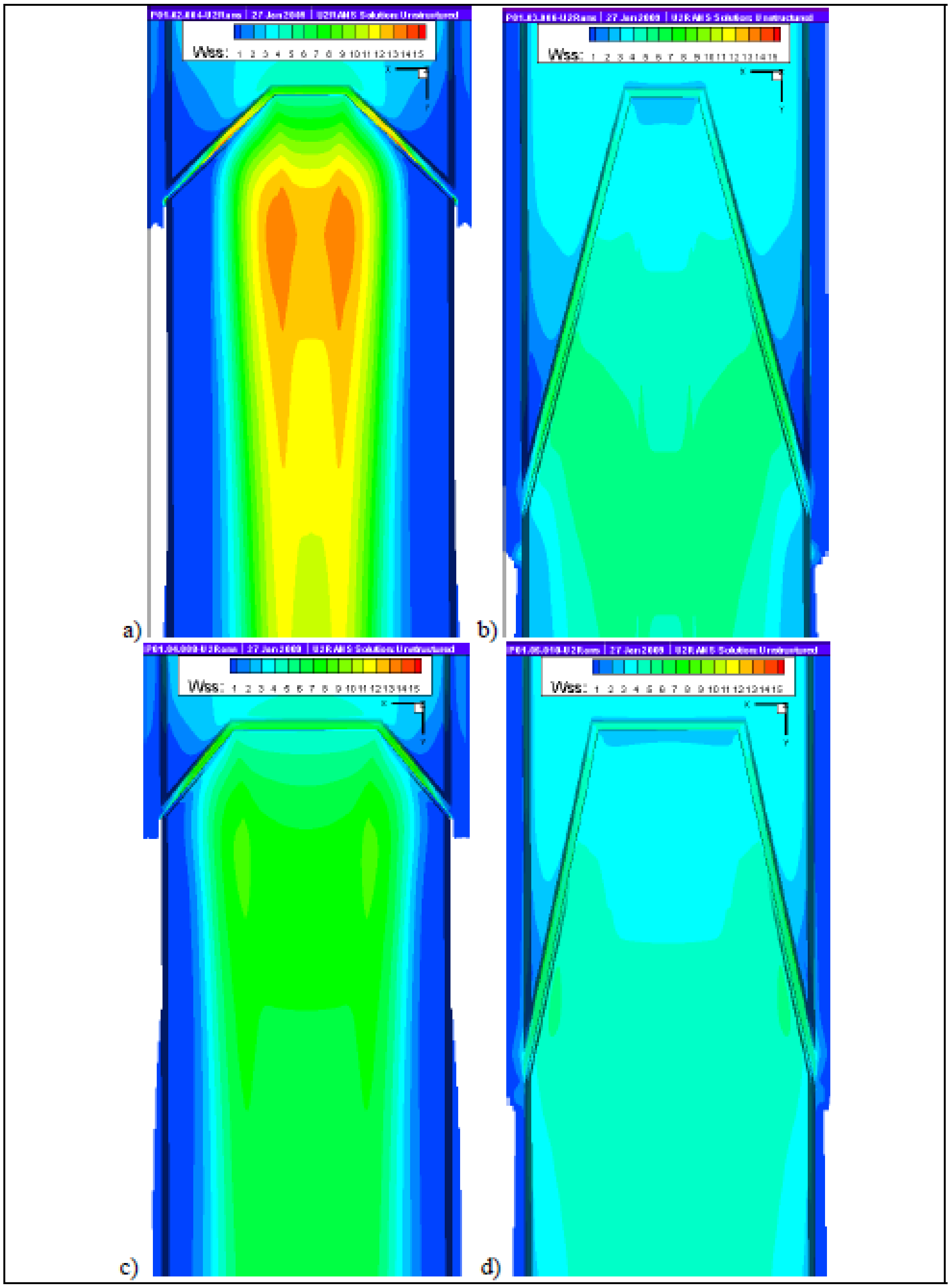
The relative spacing of structures also affects the hydraulic force imparted upon each individual structure within the sequence, the flow resistance through the reach, and the relative effect of each structure on the bed and banks. Morris[20] first discussed the spacing of elements in a channel and separated them into three classes, isolated-roughness flow, wake-interference flow, and skimming flow. He originally conceived these categories for flow in conduits, yet the concepts are useful on a larger scale. Placed very close together, structures appear hydraulically smooth at higher flows, producing little flow resistance and associated turbulence (this effect is dependent upon stage of flow relative to the height of the structures; at base flow, even in close proximity, structures will “appear” hydraulically rough, not smooth). As the spacing increases, wake eddies form between structures, which increase energy loss and flow resistance, but the next downstream structure is still too close for the wake to fully form. Finally, spacing increases to the point where one structure is independent of its upstream neighbor and creates maximum energy loss and flow resistance. Gippel et al.[21] showed this with wood spacing, observing that when model cylinders were grouped less than 3 or 4 diameters apart, skimming flow occurred, producing similar backwater elevation to a pair of closely spaced logs. Two cylinders spaced 2 diameters apart have a combined drag of less than one isolated cylinder. Maximum backwater occurs when groups of logs are spaced more than 5 diameters apart.

As with structure angles, heights, and orientation discussed in Section 5.4.2, design guidance often provides specifications for structure spacing. These uniform specifications should be used with caution as they do not necessarily incorporate knowledge of specific hydraulic effects of the structures in the project reach.

5.4.4 *Effects on sediment scour and deposition*

Effects of instream structures on channel shape will affect how sediment is scoured and deposited. Hydraulic modeling is often used as a method to investigate how much change is likely to occur (see Figure 8). Whereas hydraulic modeling does not estimate sediment transport or competency directly, the output parameter of bed shear can be used as a crude estimation of the degree of change and how that will manifest in sediment grain distribution. This analysis assumes that various grain sizes become mobile at fairly specific bed shear estimates and re-deposit at lesser bed shear estimates. If the objective is to increase the local bed shear of a particular flow from something that currently moves a 2-inch particle to something that can move a 4-inch particle, modifications to the proposed structure dimensions in the hydraulic model can provide an estimation of effect. Conversely, if the objective is to lower bed shear, there will likely be a change in streambed composition and perhaps significant deposition following the first flood event.

Figure 8. Three-dimensional modeling of the effect of structure shape and orientation on bed shear stress. Adapted from Holmquist-Johnson.[22]



5.4.5 *Addressing failure mechanisms*

A design process that starts with goals and objectives, distills those into design criteria, and follows with a series of trial designs with each subsequent design building on the last, helps reduce the chances of failure. Detailed design criteria guides design, but they also describe a framework for measuring success. Failure occurs when one or more of these success criteria are not met.

Structural failures frequently occur because assumptions regarding the stability of surrounding materials are incorrect or calculations of scour were not conservative enough. This is especially common when structures are placed in areas subject to shifting channel configurations. Existing literature[23] [24] [25] describes some commonly observed failures, primarily associated with undermining the structure (scour or subsurface flow) or end-running the structure.

A common and intended characteristic of all weir and vane structures is that a scour pool develops downstream of the structure in response to plunging or impinging flow. The scour pool has the potential to undermine the structure, causing loose rock and other material to fall into the scour pool and leaving rigid structural elements that fully span the pool (e.g., logs) exposed and suspended over the channel bed (Figure 9).

Figure 9. Example of failed log/rock weir.

A method utilized to minimize the risk of undermining a weir or vane structure is to line the scour pool with immobile material to limit the extent of its formation. However, lining the scour pool to prevent structure undermining carries potential risk. By lining the pool, the resulting pool volume may be inadequate to fully dissipate the energy caused by the hydraulic jump. The excess energy can be transferred horizontally into the banks or longitudinally into the next downstream structure, where it may scour the channel bed or banks or lead to failure of downstream structures. Alternatively, undermining can be prevented by ensuring that the structure is keyed into the bed to a depth that exceeds the potential scour depth of the pool. This can generally only be adequately determined through hydraulic analysis.

There is a risk that if a lower weir structure of a series fails, those above it will be undermined and fail in a chain reaction due to headcutting of the channel. The same is true for a series of vane structures. To limit this risk, it is recommended that if a number of channel profile control structures are placed in a series, the first or downstream most structure should be designed as an independent structure using very conservative stability criteria to ensure there is no risk of physical failure.

End runs, or flanking of a structure, most often occur when water surface elevations upstream of the structure flow onto the floodplain (due to the structure's backwater effects), while channel flows downstream of the structure are still carried within the banks. As floodplain flows re-enter the channel downstream of the structure, a headcut forms that eventually flanks the structure. This is a common failure most often attributed to a lack of adequate modeling of flow elevations and inadequate keying of the structure into the streambank. Structures in a series must all inundate adjacent floodplain surfaces evenly and at the same time; otherwise, floodplain flow returning to the channel may headcut and create a new avulsion channel that may flank the structure(s). Any departure from an even and synchronous inundation pattern must be thoroughly investigated and protective measures taken.

The various failure mechanisms common to weir structures has led many designers away from this technique and toward roughened channels for grade control. The redundancy inherent in roughened channels makes them much more reliable and easier to build. On the downside, roughened channels tend to be more expensive; however, if properly designed, they have a longer life span and lower long-term maintenance costs.

5.4.6 Fish Passage Considerations

In fish bearing waters, it is a requirement that any obstruction across or in a stream must freely pass fish [RCW77.55.060]. In the past, the standard for what is "fish passable" was often based on the culvert design criteria provided in WAC220-110-070. These common criteria have been inappropriately applied to all kinds of structures, many not associated with culverts at all, and they often lead to situations where native, non-target species are blocked. A more conservative approach is to develop fish passage standards using the characteristics of the natural channel in reaches adjacent to the project reach. If the adjacent reaches have been degraded or do not provide a good example of fish passage, a healthy example along the same stream or similar nearby stream should be sought. In principle, the approach is fairly robust; closely matching the profile, cross section, and bed texture of the reference reach usually insures fish passage; deviating significantly from these characteristics leads to poor fish passage. This approach is another reason why roughened channels and constructed riffles are gaining popularity, since they tend to match natural conditions better than discrete drop structures.

Some conditions are clearly barriers to fish and should be avoided in designs for fish bearing streams:

- Free nape hydraulic drops. These include weirs with a drop that flows completely surrounded by air. Many fish do not jump free of the water surface and must swim mostly submerged. These types of drops will block these fish.
- Excessively high drops. Salmon and trout are very vigorous fish, mounting most obstacles with ease. However, non-salmonids and small fish typically require lower drops to pass upstream.
- Confined high gradient flow. A narrow jet of high velocity water will block many fish species. It is better to disperse flow over a variety of passage pathways in order to provide a diversity of opportunities for different fish.

Fish passage can be hindered in areas where subsurface flow occurs through a poorly backfilled structure. This usually occurs between the boulders of a weir or even through bank riprap adjacent to the weir if backfilled sediments are excessively permeable. Sealing of the voids in a structure is most often achieved by using a well-graded mix of sediment (including at least 5 - 10 percent fines) as backfill upstream of the structure and within the voids of any rock (e.g., boulders and riprap) utilized in the design.

5.4.7 Deformability

In some cases, structures may be designed to deform over time through undermining, end scour, or entrainment of structural components. Deformation is generally allowed to occur during high flow events that exceed the stable design flow. Deformation differs from reduced design life or failure – deformation implies that the function of a structure is to evolve or change over time through gradual mobility of materials rather than catastrophic and sudden failure. For instance, the function of a boulder weir may change from a drop structure to a low cascade and, eventually, to a short roughened channel as rocks roll and disperse before settling into the bed through natural scour and settling processes. In contrast, structures designed to remain static do not adjust to changing flows, stream profile, cross-section, or planform.

Deformability is typically achieved by sizing a portion of the materials to deform or become mobile at specific target flows. Designers should note that there is a high degree of uncertainty in the final form of a deformable structure once it deforms.

6 PERMITTING

Various permits will be required at the local, state, and federal levels. Installation of structures necessarily involves in-channel work, streambed and bank excavation, and the placement of fill within the channel - the work will likely impact a water body and may be restricted to the in-water work window as designated by the state for protection of aquatic species. All projects that can affect the bed or flow of water of the State require a Hydraulic Project Approval permit from the Washington Dept. of Fish and Wildlife. In-water work requires a US Army Corps of Engineers Section 10 or 404 permit with a Section 401 certification for water quality, which is usually obtained from the Department of Ecology. Refer to the *Typical Permits Required for Work in and Around Water* Appendix for further information.

Any changes to flood elevations will require additional permitting from the state and county, and may require a Letter of Map Revision (LOMR) from FEMA that is required in order to amend the FEMA flood hazard maps (Flood Insurance Rate Maps). Construction related permits, including sediment control, spill response, reclamation, and a safety plan, will also be required.

The applicant should contact the U.S. Fish and Wildlife Service and NOAA Fisheries to determine if there are ESA-listed species on the property or in the area; if so, ESA consultation will likely be required.

7 CONSTRUCTION CONSIDERATION

As with all in-channel construction, the installation of structures can result in considerable instream disturbance in the form of increased turbidity and rearranging of bed and bank material. Construction of instream structures requires careful excavation and placement of material within the stream channel and banks while reducing impacts to adjacent features and vegetation. The *Construction* Appendix provides detailed guidelines and practices for in-channel construction relevant to the considerations presented below.

Most design plans include construction staging and access plans. These plan sheets outline where materials can be safely stored and what travel routes equipment will be allowed on. Oftentimes, pre-construction meetings in the field with the equipment operator and permitting agencies modify these plans somewhat; however, it is very important to have changes to the plans written down and agreed by all parties prior to commencing work.

Temporary erosion and sediment control procedures are typically included in the design plans. Components vary by site but the goal is generally to contain any disturbed materials to the construction site and to restore the site to pre-construction conditions to the extent possible. At project completion, disturbed areas, including staging and access areas, will need to be re-graded, seeded, and planted according to approved plans.

Except under special circumstances, construction is not typically permitted to occur in flowing water due to the potential impacts to instream habitat and biota. To facilitate construction and meet regulatory restrictions, the work area surrounding each structure or series of structures will need to be isolated from flowing water during construction using some form of diversion dam, flow bypass, or similar technique. The design team will typically need to develop a dewatering plan detailing methods and sequencing of diversion efforts. This also includes proper containment of any dirty wastewater that is generated. Additionally, the design team must be confident that the selected diversion technique can handle the flows expected to occur during the entirety of construction. This includes the possibility of storm flows. Fish will need to be removed and excluded from the dewatered work area. Means and methods for fish handling must be coordinated with local Washington Department of Fish and Wildlife representatives.

During construction, a design team representative is often on site to ensure that features are built as designed and that approved materials are used. A design team representative can also handle changes in anticipated site conditions that may require adjustments to design or construction methods. Construction conducted without careful oversight and done with tight contracting specifications will likely result in uniform structures that do not maximize the potential added value resulting from creative and variable placement of features, which can often be accomplished while still meeting structural and functional requirements. Using experienced contractors with a proven record of installing instream projects will facilitate construction and will reduce costs. Bonding of construction activities is a good idea, particularly given the relatively few numbers of experienced contractors.

7.1 Equipment Required

Equipment required to install instream structures usually depends on the following variables:

- Access limitations
- Size of materials used in construction
- Size of channel
- Volume of diversion or dewatering methods

Tracked excavators, dump trucks, and front-end loaders are typically the most appropriate type of equipment to perform the majority of the instream work, including excavation and installation. However, some features, particularly re-vegetation efforts and installation of erosion control materials, are best installed by hand labor and tools.

Access or other restrictions may require the use of spider-hoe excavators. Material delivery may require street-legal dump trucks and 4-wheel drive loaders to move material from stockpile areas to the project site. Regardless of access limitations, all equipment should be capable of placing materials (e.g. rocks and logs) in precise locations and orientations. Motorized wheel barrows, rock bars, winches, and other hand tools may be required where heavy equipment access is limited and to fine-tune the placement of structural features. Pre-construction planning in the field with the equipment operator during installation is very important in order to facilitate construction and achieve the desired results.

Refer to the *Construction* Appendix for further information regarding equipment.

7.2 Timing Considerations

Instream structures are most easily constructed during low-flow conditions to minimize dewatering efforts. Access considerations usually dictate working during the driest time of the year. Some high altitude projects are best done during the winter months when ground conditions are frozen and instream flows are at their lowest.

Construction is typically only allowed by permitting agencies during a time when impacts to critical life stages of fish and wildlife can be avoided. Instream work windows vary for different streams and in some cases different reaches of the same stream. Contact the Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows. Further discussion of construction timing can also be found in the *Construction* Appendix.

8 COST ESTIMATION

Project costs typically include services associated with grant application, design, permitting, project bidding, construction, construction observation services, monitoring, and maintenance. Costs vary widely with project size, duration, and scope. Grant application services often require 10% of the grant value for their efforts. Due to the analytically intensive nature of design for instream work, design services can be upwards of 25% of construction costs. Permitting varies but 10% of the construction cost is common.

Construction cost estimation is typically done on the various components of the design at the 30, 60, 90, and 100% completion stages. Each phase tightens up the budget on things completed in the recent phase, with the last phase including an engineer’s estimate of probable bid price.

Construction cost estimates are often compiled using various references for construction implementation costs. These references are published yearly (see RS Means Manual for earthworks cost estimating at http://www.reedconstructiondata.com/rsmeans/estimating-tips/earthwork) and provide labor, equipment, and estimates of time for various procedures.

Material prices should be researched on an individual project basis as availability and transportation costs vary considerably.

The design engineer should estimate material quantities with allowances made for wastage. Bulk excavation quantities often have a fluff factor applied to account for the natural compaction of materials in place. This compaction is disrupted when excavated and placed in a truck and hauled off. Other materials are estimated on a per-yard placed or per-yard delivered basis, or by the number of units installed. Dewatering and mobilization/demobilization are often estimated by a lump sum. Costs of temporary access roads, bridges, and erosion control features vary considerably. It is not uncommon for the estimating engineer to work with a construction contractor to determine pricing of various procedures or materials.

Log prices vary widely and usually reflect the current value of saw logs. This figure fluctuates and is often market-driven as well as geographically-driven. In 2010, 40-foot-long fir logs 18”-24” in diameter, and sound with no apparent rot, cost $250 - $400 each. Extra cost is charged for delivering, handling at the site, and installation. All accounted for, $600 to $1,000 per log placed is a typical cost.

Rock materials typically range in cost from $50 to $80 per cubic yard delivered. Typical costs for installing rock range from $100 to $160 per cubic yard depending on source and access. The cost will be determined primarily by the cost of available rock, the proximity of the source of material to the construction site, and equipment and operator rates. It is not uncommon to have higher unit costs for sites with difficult access.

Re-vegetation efforts can vary in cost with hydroseeding costing $0.25 to $0.50 per square yard and planting of containerized trees and shrubs upwards of $1 to $2 per square yard, not including the price of amendments, erosion control fabrics, weed suppression activities, and animal browse control.

9 MONITORING

Monitoring typically consists of two actions, Implementation Monitoring and Effectiveness Monitoring.

- Implementation Monitoring typically occurs soon after implementation and entails some form of inspection or as-built survey to verify that the project was built according to plan and to document any deviations to the plan. Implementation monitoring typically confirms that projects are implemented according to specific criteria. While a project may be implemented according to criteria, this does not necessarily imply that it has achieved objectives.
- Effectiveness Monitoring (or Post-Project Assessment) is a formal program of repetitive site assessment and monitoring performed over a long time scale (e.g., years), which evaluates how well a project meets intended objectives.

Both implementation and effectiveness monitoring are fundamental components of a complete monitoring plan. They are both required by state and federal agencies for mitigation work so that project developers can determine if the completed project satisfies the individual project objectives and overall project goals. In order to be useful, monitoring data must be analyzed and incorporated into a report. Funds and office time need to be committed to writing a report after each scheduled monitoring exercise. For further detail, guidance, and references to monitoring protocols refer to the *Monitoring* Appendix.

9.1 Implementation Monitoring

Project funders or regulatory agencies typically require some form of implementation monitoring. Funders want to verify that the work that they funded is actually built in the way it was planned. Regulators want to verify that the project is built in accordance with the plans and documents used and approved in the permitting process.[26]

Implementation monitoring may consist of a number of actions. As-built surveys are used to verify that constructed works (e.g. instream structures, channel profile adjustments, channel grading, etc.) are built to the tolerances specified in plans. Additional surveys might be performed to verify construction quantities (e.g., volumes of excavation or supplied gravel), number or dimensions of installed structures, or number and types of plants. This information might be used to process payments for contractors. Projects are rarely built exactly as designed, so implementation monitoring provides an important post-project baseline for future effectiveness monitoring.

9.2 Effectiveness Monitoring

Effectiveness monitoring is a more complex undertaking than implementation monitoring, but is critical to determining if the implemented project has met its goals and objectives, and to guide future management actions. Effectiveness monitoring is typically performed over longer periods of time and often employs a formal program of repeated surveys or measurements. This type of monitoring must be tied to the specific goals, objectives, and design criteria of the project, which are sometimes specific to individual features. Take the example of a structure intended to provide juvenile rearing habitat during annual winter flows up through the 5-year return interval event. Specific measurements of velocities and depths suitable for juvenile rearing must be performed around the structure to verify that these conditions are being met. Obtaining these measurements at the 5-year flow may require the monitoring program to span sufficient time to allow for these conditions.

Results of effectiveness monitoring can also support adaptive management procedures which review project outcomes and, if necessary, implement adjustments to the project or individual features.

10 MAINTENANCE

Project maintenance is typically done following procedures outlined in a maintenance document prepared for the project to assure successful performance over time. Most project features have regular maintenance requirements; the most common deal with features that are expected to change with time or require long periods of implementation to achieve the desired objectives. One example is the fostering of planted vegetation to achieve late successional characteristics. This may involve the regular removal of unwanted invasives, pruning or thinning of crowded tree species, and the under-planting of vegetation over time.

11 EXAMPLES

11.1 Satus Creek Dam Removal and Constructed Riffle

The Satus Creek Dam removal project was conducted by the Yakama Nation on Satus Creek, WA in order to provide fish passage past an approximately 4 foot high barrier created by an irrigation dam no longer in service. The project was conducted in 2009. Components of the project included removal of the dam structure, construction of 330 feet of in-stream roughened channel riffle, and restored floodplain habitat to provide passage and stability to upstream reaches. Field investigations, survey, and hydraulic modeling determined that the dam had prevented downstream channel incision from migrating to upstream reaches. The grade and stability of the roughened channel were designed to prevent this incision from advancing upstream. Floodplain restoration included placed woody debris and vertical snags to provide immediate floodplain roughness. Native vegetation was planted in the riparian area and floodplain to provide future stability and roughness.

Project objectives included: 1) year-round upstream and downstream fish passage for juvenile salmonids, and 2) vertical channel stability up to 100-year flows to prevent stream base level lowering from migrating upstream and potentially threatening a side-channel enhancement project located upstream. Figure 10 and Figure 11 show before and after photos of the project.

Figure 10. Satus Dam prior to removal (May 8, 2008). Source: Inter-Fluve, Inc.

Figure 11. Roughened channel / constructed riffle constructed following dam removal (February 9, 2010). Source: Inter-Fluve, Inc.

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TECHNIQUE 7

LARGE WOOD AND LOG JAMS

Large Wood and Log Jams

1 DESCRIPTION

The Large Wood and Log Jams technique refers to projects that involve the placement of wood in stream channels to restore channel processes dependent upon in-channel wood and to enhance aquatic habitat. The general emphasis is on large wood (LW), also commonly called large woody debris (LWD). Large wood plays a critical role in many Washington streams through its influence on aquatic habitat and stream geomorphic processes. In many forested streams, wood is a fundamental driver of stream morphology. The quantity, size, and function of LW in many of these stream systems has been altered through decades of timber harvesting, channel clearing, snag removal, and human alteration to stream channels and riparian zones. This has resulted in changes to stream channel form and function and the degradation of aquatic habitat. Restoration of instream LW has, therefore, become a common restoration practice in Washington and throughout the Pacific Northwest. Placement of LW can provide a variety of physical and biological benefits to stream morphology and aquatic habitat including habitat cover, complexity, and natural levels of streambank stability. LW may also provide indirect benefits through its influence on pool scour, sediment trapping, hydraulic roughness, and lateral channel dynamics. This technique focuses on LW projects specifically intended to enhance aquatic habitat and stream geomorphic function.

The Large Wood and Log Jams technique may be the main emphasis of a stream habitat restoration project, or it may simply be part of a broader technique set done together. Prior to embarking on designs for specific techniques, restoration practitioner should have already completed a site, reach, and watershed assessment to identify causes of observed or perceived problems, to determine constraints to addressing these problems, and to frame the project in the broader context of a watershed restoration strategy (Chapter 4). Because restoration practice is most effective when it addresses root causes of problems rather than observed symptoms, a robust assessment that addresses potential causes at site-, reach- and watershed-scales will contribute to a more effective restoration strategy. In addition, design should only proceed when project goals, specific objectives, and design criteria (Chapter 5) have been clearly defined and a restoration strategy has been developed to meet these objectives. A site- or reach-scale technique may ultimately provide little value if not consistent with overall watershed priorities or integrated with other techniques as part of a restoration project.

Most LW and log jams placed in streams function as instream structures and, therefore, the information provided in the *Instream Structures* technique may apply to many LW projects. Large wood is covered in this separate technique because of the many types of LW projects, the unique conditions associated with these projects, and the frequency of their use.

Definitions of what constitutes instream LW vary by agency, application, and context. LW includes whole trees with rootwad and limbs attached, pieces of trees with or without rootwads and limbs, and cut logs. Most Washington State resource agencies define LW as logs with a diameter of at least 10 cm along 2 m of their length; LW qualifies as a rootwad if it has a recognizable bole and root system and has a minimum bole diameter of 20 cm.[1,2]

The definition of LW is generally used to give restoration practitioners a general minimum functional diameter size and establish an affordable minimum. It does not inform about the historical size of mature LW in any given system. Smaller wood in streams decays rapidly and is more transient than LW. Although small wood is not discussed in depth, it also provides important ecological functions and often comprises a significant portion of log jams.

Large wood is typically applied to address a deficiency of habitat and natural channel-forming processes associated with wood accumulations in the channel. These deficiencies may have resulted from LW removal as part of logging, agriculture, splash damming, road building, urbanization, or flood control. Wood removal for the benefit of fish passage also occurred prior to widespread understanding of LW benefits. In these instances, LW and log jam placement may accelerate the natural recovery of streams. Large wood may also be used to promote stability while providing additional habitat value in incising channels or where bank protection is warranted. Placement of LW should be viewed as a short-term improvement that provides habitat and contributes to geomorphic controls and processes while natural rates of woody debris recruitment are restored through riparian forest regeneration or other means (see the *Riparian Restoration and Management* technique).

The following are three approaches to establishing log structures:

1. *Placed large wood.* Placed LW is designed to function at a discrete location within the stream channel. This approach includes LW placements ranging from single logs to log jams of various sizes. Placement locations include direct placement in streams, along streambanks, or in floodplains. Although some degree of adjustment, deformation, or even relocation may be allowed, LW placements are expected to remain relatively stable within the channel and to provide benefits to natural channel processes and aquatic habitat within their zone of influence. Placed LW and log jams (also frequently termed "Engineered Log Jams" [ELJs]) create habitat directly, but also use natural processes that scour and deposit bed and bank material to create and maintain new stream habitat. Habitat benefits are both immediate and long term.

2. *Large wood replenishment.* This approach involves adding unanchored wood directly to the channel or to adjacent floodplains, side channels, or banks where it can be readily recruited and/or redistributed by the stream. Replenishment may involve the delivery of various piece sizes depending on the needs of the system. The intent is to re-establish natural LW loading volumes and distributions. Results may be immediate, or take years to develop, and are typically part of a long-term strategy of system level restoration. A typical objective is to achieve LW volume targets, such as those developed in the Timber, Fish and Wildlife (TFW) process or in more localized analyses. LW replenishment may result in the movement and transport of placed wood and, therefore, risks to public safety and infrastructure need to be well-understood and addressed as part of design (see the *Public Safety* Appendix).

3. *Trapping mobile wood.* This approach describes the introduction of wood or structures to a stream with the intent of trapping mobile wood during high flow events. The trapping technique uses the natural process of delivery, transport, and

storage of wood in a stream to create habitat-forming structures. The goal is to reduce LW mobility in the stream and create complex log jams in geomorphically appropriate locations. It can be used in concert with the LW replenishment approach. Unlike LW replenishment, this method offers more assurance regarding the location at which mobile wood will accumulate. However, the lateral, longitudinal, and vertical extent of the log jams that form is difficult to predict.

Besides the above techniques, LW can be used as a structural element of other techniques, including drop structures and a number of bank protection techniques. The use of LW in other techniques is detailed in those techniques and in the Integrated Streambank Protection Guidelines (ISPG).[3] Large wood can also be incorporated in most other techniques as a supplemental feature to enhance habitat.

2 PHYSICAL AND BIOLOGICAL EFFECTS

2.1 Physical Effects

Large wood influences the physical form of the channel, channel processes, and physical habitat structure and configuration.[4, 5, 6 ,7, 8] These natural physical effects may be achieved through wood placement projects. The following physical functions of insteam LW underscore the fundamental importance of wood in dictating channel morphology and geomorphic process:

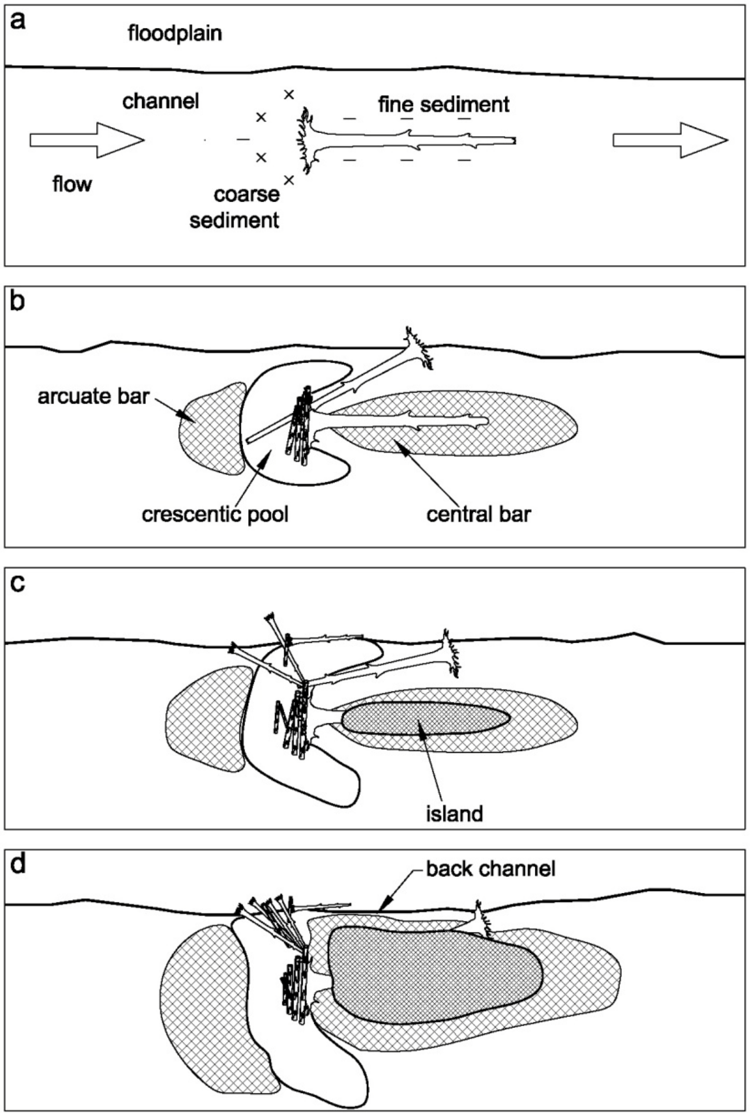
- Creates scour pools, alcoves, back eddies, and side channels.
- Influences bank erosion rates either through accelerating erosion or providing streambank stability.
- Influences channel sinuosity and hydraulic complexity.
- Influences lateral channel dynamics and development of secondary channels.
- Recruits additional wood and gravel via stream bank erosion.
- Maintains connectivity between the channel and floodplain.
- Retains and sorting streambed substrate and sediment.

Large wood has a dominant influence on stream habitat and channel formation across the spectrum of time and space.[9] On a watershed scale, LW can influence sediment recruitment, storage, and transfer. On a reach scale, channel-spanning log jams can influence the routing of water, sediment, and wood as well as the processes of channel formation, floodplain formation, floodplain hydrology[10], nutrient supply and storage, and the flux of water across the hyporheic zone. At the site scale, wood is essential in creating and maintaining pool habitat, sorting and storing sediment and organic material, and providing fish refuge from predators, competitors, and high flows. In many streams, wood frequently “forces” the channel morphology, creating an entirely different suite of habitat unit types than would exist in the absence of LW.[8] A more complete discussion of channel and floodplain processes and habitat formation is found in Chapter 2: *Stream Processes and Habitat*.

Studies have shown that channel size and the size and position of LW are key in determining its structural stability and retention.[11] [12] For example, whereas small woody debris pieces may be unstable and transport easily, whole trees may be large enough to bridge the stream or the entire floodplain, or may be completely immobile on the streambed. Large enough LW can accumulate fluvially transported wood that would otherwise be transported downstream. Over time, a single original piece of LW, if sufficient in size and complexity, can grow to a lateral or channel-spanning log jam that will backwater an entire stream reach. As channel size and flood flows increase, the size of LW required for stability (key pieces) also increases.

The effect of LW varies by stream type. In small, steep, and low order headwater channels, in-channel wood traps substrate and can form steps within step-pool channels.[13] In low-gradient, higher order, large streams, LW creates scour pools and may influence bar formation and side channel development.[14, 15, 16, 17] Carlson et al.[18] found that pool volume was inversely related to stream gradient with a direct relation to the amount of LW. Collins and Montgomery[19] found that pools associated with wood are commonly up to 3 times deeper than free-formed pools, which also typically lack the cover and complexity offered by wood. Pool formation in forested channels is highly dependent on scour around LW. Collins and Montgomery [19] found that pool frequency was 2-4 channel widths per pool in areas with high wood loading, which is less than the 5-7 channel widths per pool indicated by Leopold et al.[20] for unobstructed alluvial channels. Log jams in alluvial environments create flow obstructions, scour, and hydraulic constrictions that may induce erosion and create back channels, alcoves, side channels, and flood overflow channels. Figure 1 demonstrates how a back channel may form along the margin of a log jam.

Figure 1. Large Wood and Log Jams. Schematic of side channel formation against the bank at a logjam (courtesy Tim Abbe). Morphological stages in alluvial topography associated with construction of a woody debris (barapex) jam. (a) Deposition of an especially large tree with the root wad intact. (b) Formation of a coarse gravel bar upstream, a crescent-shaped pool immediately upstream of the root wad, and a downstream central bar of finer sediments along the axis of the tree. (c) Island development along the central bar. (d) Integration into the broader floodplain. Modified from Abbe and Montgomery.[21]



Log jams can affect reach-scale channel characteristics. Large log jams or a series of log jams can increase the hydraulic roughness of a reach, thereby reducing average velocity and increasing water surface elevation. Log jams may reduce velocity sufficiently to increase reach-scale sediment deposition, induce bed aggradation, and thereby increase the frequency of overbank flooding and the potential for channel avulsion. Log jams may also induce local bar formation that progresses to the development of islands within low gradient pool-riffle channels.[21]

Sediment retention associated with log jams provides valuable habitat and maintains sediment transport equilibrium. Research has shown that wood retains sediment and removal of wood can increase reach bed scour and lead to channel instability.[22] Increased sediment deposition and roughness improves hyporheic flow and related benefits of temperature regulation, invertebrate production, and nutrient processing.[4]

2.2 Biological Effects

Large wood influences aquatic habitat, biological processes, and biological community composition in numerous ways.[4, 5] In particular, the presence and abundance of LW is correlated with growth, abundance and survival of juvenile salmonids.[23, 24, 25] The biological benefits of LW may be achieved through wood placement projects. A summary of the biological functions of instream LW is provided below:

- Provides fish habitat complexity and cover from predators
- Provides fish velocity refuge during high flows
- Traps and sorting spawning gravels
- Influences the movement and storage of particulate matter
- Provides a substrate and food source for macroinvertebrate production
- Retains organics (wood, detritus, carcasses) that provide nutrients to aquatic organisms
- Influences riparian successional processes

Placement of LW in streams creates pools and habitat cover that influences the distribution and abundance of juvenile salmonids.[26, 23] Large wood also provides visual and physical refuge cover within the stream. This cover is essential for salmonids, other fish, stream-associated amphibians and invertebrates. These organisms need secure refuges that allow energy-efficient foraging and cover from predators and competitors. The greater the complexity of a log jam, the greater visual and physical isolation for fish (Figure 2). In addition, deep pools created by scour around LW protect against overhead predators. Cover habitat provided by wood changes with the rise and fall of a stream. For example, trees or wood above the low flow level may become important during flood flows. In alluvial channels, floodplain wood plays an important role in providing high flow cover habitat. Wood on floodplain surfaces, or within flood overflow channels or backwater sloughs, may be used by juvenile salmonids for refuge (velocity refuge) during floods (Figure 3). In many stream systems, channel margins are important areas for hydraulic refuge. Providing cover locations across the anticipated range of hydrologic conditions (stage) can improve the quality of aquatic habitat for fish and other aquatic organisms.

Figure 2. Large Wood and Log Jams. Visual and physical isolation provided by a rootwad for juvenile coho salmon (photo from NF Stillaguamish River, Snohomish County, Washington, Source: Roger Peters, USFWS).

Figure 3. Large wood in stream, in overflow channel and on floodplain (Whatcom Creek, WA Inter-Fluve, Inc.)

The decay of organic detritus adds nutrients to the stream and LW accumulates smaller twigs and leaves that decay rapidly and support the aquatic invertebrate food web. Large wood also traps and retains fish carcasses that add nutrients, such as carbon, nitrogen, and phosphorous, to the stream system.[27]

Large wood plays an important role in trapping and stabilizing spawning gravels used by salmonids. Large wood stabilizes spawning beds by dissipating peak flow energy. Pool scour created by LW may also provide high quality pool tailouts for spawning. In channels that have been simplified through removal or reduction of LW, higher stream energy may scour salmon redds and transport spawning gravels through the reach.

Besides providing aquatic habitat at high flows, wood within riparian areas and floodplains provides substantial habitat values to terrestrial wildlife. Smaller logs provide escape cover and shelter for small mammals, amphibians, and reptiles and increased log volume may increase densities of certain amphibians and small mammals.[28] Larger diameter logs, especially hollow logs, provide denning, resting, and litter rearing sites for larger mammals such as marten, bobcat, and black bears. High densities of large logs and upturned stumps provide security cover for lynx kittens.[29] Logs also provide prime foraging habitat for mink, marten, and cougar.[30]

Most in-channel wood, whether naturally recruited or placed, will be transported downstream at some point. Slow decomposition and episodic fragmentation from peak flows will reduce wood to the size where it can be mobilized. This wood then has a role in downstream channel and marine habitats. Wood deposited on downstream gravel bars encourages fine sediment deposition and sites for riparian vegetation development. Large wood provides cover for juvenile fish in estuaries much as it does in upstream areas. Historically, the Northwest's estuaries contained much higher concentrations of LW, the ecological value of which is now only beginning to be understood.[31] Wood accumulations on ocean beaches provide habitat value to shoreline wildlife and aquatic species. Large wood provides habitat for inter-tidal species (barnacles, isopods, mussels), and in turn provides food for the shorebirds that feed on them. Some wood reaching the ocean becomes water logged, sinks, and ultimately provides cover habitat for colonization for a variety of benthic marine species such as annelid worms, bivalve mollusks, crabs, and various marine fishes.

3 APPLICATION OF TECHNIQUE

Large wood can be used for many of the same applications where other structures are appropriate. Wood, however, is a natural structural and habitat component of most stream systems, and therefore, its use can add considerable value and reduce the potential detrimental side effects of other materials (rock, ecology block, etc.). Refer to the *Instream Structures* technique for a general discussion of the application of structures and their variations in streams.

Addition of LW and log jams may be appropriate where:

- a biological or geomorphic need for in-stream wood and wood-related habitat has been identified,
- large wood has been removed from the channel in the past,
- existing riparian trees are absent or too small to provide natural function within the stream channel when recruited,
- local or upstream recruitment processes have been lost (e.g. bank armoring, confinement, and instream LW removal),
- the potential for retention of LW in the channel is reduced due to anthropogenic impacts, or
- existing constraints preclude the use of other measures to restore natural LW recruitment and retention.

LW projects may not be appropriate where LW is not a natural part of the system or where LW projects may create undue risk to human safety or property. In the latter case, ways to use wood may exist that provides habitat benefit while also addressing property risk or safety concerns (see the *Public Safety* Appendix). It should also be recognized that in many cases LW projects may not address the underlying causes of LW depletion and this has been a frequent criticism of LW projects.[32] In other cases, however, LW projects may be effective where the underlying causes of LW depletion cannot be adequately addressed through other means as a result of property constraints, risk, or the legacy of past land use. Evaluating where LW projects are most appropriate will, therefore, require an understanding of the fundamental causes of LW depletion, the suite of viable restoration strategies that may be available, and the limitations, risks, and potential utility of LW additions.

LW may be inappropriate[33] or its use may require more detailed analysis and design in stream systems with significant instability, such as rapidly degrading (incising) reaches, rapidly aggrading reaches, or reaches subject to debris flows. Where instability is related to human activities, it may be more appropriate to focus restoration work on addressing the fundamental causes of instability. Many past failures of LW projects have been related to an inadequate consideration of stream hydraulics and channel dynamics and a lack of recognition of channel instability.[32] It is therefore critically important that designers have a thorough understanding of stream geomorphic processes and that a multi-disciplinary approach is taken to LW project planning and design.

Large wood placement projects that are not coupled with riparian forest restoration should be considered short-term solutions that may require future maintenance or replacement. Collins and Montgomery [19] encourage riparian reforestation in order to provide a future source for sustainable instream LW in the form of key pieces and log jams. Their recommended approach includes riparian reforestation, acceptance of bank erosion and avulsion to supply LW to the river, as well as using constructed log jams for short-term function and to provide key pieces for wood accumulation. Riparian forest restoration is discussed further in the *Riparian Restoration and Management* technique.

Log jams can also be used to protect eroding banks, where appropriate or necessary. For further details on the use of log jams for protection of streambanks, refer to the *Integrated Streambank Protection Guidelines* (ISPG).

3.1 Placed Large Wood, Large Wood Complexes and Constructed Log Jams

Constructed log jams and relatively immobile LW placements are appropriate at sites where a high degree of certainty with regards to outcome is required. They are more appropriate than LW replenishment or wood-trapping structures at sites with moderate to high risk to infrastructure, property, public safety, and habitat. In situations without significant risk to property or safety, LW and log jams can be designed to adjust or even relocate to some degree within the channel. Wood placements that are designed to be more highly mobile in the channel are discussed under Section 3.2 below. Large wood and log jams can be placed within the stream corridor where wood would naturally occur. Researchers have noted that instream structure failures are often due to a poor understanding of stream response to hydrology and hydraulics; a lack of experience and/or documented procedural guidelines. These constraints limit pre-project research, lack state-of-the-art knowledge in the applicability of structures to field conditions; or have the tendency to install the same structure on all stream types with a one-size-fits-all approach.

Generally, constructed log jams work well in alluvial channels having less than a 2% slope.[34] They may not be appropriate in alluvial channels with high sediment loads such as braided glacial channels. The high sediment loads can cause frequent channel avulsions and lateral migrations that can abandon log jams shortly after construction. Creating log jams in non-alluvial channels with up to 4% slopes may be appropriate in some cases. However, channel-spanning log jams in confined non-alluvial channels may create fish passage barriers, particularly if they collect additional wood. Step-pool morphology, high stream power, and steeper valley walls in channels with slopes greater than 4% tend to prevent the natural formation of log jams.

Large wood or log jams can be used in association with constructed or natural side channels. Side channels provide fish rearing and spawning habitat in many streams. In particular, side channels provide important protected habitat in streams that experience frequent, large magnitude flows that destroy redds or flush juveniles from the main channel. Jams can be assembled at the inlet of side channels to regulate the amount of flood flow entering the side channel (Figure 4). This can slow or delay channel avulsion while allowing riparian vegetation to mature. Log jams can also be used downstream of backwater sloughs or side channels to increase backwater elevation, and thus habitat capacity, in the side channel.

Figure 4. Constructed Side Channel Entrance (Clackamas River, OR, Inter-Fluve, Inc.).

Large wood or log jams can be used in incised alluvial channels to speed channel evolution and recover aquatic habitat. In incised channels, the channel capacity increases such that discharge that previously accessed the floodplain is now confined within the channel. Over time, the channel erodes laterally, eventually building inset floodplain terraces.[35] Large wood placements or log jams can induce bank erosion to facilitate this lateral adjustment and channel evolution process that will eventually develop a new floodplain at a lower elevation. Further, the log jams may also stabilize some of the mobile sediments in the channel and build up the bed of incised channel (Figure 5).

Figure 5. Significant gravel accumulation one year after construction. Adult Chinook, coho and steelhead observed spawning in front of structures (Washougal River, WA, Tony Meyer)

(a) post-construction (b) one year after construction

Log jams placed in aggrading reaches typically cause rapid channel response and adjustment, including bar formation, split-flows, and channel avulsion. In particular, the potential risks or benefits associated with avulsions should be considered. Floodplains with immature vegetation, lack of downed wood, and low topographic variability may be more subject to avulsions during flooding. In these systems, a repetitive avulsion cycle can hinder the development of mature floodplain vegetation and may lead to persistent instability that reduces the health and productivity of the stream. In contrast, where the riparian area is healthy, occasional avulsions may be a natural process and may benefit the stream through creation of new habitats and recruitment of substrate, wood, and nutrients to the channel.

3.2 Large Wood Replenishment

Large wood replenishment can achieve many of the same objectives as LW placement (see Section 3.1), although results may be more uncertain and take longer to accrue. In some cases, however, allowing the stream to redistribute LW may best restore natural dynamic wood processes assuming other supporting processes are intact. Replenishment may not be appropriate in channels where wood retention is unlikely. In channels without a recruitment source to replace wood that is moved through the system, LW replenishment may have to occur repeatedly as part of a long-term program. An advantage of wood replenishment over other LW techniques lies in its lower cost and less restrictive access requirements.

Large wood replenishment may not be appropriate in small, shallow channels with limited ability to transport wood.[36] Although mobile wood may be added to infrequently flooded areas outside the immediate path of channel migration, aquatic habitat benefits may be delayed and short-lived, and the areal extent of redistribution limited.

Floodplain wood may also be more vulnerable to rot, and by the time it is recruited to the channel, its integrity may render it relatively ineffective. Large wood replenishment in steep mountainous regions prone to debris torrents may add to channel impacts and should be avoided or considered with caution.

Greater risk may be associated with adding mobile wood to certain stream types. The risk of wood transport increases with channel gradient, channel depth, and channel width. As the velocity and depth of flow increases, so do the buoyant and drag forces available to transport wood. Furthermore, as the width and depth of the stream increases, the likelihood of wood becoming wedged between the banks or impinged on channel obstructions decreases. Wood replenishment should be conducted where there is a high likelihood of wood retention in the channel, otherwise habitat objectives may not be realized. Combining wood replenishment with secure LW placements designed to trap wood (see Section 3.3) is often an efficient and effective strategy.

As the formation of wood structures and habitat is flow-dependent, and flows are variable and uncertain, use of a wood replenishment technique is only appropriate where immediate results are not necessary or expected and where risk associated with wood re-distribution is limited (see the *Public Safety* Appendix). Ideal locations for wood replenishment include less developed watersheds where infrastructure is not located within or immediately adjacent to the stream. It is also appropriate upstream of natural or manmade impoundments (reservoirs) where wood that does not become trapped in jams can be recovered or retained before reaching heavily developed areas.

3.3 Trapping Wood

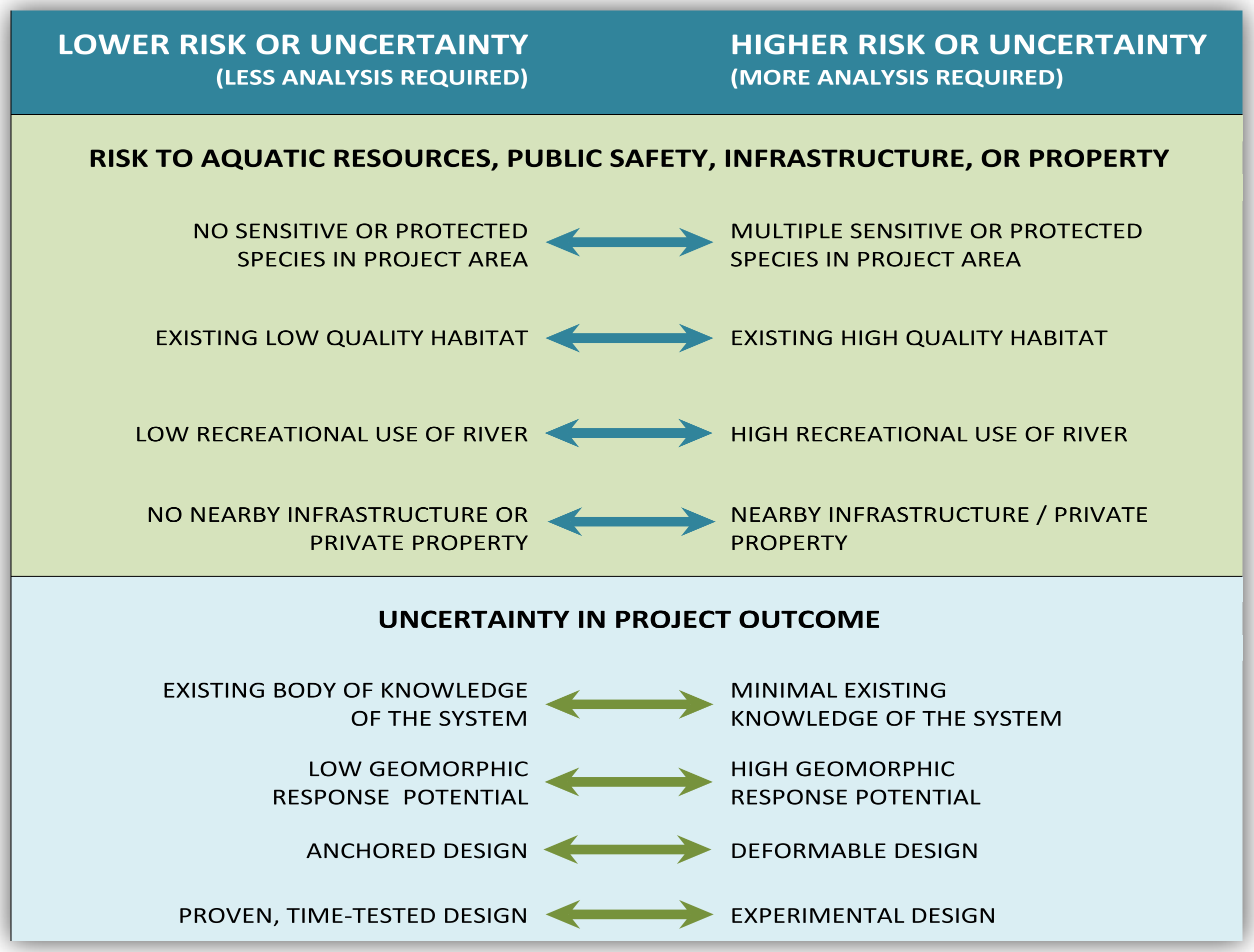
Trapping wood refers to approaches that rely on key pieces of immobile wood, wood pilings, or other structures to trap (“rack”) mobile wood and form LW complexes and log jams. Large wood trapping structures should be built at hydraulically appropriate locations, similar to LW complexes and log jams (see section 3.1). Because they are expected to grow as they collect wood, placing them close to infrastructure involves some risk. As the formation of wood structures and wood-related habitat is flow dependent, trapping wood is only appropriate where immediate results are not necessary or expected and the uncertainty of results is acceptable. If the watershed is relatively devoid of mobile wood this approach may need to be combined with LW replenishment. Figure 6 shows a log jam that has collected racked wood.

Figure 6 Log jam with racked woody debris (Whatcom Creek, WA, Inter-Fluve, Inc.).

4 RISK AND UNCERTAINTY

Project risk is a function of the probability that the project will result in undesirable outcomes and the extent of those outcomes; whereas uncertainty refers to the limits of our knowledge about how a project will perform in the future (Refer to RiverRAT Appendix 3.5 for a thorough discussion of accounting for uncertainty and risk in stream habitat restoration design and management). Uncertainty also refers to those things that are unknown in the process of design. For example, it may be possible to predict how a project will perform under a given flow, but the actual flows the project will experience may not be known. Project risk and uncertainty should be considered as an integral component of design. Not all projects carry the same amount of risk or uncertainty. Risk to property tends to be higher if nearby or downstream properties or infrastructure exists. Risk to human safety may be higher if there is public use of the waterway. Risk to aquatic species may be higher if there are sensitive species or habitat that could be impacted by project failure. Uncertainty tends to be higher where greater inherent natural variability is associated with a project (e.g. within a geomorphic response reach) or where less knowledge exists about how the system operates. In general, where greater risk or uncertainty exists, a greater amount of analysis will be required as part of design. Figure 7 shows how the level of analysis might differ depending on the level of risk and uncertainty for a number of considerations; note that many other factors exist that could be added to this list depending on the project and setting. Although a comprehensive analysis should be used to reduce risk and uncertainty to the extent possible, it may be reasonable to address some risk and uncertainty through post-project monitoring and adaptive management.

Figure 7. Change in level of analysis required versus risk and uncertainty for various project elements. These are only a sub-set of many potential considerations that may influence the required level of analysis.



LOWER RISK OR UNCERTAINTY (LESS ANALYSIS REQUIRED)	HIGHER RISK OR UNCERTAINTY (MORE ANALYSIS REQUIRED)
RISK TO AQUATIC RESOURCES, PUBLIC SAFETY, INFRASTRUCTURE, OR PROPERTY	
NO SENSITIVE OR PROTECTED SPECIES IN PROJECT AREA	MULTIPLE SENSITIVE OR PROTECTED SPECIES IN PROJECT AREA
EXISTING LOW QUALITY HABITAT	EXISTING HIGH QUALITY HABITAT
LOW RECREATIONAL USE OF RIVER	HIGH RECREATIONAL USE OF RIVER
NO NEARBY INFRASTRUCTURE OR PRIVATE PROPERTY	NEARBY INFRASTRUCTURE / PRIVATE PROPERTY
UNCERTAINTY IN PROJECT OUTCOME	
EXISTING BODY OF KNOWLEDGE OF THE SYSTEM	MINIMAL EXISTING KNOWLEDGE OF THE SYSTEM
LOW GEOMORPHIC RESPONSE POTENTIAL	HIGH GEOMORPHIC RESPONSE POTENTIAL
ANCHORED DESIGN	DEFORMABLE DESIGN
PROVEN, TIME-TESTED DESIGN	EXPERIMENTAL DESIGN

An evaluation of risk for LW projects should consider the probability of failure or undesired outcomes along with the potential consequences of those outcomes. Risk of failure is often related to uncertainties, including those associated with flooding, sediment flux, additional LW inputs, channel adjustment, and material deterioration (e.g. logs and anchoring hardware). Consequences of outcomes are related to what may be harmed if the project were to fail, such as downstream infrastructure or property. If LW is designed to remain stable up to a certain flood level, then failure risk can be described in terms of the probability of flows above the design flood occurring. The potential for channel changes should also be considered. Sources of information that may help characterize risk include past channel migration rates, flood inundation/avulsion potential, observations of channel response during past flood events, and an evaluation of potential upstream sediment and wood inputs.

Except for very small-scale projects or projects in remote areas where little is at risk, placement of LW in rivers and streams is considered an engineering practice, and the Washington State rules that apply to engineering practices also apply to LW placement. Designers must have the proper licensing credentials and must practice due diligence to ensure the protection of life, health, and property.

An evaluation of uncertainty for LW projects should consider the natural variability of the system as well as the uncertainty associated with the quantification and analysis of it. Things to consider include the resolution/accuracy of survey data, accuracy of hydrology data (e.g. How long is the period of record?), potential model errors (e.g. Can the model be calibrated?), potential design calculation errors, and the potential for constructed elements to vary from the design. If high natural variability of the stream system exists, such as frequent disturbance events, then greater uncertainty should be anticipated.

4.1 Risk to Habitat

Because wood is a naturally occurring feature in stream channels, it poses little long-term risk to habitat even in situations where the primary objective of the structure fails or is not realized. As with any structure, placed wood may disrupt existing habitat through scour, sediment deposition, wood accumulation, or avulsions, but these are also potentially beneficial functions provided by natural LW. Wood projects that are heavily anchored to prevent failure may, in some cases, pose a risk to habitat-forming processes over the long-term through their impact on channel migration. This is particularly true for wood projects along the outside of meander bends in free-formed alluvial channels. Such projects may impose an unnatural constraint on the channel that prevents future channel migration, and thus long-term habitat-formation, from occurring. This risk can be addressed by ensuring that the project has a limited design life (e.g. 25-75 years) and that future lateral channel adjustment will be able to occur. This can be achieved, for example, by limiting the use of non-natural materials (e.g. large rock or cable) for anchoring.

Some of the risks to habitat associated with wood techniques result from their installation including access and construction disturbance. Projects undertaken to emulate natural wood habitat often require heavy equipment access and delivery of wood to restoration sites. Proper erosion control measures and best management practices should be followed to minimize the impact of construction activities and access roads on stream water quality. Examples of BMPs can be found in the most recent version of the Fish Passage and Restoration Programmatic (NMFS 2008, http://www.nws.usace.army.mil/PublicMenu/Menu.cfm?sitename=REG&pagename=2008FishRestoration). Removal of mature streamside trees should be weighed carefully as it may be 30 or more years before small planted trees replace the function of existing mature riparian trees and more than 150 years before contributing to LW recruitment. See the *Riparian Restoration* technique for more information on protecting and restoring riparian areas.

4.2 Risk to Infrastructure and Property

The hydraulic effects of LW and log jams that create habitat (e.g. creating local scour, re-directing flow, increasing floodplain connectivity, or initiating avulsions) are undesirable in some locations. These actions may cause property loss through erosion, may threaten the structural integrity of nearby infrastructure, and may increase the risk of flooding. Mobile wood may block culverts, may become lodged on bridge piers leading to scour at the pier, or may cause other structural damage. Blocked culverts can sometimes trigger debris torrents that can severely impact downstream habitat. Log jams immediately upstream of culverts or bridges or next to infrastructures or denuded riparian zones should not be attempted without careful consideration of risks. Similarly, LW replenishment or wood trapping projects utilizing unanchored wood are not recommended in urban environments unless the risks are made clear to all parties. Discussing these risks, as well as habitat benefits, should be part of the public process of developing a local or regional Flood Hazard Management Plan (FHMP) or Sensitive Areas Ordinance (SAO).

4.3 Risk to Public Safety

Structures that protrude into the channel, block the channel, or are designed to trap floating materials can be hazardous to recreational users and boaters. These safety hazards can be somewhat reduced by placing warning signs at access points and upstream from the log jams to alert the public. In some cases, requirements for human safety may negate the habitat and channel process benefits of LW placements and may therefore deem projects ineffective. River recreation user groups should therefore be incorporated early into the planning process to ensure that resources are not spent towards a design that is incompatible with existing uses. See the *Public Safety* Appendix for additional information on addressing public safety concerns.

Some concerns regarding LW structures stem from the fact that materials used in anchoring often persist long beyond the functional life of the structure. Cables can pose significant public safety concerns as they can form traps for recreational users and often have sharp ends. If secured wood becomes mobile, the cables often remain attached to the wood resulting in non-natural and hazardous materials in unintended locations. Steel bar used to pin LW together may also be a hazard when exposed.

4.4 Uncertainty of Technique

Uncertainty in stream habitat restoration stems from natural variability that cannot be predicted and from limits to understanding, measuring, or modeling the stream system. Wood structures present additional and greater design challenges than structures composed of rock or other materials because wood is buoyant, irregularly shaped, and may collect additional material floating downstream. Consequently, some uncertainty exists in the performance of wood structures from the perspectives of structural integrity and intended function in the stream. Whereas the uncertainty in structural integrity can be reduced through more comprehensive analysis and design, the uncertainty in structure performance is more difficult to address. Specific habitat benefits resulting from wood structures may prove difficult to predict or achieve as intended. For example, a wood structure may generate scour as predicted, but the effectiveness in providing desired habitat may be uncertain, and the longevity of the habitat value may be limited or diminish over time.[37] The best chance for creating the desired habitat is by placing LW in locations and orientations that mimic those of naturally formed wood jams that are known to provide habitat and fostering the natural succession of habitat through LW recruitment and formation of log jams.

Wood replenishment and wood trapping are particularly uncertain because they rely on the redistribution of wood during high flow events. This increases uncertainty with respect to: 1) the lag time until effects are realized, 2) the longevity of effects, and 3) the final configuration of wood and habitat. Though trapping wood provides a greater certainty than wood replenishment with regards to the ultimate location of wood in the system, the size and orientation of log jams that form as a result of these actions will vary.

5 METHODS AND DESIGN

Large wood and log jam projects generally require a high level of planning and design; however, the level of effort will vary considerably depending on the project size, stream size, and potential risks. Most projects will require input from an interdisciplinary design team with members representing hydrology, hydraulics, engineering, fluvial geomorphology, aquatic habitat biology, and riparian ecology. For most projects, design of LW or log jams will require a professional licensed engineer. Prior to embarking on project design, project objectives should be identified and a set of design criteria should be established that will guide the design process. See Chapter 5 *Designing and Implementing Stream Habitat Restoration Techniques* for additional information on the generalized design process for stream habitat restoration project elements. The basic assessment and data needs are discussed below, although individual project needs may vary considerably.

5.1 Data and Assessment Requirements

Generally, the required amount of data and assessment is proportional to the level of risk and uncertainty (see section on Risk and Uncertainty above). Wood placements in small remote streams may require little in the way of data collection and assessment, whereas large-scale projects in proximity to infrastructure will require a high level of data collection and analysis. Many of the data and assessment requirements presented in the *Instream Structures* technique will also apply to LW and log jam projects. This section focuses only on data and assessment requirements that are unique to wood placement projects. Data and assessment needs will vary by project; general considerations are provided below.

Documentation of baseline conditions. Baseline conditions should be documented through survey, sketches, and/or photographs in order to inform project designs and to provide a baseline for future effectiveness monitoring. Existing channel planform conditions, location of existing wood in the channel or floodplain, and channel complexity or habitat features should be documented to determine appropriate LW placement locations and configurations. Further, any infrastructure that may be at risk should be located. This may include buried utilities, roads, bridges, culverts, or buildings.

Hydrology. Hydrology data are used for stability analysis and to evaluate stream response and project risks. The required hydrologic analysis depends on the energy of the stream, the risk level, and the experience of the designer. A design discharge for structural stability should be chosen. The stability discharge can vary depending on local concerns with 20-100 year flood recurrence intervals being commonly used values. With the exception of LW replenishment, a minimum of a 20-year return interval flood is recommended for stability criteria such that the probability of failure is reduced to 5% or less in any year. Unless a specific species life-stage target dictates otherwise, LW should be designed to provide habitat and function through a wide range of flows from baseflow for low flow refuge through bankfull and flood flows for high flow refuge. Refer to the *Hydrology* Appendix for additional details on assessing and analyzing hydrologic data.

Geomorphology. A stream geomorphic assessment will be necessary for most LW projects (refer to the *Fluvial Geomorphology* Appendix for details on geomorphic assessments). A geomorphic assessment can characterize the historical and potential function of LW in the channel system and provide target design values for quantity, size, and configuration of LW structures. The equilibrium condition of the channel (i.e. aggrading versus degrading) and expected future trends in sediment transport should also be well understood as they relate to wood placements. Other geomorphic considerations include the potential for LW to affect channel planform, scour, erosion, floodplain activation, avulsion, and accumulation of additional wood. The existing and future potential for LW recruitment from riparian areas should be evaluated. This can be accomplished through an examination of riparian stand ages and through counts of "lean" trees that are likely to be recruited to the channel in the near future.

Analog site data. Stream reaches with naturally functioning wood dynamics may provide good analog (reference) data. The following attributes can be measured within analog reaches and used to inform project design: 1) quantity of wood, 2) size of wood, 3) orientation of wood, 4) location of wood, 5) bankfull indicators, 6) geologic conditions, 7) cross sectional and longitudinal characteristics of the channel, 8) substrate conditions, 9) riparian vegetation, and 10) bank conditions. If not available from specific analog reaches, wood loading targets can be obtained from regional studies of wood loading in unmanaged streams (see Section 5.4). Other restoration projects that have functioned well over time are also valuable as reference sites. The relevance and applicability of analog (reference) sites should be carefully considered. Refer to the Design Approach section of Chapter 5 for a discussion of the utility and limitations of the use of reference sites or reaches.

Biological assessment. A survey of the quantity and quality of existing stream habitat and a survey of fish distribution and use of habitat prior to design will help determine habitat restoration targets and will provide a baseline for future effectiveness monitoring. Directly monitoring for usage by fish species will be valuable to understand how project elements will affect local populations. State and federal guidelines are available for aquatic habitat monitoring and are listed in the *Monitoring* Appendix for additional information.

Hydraulics. Hydraulics analysis will be necessary to predict structure stability, stream response, and potential failure mechanisms. Depending on project size and site conditions, requirements for hydraulics analysis may range from simple at-a-station hydraulics to complex multi-dimensional models (refer to the *Hydraulics* Appendix for further discussion of model applications). At a minimum, hydraulics analysis will be needed to predict the forces acting on instream LW, including buoyancy, lift, and drag forces, as part of the design process. Hydraulics may also be necessary to quantify the effects of LW placements on flood elevations. This may be required by local jurisdictions as part of the permitting process (additional information is included below under Permitting). Scour analysis may be required to determine the placement or depth of a log jam or its anchoring members (e.g. vertical pilings). For more information on hydraulics analysis, see the *Hydraulics* Appendix. See the *Placement and Anchoring of Large Wood* Appendix for more information on anchoring LW in the channel.

Wood mobility. Use of hydraulics analysis for wood mobility is discussed above. In some cases, however, empirical data can be used to predict wood mobility thresholds. Some researchers have compared the size and dimensions of stable wood in channels (i.e. key pieces) to channel dimensions such as bankfull width or depth.[38, 39, 40, 41] This information is also discussed in Section 5.2. These data may be used to develop size criteria for LW that would be expected to be stable under certain flow conditions. This approach carries some risk and uncertainty, and may be most appropriate for designing wood replenishment projects where the risks associated with mobile wood are low.

Safety. Depending on the degree and type of public use of the waterway, an assessment of public safety may need to be included as part of the design process. Refer to the *Public Safety* Appendix for additional information.

5.2 Factors that Influence the Stability of Wood in Streams

Many factors influence the stability of both natural and artificially placed LW in stream channels. These include: 1) factors related to the wood itself, including size, buoyancy, and decay rate, 2) factors related to the channel type and hydrologic regime, and 3) factors related to the location and orientation of wood within the channel. Ultimately, wood is stable when the sum of the resisting forces (friction and weight of wood) exceeds the sum of the driving forces (e.g., drag force and buoyancy).[42] These forces are discussed in the *Placement and Anchoring of Large Wood* Appendix.

In general terms, the size and buoyancy of wood relative to stream size influences its stability. The size of stable wood generally increases with the size, depth, and gradient of the stream. Because wood is buoyant, larger pieces are needed as stream depth increases to prevent the wood from being mobilized (see Section 7.1 for more discussion of buoyancy). Also, wood that is as long or longer than the width of the stream is more likely to become wedged between banks or channel obstructions than shorter wood. Using short, undersized material for LW placement often requires artificial anchoring or ballasting to compensate for lack of mass and length. A piece of wood large enough to be generally stable within the stream system is termed a “key piece.” Key pieces are at least temporarily immobile and serve as a foundation for other pieces of a structure or log jam. In some cases, it may be appropriate to use a key piece to serve as a stable anchoring piece for a constructed log jam. The ideal key piece is a tree complete with rootwad and limbs intact. The minimum size of wood necessary to function as a key piece varies with the size of the channel. See Table 1 for key piece criteria developed for monitoring protocols for the Timber-Fish-Wildlife (TFW) program.

Table 1. Key piece volume matrix including the minimum length and volume of wood to qualify as a key piece according to the TFW monitoring protocols (Schuett-Hames et al.[1]).

Min Log Diameter (m)	**Bankfull Width 0 to 5m**	**Bankfull Width 5 to 10m**	**Bankfull Width 10 to 15m**	**Bankfull Width 15 to 20m**
	Minimum Length (m)			
0.50	6	13	31	---
0.55	5	11	26	---
0.60	4	9	22	32
0.65	3	8	19	28
0.70	3	7	19	24
0.75	3	6	14	21
Min Volume (m^3)	1.0	2.5	6.0	9.0

Fox[43] determined that the key piece minimum volumes in Table 1 were appropriate for eastern

Washington streams. Fox also proposes minimum volumes for larger channels as follows: 9.75m^3 for 20-30 m width channels; 10.5 m^3 for 30-50 m width channels; and 10.75 m^3 for channels wider than 50 m. In addition, LW in channels wider than 30 m should have an attached rootwad to qualify as a key piece.

The presence of rootwads influences the stability of wood by concentrating much of the mass of the tree onto a relatively small area of the channel bed.[44] In a study of streams draining unmanaged forested basins in Washington, Fox [43] found that in channels with bankfull widths over 30 m, more than 91% of key pieces had root wads attached. Without rootwads, the minimum volume of stable key pieces would have been much larger. Sedimentation in the "hydraulic shadow" of the rootwad often buries the bole of the tree further increasing its stability (Figure 8). Using trees with intact branches will provide additional complexity particularly when using a single wood piece. In addition, the more complex the wood configuration, the more living space, refuge and stability it provides. Green trees in the spring have the most water content and if moved shortly after being felled or pushed over, the branches are more resilient to breakage. Maintaining limbs, however, may be impossible or impractical if wood must be transported by truck. Typically, maintaining limbs is only possible for wood material salvaged on site or transported by helicopter. In situations where large logs are impossible to deliver to a site due to their size, weight, or access limitations, key piece sized wood can be emulated by constructing an artificial large log from smaller logs. A variety of configurations can be used depending on the material available (Figure 9).

Figure 8. Large Wood and Log Jams. Deposition in the hydraulic "shadow" of an instream tree burying the bole of the tree (courtesy Tim Abbe).

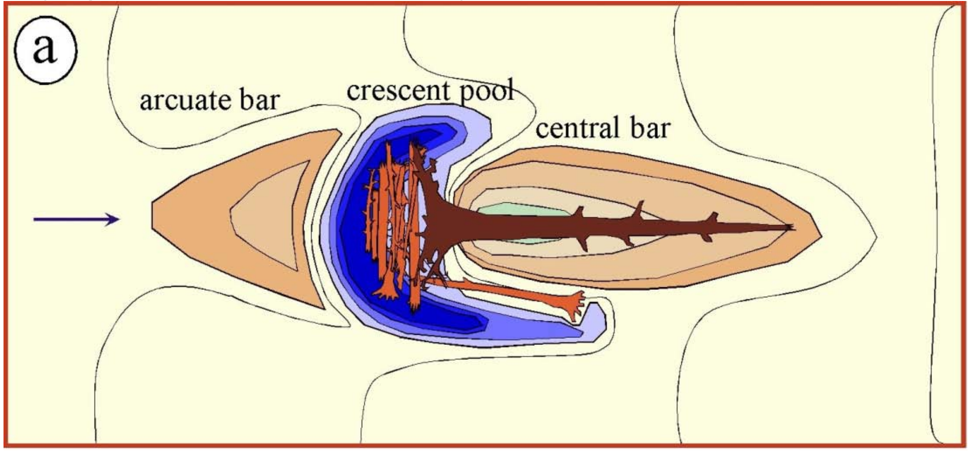
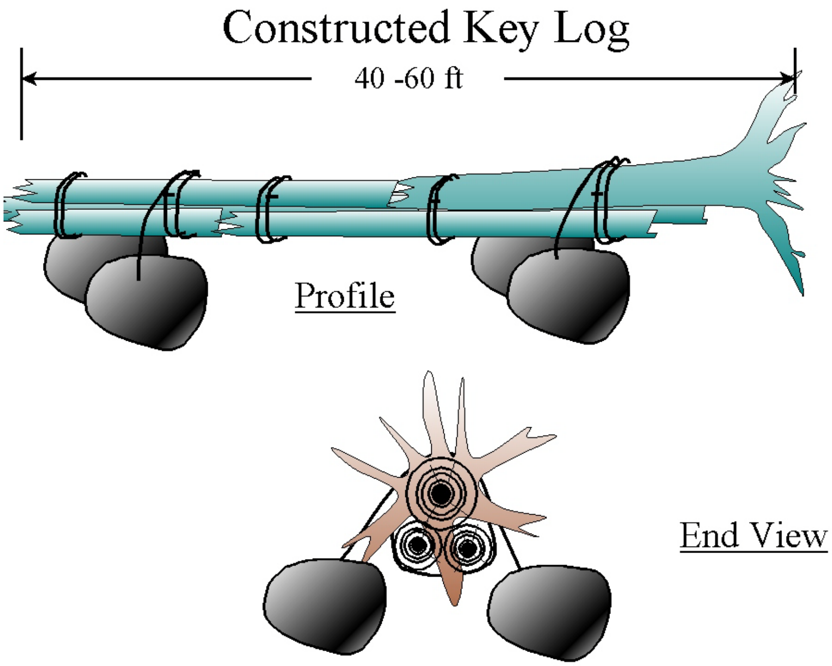


Figure 9. Large Wood and Log Jams. Concept of constructing LW key piece by cabling together smaller logs. Boulder ballast may or may not be required depending on site conditions (courtesy Tim Abbe).



When designing LW and log jam projects, it is critical to understand the size of wood that was historically available to serve as key pieces in the channel. For most streams in Washington, prior to harvest of riparian timber stands, trees were more frequently available to meet or exceed the minimum key piece sizes listed above in Table 1. In many cases, these large trees took many hundreds of years to grow and it will be many hundreds of years from now until they are again available to naturally function as key pieces in the channel. This is especially true for larger streams that require larger trees to serve as key pieces. This lack of available wood for in-channel needs must be considered when planning and designing LW projects. In particular, designing for anchoring and stability will need to consider the lack of future natural recruitment of key pieces, as well as the difficulty in acquiring or importing key piece sized material.

Durability and decay rates will affect the stability and longevity of wood in streams. Differences in the durability between coniferous and hardwood species can be quite dramatic when not fully submerged. Deciduous wood lacks tannins that slow decay. Because of this, they decay much more rapidly and may lose structural integrity within a decade depending on size and the degree of wetting and drying that occurs. However, Bilby et al.[45] found that when hardwood (red alder, big leaf maple) and conifer species (Douglas fir, western red cedar, western hemlock) were fully submerged for five years, the decay rates of the hardwood species were only slightly higher than for conifer species. Of the five species included in the study, western red cedar exhibited the lowest resistance to rupture, whereas big leaf maple exhibited the highest. It is recommended that coniferous species be used for all key pieces of wood that are critical to structure stability and function when not continuously submerged. However, deciduous species could be used to make up a portion of non-key piece members in an effort to reduce costs and provide diverse nutrient sources.

Flood frequency and intensity is also a factor in the stability of LW projects. Wood placed on higher floodplain surfaces that experience infrequent floods may remain in place longer than similarly sized or larger wood placed lower on the floodplain simply because the higher elevation wood is less frequently subject to flows capable of transport. Similarly, ensuring that some of the weight is above the design discharge elevation may increase the stability of wood or log jams placed in the channel.[44] This increases the total weight of the wood complex, thus increasing resistance to the buoyant and drag forces acting against it.

Wood stability is also a function of the location, orientation, and accumulation patterns of wood in the channel. Wood tends to naturally form in certain positions and orientations as a result of stream energy patterns and obstructions in the channel. Example locations are at the downstream end of a meander bend, at the head of a side channel, at the apex of a bar, in backwatered reaches, within pools, or in relatively low energy sites. See Section 5.3 for a discussion of typical locations for natural wood accumulation. Incorporating characteristics of naturally stable wood in the design of a project will decrease the risk of log transport (where it is of concern), and will ensure a more accurate replication of natural channel and habitat features.

Techniques for orienting and arranging wood to increase stability are available. Most of these are focused on mimicking natural stable wood complexes. Wedging a log between stable features within or adjacent to the stream can increase its stability by preventing its movement in one or more directions. Stable features may include standing trees, old-growth stumps, boulders, bedrock, or log pilings (vertical or angled untreated logs driven deep into the bed or bank of a stream). Three-dimensional complexity can also influence log jam structural stability. Logs may be pinned between other logs effectively sheltering them from the full force of erosive flow. When multiple logs are “jackstrawed” together to form an intertwined complex, the stability of each log within the complex will be greater than if each log was placed individually in the channel. Burying one or both ends of a log in the bed or bank can also pin the log in place, provide ballast, and decrease the amount of material subject to drag forces. Bilby [46] found that anchoring one end or the face of a log in the bed or bank greatly reduced the probability of movement. See the *Placement and Anchoring of Large Wood* Appendix for more information on log anchoring techniques.

5.3 Natural Distribution of Wood in Streams

The natural distribution of wood in streams can serve as a reference for designing LW and log jam projects. As described in Section 2.1, wood can occur anywhere in a stream system where trees are present in the watershed. However, the distribution, size, orientation and function of wood vary with the size of the stream. In small channels, wood distribution may consist of frequent accumulations of one or two pieces.[43] As the size of the stream increases, so does the proportion of wood that is associated with jams.[33]**Error! Bookmark not defined.** Wood distribution in large streams (>5th order) is characterized by infrequent jams comprised of a number of large and small pieces of wood.[15]

In a study on the Queets River watershed located on the Olympic Peninsula, Abbe and Montgomery [21] describe nine types of stable, naturally occurring, wood debris accumulations that were organized into three main categories. These categories included 1) wood that had not moved since entering the channel except for possible rotation (*in-situ* wood debris), 2) wood that had moved downstream as a result of fluvial processes (transport jams), or 3) a combination of the two (typically comprised of stable in-situ key members with smaller material racked against and on top of it). These are described in Table 2. Refer to Abbe and Montgomery[21] for additional information.

Table 2. Jam types observed on the Queets River, Washington. Table modified from Abbe and Montgomery[21] and Abbe [44].

Category	**Types**	**Description**
In-situ		
	Bank input	Trees that are fully or partially located within the channel where they fell .
	Log steps	Trees that span the channel with each end being held in place by boulders, bedrock, wood or sediment. Sediment accumulates upstream of the tree and water flows over the top creating a step in the channel profile.
Combination Jams		
	Valley jams	Stable full-spanning jams initiated by one or more stable key members (usually oriented approximately perpendicular to the channel) that constrict a large portion of the bankfull cross-sectional area.
	Flow-deflection jams	Partially spanning jams consisting of one or more key members and large quantities of racked debris. Key members are locally recruited. Flow is deflected nearly perpendicular to the channel axis.
Transport Jams		
	Debris-flow	Jams resulting from the deposition of wood following debris flows. They tend to be chaotic, full-spanning, and retain large amounts of sediment upstream.
	Flood jams	Jams that are mobile during large floods. They may temporarily obstruct the channel and cause backwater followed by re-mobilization. They frequently deposit in the floodplain.
	Bench jams	Partially spanning jams that form along the margins of high gradient headwater channels. They consist of one or more key pieces of wood wedged into bedrock outcrops, boulders, or other obstructions.
	Bar-apex jams	Jams formed at the upstream end of a mid-channel bar or forested island. They can initiate bar and island formation. These jams readily accumulate fluvially transported wood (see **Figure 10**).
	Meander jams	Jams formed on the outside bank at the downstream end of meander bends, primarily in large, low gradient alluvial channels. These jams readily accumulate fluvially transported wood (see **Figure 11**).
	Unstable debris	Mobile wood deposited on banks and on the floodplain during floods. These have a negligible impact on channel morphology and likely continue moving downstream in the next flood event.

Figure 10. Formation of arcuate scour pool at the head of a bar apex jam, and downstream deposition (courtesy Tim Abbe).

Figure 11. Oblique aerial view of a large meander-bend log jam on the Nisqually River. The jam serves to regulate flow into a major side-channel (Thurston and Pierce Counties, WA).

Natural locations for wood accumulations discussed above can be used to help determine the location and configuration of wood placement projects. This will help ensure that the project is in line with the geomorphic and habitat context of the stream. In general, areas with lower stream energy at high flows provide good locations for LW. Also, breaks in slope and width are natural areas that collect wood that is transported from higher energy steeper stream reaches. The downstream end of sharp bends or constrictions is also where LW naturally accumulates and may serve as good placement locations. Wood placed at the outside bank near the downstream of a meander bend frequently causes flow deflection that creates deep pool scour that can provide high quality habitat.

5.4 Target Wood Loading

Objectives for LW projects frequently utilize wood loading targets. Target wood loading refers to the density and sizes of LW needed to accomplish habitat objectives. These targets may come from management targets or may be developed for the project site based on historical records or through the use of reference reaches. Management targets have been developed by a number of federal and state agencies including NMFS,[47] USFS,[48] Washington Forest Practices Board,[49] and the Oregon Watershed Enhancement Board.[50] These targets, however, do not fully consider the wide range of variability of stream systems and, therefore, their use may be inappropriate in many circumstances.[51]

Developing wood loading targets based on historical information or current reference areas is challenging due to a lack of historical data and streams undisturbed by human activities. Anecdotal accounts and limited historical records indicate the amount of LW in channels prior to removal by humans was several orders of magnitude greater than what exists today, however, records with specific and reliable wood counts are uncommon.

To estimate historical natural wood quantities, researchers have studied existing instream wood conditions in protected or unmanaged areas. Collins, Montgomery and Hass [10] studied a protected reach of the Nisqually River, a tributary of Puget Sound, which appears to be functioning close to historical conditions. The Nisqually reach had a minimum of 1,400 LW pieces/km. Based on this, they surmised that managed rivers in the Puget Sound Lowlands have 1-2 orders of magnitude less LW than the historical condition. The wood in the Nisqually River is found mostly in log jams. These create the majority (61%) of the pools in the reach and initiate the anastomosed (conjoined) channel pattern. By comparison, LW in the extensively managed Stillaguamish and Snohomish rivers only account for 12% and 6% of pools, respectively, with little of it in log jams. Montgomery et al.[52] found that in unmanaged streams, LW frequency was 0.4 pieces per meter of channel length. However, in 73% of the managed streams the LW loading was less than 0.2 pieces per meter of channel length.

Fox and Bolton[51] measured wood quantities and sizes in streams draining unmanaged basins throughout Washington State to develop reference conditions for restoration and management. These data provide a good source for wood loading targets in the absence of historical or reference data for the project site itself. The data were used to produce a linear regression that correlates wood predictions to any stream in the forested landscape of Washington based on multiple regional and geomorphic variables. See Fox and Bolton[51] for additional information. The data were also used to provide a summary of reference conditions for wood quantity, key-piece quantity, and wood volume for various forested regions of the State. These data are presented in Table 3 and include the 25th, median, and 75th percentile points of the data. Because of the low quantities of instream wood in most streams under existing conditions, Fox[44] suggests that the management target should be at least the 75th percentile to achieve central tendencies at the basin-scale.

Table 3. Distributions of LW (number of pieces, volume [m^3], and number of key pieces, all per 100 m of channel) by region and bankfull width (BFW) class. Large wood is defined as pieces exceeding 10 cm in diameter and 2 m in length (Reproduced from Fox and Bolton[51]).

Region	BFW Class	75th Percentile	Median	25th Percentile
		Number of Pieces		
Western Washington	0-6 m	>38	29	<26
	>6–30 m	>63	52	<29
	>30–100 m	>208	106	<57
Alpine	0–3 m	>28	22	<15
	>3–30 m	>56	35	<25
	>30–50 m	>63	34	<22
[1]DF–PP forest zone	0–6 m	>29	15	<5
	>6–30 m	>35	17	<5
		Volume (m^3)		
Western Washington	0–30 m	>99	51	<28
	>30–100 m	>317	93	<44
Alpine	0–3 m	>10	8	<3
	>3–50 m	>30	18	<11
[1]DF–PP forest zone	0–30 m	>15	7	<2
		Number of key pieces		
Western Washington	0–10 m	>11	6	<4
	>10–100 m	>4	1.3	<1
Alpine	0–15 m	>4	2	<0.5
	>15–50 m	>1	0.3	<0.5
DF–PP forest zone	0–30 m	>2	0.4	<0.5

[1] DF = Douglas fir; PP = ponderosa pine

5.5 Placed Logs and LW Complexes

The following are design considerations specific to placing individual logs and LW complexes in streams. The size of the structure, site selection, placement, and orientation of wood vary based on project objectives. Construction of larger log jams is discussed in Section 5.6. Refer to the *Instream Structures* technique for additional information on the use of logs for drop structures, weirs, sills, or grade control.

5.5.1 *Size of Complex*

Multi-log structures generally provide better habitat than single logs due to the greater amount of cover and complexity. These structures are more likely to be hydraulically active through a broad range of flows. The diversity of microhabitat features (e.g. velocity, depth, substrate, and cover) and the depth and volume of pool habitat created by wood typically increases with the number of pieces and the degree of interaction between complexes. Because of the interstices formed between logs, wood that is grouped in complexes can provide far greater cover and refuge habitat than that provided by the same number of logs placed individually within the stream channel.

A diverse assemblage of microhabitat can appeal to a variety of species and age classes. Ideally, where single log structures are applied, they should have a rootwad and/or branches left attached.

5.5.2 *Site Selection*

When choosing a site for placed logs or log complexes, consider the location that will provide the most biological benefit while at the same time meeting project goals for hydraulics and sediment transport. Projects should be designed to replicate natural LW accumulation patterns that demonstrate persistence and ecological benefit. For instance, if the project objective is to create and maintain pools in a low gradient stream, wood placement along the outside of meander bends may be appropriate. Alternatively, in higher gradient systems where pools form in association with larger substrate or geologic features, log complexes can be designed to encourage energy dissipation through steps where plunge pools might be a significant habitat component. Bilby and Ward [53] found that the type of pool, and the debris accumulations associated with them, changed with stream size. By replicating the structures and processes that would occur in a natural stream reach, appropriate habitat will be created for the various species and life stages adapted to that stream type.

Logs placed for in-channel fish cover are most effective where hydraulics favor resting such as in pools, glides, and side channels, or other low-energy environments (Figure 12). Many fish and some stream-associated amphibian larvae prefer to feed in and around glides and pools where they expend minimum energy. If the objective is to provide cover during low and moderate flows, wood should be located in, around, or suspended above pool and glide areas and along the margins of the channel thalweg.

Figure 12. Constructed log complex in a pool (Klickitat River, WA, Inter-Fluve, Inc.).

5.5.3 *Placement and Orientation*

Wood placement and orientation should consider the characteristics of naturally occurring wood in streams to provide habitat complexity and cover that is most appropriate for aquatic species.

Projects that rely on geometric structures placed with cookie-cutter regularity in the channel will not provide the complexity of habitat that occurs in natural systems and to which aquatic species have adapted. Robison and Beschta[54] studied natural LW distribution and orientation in coastal streams in Alaska. They found that 80% of the woody debris associated with 1st (and some 2nd) order streams was suspended above (spanning) or lying outside the bankfull channel; whereas in 4th order streams, 60% of the wood observed lay within the bankfull channel area. Approximately 1/3 of all woody debris was oriented perpendicular to the channel, regardless of stream order. Bilby and Ward[53] found that the majority of wood in second to fifth order streams draining old-growth forests in western Washington was oriented either perpendicular or angled downstream to flow. Wood oriented upstream to flow had the least frequent occurrence. It was also noted that the occurrence of wood perpendicular to flow decreased with increasing stream size while that of wood angled downstream to flow increased with increasing size, probably as a result of the stream's increasing capacity to rotate and transport wood.

Based on these and other studies, recommendations for placement of woody debris are as follows.

> *Smaller streams (<10m wide)*: Single or multiple pieces of wood can be effectively used to create habitat, stabilize the channel, dissipate energy, and store sediment. Logs most often lie perpendicular or are angled downstream to flow, but any orientation is feasible. They may span the channel or intrude partway into the channel. Logs in small streams may be used to create step pools (i.e. plunge pools). Because small streams generally have less energy to move LW, a greater variety of LW locations and orientations can be employed without excess risk.

Medium-sized streams (10 to 20 m wide): Wood tends to accumulate in jams, but single pieces and small complexes also occur. Woody debris should lie within the active channel, or intrude into it significantly (Figure 13). Channel-spanning wood structures may be applicable but the results are less predictable than for small streams and their vulnerability to flood damage is relatively high. The outside of bends and the head of natural gravel bars tend to be relatively stable locations for wood jams.

Figure 13. Constructed meander bend log jams (Elwha River, WA, Mike McHenry, Lower Elwha Klallam Tribe.).

Large streams (>20 m wide): Stabilizing woody debris becomes a significant concern on larger streams. Wood placement in the main stem of the channel is only recommended in the form of anchored structures (i.e. log jams, LW complexes, and wood trapping structures), unless transport can be tolerated. Key pieces and log complexes can be effectively used in side channels and floodplain habitats. Woody debris should lie within the active channel or intrude into it significantly. Lateral jams, as opposed to full-spanning jams, are a common feature. As with medium-sized streams, locations at the outside of bends and the head of natural gravel bars tend to be relatively stable.

Distributing individual logs and log complexes among low flow, near bank, and floodplain habitats will most closely mimic the characteristics of natural channels, and therefore, will likely achieve the best results during restoration or enhancement projects.[43] As an example, in-channel wood may provide summer cover and winter refuge habitat, wood along channel margins may provide juvenile rearing and roughness, and wood in the floodplain may be important for high water refuge.

Most structures are intended to change channel hydraulics in order to impact sediment deposition and scour patterns. Scour is induced by increasing water velocity, either through lateral channel constriction or with a vertical drop (plunging flow). Large wood structures can be designed to do either or both functions simultaneously. Various configurations will cause different patterns of erosion and deposition. In general, the more of the stream channel that is obstructed by the structure, the greater will be the response in terms of scour and sediment accumulation.

Large wood placements on the floodplain can serve a number of important functions (see Figures 14 and 15). Floodplain wood can be used to provide hydraulic roughness that is otherwise lacking due to impacts to floodplain vegetation or past filling and grading. Increased roughness can reduce the energy of overbank flows and reduce the potential for channel avulsions.

Floodplain wood can also be placed with the acknowledgement that channel shifting is likely and once it occurs, the wood will be available to function as instream wood. Floodplain wood also provides important habitat for terrestrial species. Floodplain wood is more subject to rot than wood placed in the active channel, and this needs to be considered as it relates to project function over the long-term.

Figure 14. Floodplain wood placements associated with LW placed for in-stream habitat. The objective of the floodplain wood was to provide short-term hydraulic roughness until the regeneration of riparian vegetation, which was lost through channel incision, grazing, and timber harvest practices (Teepee Creek, Klickitat Co, WA, Inter-Fluve, Inc.).

Figure 15. Floodplain wood placed on a constructed bar to roughen the former active channel where it previously abutted a rip-rap roadbed. The logs are braced against and attached to vertical log pilings (Klickitat River, WA, Inter-Fluve, Inc.).

5.6 Constructed Log Jams

Constructed log jams are typically defined as being comprised of 10 or more pieces of LW. They are discussed separately from placed logs and LW complexes because of their size, complexity, and risk.

5.6.1 Site Selection

Placing log jams where they would naturally occur will enhance longevity, habitat value, and will reduce the risk of failure. Natural locations and types of jams are discussed in Section 5.3. Other factors may also influence site selection such as access, infrastructure, bank erosion potential, or the condition of riparian vegetation. These conditions are site specific and will require careful analysis by the design team.

5.6.2 Orientation, Anchoring and Jam Design

The size, shape, orientation, and degree of anchoring of constructed log jams depend upon many factors including habitat objectives, channel hydraulics, geomorphic response, risk, access, and cost. These factors should be addressed and planned for early in the design process. Public safety is of particular concern in areas where recreational use of the river is high (see the *Public Safety* Appendix for more information).

Log jam designs typically consist of three basic elements: 1) one or more key pieces that consist of large immobile logs (ideally with attached rootwads), usually placed more or less parallel to the channel with the rootwads facing upstream; 2) stacked members that consist of logs of varying size placed on top of the key pieces and/or interwoven to form the matrix of the jam; and 3) racked members of smaller wood placed against the upstream face of the jam, generally perpendicular to the direction of flow. Log jams, however, can take many alternative forms (see Section 5.3) depending on project objectives and site-specific conditions.

A log jam can be designed with a single key piece or with multiple key pieces. Key pieces should ideally be large enough to self-anchor, meaning that their weight and size is sufficient to counter the forces acting to mobilize them. Using key pieces with attached rootwads is preferred as it increases log stability as well as habitat complexity. Stacked members that are above the water surface elevation can add weight to the key piece without adding buoyancy, thereby increasing the effective weight of the key piece (Figure 16). Use of multiple key pieces may allow for the construction of stable jams that require minimal or no artificial anchoring. Stacked and racked members can be “weaved” among the key pieces and with each other to increase stability. Unanchored log jams must be dense, with key members and stacked pieces carefully interlocked. Scour under part of a loosely assembled structure may destabilize it and allow portions to be washed away. Dense structures, on the other hand, act as a unit. They settle uniformly and hold position well.

Figure 16. Use of large key pieces and additional stacked logs to increase stability (Elwha River, WA, Mike McHenry, Lower Elwha Klallam Tribe.).

In most cases, log jams that allow for flow of water through the jam will provide the greatest fish habitat benefit. The interstitial spaces created within jams can provide important velocity refuge and overhead cover for rearing fish. When designing and building porous structures, care should be taken to ensure that potential scour within the structure will not cause undesirable destabilization of the structure.

Racked members can be placed on the upstream face of log jams and slash material can be placed within the log jam structure. The number of pieces racked against the upstream face of the jam depends upon the need for immediate scour and deposition, and the likelihood of recruiting additional LW. Racked pieces do not usually function as structural members of engineered log jams, so they can be any size. These additions mimic conditions found in natural jams and can contribute to hydraulic and habitat complexity. In cases where alluvial material is incorporated into the jam to provide ballast, the use of slash can prevent the ballast material from being scoured from the inside of the jam.

Jams are likely to accumulate additional fluvially transported material over time (see Figure 17). The collection of additional wood on a log jam during floods will potentially change its shape and dimensions. When additional accumulation is anticipated, increasing the factor of safety for the structure in the design is recommended to account for additional drag or buoyancy forces that may be encountered.

Figure 17. Collection of additional wood on a constructed meander bend log jam (Clear Creek, OR, Inter-Fluve, Inc.).

The desired level of stability for log jams should be clearly defined and accounted for in project design. In some cases, it may be desirable for jams to function as they do in natural systems, where they are allowed to adjust, move, and even break apart and relocate downstream during floods; in other cases, greater stability may be necessary. The need for and methods of stabilization/anchoring depend on several factors including habitat objectives, risk to property or infrastructure, stream size and hydraulics, the size of material that is available, and the likelihood of future LW recruitment (i.e. replacement) if wood is transported out of the system. Placement of a log jam on a stream with a downstream bridge or with stream-adjacent residences may need to be stabilized in place to manage for risk to infrastructure and public safety. In contrast, a log jam on a wilderness river with no downstream infrastructure could be designed to adjust or mobilize during floods.

Many techniques for anchoring logs and providing stability to jams have been developed. These include burial, backfilling with alluvium, cabling or pinning logs together, and anchoring to bedrock, boulders, pilings, deadman anchors, or existing trees. These techniques are described in the *Anchoring and Placement of Large Wood* Appendix. This appendix also describes force balance equations and methods that can be used to evaluate the stability of logs of given dimensions; information that is critical to determining if and how much anchoring will be required.

5.7 Large Wood Replenishment

Adding significant volumes of mobile wood to a stream requires both good access to the stream and proximity to sufficient sources of wood. Mobile wood can be added directly to the channel, placed on streambanks to fall in as banks erode, or placed loosely on the floodplain or in channel margins such that it becomes entrained at high flows. The delivery of entire trees with rootwads and limbs is emphasized.

Generally, key piece wood additions should be large enough to develop a log jam without significant movement downstream. However, size mobility calculations are not critical when the goal is to allow wood movement downstream. The minimum size of wood necessary to qualify as a key piece is further discussed in Section 5.2. Where it is necessary to predict rates of wood mobility, flood frequency will need to be paired with force balance analyses on the placed wood. This will require a detailed hydrology and hydraulics analysis as well as an understanding of geomorphic processes in the project reach and in downstream reaches.

Ideally, LW replenishment is paired with log jam projects or structures specifically designed to trap mobile wood.

5.8 Trapping Mobile Wood

The design of wood-trapping structures follows the same general methods as LW complexes or log jams except that racked members are provided naturally through mobile wood transport. To catch mobile wood more efficiently, wood trapping structures must be designed and located to maximize contact with, and minimize passage of, smaller mobile pieces. Capture of wood is more likely when the structure is oriented perpendicular or angled upstream to the flow direction where wood can be captured in the pocket formed between the structure and the streambank. When designing for structure stability, it will be necessary to anticipate the eventual size of the jam once mobile wood is captured.

Trapping structures are appropriate in the same locations as placed LW and log jams. They should be placed to intercept surface flow during high flow events as most wood is buoyant and only mobile during high flow. Types of wood collectors can include single key pieces, log pilings, or logs anchored in a trench in the bank. Single key pieces are simply single logs, ideally with root wads attached, that are large enough to be relatively stable within the channel and capable of catching and accumulating fluvially transported wood. Log pilings are vertical logs buried into the streambed or banks. Pilings can be angled upstream and placed in configurations that will maximize capture of fluvially transported wood. In addition, horizontally placed logs can be partially buried in the streambank with their exposed ends angled upstream to maximize capture of wood. Choosing a strategy for wood trapping depends on the size of the stream, stream energy, location within the channel, availability of materials, and construction considerations.

6 PERMITTING

Large wood projects frequently require the full suite of local, state, and federal permits required for work in and around streams. Refer to *Typical Permit Requirements for Work In and Around Water* Appendix for more information regarding each of these permits and checklists. Large wood projects generally qualify for streamlined permitting through the JARPA processes which exempts the project from SEPA and local permits.

Information generally required to obtain permits includes the volume of the wood and rock ballast incorporated in the project, wetland locations, design drawings, site maps, access areas, sediment control plan, re-vegetation plan for disturbed sites, relevant information regarding physical and biological effects, and risks and uncertainty. Safety issues, while not necessarily a part of the standard permit requirements, may need to be addressed for wood placement projects. Coordination with river user groups is advised early on in the planning process. If implementing a project on State-owned aquatic lands, obtaining a Washington Department of Natural Resources Aquatic Land Use Authorization may require certain safety precautions, such as adequate visibility of structures and clear warning signs of their location. More information can be found in the *Public Safety* Appendix.

In some cases, LW projects may require a “no-rise” analysis to demonstrate that LW placements will not result in a rise in the Base Flood Elevation (i.e. 100-year flood). This is a Federal Emergency Management Agency (FEMA) requirement as part of the National Flood Insurance Program (NFIP). A no-rise analysis may be required by the local jurisdiction responsible for managing the NFIP program. A no-rise analysis must be conducted by a licensed engineer or hydrologist, and can be a burdensome and expensive process. However, FEMA Region 10 has issued a policy statement that may reduce the analysis burden for fish enhancement structures. This policy statement is included in the Region 10 NFIP Guidebook.[55]

7 CONSTRUCTION CONSIDERATIONS

7.1 Buoyancy

Buoyancy of wood presents a unique construction challenge. The main issue occurs when working in water and trying to keep a log in place while anchoring it or adding additional LW to the structure. Buoyancy issues can be greatly reduced by using saturated logs; however acquisition of saturated logs or soaking of dry logs can be difficult and expensive. If two excavators are on the same site, one can hold a log in place in the water while the other machine places additional logs, ballast, or other means of anchoring. Even this approach may be difficult when building large structures. Consequently, log structures are best constructed in dewatered conditions to avoid buoyancy during installation. Dewatered site conditions have the added benefit of minimizing water quality issues. For further discussion of dewatering, refer to the *Construction* Appendix.

The stability of a structure will increase as its weight increases relative to the buoyant and drag forces acting against it. This can be achieved by placing wood so that some of its weight is supported on banks above the bankfull channel[44] or by stacking wood such that much of it is located above the bankfull channel and not in contact with low to moderate flow events. Burying either end of a log or lateral burial of some portion of its diameter can also pin the log in place, provide ballast, and decrease the fluid drag forces on the log. The more wood above design flow elevations, the more ballast and strength is provided to the submerged portion of the log jam. Attaching boulders to LW also counteracts buoyant forces. If the LW structure is sufficiently large and complex, then boulders can be placed in the complex without mechanical anchoring (Figure 18). Pilings may also be used for anchoring as discussed in Section 5.6.2.

Figure 18. Boulders for stability (Klickitat River, WA, Inter-Fluve, Inc.).

7.2 Equipment

Equipment needed to move wood can include self-loading log trucks, excavators, end dumps, skidders, and dump trucks. Large wood is most often placed using an excavator with a hydraulic thumb attachment. Wood placement can also occur using a track log loader. Disadvantages of using a loader are the inability to dig or move rocks if any ballasting is needed. A relatively low-impact machine is a “spyder” or walking excavator. The four articulating arms and two rubber tires allow movement in riparian zones with minimal need to remove trees and they work on steep slopes. Their main disadvantage is relatively slow movement which can be a time/cost issue if they are used to transport materials very far. It is recommended that equipment operated in the stream use biodegradable hydraulic fluid and that it be steam cleaned prior to use to remove residual hydraulic fluid and oil. The local logging industry is often a good source of expertise with this equipment.

In areas where ground based equipment access is difficult or when helicopters are being considered, it is recommended that logging and helicopter contractors are consulted early. Their knowledge may change project designs or design locations. Helicopter time is usually the major cost for the project. That time can be minimized by finding the best location for a materials staging area, by having all materials on site and prepared for installation, and having LW placement locations clearly identified. Large wood can usually be placed precisely if there is a person on the ground that can communicate with the pilot.

Other methods of LW placement include the use of horses or portable winches and pulleys (diesel donkeys). These approaches are better for remote sites where a few logs are to be placed, or where riparian zone protection is critical. They work well for LW replenishment of key pieces and may be combined with hand labor to cable LW to trees, boulders or bedrock.

7.3 Access

It is important to communicate expected limits of ground disturbance associated with access. Sensitivity to impacts can be highly variable between people depending on background and experience. The degree of ground disturbance can vary with the type of equipment, slope, size of wood, number of trips, and soil moisture. Disturbance relating to wood projects normally occurs when logs require skidding to a site from a stockpile area or when an access road is built.

Unless a road immediately adjacent to a stream exists, access into a stream channel works best at a single point. Moving wood over un-vegetated gravel bars or in the channel during allowable work windows likely produces fewer impacts than adjacent temporary or permanent access roads along riparian areas. Disturbance relating to LW projects can be repaired by de-compacting access areas, re-routing drainage, and replanting with native seed.

8 COST ESTIMATION

8.1 Material availability and costs

Buying and hauling wood can be expensive and is generally the biggest cost variable in a wood related habitat project. Prices vary widely depending on market conditions, so providing unit costs is not practical. In relative terms, a single large tree with rootwad attached may cost as much as a log truck load of chip-quality logs. Cull logs may be available for the cost of transportation and loading.

Buying wood on the open market or from a private landowner is one source of LW. Other sources include local, state or federal government, or private developers. Some large timber companies will donate cull logs or even some merchantable timber. Other sources include blow down timber, wood removed from dams, lakes or reservoirs, or LW collected during bridge or culvert maintenance. Cities or counties may have trees from clearing operations or hazard tree removal. In these latter cases, the main cost is transportation to stockpile locations and eventually to the project site.

Some basic understanding of log value/worth is helpful when approaching timber or mill owners for wood purchase. Stumpage value and pond value are two ways to assess what a log or tree is worth. Stumpage value is what a tree is worth standing in the woods or on the stump. Pond value is what a mill is willing to pay for a log delivered to the mill or what a log is worth in the mill holding pond. The unit of measure for wood is per thousand board feet (MBF). For reference, a loaded log truck typically carries approximately five thousand board feet. This can vary depending on the weight of the wood.

In forestlands, live trees near the stream may be the most cost effective source. Using nearby riparian or upland trees for in-channel placement can reduce impacts associated with vehicle access and hauling of off-site trees. Using trees from on-site also frequently allows for the incorporation of much larger trees than can be effectively trucked to the site. The limit for trucking is typically around 50 feet long with a 12 foot diameter rootwad. With only one tree per load, this is very expensive. Using trees from on-site allows for the use of whole trees, complete rootwads, and with all branches intact. These trees typically provide much greater stability in the channel and provide more habitat cover and complexity. However, regulations and forest management practices often discourage taking trees from riparian buffers. Some riparian buffers are too narrow to risk harvesting trees or are still recovering from recent timber harvest or land clearing. Trees from adjacent upland stands may be available by purchase or donation, and hauled into the riparian zone via cable or diesel donkey, thus avoiding the need for heavy equipment access. The following issues should be considered when using nearby riparian or upland trees:

- Snags or downed wood provide nutrients and important benefits for terrestrial wildlife and, therefore, may not be the most appropriate for in-channel placement.
- Trees rooted in the bank of the stream may be providing an important function as bank stability. They also will likely recruit naturally to the stream in the future.
- Riparian trees that shade the stream may be important for control of water temperature.
- Avoid significant impacts to long-term LW recruitment. Light thinning will not have much impact on long-term LW recruitment. Harvesting clusters of riparian trees or narrowing the buffer width will impact recruitment.
- Applicable regulations, such as forest practices, may be more restrictive than the above guidelines (i.e., forest practices).

8.2 Delivery costs

Delivering wood by truck directly to a work site will reduce costs. If wood has to be moved from a stockpile site into a work area through the woods, it is much cheaper to move it using a skidder rather than shuttling it with an excavator. This process will invariably remove most limbs and often parts of the root wad. Skidders can move several trees at once with a set of choker cables. The haul distance from a stockpile site to the work site will determine costs.

Lowboy trailers can haul root wads and trees with difficulty. Self-load log trucks are good tools to haul logs and/or trees with root wads. The efficiency of hauling trees with root wads is poor and therefore the cost is much higher than hauling logs with a log truck.

Key piece trees too large to be transported whole may need to be sawn in half and reassembled on site. This is best accomplished by cutting the log on a diagonal and reattaching the pieces on site using bolts, cables, and adhesives.

As discusses previously, helicopter use is a significant cost issue. Helicopter flight distance will affect the cost, so the faster the turn around time the more cost effective a helicopter becomes. Depending on size and hauling capability, costs for helicopters can range significantly.

8.3 Unit costs for structures

Cost estimates can vary greatly depending on access, mechanism of delivery, wood availability and materials costs, and anchoring costs. Placing a log in a remote area with a helicopter is far more expensive than with an excavator standing on a road. Large wood structures installed in remote sites often require considerable hand labor and can be very time consuming and expensive to assemble. For example, cabling projects using rock drills can add up to 25% to the total project cost in remote areas.

At sites accessible to machinery, the placement cost of individual log units may range from $100-$400 per log or tree (not including purchase or delivery) depending on the complexity of placement. Using a unit cost of $600-$1000 per log for purchase, delivery, and placement is fairly typical for sites without special hauling or placement circumstances. Depending on size and complexity, log jam construction can range from half a day to several days. Total costs for log jams may range from approximately $5,000 to over $100,000 for large jams on large rivers.

Large wood replenishment is the least expensive type of LW project. A self-loader or dump truck and hand labor may be adequate to place LW off a road or a bridge. Costs can be greatly reduced if replenishment is done in conjunction with timber harvest or log yarding.

8.4 Contracting

Large wood projects lend themselves more towards a time-and-materials contract with an experienced designer directing wood placement than with a traditional construction contract. This is primarily a result of the variability in wood material and challenging construction environments. Regardless of contract type, it is recommended that experienced oversight from a member of the design team be provided to ensure habitat and stability requirements are met.

See the *Construction* Appendix for additional details such as construction timing issues, sequencing, access, and reclamation of disturbed areas.

9 MONITORING

Project effectiveness monitoring is recommended to evaluate if objectives are being achieved and if adaptive management of the project is necessary. It is critical to monitor according to the objectives of the specific project. Monitoring programs that are not based on the project objectives, or that assume different or additional objectives, may fail to accurately evaluate project effectiveness. This section describes considerations for project monitoring with the understanding that certain monitoring elements may not be appropriate and additional elements that are not presented here may be required.

Monitoring of LW projects is important because design methods are still somewhat experimental especially on larger rivers. The performance of LW structures may be less predictable than non-wood structures. Projects should have performance objectives that can be effectively and meaningfully measured and monitored. Designs should specify procedures for pre- and post-construction studies so resulting physical and biological changes can be evaluated.[56] Further discussion of the relation of design criteria to monitoring is provided in the *Monitoring* Appendix. In some cases, independent monitoring is provided by the funding agency (e.g., SRFB), reducing the need for project proponents to conduct it.

The Salmon Recovery Funding Board (SRFB) Reach-Scale Effectiveness Monitoring Program[57] evaluates a subset of SRFB-funded projects to determine project effectiveness. Monitoring components for instream habitat projects include habitat metrics (i.e. pool area, pool depth, LW volume) and fish metrics (i.e. salmonid rearing density). Monitoring was not conducted for any large-scale channel modification projects and results are only preliminary. The report recommends monitoring of more projects for additional years. Recommendations for monitoring elements in the report include incorporating additional metrics (i.e. velocity), focusing on structure-specific effects, and increasing the sample size. In the case of experimental methods and controversial projects, every project should be monitored.

LW projects generally should include comprehensive monitoring of both channel and bank features with particular attention to habitat monitoring. For a comprehensive review of habitat-monitoring protocols, refer to *Inventory and Monitoring of Salmon Habitat in the Pacific Northwest –Directory and Synthesis of Protocols and Management/Research and Volunteers in Washington, Oregon, Idaho, Montana, and British Columbia.*[58]

Monitoring to evaluate structural integrity and maintenance requirements should be conducted annually and following any flow events that meet or exceed design flow. Projects in high-risk areas should have more intensive monitoring to insure stability criteria are met. New anchoring techniques or designs that emulate natural function should also be closely monitored for stability and effectiveness. Successful new and/or better designs should be shared to allow more widespread application.

In some projects, component pieces of wood have been tagged so their source location can be determined if they become mobilized. While GPS locations may be appropriate for single pieces placed throughout a reach, structural integrity is best monitored using detailed site surveys. The resolution of GPS is not sufficient to detect rotation or other movement of pieces within a structure. At low risk sites, a good photo record may be sufficient to identify movement of pieces or entire structures.

10 MAINTENANCE

Maintenance of LW projects may be required where the project is no longer meeting objectives or unintended and unacceptable consequences have occurred. Maintenance or repair should be completed only after careful evaluation to determine the cause of project failure and to minimize future project maintenance costs. Maintenance may include replacement, realignment, or removal of pieces. If anchored, the anchoring hardware may also need to be readjusted, replaced, or removed. Anchoring hardware may need to be removed from failed structures if these materials present a hazard.

Public outreach may lower maintenance costs by preventing loss of project LW. For instance, local landowners may view LW projects as a source of firewood and rafters have been known to cut up log jams or LW complexes. Notifying and educating local residents, governments, and recreational user groups is an important part of LW projects.

Wood placements used to supplement downstream habitat should be monitored and adjusted if the size or volume of wood does not fulfill desired objectives. Periodic supplementations may be necessary to maintain habitat until a source of material is reestablished through riparian zone restoration. The frequency of periodic supplementation should be based on monitoring of the project reach.

11 EXAMPLES

Constructed Log Jam--- West Fork of the Hood River, Hood River County, Oregon (Inter-Fluve, Inc.)

A channel-spanning log jam was constructed at the upstream end of an alluvial fan that was historically subject to debris torrents. The site in Hood River County is a natural area of deposition within the Pacific Silver Fir vegetation zone. The size of historical LW was up to 5 feet in diameter. Over time, the initial log jam accumulated more wood from upstream sources. This caused the channel to aggrade to a depth of 4 feet near the log jam, with the sediment wedge extending approximately 700 feet upstream. This reconnected a large area of valley bottom to bankfull discharges and substantially reduced average substrate grain size. Complex over-bank habitat was increased and historical side channels were re-watered during low flow. Off channel beaver activity increased. The log jam was constructed in 1991 and has sustained numerous over bank flows and one 25-year return interval flood. A September 2006 debris torrent event deformed the jam and removed accumulated smaller LW from 1991 to 2006 but the original jam foundation stayed intact and continues to backwater and maintain the habitat that was created following original 1991 construction. Another channel spanning jam was constructed in 2007 approximately 3,000 feet upstream of the 1991 jam (see Figure 19); it caused a similar response with respect to backwater habitats. Substantial new spawning habitat has been created within the gravel deposition that was a result of the backwater. This area was formerly a plane-bed cobble channel.

Figure 19. Log jam constructed in 2007. Photo taken 2 years after construction and after a 5-year return interval flood event (West Fork Hood River, OR, Inter-Fluve, Inc.).

LW Replenishment --- Palix River, Pacific County, Washington (Allen Lebowitz, Coastal Watershed Consulting)

Palix River LWD Placement Project, 1998: Canon River, WRIA 24.0435, RM 2 – 7. The Palix River Watershed Analysis LWD Placement Protocol was implemented in 1998. This is one of the largest LW placement projects recorded with over 800 key sized LW pieces and several thousand functional sized LW pieces placed in 5 miles of a large river. The project site is in a roadless section of two private forest harvest management areas in Pacific County. The Palix River was catastrophically splash dammed to bedrock during the 1900s. The project focused on re-establishing natural processes that provide habitat functions and recognized the dynamic nature of streams, including disturbance processes. LW loading met estimated old growth conditions within the permitted LW placement area. Permitting requirements reduced the original designed scope of this project by not allowing wood placement in the lower 2 miles of the project area. This is the area where the river begins confluence with Willapa Bay and was a key part of the original design. Live trees were cut from the forest close to the river. Harvest trees were carefully selected for project LW to avoid impacting existing forest stands, habitat potentials and riparian zone functions. Some key pieces were pinned between live trees or wedged against bedrock formations. No wood was mechanically anchored. Most LW was simply placed in the river proximate to harvest sites at low impact access points. All LW, including project placed and existing LW, was tagged and tracked. Natural recruitment of LW was tagged and tracked for two years following project implementation. Tree boles were yarded in place using a high capacity winch vehicle which moved as a sled over terrain. This vehicle could be positioned, cabled down, and used almost anywhere within the stream corridor with little or no riparian damage. Professional loggers crewed the LW placement operation and the project's lead scientist provided guidance in wood selection and placement. Many very large volume pieces of fir, cedar and hemlock were placed in the channel. Most LW did not include rootwads.

Monitoring has been a major element of the project and continues from project inception to the present. Monitoring includes instream flows, LW volumes and movements, gravel bed scour and deposition, and fish population monitoring of most life stages. Because this project developed with a broad social, technical and administrative base, compliance monitoring was intensive. Permit, grant, and landowner plan compliance was excellent. Since project construction in 1998, the Palix River has been exposed to several large storm events and at least one event of 100-year recurrence magnitude or greater.

Habitat quality and quantity in the Palix River has increased since project construction. Monitoring results show increased salmonid population diversity in life stages and number of juveniles rearing in the area. All freshwater life stages of cutthroat and steelhead trout, coho, chinook and chum salmon are now found at times rearing in the project area. Prior to the project, fish life stage diversity in the area was low and some life stages were not observed. Chum salmon are a key species to restoration of productivity in this river. Chum salmon spawn as large groups intensively using gravel bed reaches of the lower river. Prior to this project, many of the spawning beds were shallow veneers over bedrock. Some of these beds were controlled by channel spanning alder log sills. The high decay rate of alder and the lack of LW stabilization of other gravel beds resulted in periodic scour of entire gravel beds including any fish redds present. This population was impacted because the most powerful flows tend to occur when chum redds were incubating in these beds. Chum salmon spawner recruit analysis showed that over the 27 years of record an average of one of three chum generations failed to reproduce brood year replacement number. Because three years is the average chum generation period, this population was being significantly impacted by conditions other than harvest prior to the project. Now cedar and fir have stabilized many of these spawner beds so that broadcast scour is reduced. Gravel beds in the project area, including the lower river, now are less compacted with fine sediments as a result of LW in the channel. Juvenile chum salmon now commonly use porous gravel substrate as shelter and transient rearing habitat during seaward migration. Additional LW placement based on the 1998 effort appears warranted for the Palix River.

Figure 20. Palix River LW replenishment project. (a) Typical channel condition before project; (b) logjam to provide cover habitat; (c) channel-spanning logjam photos of Palix River, Pacific County, Washington, courtesy of Allen Lebovitz, Coastal Watershed Consulting).

(a) (b)

(c)

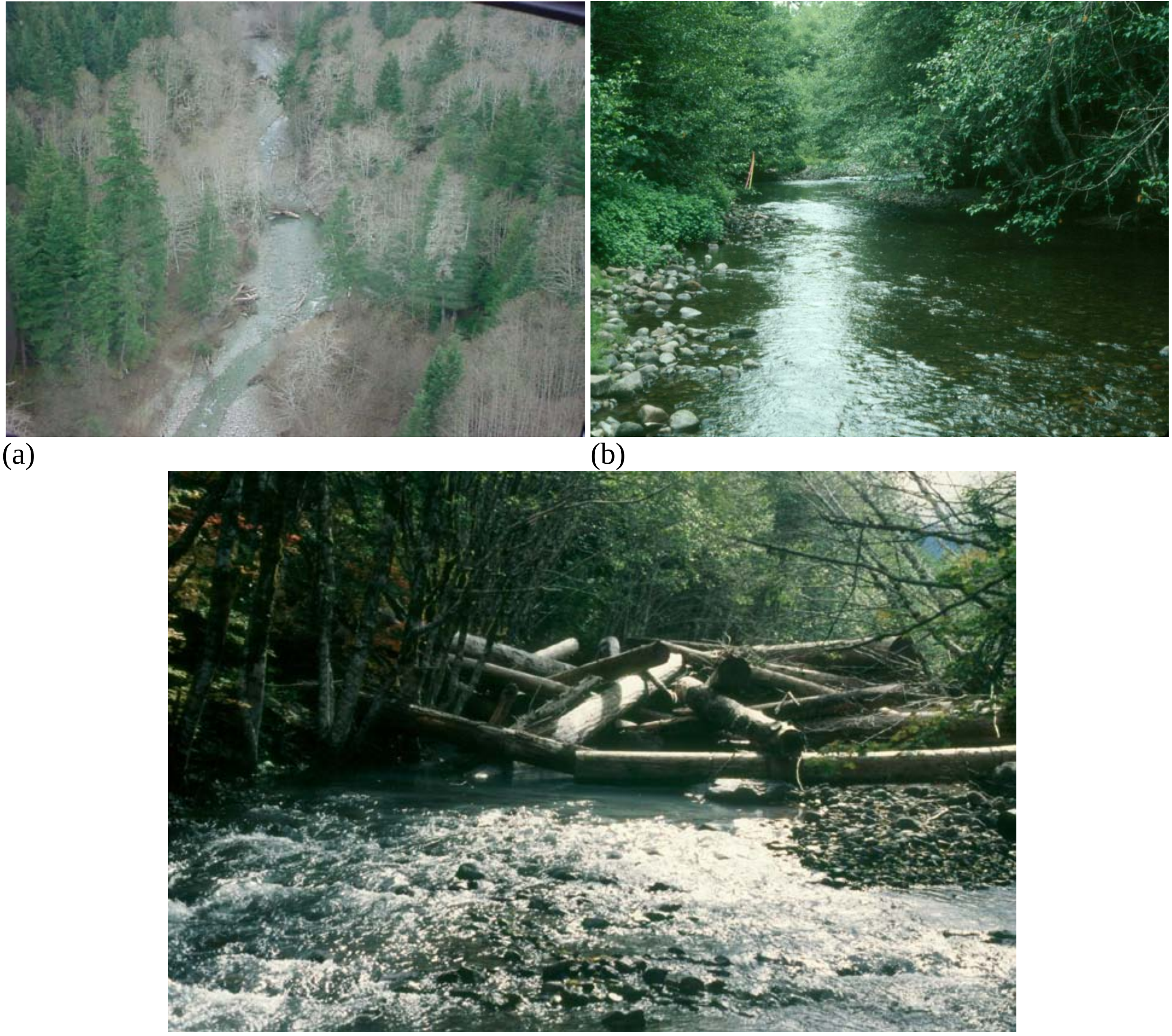
Upper Finney Creek Log Jams, Skagit County, Washington (Roger Nichols, USFS)

Finney Creek channel in Skagit County has received substantial damage from a series of high intensity storms beginning the winter of 1983 and delivery of course sediment accumulations to reach RM 18.8-RM 20.6. Stream surveys described the 1.8-mile project reach as deficient in LW from a combination of past timber management practices and flood events. This sediment accumulation and the lack of channel structure have resulted in a wide, shallow channel. Stream temperature studies have shown water quality impacts for eight miles downstream. These elevated temperatures have increased impacts to fisheries and aquatic habitat values of Finney Creek downstream of the site, as well as have impacted water quality (Finney is on 303d listing).

The project addressed these impacts with strategically placed log jams between RM 18.8-RM 20.6. The project consisted of two phases. Phase I involved 378 logs (1,079,200 lbs) in 37 structures placed in 1999. Phase II involved 406 (1,127,500 lbs) in 45 structures placed in 2000.Logs (>18" diameter small end) where transferred and staged with a helicopter and then placed by track excavator in log complexes upstream of the bridge at MP 11.3 FS road #17 between RM 18.8 and RM 20.6. Logs complexes are designed to reinforce natural accumulations of debris and to mimic large structural logs. Each of the jams consisted of three to four base logs (>24" dia) and eight to ten filter or brace logs. Cabling of the complex was done to increase the effective complex mass to duplicate the mass that would have occurred naturally with large tree recruitment (key logs > 60"dia). LW for the project was salvaged from hazard trees located either in campgrounds or along forest roads.

Local deposition and scour has resulted from placement of the log jams. Channel deepening and narrowing has been measured. The riparian area adjacent to this reach lacked large diameter trees for LW recruitment due to past timber harvest and channel cleanout. The log jams have collected wood passing through the system as well as increasing gravel storage in gravel bars. Riparian vegetation has re-established and significantly increased canopy closure. The net effect has been reduced stream temperatures and improved fish habitat.

Figure 21. Upper Finney Creek channel restoration project. (a) Aerial view of placed logjams; (b) canopy closure following logjam construction; (c) logjam initiating channel re-configuration and instream habitat Photos of Finney Creek, Skagit County, Washington, courtesy of Roger Nichols, USFS).



(a) (b)

(c)

Klahowya Creek, Skagit County, Washington (Skagit Fisheries Enhancement Group – Kay Caromile, WDFW)

Klahowya Creek is a 3.2 mile long tributary to East Fork Nookachamps in Skagit County. The project reach was channelized in the past and is now perched on the side slope of the valley rather than in the valley bottom. Dikes were constructed on both sides of the stream. Prior to project construction, habitat diversity was low. The stream reach was generally a long riffle with no side channel habitat, deep pools or in-stream cover. The substrate in the straightened reach consisted of poorly sorted gravels and cobbles with patches of spawning habitat. Because the channel is perched, high flows that overtop the dike spill onto the abandoned floodplain and cause the channel to aggrade.

Some base flow seeps laterally through the streambed into areas down gradient. Within the project reach the stream width is 10.5 feet and its slope ranges from 1 to 3 percent.

The enhancement project, constructed in the fall of 1998 by the Skagit Fisheries Enhancement Group, consisted of adding LW complexes to the stream to define and maintain the channel thalweg, create pools, provide cover and sort bed material. True restoration consisting of re-meandering the stream in the valley bottom was not considered. As a result, high flows that overtop the dikes may cause the stream to abandon its perched channel at some point in the future. The wood was stabilized using pilings, boulders, burial and pinning to existing vegetation. Cable was used to connect logs to each other and to pilings. Complexes consisted of 2 to 5 pieces of wood. Most structures were placed such that flow was directed from one structure into another. These structures were located on the banks, generally on alternating sides, with a significant volume of wood in the channel. Some structures collectively pointed downstream, some pointed upstream, some were parallel to flow, and some were somewhat triangular in shape and protruded perpendicular to flow. The intent was to create an obstruction to flow to induce scour. The theory was that the wood structures would improve sediment storage and transport and force the aggrading reach toward equilibrium.

In a survey conducted along 650 feet of treated channel in 2000, it was noted that the main benefits of the wood placements have been pool formation and gravel sorting. No pools are present in the 100-foot long wood-poor reach downstream of the project area, and the gravel and cobble-sized bed material is uniformly distributed. Pool spacing in the wood-rich survey reach averaged 29 feet, only 2.8 channel widths apart. Ninety-one percent of pools in this reach were associated with wood. In the most recent spawning habitat availability survey, 75% of the treated reach had spawning gravel. Wood loading within the bankfull channel of the survey reach was 8.2 ft^3/channel width. This compares reasonably well with the average of 11.7 ft^3/channel width measured by Robison and Beschta [59] in two similarly sized, low order, old growth streams in Alaska.

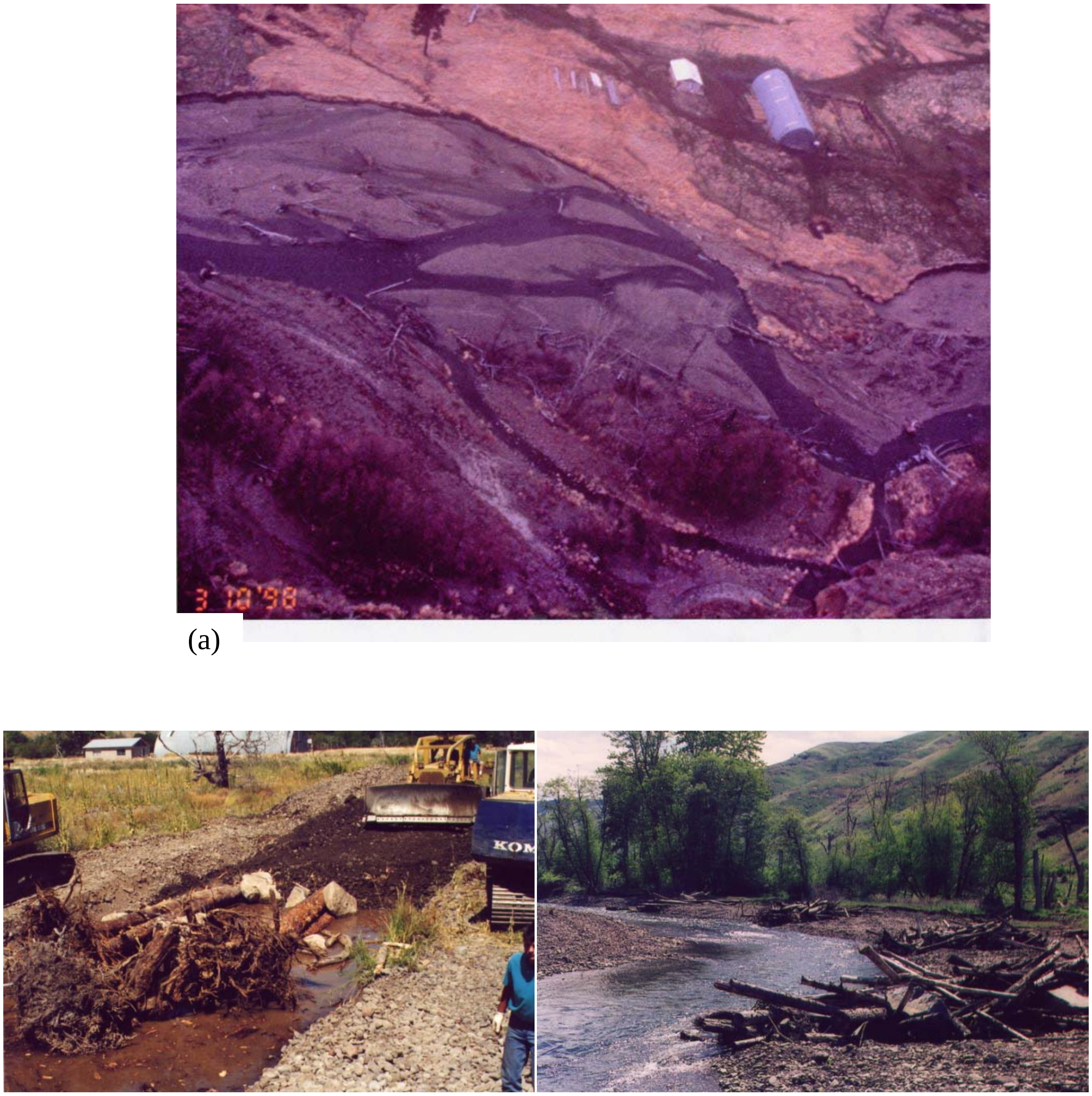
Figure 22. Constructed Log Complexes on Klahowya Creek, Skagit County, Washington. (Source: Robison, E. G. and R. Beschta. 1990. Characteristics of coarse woody debris in several coastal streams in southwest Alaska, USA. Canadian Journal of Fisheries and Aquatic Science 47:1684-93.)

Tucannon River Log Jams, Columbia County, Washington (Bruce Heiner, WDFW)
A small stretch of the Tucannon River in Columbia County, owned by WDFW, had significant erosion during the 1996 flood that resulted in multiple small, shallow channels. This portion of the river experiences high water temperatures in the summer. The objective of the project was to restore a single channel and riparian zone to help reduce temperatures. A secondary goal was development of holding pools for spring Chinook adults. In 1998 five log jams were constructed along a designed new channel meander. The concept was that during high flows each log jam would keep the main flow trained in the new channel until it met the next log jam. Flood flows could still spread into the flood terrace created by the 1996 flood, but with less volume or energy than before. The log jams also created excellent habitat in the form of pools and cover. Each jam was anchored by key pieces made from a log with attached rootwad that was cabled to an additional bare log. Four 3-ft diameter boulders were cabled to each key piece and all but the rootwad was buried in a trench. Smaller pine logs (donated) were racked against the rootwads and interwoven to act as a unit. One or two 4-5 ft diameter boulders were placed on the rack matrix as additional ballast. The disturbed riparian area was planted with cottonwood, willow, red-osier dogwood and wild rose. The success of cottonwoods germinated on the flood terrace by the 1996 flood had far outstripped any planted vegetation. The last high flow season was the first since construction that resulted in much over-bank flow. All jams have collected small wood, but the fourth has also collected some LW and caused some minor channel shifting.

The lower end of the abandoned 1996 flood channel intercepts groundwater and flows year round.

In spring 2008, a moderate runoff year, a natural log jam formed between the downstream two log jams and spanned the entire active channel. Several feet of gravel deposited in the main channel and caused the majority of the flow to leave the channel upstream and create channels on both sides of the main channel. At low flows, all the flow is in the new channels, and the old channel is dry for 100-150 ft. The new channels are heavily used by juvenile steelhead and Chinook and beaver have moved in and created a pond on a portion of the left bank channel. No apparent fish passage issues have resulted from the changed channel. The new log jam is not physically connected to either of the adjacent log jams, but it is uncertain if they had any effect on formation of the new jam. The channel change is viewed positively by local biologists, especially due to the recovery of the riparian zone that the new channels flow through.

Figure 23 Large Wood and Log Jams. Tucannon River channel re-construction and logjams (Columbia County, Washington): (a) pre-construction aerial view following 1996 flood; (b) key piece log construction; (c) post-construction logjams 1998; (d) Logjams and re-vegetated flood terrace, spring 2002; (e) site view on April 4, 2003; (f) aerial view 2007



(a)

(b)

(c)


(d)


(e)


(f)

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NUTRIENT SUPPLEMENTATION

This protocol was developed independently from the Stream Habitat Restoration Guidelines and it appears here in its original format. It has not been altered to fit the format of the current document.

PROTOCOLS AND GUIDELINES FOR DISTRIBUTING SALMONID CARCASSES, SALMON CARCASS ANALOGS, AND DELAYED RELEASE FERTILIZERS TO ENHANCE STREAM PRODUCTIVITY IN WASHINGTON STATE

The declining abundance in many wild salmonid populations in Washington is attributed to a combination of factors including harvest and hatchery issues, hydroelectric operations, habitat degradation and loss, altered stream flow and basin hydrology, and reduced stream productivity. Restoring salmon populations to levels capable of sustaining ecosystem functions approaching those of historic conditions and simultaneously supporting consumptive fisheries require addressing the entire suite of possible factors contributing to their declining abundance. Nutrient supplementation (also termed restoration) is a remediation option that addresses one part of this problem.

Four options are currently being considered to increase the level of marine-derived nutrients in freshwater ecosystems to help restore ecosystem productivity to something approaching “historic levels”. These are:

1) Distributing salmonid carcasses from fish hatcheries.
2) Applying fertilizers.
3) Depositing carcass analogs (processed fish cakes).
4) Allowing increased levels of natural spawning by anadromous fish.

The protocols and guidelines in this chapter discuss the first three methods of returning nutrients to ecosystems; increasing spawner escapements is not part of these protocols.

The most common method currently used to increase nutrients in freshwater and terrestrial ecosystems is distributing carcasses of salmonids that have returned to hatcheries. Determining ecosystem nutrient capacity, and whether it may currently be limited, is based on manipulative experiments (Bilby et al. 2001; Wipfli et al. 2003). These experiments indicate that carcass supplementation above particular levels only slightly increase fish growth. Further research, particularly that which may highlight ecosystem differences and differences in salmonid species composition in response to carcass supplementation, may suggest modification of these carcass supplementation levels. Escapements below levels that naturally provide this level of nutrient loading are assumed to not meet basal ecosystem needs. Other measures, such as reduced smolt size and survival, analyzing benthic sediments, analyzing sequestration of marine-derived nutrients in trees, and testing water quality, may also be used to identify whether nutrient levels are lower than optimum.

The application of fertilizer has been conducted in the Pacific Northwest for years to increase wild fish production. Currently, two methodologies are used. The first is introducing liquid fertilizer into the water, either through intermittently-applied dosages or through low-level drip. The second is placing solid pellets that dissolve at a predetermined rate, releasing nutrients over a period of months. Both methods have been shown to increase fish growth, survival, and condition factors (Slaney et al. 2003; Ward et al. 2003). Water quality monitoring associated with the application of fertilizer has shown that primary producers rapidly absorb the fertilizer and it is not generally detectable in the water column outside of the treatment reach (Wilson et al. 2003). However, uptake can vary depending on stream conditions and the length of stream ecosystems through which nutrients “spiral”. The term nutrient spiraling has been applied to the path traced by nutrients as they are assimilated by living organisms, returned to the stream by decomposition, respiration, or excretion, and eventually reincorporated into the aquatic community further downstream (Bisson and Bilby 1998). Stream conditions should be reviewed to optimize any treatment plan (Ashley and Stockner 2003). To avoid excessive phosphorus or nitrogen, water quality should be sampled beforehand to determine if supplementation is needed. To avoid water quality problems, fertilizer application will be tracked for the foreseeable future as part of a comprehensive study that documents site conditions and treatment steps.

The use of carcass analogs is an emerging technology that is currently being developed and tested (Pearsons et al. 2007). Carcass analogs are made by processing fish carcasses and other fish processing waste material into a solid cake. The cake is then treated to kill fish pathogens. The advantages of analogs are that they are lighter in weight per unit of nutrient than carcasses and present a far lower risk of pathogen transfer. Research conducted to date reveals that carcass analogs are a viable option when carcasses or pathogen-free carcasses are not available (Wipfli et al. 2004; Kohler et al. 2008).

GOAL OF NUTRIENT RESTORATION ACTIVITIES:

The goal of these activities to is to increase the biological productivity of Washington’s streams, riparian areas, upland areas, and estuaries by returning the nutrients originally supplied by anadromous fish carcasses back to the anadromous spawning zone of streams. Ideally, the ecosystem functions formerly supported by naturally spawning anadromous salmonids will be restored. Restoring this functionality will require restoring terrestrial and aquatic plant and animal communities in addition to anadromous fish. It will also require restoring hydrologic cycles, the relationship between rainfall and streamflow, and aquatic habitat. Restoration is considered complete when nutrients are delivered to the ecosystem by naturally spawning fish, not through artificial methods.

OBJECTIVES:

1. Enrich the nutrient supply to all functional elements of an aquatic ecosystem (primary producers, scavengers, browsers, and predators), enabling their increased biomass/population to be used for the trophic benefit of all interdependent species. This will result in increased individual size, condition factor, and survival of juvenile salmonids in the streams.

2. Increase productivity in riparian zones and associated upland areas that benefit the animals and plants that depend upon them.

3. Provide analogs or carcasses for direct consumption by juvenile fish and aquatic macroinvertebrates.

4. Where anadromous salmonid carcasses are not available, provide alternatives to using carcasses.

5. Where appropriate, monitor water quality to document the uptake of nutrients while maintaining water quality for non fish-producing purposes. Use a statistically valid monitoring design so that the project can be written up and submitted to appropriate, peer-reviewed scientific journals for publication.

6. Increase the production of salmonid smolts and adults so that more adults will return to spawn and transport nutrients to the ecosystem.

PREMISES:

Nutrient restoration actions to restore a stream's productivity should not be viewed as permanently supplanting or supplementing natural spawning by wild salmonids. The ultimate goal is to provide the nutrients necessary in the short term to redirect the ecosystem toward self-reliance on naturally-spawning anadromous fish in the future.

Streams identified for nutrient enhancement using carcasses must be located within a designated Fish Health Management Zone (FHMZ) that contains the source hatchery facilities. To protect the health of the watershed and wild fish, specific requirements must be met before any streams are enhanced with carcasses. These requirements are found in "The Salmonid Disease Control Policy of the Fisheries Co-Managers of Washington State" (WDFW and NWIFC 2006).

In stream reaches formally identified as being impaired because of excess nutrients, no nutrients will be placed or applied without the express written approval of the Department of Ecology (DOE). The DOE will provide Washington Department of Fish and Wildlife (WDFW) with a current list of impaired water body segments and, if appropriate, the specific seasonal timing of that impairment.

All projects that exceed the identified biomass densities, or those applying fertilizer, will be part of a formalized research program that is designed to be submitted to peer-reviewed journals for potential publication. The project proponents will be required to monitor water quality at at least three locations: immediately upstream of the uppermost input point to serve as a control, at the downstream end of the calculated "treatment zone", and half a kilometer downstream from the point where calculations of nutrient spiraling suggest 100% consumption of the nutrient, accounting for water flow (Thomas et al. 2003). Samples will be collected monthly during nutrient introduction and will continue until two months after the last of the following: the date of pellet disintegration, the date of last application of liquid fertilizer, or the date of final degradation of carcasses or analogs. The Memorandum of Agreement (MOA) specifically developed for each project identifies the parameters to be measured.

All projects will be formally approved by WDFW and DOE through individual project MOAs. For all projects, a copy of the MOA must be on hand during transport and distribution of nutrient enhancement materials.

Under these protocols, all distributed carcasses shall be obtained from WDFW or WDFW-supported cooperative hatcheries or from fish collected during a WDFW-authorized wild broodstock capture project. The National Pollution Discharge Elimination System permits issued to each hatchery allow use of carcasses resulting from mortality during rearing or holding at a hatchery or eggs that are "picked" or otherwise determined to be non-viable following placement into incubators. The permit describes the procedures for disposal of carcasses.

Once approved, the requested number of carcasses will be added to the subsequent year's hatchery planning processes. Because the number of fish returning to fresh water is controlled by many factors, some of which are outside of WDFW's control, such as ocean conditions, no one can guarantee that a certain number of fish will be available for distribution.

CRITERIA FOR TREATMENT STREAM IDENTIFICATION:

1) Treatment reaches shall be located within a watershed’s current anadromous zone or within areas historically accessible to anadromous fish. Exceptions will be based on needs of specific research studies.

2) During project planning, high priority will be given to streams that have historic datasets and/or ongoing assessment projects that nutrient restoration can complement. Conversely, project planners will avoid streams with ongoing ecosystem assessment studies that would be adversely affected by nutrient enhancement.

3) Streams or stream reaches where treatment ends less than 2 km upstream from municipal water supplies will be considered only with the expressed written concurrence of the water purveyor. Private domestic water diversions recognized by DOE will receive similar consideration.

4) Streams or stream reaches with identified water quality constraints for nutrients will be avoided. Exceptions will be made only with written concurrence of the regulatory authority.

5) To facilitate nutrient placement or application and monitoring, treatment streams should have easy access, such as bridges, wet crossings, or culvert crossings, to the treatment reaches.

6) Project proponents will obtain written landowner approval for access to deposit nutrients.

7) Spawner index streams and smolt evaluation streams will not be selected for nutrient restoration unless project proponents resolve potential impacts with the research or evaluation agency or organization beforehand.

8) To avoid surveyors mistaking deposited carcasses for naturally spawning fish during spawner surveys, whole carcasses may be marked with an easily identified external mark or biodegradable tag. Other acceptable forms of marking may be cutting off the tails of fish or using a shredder that tears carcasses in half.

CRITERIA FOR DISTRIBUTING ADULT CARCASSES:

1) Temporal and spatial distribution of carcasses should reflect historic anadromous spawn timing and abundance, when known, for all species in a particular stream (Compton et al. 2006). Ideally, carcasses will be deposited over several dates to further mimic natural spawning pulses and lengthen the timeline for available food resources. Deposition outside this timeline should be discussed on a case by case basis to determine the need and how it might alter the natural seasonal processes of the entire terrestrial and aquatic ecosystem. For this program, all carcasses are considered equal from a nutrient per weight basis. Consequently, the actual distribution goal may be calculated as biomass and then converted to fish numbers. In practice, Chinook carcasses may substitute for coho carcasses, and vice versa, depending upon availability. Further, when setting up distribution schedules, project proponents shall consider testing for pathogens, availability of access due to snow, and other factors.

2.) Collectively, available studies suggest that a minimum overall target of 1.9-2.0 kg of carcasses per square meter is an inflection point above which the benefits to fish production continue to increase but at a rate considerably slower than below that point (Bilby et al. 2001; Wipfli et al. 2003; H. Michael, pers. comm.; L. Shaul, pers. comm.). This target represents a collective value for the contribution of all salmonid escapements in a stream system, and can be used in streams where estimates of natural spawning escapement may be unavailable. In streams where natural spawning escapement is routinely estimated, carcass numbers will be reduced by the recent 5-year moving average for natural escapement to the treatment reach. To determine carcass deposition values for a particular stream where salmonid species composition is known, the area historically available to each species must be determined to calculate loading rates. This results in a separate calculation for each species/timing segment.

Table 1. Carcass equivalents required to mimic species specific spawner densities.

Species of Salmon	Carcass Equivalents	Sources
Coho	0.15-0.20 kg/m²	Bilby et al. 2001
Chinook and chum	0.8-1.0 kg/m²	Michael 1998; H. Michael, Washington Department of Fish and Wildlife (retired), pers. comm.
Sockeye	0.78 kg/m²	Johnston et al. 1997
Pink	1.0-2.0 kg/m²*	Wipfli et al. 2003; H. Michael, pers. comm.; L. Shaul, Alaska Department of Fish and Game, Commercial Fisheries Division, pers. comm.
Steelhead	Not addressed because only a small, unknown fraction of the population dies each year.	

* For pink salmon, a value of 2.0 kg/m² should be used when only pink salmon are present in the system, but values toward the 1.0 kg/m² level should be used where up to five salmon species co-occur.

3) Carcasses will be used within designated watersheds or FHMZ as identified by WDFW Fish Health Specialists.

4) Distributed carcasses will be from stocks that have been screened for pathogens as prescribed in the Co-managers Disease Control Policy (WDFW and NWIFC 2006).

5) If necessary to avoid duplicate counting, interference with spawner enumeration, or other studies such as genetic sampling, whole carcasses used for nutrient enhancement will receive a distinctive external mark, biodegradable tag, or be modified by shredding or tail cutting. As described in (1) above, one species may be substituted for another to avoid surveyors mistaking deposited carcasses for naturally spawning fish.

6) All use of carcasses for nutrient restoration will follow the specific plan submitted by the applicant and approved in the formal project review process.

7) A copy of the annual project authorization will accompany transport and deposition of carcasses.

8) Carcasses should not be deposited at certain flow levels, such as during high flows or freshets, that may compromise carcass placement objectives, or during poor water quality, such as low dissolved oxygen levels.

9) Artificial deposition of salmonid carcasses must not create a direct human health hazard.

10) Frozen carcasses can be used to approximate historic run (mortality) timing and to improve distribution to inaccessible stream reaches.

11) Distribution of carcasses should include shoreline and shallow water reaches of the stream.

12) The WDFW Regional Fish Program Manager will approve or deny the final project plans after appropriate internal review. He or she will ensure that co-managers, DOE, and other affected fish management entities have been consulted during project approval. The WDFW Fish Program Science Division will distribute the final approval or disapproval.

13). Concerns may exist about within-stream fish pathogen transmission or about contributing to existing degraded water quality. In either case, adult carcasses or juvenile hatchery pond mortalities (due to a mechanical failure at the hatchery only) may be placed in the terrestrial riparian zone (outside ordinary high water mark [OHW]) as long as they are not placed within 20 m of OHW. This placement meets the nutrient needs of terrestrial resources known to utilize carcasses.

14). Carcasses from fish treated with antibiotics or other chemicals such as anesthetics can be distributed if the fish meet the withdrawal period listed on the product label.

CRITERIA FOR FERTILIZER APPLICATION/TREATMENT:

1) Fertilizer application is designed to be a short-term enhancement of stream productivity directly tied to increasing smolt production and survival to spawning. The application of fertilizer mimics only the dissolved nutrient fraction contained in a salmonid carcass. Consequently, application levels must be controlled to achieve enhancement without degrading water quality. Applications should be timed to promote maximum uptake by aquatic plants and algae. Since fertilizers are not taken up directly by fish, research has shown the best time to add them is during the growing season allowing trophic levels to adjust so food supply is available in time for juvenile fish (Pearsons et al. 2007; Wipfli et al. 2010).

2) Determining the need to apply fertilizer will be based on specific water quality sampling undertaken at least one year before the intended time of treatment. For lakes, sediment core studies showing historic phosphorus deposition and/or zooplankton communities will be used to justify programs and to determine natural levels of nutrient input to the system. Guidelines for this testing and the minimum concentrations needed of phosphorus and nitrogen for a healthy system can be found in Ashley and Stockner (2003).

3) The maximum amount of fertilizer to be applied will be based on the recommendations of Ashley and Slaney (1997) and Ashley and Stockner (2003). Recommendations in these documents aim to achieve an instantaneous soluble reactive phosphorus level over the 120-day treatment of 3-5 micrograms per liter (= 3-5 ppb) at average stream flow during application/release, with an end goal of a nitrogen to phosphorus (DIN/TDP) ratio of 10:1. Treatment reach will be defined based on the Ashley/Slaney or Ashley/Stockner calculations or other methodologies as information is developed.

4) The fertilizer formulation used in streams must be food or pharmaceutical grade, as indicted on the product’s label. Liquid fertilizers used only in lakes shall be agricultural grade and must be certified for use on food crops. If a water right certificate has been issued for domestic water use from the water body, fertilizers must be food or pharmaceutical grade. Chemical evaluation of fertilizer formulations must include screening for heavy metals.

5) Use of fertilizer for restoring nutrients will follow a specific plan agreed to among water quality and fish management agencies. This plan will serve as a pre-deposition template for evaluating and directing carcass distribution requests or applications.

6) A copy of the appropriate approvals will accompany transport and deposition of fertilizer.

7) Placing fertilizer during flow levels such as high or low flows or freshets that may compromise the application objectives should be avoided. Adding fertilizer during high flows might limit the uptake in the targeted area, instead transporting the fertilizer to downstream areas where nutrients might not be limited. Conversely, adding levels during extreme low flows might cause water quality problems.

8) Each fertilizer application project will include a water quality monitoring component. The project proponents will be required to collect soluble reactive phosphorus, total dissolved phosphorus, nitrate, nitrite, and ammonia samples from at least four locations: a point 50 m upstream of the uppermost

fertilizing site, the midpoint of the treatment reach, the calculated bottom of the treatment reach, and 500 m downstream of the point where calculations expect nutrient spiraling to have consumed the added nutrients (Thomas et al. 2003). Samples will be collected monthly starting one month before fertilizer deposition and will continue until two months after the calculated release of the last of the fertilizer. For example, if 120-day release formulation is used, samples would be collected on day -30, 0, 30, 60, 90, 120, 150, and 180. The minimum detection level will be one part per billion. Sampling protocols will be designed to meet this detection standard.

9) The WDFW Regional Fish Program Manager will approve or deny the final project plans after appropriate internal review. He or she will ensure that co-managers, DOE, and other affected fish management entities have been consulted during project approval. The WDFW Fish Program Science Division will distribute the final approval or disapproval.

CRITERIA FOR DEPOSITING CARCASS ANALOGS:

1) Temporal and spatial deposition of carcass analogs should reflect historic anadromous spawn timing and abundance, when known, for all species in a particular stream. Since complete breakdown of analogs can occur within four weeks, multiple depositions during a typical spawning season may occur to mimic natural food supply conditions. For this program, the amount of analogs to be deposited will be converted to carcass biomass by correcting for the moisture/nutrient content of the analog. The actual deposition goal will be calculated as biomass and then converted to analogs.

2.) The number of analogs deposited within a stream segment will be based on the target carcass levels developed from Wipfli et al. (2003) and then converted into specific nutrient levels based on analog composition. The target level is 0.0063 kg P/m^2 of stream surface area (if using USGS - Mesa this number is 0.30 kg/m^2). Summer low flow area will be substituted as a conservative density. In streams where estimates of natural spawning escapement are routinely made, analog biomass can be reduced by the recent 5-year moving average for natural escapement to the treatment reach. For determining analog deposition maxima, the area historically available to anadromous species will be used to calculate loading rates.

3) Analogs will be processed so that fish pathogens present in the raw material are destroyed during processing.

4) Use of analogs for nutrient restoration will follow the specific plan submitted by the applicant and approved in the formal project review process.

5) A copy of the final project approval will accompany transport and deposition of analogs.

6) Depositing analogs during flow levels such as high flows or freshets that may compromise the analog objectives should be avoided. If, while trying to mimic the natural spawning cycle, depositing analogs during high flows or freshets is unavoidable, placing analogs in side tributaries or upper stream reaches could allow water flows to displace analogs into the desirable reaches.

7) Deposition of analogs must not create a direct human health hazard.

8) The WDFW Regional Fish Program Manager will approve or deny the final project plans after appropriate internal review. He or she will ensure that co-managers, DOE, and other affected fish management entities have been consulted during project approval. The WDFW Fish Program Science Division will distribute the final approval or disapproval.

CRITERIA FOR TERRESTRIAL PLACEMENT OF CARCASSES:

Carcasses or analogs distributed in riparian areas within 20 m of flowing water will be treated as if they were placed in the stream and must comply with the conditions listed above with regard to FHMZs. Under normal deposition plans, some of the carcasses or analogs should be placed terrestrially or in shallow water. Hatchery pond mortalities can be used terrestrially.

CRITERIA FOR ALL PROJECTS:

1) Approval is continuous as long as all operational requirements of that specific project are met.

2) Proponent must report to the WDFW Fish Program Science Division annually under the MOA. The report will indicate source of materials (such as carcasses, analogs, or fertilizer), formulation (if appropriate), dates of deposition, location of deposition, and amount deposited. Proponent will indicate plans for the next year's activities and any changes proposed. This report will serve as the application for renewal for the next year's program. To be automatically approved for the next year, the report must be received by the June 30 after deposition. WDFW will ensure that interested agencies receive data summaries and results of monitoring. WDFW will issue an MOA annually, based on receipt of the annual report, which will be supplementary to the original approval document and must be present when carcasses, analogs, or fertilizers are transported and placed or applied.

3) These criteria apply only to projects reviewed by the WDFW procedure. For carcass distribution projects, these protocols apply only to WDFW-operated facilities or to WDFW-associated cooperatives. Carcasses from federal or tribal hatcheries can be covered by these protocols if the agency supplying the carcasses has met the necessary environmental review required by the appropriate governmental entity.

4) Applications will be reviewed and approved on a year-round basis. Applicants must apply by July 1 to have approval by September 1.

5) Each project will be required to conduct some level of annual monitoring. This monitoring will be tailored to resources available to the project applicant. Monitoring can include measurements of fish growth and abundance, insect population size, growth, and diversity, predator and scavenger use, aquatic or terrestrial plant growth, and water quality (required for fertilizer application).

APPLICATION AND REVIEW PROCEDURE FOR ALL PROJECTS:

1) Contact WDFW Fish Program Science Division for copies of the protocols and an application form. Specific technical assistance will be available from the Technical Assistance List accompanying the application package.

2) Mail the completed application form to the WDFW Fish Program Science Division who will initiate the review process. The address is:

WDFW Fish Program Science Division
Nutrient Enhancement Section
600 Capitol Way N
Olympia, WA 98501-1091

For applications for carcass distribution ONLY:

1) The WDFW Aquaculture Coordinator will review the completed application and will approve or deny use of carcasses.

2) WDFW Fish Health Manager will forward a copy of the application to the Northwest Indian Fisheries Commission for review. The application will then be forwarded to the appropriate Hatchery Complex Manager for review and approval, and then returned to the Fish Program Science Division. This review process should be completed within 30 days of application.

3) Applications for which denial is recommended will be returned to the applicant with explanation. If the Fish Program Science Division recommends changes to the application, division staff will contact the applicant to address necessary modifications.

4) All completed applications for fertilizer, analog, or carcass deposition will be forwarded to the Regional Fish Program Manager for local review. Regional review will include signed approval by all WDFW Regional Programs, treaty Indian tribes within whose Usual and Accustomed Area the application is proposed, landowners controlling access to application sites, and the DOE Regional Office. This review process should be completed within 60 days of application.

5) Following the regional review, the Regional Fish Program Manager will approve or deny the application.

6) The approved application and review forms will be returned to the Fish Program Science Division for distribution. An MOA will be developed for each project based on the approved application and will be appended to the WDFW approval.

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BEAVER RE-INTRODUCTION

****This technique is the 2004 edition and has not been updated. The Aquatic Habitat Guideline Program will be working to update it in the future****

1 DESCRIPTION OF TECHNIQUE

Beaver can be important regulators of aquatic and terrestrial ecosystems, with effects far beyond their food and space requirements[1]. Beaver have the potential to modify stream morphology and hydrology by cutting significant amounts of wood and building dams. This in turn influences a variety of biological responses within and adjacent to stream channels. Historically, beaver have been key agents of riparian succession and ecology throughout North America. They can naturally transform pioneer woody vegetation into physical features that result in the expansion of floodplains, riparian community structure, diversity, and productivity[2].

The predominance of beaver in the Pacific Northwest drew many early trappers and explorers to this part of the country. By 1900, unregulated exploitation left beaver almost extinct. Their removal, by extensive trapping, resulted in incised channels, loss of riparian and wetland areas, and loss of channel complexity critical to fish and invertebrate production. The beaver population in the U.S. has been reduced from a pre-European estimate of 60-400 million to a current level of 6-12 million[1].

As the role of beaver in managing and maintaining stream and riparian ecosystems has gained recognition, interest in the potential for reintroducing beaver to recover stream and riparian function in degraded ecosystems has grown. Beaver have been successfully transplanted into many watersheds throughout the United States during the past 50 years. This practice was very common during the 1950s after biologists realized the loss of ecological function resulting from over-trapping of beaver by fur traders before the turn of the century. Reintroduction has restored the beaver populations in some areas, but many areas are still devoid of beavers. For example, a Wyoming survey found that beaver had been extirpated from 25% of all 1st- to 3rd-order streams originally occupied by them. Furthermore, many areas that still held beaver were not ecologically functional because their numbers were so low that they did not mean much to the system. Much unoccupied habitat or potential habitat still remains, especially in the shrub-steppe ecosystem, hard hit by trapping and over-exploitation. In forested areas, where good beaver habitat already exists, reintroduction has been used to restore some areas[3]. In rangelands, where loss of riparian functional value has been most dramatic, the potential role of beaver in restoring degraded streams is most appreciated but least understood[3].

Transplanting beaver may create the conditions needed to both establish and maintain riparian shrubs or trees. In the case of newly restored habitat or areas far from existing populations, reintroduction of beaver without further habitat improvement might be warranted[3]. Transplanting success rates can be high, but this depends on the site, the condition of the predator community, the time of year they are moved, and the age class of animals transplanted[2, 4].

2 PHYSICAL AND BIOLOGICAL EFFECTS

Successful reintroduction of beaver has demonstrated: 1) an elevated water table upstream of the dam, which in turn improves vegetation condition, reduces water velocities, reduces bank erosion, and improves fish habitat (increased water depth, better food production, higher dissolved oxygen, and various water temperatures), 2) reduced sedimentation downstream of the dam, 3) increased water storage, 4) improved water quality, and 5) more waterfowl nesting and brooding areas[5]. These effects, at the landscape level, influence the population dynamics, food supply, and predation of most riparian[1] and aquatic species. Beaver dams on coastal streams increase landscape-scale habitat diversity by creating a unique wetland type for that area[6].

Beaver ponds can alter water chemistry by changing adsorption rates for nitrogen and phosphorus, by trapping coliform bacteria[5], and by increasing the retention and availability of nitrogen, phosphorus and carbon[1]. Beaver-altered streams also cause taxonomic and functional changes in the benthic macroinvertebrate community due to the effects of impoundment and subsequent alteration of water temperature, water chemistry and plant growth[7].

Beaver can also influence the flow regime within a watershed. Beaver ponds can improve infiltration and ground water storage by increasing the area where soil and water meet. Headwaters can retain more water from spring runoff and major storm events and release it more slowly~~,~~ resulting in a higher water table and extended summer flows. This increase in water availability, both surface and subsurface, usually increases the width of the riparian zone and, consequently, favors wildlife communities that depend on that vegetation. The richness, diversity, and abundance of riparian-dependent birds, fish, herptiles, and mammals can increase as a result. Beaver ponds are important waterfowl production areas and can also be used during migration. In some high-elevation areas of the Rocky Mountains, these ponds are solely responsible for the majority of local duck production[5]. In addition, species of high interest, such as trumpeter swans, sandhill cranes, moose, mink, and river otters, use beaver ponds for nesting or feeding areas[3]. Beaver ponds also provide very important salmon habitat in western Washington and Oregon. Juvenile coho and cutthroat are known to over-winter in beaver ponds and the loss of beaver pond habitat has resulted in the loss of salmon production potential[8].

By introducing beaver into the lower watersheds of first-, second-, and sometimes third-order drainages, or below areas of erosion, beaver activity and stream sediment transport can re-elevate the bed level of incised channels; reactivate floodplains; increase stream bank water storage and aquifer recharge; and increase sediment deposition and storage, creating favorable micro-site conditions for maximizing natural vegetative stabilization of the drainage[2]. Once viable beaver complexes become established and are self-sustaining (3 to 4 years), the complexes themselves will begin to form natural gully plugs of a quarter- to a half-mile in length, accelerating sediment deposition and riparian recovery further upstream. By facilitating the establishment of beaver dam complexes at intervals throughout a watershed, this process can create a leapfrog effect, helping to accumulate or stabilize sediment throughout the system[2].

Beaver can be used to initiate or accelerate the natural restoration of degraded or lost riparian systems. Identifying limiting factors and providing supplemental management techniques to compensate for these factors are important. When physical site conditions can be improved for initiating natural riparian establishment, the system can develop to a self-sustaining level in as little as 3 to 4 years. By transplanting beaver to degraded sites, providing supplemental dam material during initial construction (to reduce dam washout prospects), and maximizing vegetative re-growth and establishment, riparian recovery and succession can be accelerated[2].

3 APPLICATION OF TECHNIQUE

Beaver can be reintroduced to any watershed where they have been extirpated within the following parameters:

- The channel is less than 3% slope to minimize dam blow-outs
- The water supply is perennial or beaver are released on ephemeral streams during a period with sufficient water to create a dam and lodge.
- The stream geomorphology is such that beaver activities will be supported. For example beaver do not seem to colonize as well in volcanic stream systems due to the instability of the channel.
- Beaver will not cause unacceptable damage to public or private property or facilities (See McKinstry and Anderson[9], for problem areas to avoid as well as benefits that landowners feel they receive from beaver.)
- There is an adequate food source (at least 18 acres of willow or 6 acres of *Populus* species within 100 feet of the stream)[10] and dam building materials.
- Their activities will not conflict with other management prescriptions, such as endangered species management or instream flow issues.
- The valley is at least 60’ wide (150’ or more is best)[10].
- The site is below 6,000’ elevation. The short growing season and heavy snowfall above this elevation may be limiting factors for beaver[10].

4 RISK AND UNCERTAINTY

4.1 Uncertainty of Technique

Perhaps the most difficult aspect of this technique is trapping beaver. The process can be time-consuming and requires dedication. However once they are captured, they are easy to handle and transport[11]. Transplanting beaver is not an exact science. On average only 15-20% of relocated beaver stay in their new stream systems[4]. Translocated beavers in Wyoming lived an average of 86 days post-release and predation and emigration accounted for 30% and 51% of the losses, respectively[4]. Beavers in the 2.5 year-old age class were the most likely to survive and modify habitat, although older beavers had similar survival rates. All beavers < 1-year old died within 60 days of release. Other researchers have found that the average distance from the release site to the area of establishment is eight miles, and many move further[12].

Reintroduction into degraded riparian areas within the shrub-steppe zone is controversial. Conventional wisdom holds that a yearlong food supply must be present before reintroducing beaver. In colder climates, this means plants with edible bark, such as willow, aspen, or cottonwood must be present to provide a winter food supply. But often these species are the goal of restoration. In some cases, willow or other species can be successfully planted as described in the *Riparian Restoration and Management Technique*. In other areas, conditions needed to sustain planted cuttings, such as high water table and minimal competition with other vegetation, might preclude successful establishment. Transplanting beaver before willows are established might create the conditions needed to both establish and maintain riparian trees and shrubs. In these cases, supplemental food should be provided at or near the reintroduction site[13].

With the dramatic drop in beaver trapping that has occurred since Initiative 713 in Washington, the population is expected to increase, making available vacant beaver habitat increasingly scarce. Being territorial, their numbers are self-limiting, but they will continue to increase stream occupancy in the streams of Washington if left untrapped.

4.2 Risk to Infrastructure and Property

Moving beavers during spring and summer can result in them emigrating and becoming a nuisance downstream. However, transplants in spring have been used in Wyoming to effectively colonize ephemeral streams that might otherwise be dry by late summer[4]. Potential conflicts with other stream restoration or management activities should always be considered in transplant operations[2]. Common problems include cutting or eating desirable vegetation, flooding roads or irrigation ditches by plugging culverts, and increasing erosion by burrowing into the banks of streams, reservoirs, or dikes[9]. In addition, beaver carry Giardia pathogens, which can infect drinking water supplies and cause human health problems. In these areas, it is important to work in cooperation with adjacent landowners[3].

4.3 Risk to Habitat

Beavers can disrupt the habitat of other wildlife species. Negative impacts include loss of spawning habitat, increase in water temperatures beyond optimal levels for some fish species, alteration of riparian vegetation and habitat, barriers to migration for some fish species, and habitat conversion from lentic to lotic systems. Therefore, caution should be used in introducing beaver into areas where they were not endemic[3].

5 METHODS AND DESIGN

5.1 Data Collection and Assessment

In any stream where beaver restoration is being considered, first evaluate whether the habitat is suitable and if beavers once used the area. Eight variables are helpful in this evaluation: (the following information is adapted from Vore 1993[10])

1. Previous beaver activity – indications of previous beaver occupancy include old dams and lodges, beaver cuttings, collapsed bank dens, and old beaver runways. If there has been no beaver activity for many decades evidence may be overgrown and appear as humps or small ridges. Interviews with people who have long lived in the area and/or trappers can also be useful in this assessment.
2. Water – a relatively stable, perennial water source is important. After damming, the water depth should be sufficient to accommodate lodges or bank dens and winter food caches.
3. Stream gradient – this is one of the most important factors. Beaver favor streams with low gradient. Less than 3% is ideal, although they will use higher gradient streams.
4. Valley width – beaver prefer valleys that are a minimum of 60’ and preferably greater than 150’ wide to provide sufficient quantities of their preferred food sources.
5. Food – winter food is often a limiting factor. There should be at least 18 acres of willow or 6 acres of *Populus* species within 100’ of the stream per beaver colony.
6. Dam building material – The same species used for winter food are used to build dams.

Heavy conifer cover is not thought to be good beaver habitat.

7. Stream substrate - beaver do not seem to colonize as well in volcanic stream systems due to the instability of the channel
8. Elevation – the short growing season and heavy snowfall above 6,000’ elevation may be limiting factors.

Additional considerations for managing beaver include watershed erosion rates and volumes, dam and pond cycling frequencies, carrying capacity, population dynamics and their management, and site-specific factors, such as bank stability, soil type, stream order and size[1]. Note the presence of culverts, irrigation structures, or other structures the beaver may plug and infrastructure that may be flooded. A contingency plan should be developed if that occurs (see section 10 *Maintenance*). Determine the level of cooperation or concern from the neighboring landowners.

5.2 General Design Information

- Transplant beaver during their principal dam building period, August-October. This will allow for time to gather a food cache, but limit their time to emigrate prior to constructing a dam, lodge, and food cache for the coming winter.
- Transplant at least 4 beavers (2 of each sex) to a site, preferably from the same colony[10]. See section 5.5 *Aging and Sexing*, on sexing beaver.
- Target trapping to dam- and lodge-building beaver (as opposed to river-dwelling beaver) since that is the habitat type you are trying to restore.
- Target trapping to 2.5 year old beaver as much as possible since they are the most likely to survive and modify habitat[4]. See section 5.5 *Aging and Sexing,* on aging beaver.
- Expect beaver to cut and use a large number of trees for dam construction during the first year or two after transplant.
- It may be helpful to provide beaver with additional building materials to use near the reintroduction site. This can encourage beaver to stay near the site and strengthen dams built of sagebrush or other shrubs[13]. The primary criteria for placing wood to encourage beaver use are:
    - the height of the structure above the water (< 0.2 m)
    - the proximity of a structure to a bank den (< 70 m)
    - the proximity to a deep pool (< 70 m)
    - and an unconfined stream channel[14].
- Do not allow harvest of beaver in newly established colonies for at least three years. If the project is on private property, “No Trapping” signs should be posted to identify the area off limits to trapping. If the project is on public property, the Washington Department of Fish and Wildlife will need to develop trapping closures for that area.
- Grazing may need to be delayed or deferred for several seasons, depending on riparian condition. When resumed, use a grazing system beneficial to riparian systems, especially one that benefits willow and *Populus* communities.
- To be successful, there must be cooperation between adjacent landowners and local wildlife officials. A cooperative evaluation of existing habitat quality and potential adverse beaver activity is very important[2, 3].
- When evaluating sites for potential beaver releases, gradient should be less than 3%, and the site should have adequate food supply.

5.3 Trapping

Snares and suitcase-style traps are the best methods for trapping beaver[15], however, snares are illegal for use in Washington State. For Bailey live traps, select small channels and make sure the beaver frequent the shore for feeding. The water should be at least 10 to 12 inches deep. Hancock live-traps can be used in any area that beaver frequent including dry land. Most commonly they are set on lodges and dams.

Both Bailey and Hancock live traps are shaped and operate like a large suitcase. The Bailey's trap must be set in an open position, entirely under water with the trip pan 8 inches below the water surface. Some shoveling may be required to properly position the trap for optimal trapping conditions. The trigger should also be adjusted to about 4 inches under the water. This will ensure that muskrats swimming over it will not spring the trap. Remember, it is very important that you do not disturb the surroundings more than absolutely necessary when setting the beaver trap. Freshly cut willow branches, or poplar (aspen or cottonwood) less than 1¼-inch diameter can be used as bait, and placed on the shoreline where the beaver visit. If there is a chance that the beaver will not pass over the center of the trap while moving towards the bait, long sticks or small logs should be placed in the mud out from the shore, leading to the trap at an angle to form an open "V" on the lake side. The opening generated by the logs should be about 14 to 16 inches wide over the center of the trap. The open "V" forces the beaver to swim over the trip pan of the trap and through the opening to reach the willow bait on the shore at the rear of the trap. As the beaver swims over the trap, its body hits the trip pan and springs the trap. Before leaving the set trap, splash water over everything that was handled, including the area that was walked over. Wait until the water clears and look the trap over very carefully. Make sure that none of the mesh strands are over the end of the trigger arms at the hinges, and that the safety hooks are released. Once sprung, the trap is positioned about one-half of the way out of the water, capturing the beaver unharmed and able to breathe.

Hancock traps are similar to Baileys, however, water depth is not an issue and they can be set on dry ground as well. For Hancock traps, select an area where beaver are frequenting and anchor the trap so that when it is closed it is not under water. Since the back portion of the trap is out of the water you can use fresh cut willow or aspen as bait and even artificial scent mounds with commercial beaver lure can be used to attract them to the trap.

All traps need to be checked on a daily basis, preferably in the early morning since prolonged exposure may cause death to the trapped beaver. Both Bailey and Hancock traps may be used to transport captured beavers, although it may be preferable to store them in a caged area prior to transplanting to wait while other beavers are captured.

5.4 Handling

It is often necessary to keep beavers in captivity while other adult beavers of the appropriate sex are caught. Rasmussen and West, as quoted in Vore[10], discuss holding captive beaver for as long as 10 days as follows:

> "Holding live beavers to obtain pairs and numbers for transplanting should be done in specially designed holding pens and crates to insure success. Beavers held for transplanting should have access to water to enable them to partly

> submerge at all times as a necessity in performing certain bodily functions.
>
> Care must be taken in preventing the beavers from becoming chilled or overheated while being transported to new sites. Kits are particularly susceptible to extremes in temperature and all ages are sensitive to excessive exposure to heat and sunlight.
>
> A temporary collapsible holding pen was constructed which measured 6' by 4' by 4'. The top was left open, or shaded with shrubbery when in use. All four sides were made of 20-gage sheet metal, and were held together at the corners by means of iron rods pushed through a series of hasps and eyes. The bottom consisted of an angle iron frame covered with netting, and was made to fit in flanges formed by turning in the bottom of the four sides. The bottom screen must be very heavy, comparable to material used in screening gravel. This pen was placed in a stream or pond in such a way that several inches of water was present along one side or in the corner while the remainder of the pen remained dry."

If it is necessary to sedate beavers for any reason (to determine sex, for example) during handling, transport, or confinement, ketamine HCL combined with acepromazine has been used successfully[16]. Ketamine is a fast-acting non-barbiturate, general anesthetic that is an uncontrolled substance and therefore obtainable from a veterinarian. Animal sedation should only be performed by a qualified and experienced biologist.

5.5 Aging and Sexing

Sexing beaver is difficult since they do not have external sex organs and they have a cloaca, which makes identification extra difficult. Palpating for the baculum is the most common methods of sexing beaver. Teats are evident in females only while they are nursing. Beaver can be easily handled with a commercial catchpole and these allow you to handle the beaver for sexing, ear-tagging, or attaching radio transmitters.

There is no way to positively age live beaver. However, beaver can be placed into one of four age classes (kit: 0-1 year, juvenile: 1-2 years, subadult: 2-3 years, adult: 3 years or more) based on weight, total length, and tail width. Use at least two criteria to determine age[10].

Age of Beaver	Weight	Total Length	Tail Length	Tail Width
Adult	≥43lbs	≥42"	≥11.5"	≥6.5"
Subadult	30-43lbs	38-42"	10.2-11.3"	5.0-6.2"
Juvenile	10-29lbs	27.5-37.7"	7.1-10"	3.1-5.0"

6 PERMITTING

A Permit is required from the Washington Department of Fish and Wildlife to live trap and move beaver. Washington Administrative Code 232-12-271 (http://www.wa.gov/wdfw/wlm/game/trapping/index.htm) covers the Criteria for Planting Aquatic Plants and Releasing Wildlife. Check with a representative of the Washington Department of Fish and Wildlife.

7 CONSTRUCTION CONSIDERATIONS

If you are not an experienced beaver trapper, it is recommended that you hire someone who is. Contact the Washington Trappers Association for information at: Washington State Trappers Association, Box 2245, Olympia, WA 98507.

8 COST ESTIMATION

Live traps are approximately $350 each.

9 MONITORING

Transplanted beaver can be radio tracked by using tail-mounted transmitters. See Rothmeyer et al.[17] for details on this technique. Radio tracking may be desirable to determine how many of the transplanted beaver stay in the area and where they go if they emigrate. Based on the objectives of the transplant, you may also want to monitor water quality, temperature, fish presence/absence, and riparian vegetation. Infrastructure and land use constraints may require additional monitoring, including water level recording and visual inspection of culverts, irrigation structures, or other structures that may become plugged, flooded, or otherwise compromised by beaver activity. See the *Monitoring Considerations Appendix*.

10 MAINTENANCE

In cases where beaver live in close proximity to humans or features important to humans, they may need to be removed or their damage controlled. Control of nuisance beaver usually involves removing the problem animals directly or modifying their habitat. Beaver can be live-trapped (Bailey or Hancock traps) and relocated to a more acceptable location or killed by trapping (e.g., Conibear #330) or shooting[18]. In cases where the water level in a dam must be controlled to prevent flooding, a pipe can be placed through the dam with the upstream side perforated to allow water flow. This will allow the dam to be retained while controlling the water level of the pond. See Finnigan and Marshall[19] for more information on ways to manage beaver impacts.

Grazing may need to be withdrawn for several seasons, depending upon riparian condition. When resumed, use a grazing system beneficial to riparian areas.

11 EXAMPLES

North Fork Nooksack River:
http://www.n-sea.org/fishtale/fall2001/BeaverRelocationProject.shtml

Fox Creek, Oregon:
http://www.freedom-here-and-now.com/foxcreek/beaver.html

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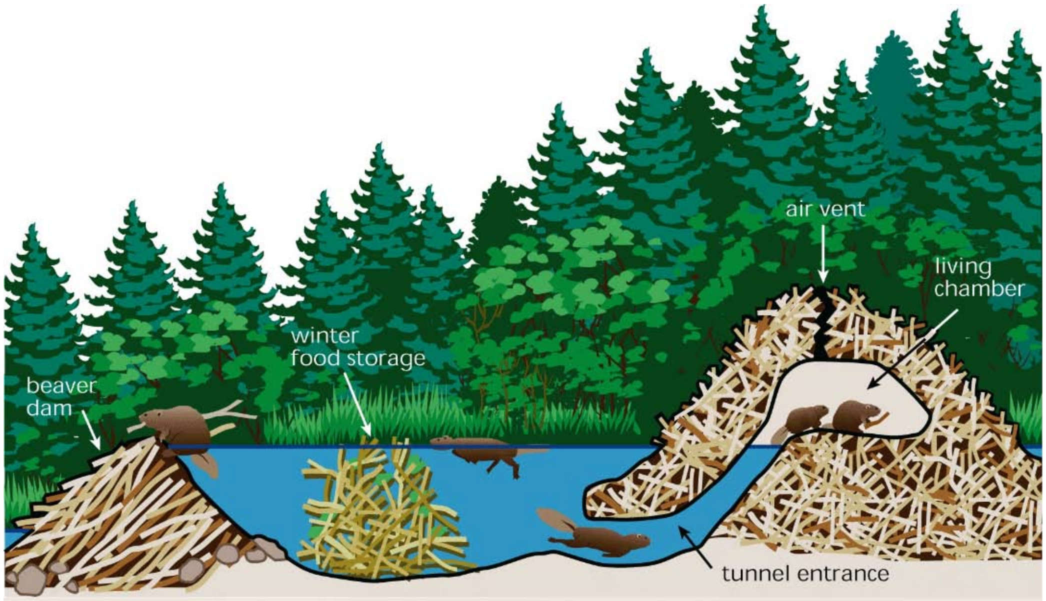

Fig. 8.21 -- A beaver lodge.
In Stream Corridor Restoration: Principles, Processes, and Practices, 10/98.
Interagency Stream Restoration Working Group (FISRWG)(15 Federal agencies of the US).

Beaver Reintroduction Figure 1: Beaver Lodge. *Source*: Federal Interagency Stream Restoration Working Group (1998)[3]

Fig. 8.18 – Beaver dam on a headwater stream. Beavers have many positive impacts on headwater streams.
In Stream Corridor Restoration: Principles, Processes, and Practices, 10/98.
Interagency Stream Restoration Working Group (FISRWG)(15 Federal agencies of the US).

Beaver Reintroduction Figure 2: Beaver dam on a headwater stream. *Source*: Federal Interagency Stream Restoration Working Group (1998)[3]

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FISH PASSAGE RESTORATION

****This technique is the 2004 edition and has not been updated. The Aquatic Habitat Guideline Program will be working to update it in the future****

1 DESCRIPTION OF TECHNIQUE

This technique focuses on restoring safe upstream and downstream fish passage to streams and stream reaches that have become isolated by culverts, dams, and other artificial obstructions. It also addresses ways to prevent or minimize harm to fish at stream diversions and water intakes. For migratory species of fish and aquatic wildlife, successful completion of their life cycle hinges on having access to and safe effective passage between reproduction, feeding, and refuge habitats. For fish, such habitats may lie longitudinally (upstream/downstream) within the stream system, estuary, and ocean or laterally within floodplain habitats such as side channels, ponds, wetlands, and periodically flooded grasslands and forests.

Man-made in-stream structures (e.g., culverts, dams, levees, or tide gates) can become physical barriers that impede fish passage and reduce connectivity through habitat fragmentation. Passage may also be impeded by stream diversions, water intakes, or other structures that injure fish or cause stranding. Even un-maintained fishways can impede or prevent fish access to critical habitat. Where fish passage is obstructed longitudinally within the stream, the downstream transport of habitat elements (sediment, water, wood and other material) is often obstructed as well, along with the upstream and downstream passage of many species of amphibians, reptiles, and mammals that use stream corridors for migration and as daily movement corridors.

This technique focuses on restoring fish passage longitudinally within the stream. For a list of techniques to consider when restoring fish passage to floodplains, refer to Chapter 4.3.2 *Restoring Habitat Connectivity*.

While salmonids are typically emphasized in fish passage projects in Washington, other species also require effective passage. The following migratory fish species rely on unimpeded access to and from upstream and downstream habitats.

Fish Passage Table 1. Migratory fish species in Washington[1]

Anadromous

Steelhead
Coho, Chinook, Pink, Chum, and Sockeye Salmon
Cutthroat Trout
Pacific and River Lamprey
Green Sturgeon
White Sturgeon
American Shad
Dolly Varden/Bull Trout

Longfin Smelt
Eulachon

Freshwater

juvenile Coho, Chinook, and Steelhead
Kokanee
Rainbow and Cutthroat Trout
Brown and Brook Trout
Bull Trout / Dolly Varden
Olympic Mudminnow
Stickleback
Sculpin (Cottids)
Pygmy and Mountain Whitefish
Cyprinids (Minnow family)
Catostomids (Suckers)
Sturgeon (adult and juvenile)
Western Brook Lamprey

The necessary timing, frequency, and duration for unimpeded access to required habitats varies with the fish species and life stage, as does the direction and length of migration. For example, juvenile salmonids need to freely disperse to find optimal rearing conditions (e.g. areas with reduced competition, good quality low velocity refuge habitat, food, and fewer predators) to ensure their survival. Required access is not limited to solely the mainstem environment, especially for fry, as they often move laterally out of rivers and into tributaries and side channels. During smoltification, the downstream migration of anadromous salmonids must occur without delay. Similarly, adults migrating upstream must be allowed to freely distribute within suitable habitat and have unconstrained access to spawning areas. Again, timing is important during adult spawning migrations.

In Washington State several laws pertain to fish passage. These include WAC 220-110-070, RCW 77.55.060 and RCW 77.55.070. Most fish passage barriers within the stream network occur at road crossings and flow control structures such as dams and weirs. Washington Department of Fish and Wildlife (WDFW[2]) reports that, as of September 2003, a total of 2,256 Washington State Department of Transportation (WSDOT) road crossings of fish bearing streams have been documented. Of these, 1036 have been identified as barriers. WSDOT road crossings represent only a small fraction of fish passage barriers in the state. It is estimated that there is a potential for 33,000 salmonid passage blockages in the state of Washington at this time[3]. The number of blockages is likely to be higher if other migratory fish and wildlife species are considered. Barriers to fish passage are typically classified as complete, temporal, or partial. Complete barriers block the movement of the entire population of an organism all of the time; temporal barriers block the movement of the entire population of an organism some of the time; partial barriers block some individuals of a population some of the time, limiting the genetic diversity that is essential to support a robust population. Refer to WDFW[4] for guidance on the assessment and repair prioritization of fish passage barriers and surface water diversion screens.

Fish passage restoration complements virtually all other habitat restoration techniques, because safe and effective passage is fundamental to the life history of salmonids.

2 PHYSICAL AND BIOLOGICAL EFFECTS

Restoring fish passage increases the amount of available habitat within a stream system. If habitat abundance is the limiting factor for the migratory fish species, its population may rise in response to access to additional habitat. However, the population response to habitat gain is also dependent on numerous other factors, such as the quality and quantity of newly available habitat, and the abundance and nature of the predators, competitors, and prey that reside there.

Where obstructions are modified (for example removing a dam or replacing a culvert), restoring fish passage may change the transport of sediment, wood, and other material to downstream reaches as well as the upstream and downstream passage of aquatic wildlife. The slope and/or elevation of upstream and downstream channel reaches and, hence, the degree of hydrologic and biologic connectivity between the stream channel and the floodplain may also change in order to reconcile elevation differences between the upstream and downstream reach. The extent of such changes may be localized or extend far upstream and downstream. These physical changes directly impact the aquatic environment by altering habitat characteristics that effect fish use and behavior. In WDFW's Fish Passage Design at Road Culverts[5] Chapter 7 on channel profile describes habitat issues related to regrade and channel incision. Castro[6] describes a geomorphological evaluation process to determine potential impacts.

The longevity of effects and benefits of fish passage restoration depends on the longevity of the passage structure, i.e., fishways, or method that has been applied. These may be very susceptible to unpredictable natural hydrologic and sediment transport events, though such events can typically be accounted for in the design of passage structures. Implemented passage projects are typically effective as soon as complete and at the next migratory season. The scale of benefits is entirely dependent upon the scale of habitat that becomes accessible as a result of restored passage. If a fishway is selected as an option for passage correction, routine inspections and maintenance must be recognized as part of the project in order for it to succeed in passing fish.

As with all instream projects, installation of passage features may result in temporary construction impacts such as increased turbidity, disturbance of substrate, and dewatering impacts. Typical construction impacts of in-stream projects are discussed in the *Construction Considerations Appendix*.

3 APPLICATION

In many watersheds, fish passage restoration projects may be the most effective use of resources to generate the greatest return on value relative to other habitat restoration techniques. In many instances, a relatively simple low-cost alternative such as retrofitting of a culvert can provide access to miles of valuable habitat that may be otherwise isolated from migratory species.

Passage projects are more likely to provide long-term benefits in channels that are vertically and laterally stable. In less stable channels, passage structures or features may become buried (in aggrading channels), undermined (in degrading channels) or abandoned (in laterally migrating channels).

4 RISK AND UNCERTAINTY

4.1 Risk To Fish And Wildlife

The primary risks to fish and wildlife associated with passage restoration are short-term construction impacts, potential long term maintenance impacts, and the risks associated with introducing or reintroducing species that compete with or prey on species already present in upstream waters. Introduction of new species may occur where native species did not historically have access to upstream waters, or where non-native species have been introduced (e.g., into lakes). In such instances, providing passage may prove detrimental to resident fish. Whether species are introduced or reintroduced, providing fish passage to habitat previously unavailable will likely cause a redistribution of competitor, predator, and prey species in the watershed.

Long-term risks may be associated with maintenance that is required to ensure design criteria are met. For example, pool and weir fishways often fill in with sediment. To maintain pool volume this sediment is excavated out of the fishway. On small streams this removal of sediment (which would have been transported downstream without the fishway) can result in a degradation of downstream spawning habitat. Concerns such as this have led designers recently to consider more natural types of fishways where sediment transport is part of the design, or operation and maintenance plans are developed to maintain the sediment budget of the stream.

4.2 Risk To Infrastructure And Property

Risk to infrastructure or property associated with passage increases with the extent and size of the structures which crosses the channel and the amount of channel and floodplain which is constricted by the structure. Examples would be when weirs, dams, and culverts are constructed in the stream channel. There have been cases where road culverts plugged with debris under a high road fill during a flood event. This causes a pooling of the water upstream that saturates the road fill and surrounding ground resulting in catastrophic failure of the road fill and stream channel side slopes, with extreme disturbances to fish life and habitat downstream. Structures also collect debris, and as debris builds up the potential for the stream scouring a new channel around the structure increases.

4.3 Risk To Public Safety

As fish passage projects often result in the installation of structures across or within a stream, there may be some risk to recreational users of the stream. Fish passage structures often attract visitors, and there is risk to people falling in the deep pools. Fences are often constructed around high risk facilities, but even these won’t keep people out.

4.4 Uncertainty Of Technique

Passage restoration can be conducted with minimal uncertainty, assuming relevant data are available to conduct analyses. Accurate hydrologic statistics, hydraulic models, and biological statistics allow for a great deal of certainty in application. Uncertainty arises from changing channel conditions, or inaccurate or unavailable data for design. Underestimating the potential of the stream to transport sediment and woody debris is often the leading cause of failure.

5 METHODS AND DESIGN

Methods of restoring upstream and downstream fish passage vary with the type of obstruction. They may include removal or replacement of culverts, construction or modification of fishways, removal or modification of dams and other obstructions, or installation of fish guards or screens at stream diversions and water intakes. The WDFW has published several documents directly related to this topic. As such, the reader is encouraged to refer to these documents for a comprehensive presentation of design and implementation guidelines relative to fish passage and fish screening. These documents are:

Fish Passage Design at Road Culverts[5]. This manual covers habitat issues at road crossings, design options, channel profile considerations, and tide gates. The appendices include details for: design flows, baffles, roughened channels, construction costs and a description of how to measure channel width which is a critical design variable. Also in the appendix is a data design form for collecting and analyzing fish passage design information and the current Washington State regulation on Water Crossing Structures.

Fishway Guidelines for Washington State[7]. This guideline contains pre-design data requirements and considerations, design considerations for fishway entrances (entrance pool and transportation channel design), auxiliary water systems (diffuser and water supply source), fish ladders (pool and weir fishways, vertical slot fishways, roughened channels, hybrid fishways), fishway exits, tributary fish passage, upstream juvenile fish passage, flap gates, and fishway flow control.

Fish Protection Screen Guidelines for Washington State[8]. This guideline contains types and applications of screen styles (drums, fixed plate, traveling, pump screens, infiltration galleries), screen design criteria, hydraulic design, fish bypass systems, and debris management.

All of the above documents are available of the Washington Department of Fish and Wildlife's web site at the Aquatic Habitat Guidelines page (http://www.wdfw.wa.gov/hab/ahg). Additional documents and references concerning fish passage issues are also available from the WDFW AHG web site. The reader is also encouraged to review the 2001 Proceedings of the International Conference on Environment and Transportation (ICOET)[9]. The ICOET's purpose is to address the broad range of ecological issues related to surface transportation development, providing the most current research information and best practices in the areas of wildlife, fisheries, wetlands, water quality, overall ecosystems management, and related policy issues. ICOET is a multi-disciplinary, inter-agency supported event, administered by the Center for Transportation and the Environment.

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SALMONID SPAWNING GRAVEL CLEANING AND PLACEMENT

****This technique is the 2004 edition and has not been updated. The Aquatic Habitat Guideline Program will be working to update it in the future****

1 DESCRIPTION

The health and reproductive success of naturally spawning salmonid populations are directly tied to the quantity and quality of spawning habitat. The quantity and quality of spawning habitat can limit the survival of eggs and fry, potentially limiting the size of the next generation. [1] [2] [3] [4] [5]. Favorable spawning sites tend to occur upstream of obstructions to flow (e.g., bedrock outcrops, boulders, large wood), and in the tailouts of scour pools associated with meander bends or structures in the channel. According to a literature search by Schuett-Hames and Pleus[6], the quality of salmonid spawning habitat is dictated by the size, permeability, and compaction of the substrate; velocity, depth, direction, and dissolved oxygen content of flow; and the proximity to cover and rearing habitat. Each of these factors may be impacted by a number of natural phenomena and human activities. Thus, the appropriate techniques for restoring salmonid spawning habitat will vary from stream to stream.

The scope of this section is limited to techniques and considerations for the addition and cleaning of spawning gravel for habitat restoration and enhancement. For other techniques that can be utilized to restore salmonid spawning habitat, including upland sediment control, water management, and restoring conditions that naturally retain and sort spawning gravel, refer to Chapter 4.5.7, *Restoring Salmonid Spawning Habitat*.

Land-use activities and catastrophic natural events may affect spawning habitat by changing the type or amount of sediment entering a stream system or by changing the patterns of sediment transport and storage within stream channel. Also, the supply of spawning gravel can be lost or reduced due to bank armoring and stabilization that restrict the natural recruitment of gravel to the stream, construction of dams that block downstream gravel movement, or gravel mining and stream channelization projects that remove gravel from channels [7] [8].

Conversely, the supply of gravel may be increased by changes in land use (e.g., agriculture, urbanization, timber harvest) that may destabilize the soil, or increase the increase the rate at which water runs off. These effects can accelerate the rates of soil erosion and mass wasting events such as landslides or debris torrents. They may also increase peak flows in streams that may accelerate erosion of the channel bed, banks, and floodplain. This in turn may cause the sedimentation of downstream habitats. Similar impacts may occur where channels have been straightened, dredged, diked, narrowed, armored, or “cleaned” (removal of roughness elements such as large wood and boulders). These activities tend to deepen flow, or smooth or steepen the channel such that the velocity and sheer stress imparted on the bed and banks of the channel increase.

Fine sediments are a natural and necessary element of streambed gravel. However, large inputs of fine sediment into the stream can bury spawning gravel thereby precluding its use [9] or result in “cementing” of the substrates that impedes redd construction by the female salmonid.

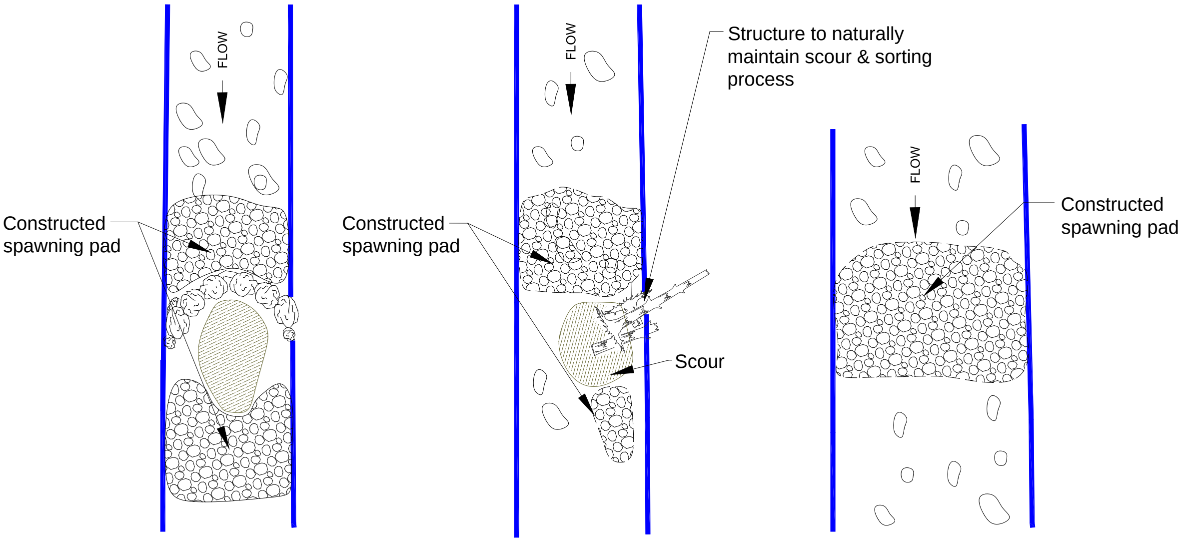
Fine sediments that settle out in spawning habitats can also cause decreased spawning success by filling the interstitial spaces between gravel partials. The presence of excessive fine sediments (<0.841 mm) within redds has been shown to reduce egg to fry survival due to a reduction of inter-gravel water flow. This reduces the availability of dissolved oxygen to eggs and fry as well as the rate at which metabolic wastes are removed from the redd [10] [11]. Excessive sediment may also physically prevent fry from emerging from the gravel in the spring [12] [13] [14] [15]. Several studies have verified that intra-gravel survival to emergence is reduced significantly when the percentage of fine sediments (<1.0. mm) in the gravel exceeds 12 to 14%.[1] [16]. Also, when the space between the gravel partials becomes filled with fine sediment, aquatic invertebrates, the primary food sources for juvenile salmonids, are often displaced.

For close to 70 years, rehabilitation and enhancement techniques have been used to mitigate for the degradation and loss of salmonid spawning habitat [17]. In the early 1970's, declines in several Pacific salmonid stocks inspired a concerted effort to create new spawning habitat and rehabilitate degraded spawning gravels. Efforts were made to increase the quantity of spawning gravel by restoring the natural gravel supply, increasing the stability of gravel in the channel, and by mechanically adding gravel. Attempts were also made to improve the quality of spawning habitat by reducing the excessive supply of fines, encouraging the natural sorting and cleaning of gravel, and by removing excess fines by mechanical displacement.

Gravel Cleaning

Gravel cleaning refers to the mechanized removal of fine material (sand, silt, and clay) from gravel to increase interstitial flow and improve the quality of spawning habitat. Mechanized gravel cleaning (See **Salmonid Spawning Gravel Cleaning and Placement Figures 3, 4, and 5**) may produces immediate increases in egg to fry survival rates. However, unless the source of the fines has been identified and effectively treated (refer to Chapter 4.5.1, *Restoring Sediment Supply*), these benefits may temporary.

The long-term reduction of fine sediments in the streambed may be achieved by upland sediment control, revegetation, and water management. The control of fine sediment transport requires the restoration of stream meanders or roughness elements (e.g., wood, boulders) that create velocity gradients that naturally sort and clean spawning gravel. When possible the stream should also be reconnected to any historic areas of sediment deposition within the floodplain. Refer to Chapter 4.5.7, *Restoring Salmonid Spawning Habitat*, the *Introduction to Structural Techniques, Large Wood and Log Jams, Boulder Clusters, Channel Modification, and Levee Modification and Removal* techniques for more information.



ROCK WEIR STRUCTURE
(Used to stabilize streambed gravel)

WOODY DEBRIS STRUCTURE
(Used where natural source of gravel has been lost, but the channel is stable)

GROUNDWATER
(No structure nessary)

Salmonid Spawning Gravel Cleaning and Placement Figure 1. Surface water dominated stream. Conceptual design.

Spawning Gravel Placement

In some cases, spawning gravel may be added to the stream to compensate for an identified loss of the natural gravel supply by constructing discrete spawning pads (See **Salmonid Spawning Gravel Cleaning and Placement Figure 1**) or through gravel supplementation. Depending on the specific conditions (flow, gradient and ambient substrate) both of these techniques may require maintenance and/or repeated application.

Construction of spawning pads is a direct habitat creation approach. Spawning pads are typically created by either building a channel constriction or installing streambed control structures across the channel. These structures may be designed to hold a specific mix of gravel that is placed mechanically or to trap the natural gravels that are mobile during high flows. With the exception of groundwater fed streams and channels, the benefits of these projects may be short lived if conditions are such that gravel is washed from the site over time and there is no compensating replacement from natural sources.

As an alternative to constructing discrete spawning pads, spawning gravel supplementation uses a managed inputs approach to create spawning habitat. In this technique appropriately sized spawning gravel is supplied to the stream and natural hydraulic processes redistribute the material downstream over time. Due to the unpredictability of high flow events capable of redistributing the material, it may take several years before the habitat benefits are realized. Benefits may be long-lived or short-lived, depending on design and on the magnitude and frequency of high flow events. In order to maintain the benefits in the long-term, gravel may need to be added periodically.

2 PHYSICAL AND BIOLOGICAL EFFECTS

2.1 Gravel Cleaning

Successful gravel cleaning may reduce the amount the fine material in spawning areas, enhance intra-gravel flow (permeability), enhance habitat for aquatic insects, and improve egg to fry survival rate of salmonids. However, gravel-cleaning operations are very intrusive as they employ the use of heavy equipment to physically disturb the streambed environment. As such, cleaning of spawning habitat, either mechanically or hydraulically, may temporally destabilize the spawning environment, alter water depths and velocities desired for spawning, and disrupt interstitial environment for aquatic insects. Also, unless the fines are removed from the stream channel during the cleaning operation, it may temporarily degrade water quality and redistribute fines into downstream habitats.

2.2 Salmonid Spawning Gravel Placement

Gravel placement techniques can increase the quantity and quality-spawning habitat when used under appropriate conditions. For example, spring-fed channels have a constant supply of high quality water and are often at least partially protected form high flow of events common to most surface streams. These conditions are ideal for salmonid egg incubation. Unfortunately, the lack of flushing flow events, which naturally recruit and distribute gravel, may also leave spring fed channel's lacking in adequate spawning gravel and dominated by fine materials. In these situations the placement of gravel pads and control structures may lead to a dramatic increase in spawning use and increase egg to fry survival rates as high as 30 to 60 percent. Conversely, constructing spawning pads comprised of spawning sized material in relatively high-energy sections of a surface-fed stream or channel, where gravel would not collect naturally, may lure salmonids to spawn there only to have their eggs and the gravel washed out during periods of high flow. Modifications to channel cross-section and profile by the addition of spawning gravel or creation of spawning pads (See **Salmonid Spawning Gravel Cleaning and Placement Figure 2**) can alter the hydraulics and energy distribution within the channel. These changes must be anticipated and planned for during project design to reduce the effects bank erosion and channel aggradation.

3 APPLICATION OF TECHNIQUE

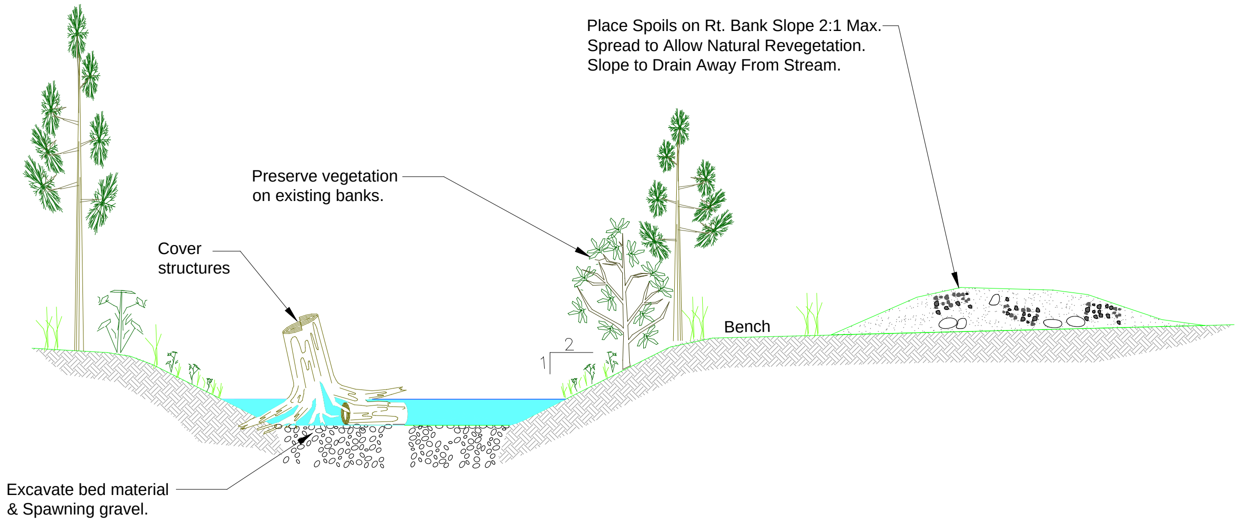
Potential rehabilitation sites must be assessed and projects carefully designed to ensure favorable results. Situations that should be avoided include channels that are laterally or vertically unstable, and streams that carry large volumes of fine sediment that can bury spawning gravels. Ideally, any rehabilitation of spawning areas would be located in areas of natural upwelling, which are typically dictated by variations in streambed elevation.

3.1 Gravel Cleaning

Mechanized methods of gravel cleaning should only be employed where excessive levels of fine sediment have been identified as a limiting factor for salmonids and in situations where the upstream source of fine sediment has been corrected so that rapid recontamination of the site will not occur. Streams with chronic, non-point-sources of excessive fine material are not good candidates for gravel cleaning, as it will provide only temporary benefits. Gravel cleaning operations are typically conducted in limited areas due to cost and logistic limitations and large-scale gravel cleaning operations are rare. Restoring natural stream processes and eliminating the sources of contamination will better correct system-wide siltation of spawning gravels.

3.2 Gravel Placement

Gravel supplementation and the construction of spawning pads are appropriate in situations where gravel has been a natural component of the sediment but its supply has been significantly reduced or interrupted. They can also be used as enhancement tools in streams that lack a natural source of material (e.g., spring-fed streams and the outlets of lakes, reservoirs, and wetlands). Gravel replacement is not appropriate as a stand-alone technique in very high-energy channel reaches where gravels may be washed out of the reach in a relatively short period of time (e.g., a single season). High-energy sites are typically dominated by cobbles and boulders where such material is available, or by bedrock or hardpan where it is not. It should be noted that some high-energy sites might have supported salmonid spawning habitat in the past, but the historic gravel deposits have been scoured out due to channel modifications that have increased the shear stress on the channel bed (e.g., dredging, steepening, narrowing, reductions in channel roughness by removing roughness elements or smoothing banks, floodplain fill, and levee construction), or watershed modifications that have increased surface runoff and peak flows. Where these activities have occurred, gravel replacement should only be conducted in conjunction with measures that restore the capacity of the reach to retain gravel. Gravel retention and project success has generally been greatest at sites downstream of lakes and reservoirs, and at groundwater-fed channels, where stream flow is relatively stable, but exhibits sufficient variability to promote sorting and moderate movement of gravel.



Salmonid Spawning Gravel Cleaning and Placement Figure 2. Constructed spawning pad at riffle. Conceptual design

Spawning pads may be constructed in channel reaches dominated by sand, silt, and/or organic material provided that there is no continuing source of fine materials entering the channel. However, they will likely be subject to a slow recruitment of these smaller sediments unless measures are taken such as installation of large wood or boulder clusters. (See **Salmonid Spawning Gravel Cleaning and Placement Figure 1**) to ensure the fines will be flushed out of the gravels rather than deposit within them. Spawning pads should not be constructed in pools or on meander bends where pools will naturally form.

Gravel supplementation involves the placement of appropriate sized gravel in or along the stream margin so that it can be naturally distributed in the reach downstream. Hence, it is applicable only in reaches capable of transporting the material being added. Gravel supplementation is not appropriate where the natural substrate is dominated by sand, silt, clay, and/or organic material. These conditions generally indicate a very low energy channel where flows will not be adequate to distribute added gravel. Gravel supplementation in general is more effective on a reach wide scale.

4 RISK AND UNCERTAINTY

4.1 Risk to Habitat

Many of the short and long-term risks to habitat are discussed in section 2 titled: *Physical and Biological Effects*. In addition to those, note that gravel cleaning and placement require in-stream work that may temporarily displace or disturb fish and wildlife species and degrade water quality. Restoration practitioners should also consider that targeting benefits toward a specific species of fish may have harmful effects on other species. For example, gravel placement techniques may create salmonid spawning habitat but result in the loss of salmonid rearing area such as pools.

4.2 Risk to Infrastructure

Gravel cleaning and placement pose minimal risk to existing infrastructure. The greatest risk to from these techniques is the possibility of aggradation resulting from gravel supplementation. If excessive gravel is added, or becomes entrained, it may accumulate in unwanted areas, such as culvert inlets and irrigation diversions.

Depending on the equipment and methodology used, gravel-cleaning operations may cause a short-term decline in water quality due to increased turbidity. This may adversely affect downstream water users (hatchery, irrigation, and potable users).

4.3 Uncertainty in Technique

There is a significant degree of uncertainty in both gravel cleaning and placement techniques. The duration and magnitude of project benefits is highly dependent on the flow and sediment transport regimes of the particular stream. Also, the spawning habitat needs of salmonids are species specific and seasonal and must be accounted for in project planning. Detailed pre-project observations and evaluation of the site can help guide the development of a project design and ensure it will be durable, effective and have a minimum of negative impacts.

Results from gravel cleaning studies are variable. Studies indicate that, while cleaning may result in a significant reduction in fine sediments in the treated areas, this does not guarantee increased reproductive success.

5 METHODS AND DESIGN

Streambed composition is a function of local and regional geologic, geomorphic, hydrologic, and hydraulic factors. Where spawning habitat exists naturally, these factors work in concert to provide and maintain the quantity and quality of gravel. Where degradation or loss of spawning habitat has occurred, the primary objective is to re-establish the conditions that provide for ideal spawning habitat. It may be necessary to precede instream restoration work with restoration of upland areas to minimize the sources of excessive levels of fine-grained sediment and to provide for a natural supply of spawning-sized gravels. This may include watershed and riparian restoration and implementation of best management practices to minimize surface erosion.

5.1 Data and Assessment Requirements

Before undertaking a spawning habitat enhancement project, it is important to understand the requirements of the particular species involved and the physical factors that effect the supply, transport, delivery, and deposition of fine sediment and gravel to the project site. For example, before initiating a gravel-cleaning project, the percent of fine sediments within the gravel should be determined. If excessive levels of fines are identified as a limiting factor effecting spawning success for salmonids, the source of fine sediment should be identified and treated.

Questions to be addressed include:

- Was the source of sediment caused by a single event or is it the result of chronic non-point source pollution or widespread mass wasting events?
- Has the supply of fine sediments increased due to land use activities within the watershed?
- If the sediment load is exacerbated by land use activities, can these be modified through watershed and riparian restoration to reduce the supply of fines to the stream?

Similarly, before adding gravel to a stream reach, the project proponent should consider why there is no suitable gravel present.

Questions to be addressed include:

- Is the supply of natural gravel lacking or is there a recruitment problem (e.g., the presence of an upstream dam or bank protection)?
- Do transport conditions in the stream channel limit gravel deposition (e.g., high gradient, confined channels with little wood or other roughness elements), or transport conditions that favor deposition of finer material (e.g. wide, low gradient, or backwatered reaches)?
- Are these conditions natural or caused by humans?
- If natural, should these conditions be altered to enhance salmonid spawning habitat (e.g., Do existing conditions provide critical habitat for salmonids during another life stage?)?
- Do existing conditions provide critical habitat for other fish and wildlife species?
- If these conditions are caused by humans, can their cause be addressed in order to restore natural gravel deposition to the reach?

Assessment needs depend on the intent of the project, the nature of the channel, and the modifications to be implemented. Data collection and assessment must allow for careful consideration and analysis of all the potential impacts and effects. Field data collection should include the following:

- Documentation of site constraints and project limits (Site Scale)
- Documentation and mapping of existing habitat features (Site Scale)
- Evaluation of existing fish and wildlife use, habitat value and conditions (Reach Scale)
- Evaluation of the biological needs of the target fish species (Reach, Watershed Scale)
- Additional data necessary to complete baseline monitoring.

Characterization of hydrologic, hydraulic, and sediment transport conditions should included when considering supplementation projects:

- Characterization of the existing bed materials and of sediment sources, both gravel for spawning, and fine-grained material, which affects spawning. (Refer to *Sediment Transport* appendix for further discussion of sediment sources and transport mechanisms).
- Determination of channel forming discharge and flood discharges. (Refer to *Hydrology* appendix for further discussion of channel forming discharge)
- Flood and over bank flow profiles of existing hydrologic conditions (Refer to *Hydraulics* appendix for further discussion of modeling flow profiles)
- Hydraulics; including velocity, shear, and scour along the channel. (Refer to *Hydraulics* appendix for further discussion of shear and scour)
- Characterization of historic and current sediment transport dynamics

Preferred Characteristics of Salmonid Spawning Habitat

The characteristics of actual spawning sites vary greatly between species and among stocks of the same species (**Table 1**). Factors such as substrate size, water depth, and water velocity appear to limit where a female is physically able to construct a redd. Body size and stamina determine the size of particles that can be moved, the ability to work in fast water, and maneuverability in shallow water. If there is extensive variation in the size of individual members of a population, differences in velocity, minimum depth, and substrate preferences may be nearly as great between members of the populations as between different stocks or species [18]. Studies indicate that there is a relatively wide range of acceptable conditions for most species[18].

Table 1. Water depth, velocity, substrate size, and area required for spawning criteria for some

salmonids [19]. (This identical table appears the Canadian Fish Habitat Enhancement Guide and is credited to Reiser and Bjornn[20].)

Species	Minimum Depth (m)	Velocity ($m*sec^{-1}$)	Substrate Mix Size Range (mm)	Mean Redd Area (m^2)	Req'd Area per Spawning Pair (m^2)
Fall chinook salmon	0.24	0.30 – 0.91	13 – 102	5.1	20.1
Spring chinook salmon	0.24	0.30 – 0.91	13 – 102	3.3	13.4
Summer chinook salmon	0.30	0.32 – 1.09	13 – 102	5.1	20.1
Chum salmon	0.18	0.46 – 1.01	13 – 102	2.3	9.2
Coho salmon	0.18	0.30 – 0.91	13 – 102	2.8	11.7
Pink salmon	0.15	0.21 – 1.01	13 – 102	0.6	0.6
Sockeye salmon	0.15	0.21 – 1.07	13 – 102	1.8	6.7
Kokanee	0.06	0.15 – 0.91	13 – 102	0.3	0.15
Steelhead	0.24	0.40 – 0.91	6 – 102	4.4 – 5.4	
Rainbow trout	0.18	0.48 – 0.91	6- 52	0.2	
Cutthroat trout	0.06	0.11 – 0.72	6 – 102	0.09 – 0.9	

The observed optimal sediment size distribution for three Pacific salmon species is provided in **Table 2**. For most species of salmonids, the general guideline is approximately 80% of 10 to 50 mm gravel with the remaining 20% made up of 100 mm gravel and a small portion of coarse sand (2 to 5 mm). More specific substrate mixes can be tailored to fish size. Small-bodied salmonids[1] spawn in gravel that is generally between 8 mm and 64 mm in size. Large bodied salmonids[2] spawn in gravel that is generally between 8 mm and 128 mm in size.

Table 2. Average size composition of gravel in redds of three Pacific salmon species (adapted from Andrew and Geen [21] and Burner [22]). Approximate average weight of each species shown in brackets.

Gravel Size (diameter)	Fall-run Chinook (9 kg)	Coho (4 kg)	Sockeye (1.5 kg)
	Percent		
Fines	10	8	12
3 – 12 mm	19	23	23
13 – 50 mm	38	43	51
51 – 100 mm	21	23	12
101 – 150 mm	12	3	2

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[1] Small-bodied salmonids are defined as species that are typically less than 35 cm long when mature, including resident rainbow, resident cutthroat, anadromous cutthroat, bull trout (Dolly Varden), brown trout, brook trout, and kokanee.

[2] Large-bodied salmonids are defined as species that are typically greater than 35 cm when mature, including pink, chum, coho, sockeye, steelhead, and chinook salmon.

The selection of appropriately sized gravels is critical to the success of spawning gravel placement projects. The criteria provided in Tables 1 and 2 represent optimal conditions. But the specific gravel size selected for a gravel placement project should consider, not only the sizes and species of target fish, but also the hydraulic conditions. In some applications, it may be appropriate to augment spawning-sized gravels with larger materials to add stability. Angular or crushed gravels should not be used as spawning substrate. Washed, round gravel is preferred over pit run gravel that often contains considerable fine-grained sand and silt.

Gravels added should not be made up of one single size of material as this lacks the diversity needed by aquatic insects and contributes to streambed instability.

5.2 Gravel Cleaning

Gravel cleaning strategies have centered on the separation of fines from the streambed by physically agitating and disturbing the bed. This is accomplished by sifting fines from the spawning bed mechanically, or by flushing fines from spawning beds with hydraulic force, so that they can be washed downstream by flow or removed from the stream with a suction device.

5.2.1 Mechanical Removal of Fines

Cleaning of spawning gravels has usually been conducted on a relatively small scale in discrete reaches of a stream. The simpler methods of mechanically removing fines from spawning gravels used in the past involved the use of heavy equipment such as a bulldozer, backhoe, or front-end loader to physically disturb the substrate. Perhaps the most common method of cleaning gravels involves the use of a bulldozer [17] (See **Salmonid Spawning Gravel Cleaning and Placement Figure 3**). The bulldozer moves up and across the stream at a 45-degree angle to the flow, angling its blade like a plow, so that gravels are turned to a depth of 10-14 inches and pushed up in the flow of the stream where fines can be washed downstream. After each pass, the bulldozer crosses the stream downstream and begins a new pass 6-7 feet downstream of the last pass. In this manner, the potential of recontamination of cleaned gravels by suspended fines in the immediate area is minimized.

R. J. Gerke[23] supervised the successful use of a bulldozer in cleaning spawning beds in several Washington streams that have suffered from heavy siltation caused by landslides. On the Cedar River, 29,000 square meters of gravels were cleaned using a bulldozer. About 3,000 sockeye salmon and 50 chinook salmon spawned following the cleaning operation.

A section of the Entiat River in Washington was also successfully cleaned using a bulldozer, according to D. A. Wilson.[24] J. R. West [25]reported that spawning by chinook salmon increased in Scott River in Northern California after gravels were cleaned there with a bulldozer.

Another mechanical method of cleaning gravel involves the use of a 5-foot wide digging bucket mounted on a G-600 Gradall to work the gravel and wash the fines using the stream’s flow. Moving downstream, the Gradall excavates the gravel to a depth of 1-2 feet. The excavated gravel is then slowly poured back into the streambed, allowing the stream to wash away the fines. Tests on the Nadina River by Andrew [26] resulted in a 32 to 44 percent reduction in the percentage of material less that 0.5 mm, and complete removal of fines 0.3 mm and smaller.

Due to environmental concerns associated with the presence of equipment in the stream, the release of sediment, and potential for contamination of downstream spawning areas, this method will have limited application. In some areas it may be prohibited by state and federal regulations.

In an attempt to minimize the release of fines into the stream flow, the International Pacific Salmon Fisheries Commission used a Gradall carrying a modified 7-foot digging bucket with a screened bottom constructed of 1/8-inch wire mesh, capable of separating fines from the gravel bed within the stream channel [27]. The machine works in a downstream direction, scooping up gravel to a depth of about two feet and hydraulically vibrating the bucket in the water so that fines within the gravel come out the screened bottom of the bucket and are deposited into the hole just created. When this has been accomplished, the cleaned gravel in the bucket is returned to the hole and the machine moves to the next spot to be cleaned. The resulting gravel bed is freed of fines for approximately the first 12 inches, under which there is a layer rich in fine sediments. It is not clear if such stratification of the gravel bed could be detrimental to spawning success.

Mechanical methods are most successful at reducing fine-sediment concentrations if conducted during relatively high stream flows.

Hydraulic Removal of Fines

Another approach to the cleaning of spawning gravels incorporates the use of a hydraulic flushing action to mobilize and collect fine sediments. The "Riffle Sifter," **(**See **Salmonid Spawning Gravel Cleaning and Placement Figure 4**) developed in 1963 by the U.S. Forest Service, was the first machine designed to hydraulically remove fines from choked spawning areas. The Riffle Sifter flushes fine sediments from the substrate by injecting a high-speed jet of water into the streambed through a series of pipes. The apparatus then collects the fine sediments through a suction system and jets them onto the floodplain. The Riffle Sifter has been shown to remove up to 65 percent of the particles smaller than 0.4 mm[28]. However, the Riffle Sifter was subject to mechanical problems in the course of cleaning in natural streambeds[29].

A prototype gravel-cleaning machine called "Gravel Gertie" (See **Salmonid Spawning Gravel Cleaning and Placement Figure 5**) was developed by Professor Walter Mih at Washington State University in 1979 for the Washington Department of Fisheries as a more advanced version of a hydraulic gravel-cleaning machine[30]. The Gravel Gertie is mounted on a low-bearing pressure tracked vehicle that drives through the riffle during operation. The hydraulic cleaning action of Gravel Gertie uses vertical jets of water, which are directed towards the streambed to flush out fine sediments. A suction system within three rectangular collection hoods removes fines from stream flow, ejects them via a high pressure nozzle, and deposits them above the Ordinary High Water (OHW) line. Gravel Gertie was field tested on the Palouse River in northern Idaho and on Kennedy Creek and several other streams in western Washington. Effective cleaning was accomplished to substrate depths of 12 inches. While variable, all of these streams showed a decrease in the percentage of fines after one pass, with reduction of fine sediments (<0.841 mm) ranging from 3 to 78 percent.

5.3 Salmonid Spawning Gravel Placement

5.3.1 Gravel Supplementation

This technique involves the deliberate placement of gravels in streamside locations where it will erode during high flow events and be deposited as salmonid spawning gravel in downstream reaches over time. Consequently, determination of the size, quantity, and location of gravel placement must take into account sediment transport processes and project objectives.
Gravel should be placed at locations within the channel such as along point bars, stream banks and the upstream end of mid-channel bars that are prone to erosion and scour.

Gravel should be sized so that the D_{50} of the gradation becomes mobile at the dominant discharge event (refer to *Hydrology* appendix). This can be accomplished using tractive force computations. Refer to the *Sediment Transport* appendix for a complete discussion of tractive force and other sediment transport analyses.

Determination of the volume of gravel to be added and the frequency of installation can be accomplished using Sediment Transport analyses detailed in the *Sediment Transport* appendix. Sediment transport and deposition within the channel is dependent on discharge, gradient, depth of flow, obstructions and channel morphology. The estimate of sediment transport is a complex science, and is often dependent upon data that is difficult to acquire and numerous assumptions. As such, sediment transport estimates should be conducted by persons with expertise in this area. The frequency of additions cannot be effectively predicted or estimated prior to installation, as transport rates are determined by unpredictable and variable natural events. Therefore, determination of the frequency, as well as the volume, will have to rely heavily on annual monitoring to determine gravel deficiencies on an annual basis.

5.3.2 Spawning Pads

Spawning pads are typically used in areas where stream flows and stream gradient are moderate such as ground water fed channels or wall based tributaries (that flow from the toe of the valley walls and across the valley floor). In low gradient areas where fine silt is prone to settle, spawning pads may be placed below channel constrictions or drop structures which provide a flushing affect that tends to keep the newly placed gravel relatively free of fine material. In areas with moderate to higher gradients, stream spanning structures such as log weirs or plank controls may be placed downstream of spawning pads to stabilize the streambed and slow the loss of new gravel during freshets. Channel constrictions and drop structures may also create a backwater upstream and a pool and tailout downstream that can collect gravel. The upstream gravel placement can also be designed to feed gravel to the tailout area. Though drop structures have been more commonly used in the past, channel constrictions can create more diversity and intra-gravel flow. Channel constrictions also have a much lower risk of creating a barrier to fish-passage. Structures that promote such constrictions include Boulder Clusters, Porous Weirs, and Large Wood and Logjams (see techniques in this guideline for design and construction details).

Spawning pads might be necessary where natural large wood has been removed, and no structure exists within the stream channel to retain gravel suitable spawning environments.

In small, low gradient streams that seldom experience flushing flows, spawning pads can become contaminated with sediment and organic material. In these cases, channel constrictions may be placed in association with spawning pads to increase the velocity of flow and flush sediment from the gravel located immediately downstream. The constrictions may be constructed of logs, lumber or rock and are designed to work over a range of low to moderate flows.

The spacing of channel constrictions is based on the channel gradient and the degree of backwatering desired. A common mistake is to place constrictors too close together, resulting in the backwatering of the upper constrictor, which, in turn reduces velocities through the upstream constriction, thereby reducing the effectiveness of the sediment flushing. Constriction design, including spacing and size, can be accomplished using either hydraulic models or through trial and error in the field.

Drop structures are commonly constructed out of logs, planks, or boulders, but other materials have also been utilized. Refer to the Drop Structures technique for details on design, material selection, minimum spacing, and passage requirements of drop structures. Note that constructing drop structures in a channel requires long-term monitoring and maintenance to ensure they do not become barriers to fish passage. This is less of a concern with channel constrictions.

6 PERMITTING

A general discussion of permitting requirements is included in *Typical Permits Required for Work In And Around Water* appendix. Permitting requirements for channel modification projects will be very site- and project-specific. Depending on the permits required and the local governments involved, securing the necessary permits may take months or even years. Because of this, permitting is a key element of project planning.

Gravel cleaning and replacement projects invariably involve physical disturbance of the channel, at least in the short term. Permits, such as the Hydraulic Project Approvals may require measures to avoid disrupting water quality and existing habitat. These measures could include isolating the project from the flowing stream, treatment of wastewater from the construction area, on-site erosion controls and replacement of native vegetation after construction is complete.

7 CONSTRUCTION CONSIDERATIONS

A general discussion of construction issues and considerations is provided in the *Construction Considerations* appendix. Key construction issues for these techniques include access for delivery of materials and equipment, in-channel disturbances, and the actual timing of construction.

Spawning gravel may be added to a channel in a variety of ways, including using a helicopter, conveyor belt, tracked excavator, dump truck, or even by hand carried bucket. Use of a conveyor belt operating from the back of a dump truck offers the advantage of controlled placement while minimizing disturbance to the stream bed and banks. Both gravel cleaning and gravel placement work should be timed to minimize disturbance, displacement, and disruption of individuals and populations of aquatic organisms, their behaviors and habitats. In-stream work windows vary among fish species and streams. Contact the Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows (see Appendix B, Washington Department of Fish & Wildlife Contact Information, in the Integrated Streambank Protection Guidelines[30] showing Washington Department of Fish and Wildlife Regional

Offices). Note that other timing restrictions may apply in order to minimize impacts to wildlife. Further discussion of construction timing and dewatering can also be found in the *Construction Considerations* appendix.

8 COST ESTIMATION

Cost is highly variable in spawning gravel enhancement projects. For gravel placement projects, the quantity, availability, and hauling distance of materials contribute to variability in costs. Sorted gravels may cost $20 to $40 per cubic yard.

Dewatering of a project site can also add significant cost to a project. Dewatering costs are greatly affected by the size of the channel and other site-specific factors.

Table 3. Approximate costs for selected spawning habitat rehabilitation projects[19].

Project Type	Approximate Costs	Comments / Assumptions
Gravel cleaning – mechanical scarification	\$5-20 per m^2	Bulldozer working instream Streams over 10m wide
Gravel cleaning – Hydraulic	\$20-50 per m^2	High pressure hose Small, shallow streams
Gravel placement	\$50-70 per m^3 gravel	Sorted gravel supplied Limited delivery distance Machine placed Does not include control structures

9 MONITORING

Biological monitoring provides the ultimate measures of project success. Annual spawner counts and redd surveys may provide a measure of spawning utilization but this does not necessarily reflect on the level of spawner success (i.e. survival from embryo to fry). Other measures such as redd capping, downstream migrant trapping, seining, and snorkeling can provide more direct information on egg to fry and fry to smolt survival rates.

Monitoring the physical conditions at a project site is also important to document project performance. Measurements of the degree of scour, distribution and abundance of gravel, gravel sorting, channel movement, fine sediment levels, and the condition of retention structures are recommended elements of a monitoring plan. Constructed spawning habitat, including bed forms and large wood, may be carefully surveyed immediately after construction and again after initial high flows to document changes that might affect spawning success. Scour chains or other devices intended for measurement of spawning gravel stability and scour can also be used. However, since the hydraulics around the structure will be quite varied, it may be very difficult to quantify impacts of bed instability.

The *Monitoring Considerations* appendix provides monitoring guidance and considerations for stream habitat restoration projects. For a comprehensive review of habitat monitoring protocols, refer to the Washington Department of Fish and Wildlife's Inventory and Monitoring of Salmon Habitat in the Pacific Northwest.[31] Monitoring the project for its integrity as a spawning site will likely require a more comprehensive schedule than that required for the integrity of the structures. Monitoring of physical characteristics and biological use should be conducted annually for both gravel cleaning and supplementation projects.

10 MAINTENANCE

Gravel cleaning should only be applied when a streambed has been adversely impacted by an isolated event, such as a landslide, or in a situation where the upstream source of fine sediment has been corrected so that recontamination of the site won't occur. Therefore, it should not require maintenance or frequent repeat treatments.

Because added gravel will slowly move downstream and will not be replenished by an upstream supply, gravel supplementation projects must be monitored regularly and periodically nourished with additional gravel to maintain long-term habitat benefits.

Spawning pads typically consist of structural components, which should be designed to withstand selected minimum flow requirements. These structures should be designed to be relatively maintenance-free. Refer to General Design and Selection Considerations for In-Stream Structures for further discussion of maintenance related to in-channel structures.

11 EXAMPLES

11.1.1 Gravel Cleaning

In 1980, WDFW conducted a study of the prototype gravel-cleaning machine known as "Gravel Gertie" (see section 5.2.1 *Mechanical Removal of Fines* for a description of the machine.) One of the sites selected for cleaning was Kennedy Creek, a small tributary (5 to 6 cubic feet per second of flow) of southern Puget Sound's Toten Inlet near Olympia, Washington. After two passes with the machine the level of fine sediment (<0.84 mm) in the streambed of the test reach was reduced from a pre-project level of about 10 per cent to 2 per cent.[32] Wither this actually lead to an increase in salmoind egg to fry survival at this site was never evaluated. However, this data suggests that "Gravel Gertie" could definitely remove fine sediments in the upper levels of the streambed.

11.1.2 Gravel Supplementation

In 1987, WDFW constructed and improved access to a tributary of the Suiattle River, North of the town of Darrington, WA. The site, know as "Suiattle Slough" was a spring fed channel which beavers had blocked off from the main river channel. In addition to providing access to several thousand square meters of off-channel over-wintering habitat for juvenile coho, a portion of the slough received substantial gravel supplementation. Gravel was placed on the bed of the channel and also stock piled in steep-sided piles at the waters edge. The energetic action of spawning coho slowly mined these gravel piles over time and the site has remained as preferred coho spawning habitat for 17 years.

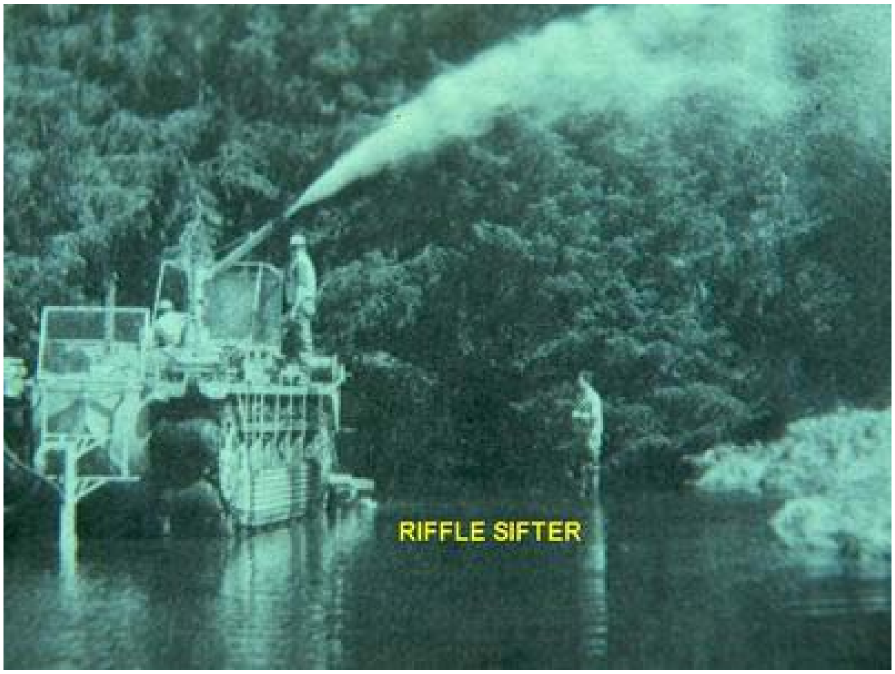
11.1.3 Spawning Pad Construction

Perkins Creek

A gravel placement project was conducted on Perkins Creek, a small tributary to McClain Creek on Eld Inlet, near Olympia, WA. Prior to the project, spawning habitat in Perkins Creek was limited to a thin layer of somewhat angular gravel, which overlaid a clay sill. The project included the installation of a series of wooden plank drop structures and the placement of clean, round spawning gravel which was evenly graded from 0.75 inch to 2.75 inches in diameter. The adult escapement to the project and fry out-migrations was carefully monitored for seven years. During this time estimated egg to fry survival ranged from a low of 3 per cent to a high of 23.2 per cent. The largest adult chum salmon escapement documented during those years was in excess of 1,100 fish.[33]

Satsop River Side Channels
In 1985 the Washington Department of Fisheries (WDF) evaluated chum salmon production in four groundwater-fed side channels of the Satsop River, a tributary of the Chehalis River near Aberdeen Washington. All four channels had either limited or highly sedimented spawning habitat. In these projects the existing streambed materials were excavated and replaced with clean, round gravel (from 0.75 inch to 2.75 inches in diameter). The adult escapement to the project and fry out-migrations were carefully monitored. Egg to fry survival rates in these projects ranged from 20 to 73 percent. [34]

Salmonid Spawning Gravel Cleaning and Placement Figure 3.
Gravel cleaning with bulldozer.



Salmonid Spawning Gravel Cleaning and Placement Figure 4.
Riffle Sifter.

Salmonid Spawning Gravel Cleaning and Placement Figure 5.
“Gravel Gertie”

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BANK PROTECTION CONSTRUCTION, MODIFICATION, AND REMOVAL

****This technique is the 2004 edition and has not been updated. The Aquatic Habitat Guideline Program will be working to update it in the future****

1 DESCRIPTION OF TECHNIQUE

Bank protection consists of a wide variety of individual techniques to directly armor or reinforce a bank, deflect flows away from a bank, decrease bank height, or increase the strength of bank material for the specific purpose of decreasing bank erosion. Banks form the lateral perimeters of natural streams, constructed channels, lakes, reservoirs, estuaries, and tidal areas. Bank protection, as it relates to habitat restoration, is a subset of the entire realm of stabilization techniques and may or may not be appropriate, depending upon the circumstances.

Bank erosion and lateral channel migration are natural and important geomorphic processes, although in many disturbed systems the erosion is occurring at an accelerated rate. Bank erosion recruits sediment and wood to the stream, creates and maintains in-stream and floodplain habitats (e.g., side channels), maintains overall habitat diversity within the stream corridor, and enables the stream to respond to changing conditions within its watershed. As a result, installing bank protection is a justifiable component of restoration projects in only limited circumstances. Bank protection is most appropriate where it is designed to reestablish natural functions and does not preclude natural stream processes from occurring in the long-term. An example is the use of large wood to reinforce a streambank, providing temporary protection while native vegetation becomes established on the floodplain and along the streambank. Without this temporary protection, it can be very difficult to establish riparian vegetation allowing enough time for maturation, especially in narrow valleys where the floodplain width is constrained. Ultimate system stability comes from the interaction of floodplain/riparian vegetation and accumulations of sediment and large wood. Note that even in this context, the project would generally still be identified as bank stabilization rather than habitat restoration. A full description of various streambank stabilization techniques is available in the Washington State's Integrated Streambank Protection Guidelines (ISPG)[1].

Existing bank protection presents a number of restoration and enhancement opportunities. Removing artificial armoring, such as riprap or concrete, and replacing it (if necessary) with natural, deformable alternatives, such as large wood and vegetation should be seriously evaluated. Removal or replacement of existing bank protection may be a viable option where the infrastructure or land use have changed such that cessation of bank erosion is no longer of concern or some degree of channel migration is now acceptable. Where neither removal nor replacement is feasible, habitat in the vicinity of existing bank protection can be enhanced by adding large wood or other roughness features to create scour, deposition, shade, cover, and complex hydraulics, and by using appropriate native plant materials to restore riparian plant communities. Such measures may be the only habitat enhancement opportunities in the affected reach where otherwise modifying existing bank protection is not an option.

2 PHYSICAL AND BIOLOGICAL EFFECTS

Bank protection projects that seek to provide or improve natural bank stability, as opposed to those that create a permanent artificial armor, generally provide the most benefits to fish and wildlife. In a restoration context, armoring or reinforcing a bank with either wood or rock should be a short-term approach to stabilization. Long-term bank stability should be self-sustaining, working with the natural tendencies of the stream system. Both approaches require careful site and reach-based assessments.

Potential effects associated with constructing new bank protection, or modifying or replacing existing bank protection, vary depending upon the type of reach (source, transport, response) and the type and extent of the treatment or modification. Potential positive effects may include:

- Providing cover – large wood, boulders, vegetation, and bank protection structures with natural analogs that create scour and thus provide cover.
- Providing a long-term source of all sizes of large wood by reestablishing native riparian forests or other appropriate native riparian plant communities.
- Providing an opportunity to increase, connect, and improve wildlife habitat by reestablishing native riparian plant communities.
- Providing an opportunity for habitat succession.
- Reducing fine sediment supply if it has been specifically identified as a limiting factor.
- Replacing existing bank protection projects that were inappropriately selected and/or designed for the site and/or reach conditions.
- Restoring the natural rate of sediment recruitment.
- Increasing shade and microclimate effects.
- Allowing natural channel migration processes to occur over time, though not necessarily in the short-term.

Potential negative impacts may include:

- Reduction of lateral channel migration; eliminating or minimizing creation of complex in-stream and side channel habitats and recruitment and deposition of sediment and large wood.
- Locking a channel into an unstable channel pattern.
- Reduction in meander belt width.
- Encouraging land use change or encroachment due to stabilization, which puts them at greater risk than if they were outside the channel migration zone.
- Unintentional downstream impacts due to sediment reduction and changes in boundary conditions.
- Loss of vertical cutbank habitat.

Removal of existing bank protection and reestablishing a natural bankline may be an option where the infrastructure or land use for which it was installed to protect has changed. Removal allows natural bank erosion and migration processes to occur, which provide many long-term benefits to the stream ecosystem as a whole. However, negative impacts derived from the short-term channel instability that is likely to occur following bank protection removal must also be considered. They may include:

- Excessive channel widening and subsequent sediment deposition within the adjacent or downstream channel where natural bank stabilizing features, such as riparian vegetation and large wood, are immature or lacking. Channel migration may occur at an accelerated rate. Nearby property and infrastructure may be placed at increased risk.

- Large wood recruited into the channel from bank erosion may redirect flow, backwater the upstream channel, or transport further downstream. Such changes can benefit habitat through increased cover and habitat diversity. But the changes may place nearby infrastructure and the public at risk. Refer to the *Large Wood and Log Jams* technique for further information regarding the effects and risks associated with adding and recruiting wood to streams.

There is an inherent uncertainty in the rate of bank erosion and channel migration once the protection is removed. The risk of accelerated bank erosion increases with the extent of the project, the degree of channel confinement, channel slope, and the degree of instability within the watershed. It varies with the soil type and depth, and with the extent and nature of vegetative cover; these collectively determine the banks' resistance to erosion. Removing bank protection requires reach and site assessments to understand possible channel responses such as lateral channel migration, chute/neck cutoff or an avulsion. Based on project objectives and risk assessment, appropriate bank protection to protect high risk infrastructure or property needs to be balanced with restoring habitat within the stream corridor and preserving habitat diversity.

3 METHODS AND DESIGN

Factors to consider when constructing bank protection (including assessment requirements in general and the application, risk, mitigation, design, construction, cost, monitoring, and maintenance considerations associated with individual techniques) are discussed in detail in the ISPG[1]. When modifying, replacing, or removing existing bank protection, many of the same factors apply; additional factors to consider are described below.

3.1 Data and Assessment Requirements

Prior to undertaking a bank protection removal, enhancement, or restoration project, it is imperative that existing habitat be identified and assessed with respect to desired habitat conditions. Minimally, a site and reach assessment, and possibly a watershed assessment are necessary to understand the underlying cause(s) of bank erosion and aid in selecting appropriate restoration and enhancement techniques. The degree of assessment will depend upon the extent of bank protection and the degree of channel stability/instability. Such an assessment should occur early in project planning. See the ISPG[1] Chapter 2, *Site Assessment* and Chapter 3, *Reach Assessment* for guidance on conducting site and reach assessments. The risk to property and habitat of leaving the existing bank protection in place versus the risk of modifying or removing the bank protection and restoring the bank also needs to be assessed. See the ISPG[1] Chapter 4, *Considerations for a Solution* for guidance on these assessments.

Gathering the design report and as-built plans for the existing bank protection project may help with understanding how and why it was originally designed, materials used, and design constraints. The design report may also have information about buried infrastructure (such as gas pipelines), hydrology, hydraulics, property lines/easements, and site, reach, risk, and habitat assessments. If a design report and plans are not available, then this information should be gathered by conducting a field survey and seeking sources such as watershed management plans, limiting factors reports, local government offices, et cetera.

3.2 Selecting Restoration and Enhancement Measures

If modifying or replacing existing bank protection, refer to ISPG[1] Chapter 5, *Identify and Select Solutions* for guidance on the selection of appropriate bank protection techniques. The selection process described there takes into account site and reach conditions, the underlying causes of bank erosion, and the risk to habitat, infrastructure, and public safety.

Because of the invasive nature of removing existing bank protection, it may be necessary to employ temporary bank protection techniques in order to leave the raw banks in a stable condition, even though the intent of the project is to permanently remove bank protection. Required techniques may range from simple bank pull-back and revegetation to installation of deformable bank toes such as coir wrapped streambed material or large wood.

4 CONSTRUCTION CONSIDERATIONS

Access and Staging

The selection of construction access and staging areas to remove bank protection and install restoration measures in mature, complex riparian areas should strive to minimize any impacts to existing riparian habitat. Riparian habitat not only benefits fish and wildlife, but it is also a stabilizing factor for banks. Several approaches to access and stage a bank restoration project may be employed; impacts to riparian habitat vary with the approach. These approaches are listed below in order of most protective to least protective of riparian habitat:

1. Access the site from the opposite bank if easier access is available, and cross the stream either using a floating platform or driving equipment across the channel during low flows. This approach has the least impact to the riparian area though it may have impacts on the opposite bank if a new access road is constructed. Impacts to the stream channel and water quality from equipment working in the channel will also need to be addressed.

2. Construct access road(s) perpendicular to the streambank. A rock platform may need to be constructed projecting slightly into the channel and sized to accommodate the turning radius of equipment, allowing for heavy equipment to reach upstream and downstream. Once construction is complete, the platform is removed and the streambank restored.

3. Construct access road(s) perpendicular to the stream and a temporary in-channel road at the toe of the streambank. The in-channel road runs parallel to the bank allowing an equipment operator to remove bank protection material and construct restoration measures. Operations start at the far end of the in-channel road and progresses to the access road, removing the road as restoration activities are completed.

4. Construct an access road on top of, and parallel to, the bank. This provides easiest construction access and staging, though has the greatest impact to the riparian area. This approach may be appropriate for low quality riparian area where a component of the restoration project is planting the riparian area. This approach is not appropriate in mature riparian areas.

For all the above approaches, access roads should be decommissioned by grading to a natural slope, decompacting the material, applying erosion control measures, and planting with appropriate riparian and floodplain species.

Hazard Trees

Whenever bank protection is removed, there is a risk of riparian trees falling and possibly damaging equipment and/or harming people. Prior to undertaking bank protection removal, flag all hazard trees and either avoid disrupting their root system or remove them. Trees should be removed with rootwad intact if possible and incorporated into the restoration or enhancement project.

Dewatering and Water Quality

Many bank protection projects are partially or completely submerged. As such, sediment control measures will be necessary so equipment operators can work the site and minimize turbidity for water quality protection. These include coffer-dam isolation or partial isolation and dewatering. See the *Construction Considerations Appendix* for guidance on sediment control.

5 EXAMPLES

Examples of various bank protection techniques are provided in ISPG[1] Chapter 6, *Bank Protection Techniques*.

6 REFERENCES

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[1] Cramer, M., K. Bates, D. Miller, K. Boyd, L. Fotherby, P. Skidmore, and T. Hoitsma. 2003. *Integrated Streambank Protection Guidelines*. Co-published by the Washington departments of Fish & Wildlife, Ecology, and Transportation. Olympia, WA. 435 pp.

INSTREAM SEDIMENT DETENTION BASINS

****This technique is the 2004 edition and has not been updated. The Aquatic Habitat Guideline Program will be working to update it in the future****

1 DESCRIPTION OF TECHNIQUE

This technique describes the design and construction of instream sediment detention basins, or gravel traps, to capture excess sediment within the stream and store it for later removal. The user of this manual should have arrived at this technique only after developing a thorough understanding of sediment sources and depositional patterns, and only after exhausting all other alternatives to deal with an undesirable abundance of sediment in a particular reach. This technique addresses only the symptom of excessive sediment accumulation, not the root cause, and should be used only as a last resort to provide a short-term solution while a long-term solution is being implemented. Sediment detention basins can provide an alternative to chronic widespread dredging. This discussion of in-channel sediment detention is intended to supplement the Aquatic Habitat Guidelines' Freshwater Gravel Mining and Dredging Issues white paper[1].

Stream sediments range from very fine-grained materials carried in suspension as turbidity, to large boulders. In-channel sediments may come from mass wasting directly into the stream (colluvial sources), they may mobilize from the bed and banks of the stream as the channel migrates in response to high flows (alluvial sources), or they may wash into the stream from the uplands and tributary streams.

A river in equilibrium can be viewed conceptually as a conveyor belt moving sediment downstream. All stream systems transport a characteristic range of sediment sizes as a natural geomorphic function. These sediments make up the streambed and bar forms, define much of the channel morphology, and provide many aquatic habitat elements[2] [3]. Sediment transport in streams occurs within a dynamic range, from low flows to seasonal high flows and episodic floods. When viewed in a watershed context at a particular point in history, a given stream reach is either in equilibrium, sediment limited, or transport limited[4]. Equilibrium reaches transport the majority of their bedload over the course of time, but transport-limited segments aggrade. It is in these aggrading reaches that sediment traps are considered when channel processes interfere with land use. Note that channel aggradation may result from natural or anthropogenic disturbance to the dynamic balance between sediment input volumes and the stream's capacity to transport sediments. These causes are described in the Application section below. Refer to the *Sediment Transport* appendix for further discussion of sediment transport dynamics.

Other complementary or alternative techniques described in this manual that can address the root cause of channel aggradation include *Bank Protection Construction, Modification, and Removal* (to stabilize banks undergoing excessive levels of erosion; this technique has limited application for the purpose of stream habitat restoration), *Riparian Restoration and Management* (to stabilize banks and intercept the transport of sediment to the stream), *Channel Modification* (where sedimentation and aggradation occurs due to historic local or reach-length channelization practices), and *Large Wood and Log Jams* (where sedimentation and aggradation occurs as a result of decreased upstream sediment detention or channel stability due to historic channel cleaning and timber harvest activities). Other methods to consider, including upland sediment and erosion control and flow regime restoration are discussed in Chapter 4.5.6, *Restoring Aggrading Channels*, of the Stream Habitat Restoration Guidelines.

2 PHYSICAL AND BIOLOGICAL EFFECTS

Instream sediment detention results in a significant disruption of existing channel dynamics and related natural functions, habitat, and passage. While the intent of detention is to address problems associated with excess sediment (such as bank erosion and flooding in the vicinity of infrastructure), allowing an "appropriate" amount and type of sediment to continue downstream should be a key consideration. This technique can have far-reaching effects - sediment detention may result in benefits or impacts to all downstream resources. The effects, whether positive or negative, will last as long as the structure remains in place and is maintained (regularly dredged). The amount of time before effects are realized is dependent upon site-specific conditions, design of the structure, and the essentially random nature of timing and volume of sediment transport. Sedimentation basin projects will impact a number of stream processes including:

- Impacts to stream hydrology and hydraulics including flooding.
- Impacts to sediment continuity and budget at the project and along downstream reaches.
- Impacts to stream geomorphology, which might include downstream incision.
- Impacts to streambed and streambank stability.

Sediment detention requires the installation of structures in a channel. Any in-channel construction will necessarily result in temporary turbidity impacts and disruption of habitat on a local scale. The *Construction Considerations* appendix provides further discussion of construction impacts and practices to reduce impacts. Routine maintenance is required as the trap fills so that it continues to function as designed. Cleanout activities require the use of heavy equipment and have a host of effects including; increased turbidity, the potential for fuel or hydraulic oil leaks or spills, stranding fish in the trap and dewatered sections downstream, physical injury to fish in the trap and other disturbances.

Sediment detention basins are intended to trap excess sediment that exists within the stream system. As such, they can be useful short-term tools employed in the recovery of sediment-laden systems. However, even properly designed detention basins must be used with care, for their potential negative effects. Large traps act as dams and create a discontinuity in sediment and debris flow. Interruption of this flow may affect downstream habitat value, particularly for spawning. Segregation of bedload into a coarse fraction (which is trapped) and a fine fraction (which may pass through the trap) may cause downstream scour and incision, potentially leading to alteration in stream-floodplain interaction downstream[5]. There is considerable discussion of the downstream effects of dams in the literature. The following references are from a survey of the current literature and are recommended reading[6] [7] [8]. Outlet structures and grade control may act as barriers to upstream and downstream passage of aquatic organisms.

A significant effect in some sediment traps is described as follows. Fine-grained sediment is deposited in the sediment trap during a storm event. As flow recedes, the water cuts down into the fine sediment, transporting it through the trap and depositing it in the downstream channel in areas where flows are insufficient to keep it moving. (This phenomenon is similar to heavy sediment runoff from a construction site, where runoff cuts down into disturbed soil, transporting it offsite and depositing it in lower gradient sections.) This fine sediment can foul spawning gravel, endangering incubating eggs (a significant concern for ESA species) and eliminating productive habitat.

Naturally aggrading reaches are part of normal valley building and the construction of a sediment trap precludes these processes. In the sense that many organisms are dependent upon ecologies supported by normal geomorphic systems, sediment traps interfere with their survival requirements for a variety of life-history stages.

3 APPLICATION

The movement of sediment to and within the stream channel is a natural and necessary process in order to maintain stream stability and habitat (see Chapter 4.5.1, *Restoring Sediment Supply*, of the Stream Habitat Restoration Guidelines for further discussion). It's only when the supply of sediment exceeds the ability of the stream to transport it that it may be considered a problem. Both supply and sediment transport capacity may be altered by humans as a result of land use activities and associated channel or flow regime modifications. The general causes of excessive sediment supply to a reach include: excessive supply from upstream or upland sources, accelerated stream bank and bed erosion and mass wasting events, channelization, loss of vegetated riparian zone capable of retaining sediment, loss of upstream sediment detention, upstream channel incision or other factors. Excessive localized sediment deposition may be caused by a channel constriction (such as an undersized bridge or culvert), general channel bed aggradation and many other factors. Upstream channel incision is a significant source of high sediment volumes to downstream reaches[9] and is discussed in detail in Chapter 4.5.5, *Restoring Incised Channels*, of the Stream Habitat Restoration Guidelines. Additional discussions on the causes of excessive sediment supply and on the causes of channel aggradation are provided in Chapter 4.5.6, *Restoring Aggrading Channels,* of the Stream Habitat Restoration Guidelines.

Excess sediment within a stream system often leads to deposition within the channel and resultant aggradation. Aggrading reaches, or reaches with excessive in-channel deposition, tend to widen as sediment accumulates, leading to high bank erosion rates. Reduction of sediment supply or trapping and removal of sediment in these reaches can slow or arrest the rate of lateral expansion and erosion in these reaches. Many stream reaches in Washington are naturally depositional and form braided channels or deltas at confluences or grade breaks. While these features are unpredictable and may interfere with land use, they provide important ecological functions[10] and play a role in disturbance that has been found to contribute to salmonid restoration[11]. Reach or watershed assessment should be used to determine whether a channel is naturally braided, or whether it is aggrading due to anthropogenic disturbances before initiating sediment control treatments.

Channel aggradation problems are best addressed by treating the source of the problem, whether it be supply or sediment transport-related, to provide the best long-term sustainable solution. Sediment traps merely address the symptoms of excessive aggradation and do not treat the cause of the problem. The goal of instream sediment detention is to remove excess sediment from the stream system before long-term measures can be implemented or before they become effective. Sediment traps are a temporary technique or a technique of last resort when source control is not possible or must be deferred and can limit the length of reach affected by sedimentation. Traps can limit the reach of stream affected by excessive sedimentation and provide an alternative to widespread and chronic dredging. Sediment traps do not constitute natural channel restoration or rehabilitation, nor do they constitute creation of habitat. As a temporary feature, it can be used to address a single catastrophic or major input of sediment supply (e.g., a landslide triggered by human causes occurred upstream and a sediment slug is working its way through the system with undesirable side effects). Instream sediment detention basins can be applied in transport or depositional reaches along alluvial or non-alluvial reaches.

Sediment detention is most effective for sediment that is categorized as gravels, cobbles and boulders, and less effective for finer grained material, including sand. In-channel sediment detention is rarely appropriate for detaining materials finer grained than sand.

Instream sediment detention basins have typically been applied on small to medium size streams. On larger streams, sediment is often removed from the channel without employing sediment detention basins (i.e., from gravel bars). The size of the detention basin and its efficiency in trapping stream sediments may be limited by available land on which to access, construct and maintain the trap.

In some cases, particularly in smaller streams, wood can be used to retain sediment (creating step pools along steeper gradient reaches), promote bed and bank stability, and thereby reduce the volume of sediment delivered to downstream reaches. Various studies have researched the role of wood in storing sediment in source and transport reaches[12] [13] [14] [15] [16] [17] [18] [19]. Although not used as a technique to control sediment routing, it may be applicable in some cases. Refer to the *Large Wood and Log Jams* technique and the referenced citations for additional information.

Channel incision or chronically unstable hill slopes can supply an endless stream of bedload that may deposit in ways that interfere with developed lands and must lead to long term solutions. Schumm[20] describes the formation of natural alluvial fans, a study that can aid planners in developing patterns found in nature into engineering solutions. In two papers, Parker *et al*.[21] [22] develops the theory and application of alluvial fan formation for optimizing a tailings basin. This model could help designers engineer alluvial fans as solutions to aggradation at grade breaks (high to low stream slope transitions at valley floors and elsewhere) or channel expansions (confined to unconfined valleys) for a long term, environmentally responsible alternative to dredging or sediment basins. An area is set aside with the proper slope and dimensions and is left to aggrade naturally. As sediment deposits in one area, the main flow channel moves to another location that is lower in elevation. This pattern continues, forming a complex network of abandoned and new channels and layers of deposited materials[23]. Maintenance of the delta trap is accomplished by excavating a shallow area on one side of the delta and allowing flow to reclaim the lowered area. It is likely that a project like this would take up more area than a conventional sediment trap, but retain some of the ecological benefits of a natural alluvial fan.

4 RISK AND UNCERTAINTY

4.1.1 Risk to Habitat

Sediment detention traps interrupt the transport of sediment and therefore affect sediment sizes and quantities delivered to downstream reaches. The ability of the sediment basins to trap bedload material is more efficient for coarse sediments than for smaller sized sediments.

The sedimentation basin structure will alter stream flow and hydraulic conditions. Traps can impede both upstream and downstream passage of fishes and other aquatic organisms. The traps will detain debris. The pools may act as an attractive nuisance, associating rearing fish with a maintenance structure and possibly stranding them during low flow or no flow periods. Cleanout operations require fish relocation, resulting in stress, injury or death to fish and other aquatic organisms within the trap.

Trapped sediment is susceptible to re-mobilization in the event of structural failure or, in some cases, simply due to the occurrence of a large runoff event. Failure to monitor and maintain sediment traps may also lead to unanticipated lateral channel migration subsequent to aggradation resulting from filled sediment traps.

Bank failure and water quality impacts may also result from use of heavy equipment for periodic maintenance of sediment traps. Grade controls installed as part of a sediment trap may also fail or create aggradation and associated lateral channel movement, if improperly designed and constructed.

4.1.2 Risk to Infrastructure and Property

Most sediment traps incorporate flow control devices that alter stream flows. Infrastructure and property adjacent and upstream of the project may be subject to increased flood levels caused by normal trap operations or debris accumulations on the trap. Failure of the trap may cause a dam-break flood and sudden release of water and sediments, impacting downstream properties. As mentioned above, failure to monitor and maintain sediment traps may also lead to unanticipated lateral channel migration subsequent to aggradation, possibly threatening nearby property and infrastructure. Risk to property and infrastructure can be minimized by accounting for it during the design process.

4.1.3 Risk to Public Safety

The consequences of a trap failure pose higher risks to public safety and infrastructure in urban areas than in non-urban areas. Sediment basins are deep pools when cleaned out and pose a risk of drowning. Restricting access may be necessary in urban or other areas where children are present. In the past, sediment basins have been built on smaller streams. If the technique is applied to a larger stream it may pose a risk to recreational river users, since many designs require diversions or channel-wide structures that could block or hang up watercrafts.

4.1.4 Uncertainty of Technique

Due to high natural variability in sediment transport conditions and individual stream conditions, there is inherent uncertainty in predictions of trapping efficiency and the size of particle trapped by detention structures. This is particularly true with small traps where it is likely that smaller sediment sizes will pass through the trap.

Sediment transport analysis provides an estimate of sediment transport potential, but does not provide accurate predictive results, particularly where the sediment supply is constrained by bed or bank armoring or for other reasons (refer to the *Sediment Transport* appendix for a discussion of sediment transport analyses and their limitations). Predictions of the size and volume of sediment transported using various transport equations can differ by orders of magnitude. And these predicted rates of transport could vary from actual conditions by orders of magnitude, especially in the absence of comprehensive bedload measurements over the range of design flows. . Due to the inaccuracies of theoretical predictions, the estimated minimum size for a sediment detention basin may be larger or smaller than what is necessary to accommodate actual transport conditions. Even when adequately sized, a single flood event in excess of design flows can prematurely fill a trap that was expected to function for several years before cleanout operations became necessary. .

5 METHODS AND DESIGN

The basic concept involved in sediment detention is to create an area of relatively low velocity in order to induce sediments to settle out of the flow. Sediment basins are typically designed with a downstream flow control in the channel that creates an upstream pool, and may include an excavated basin to enlarge the cross sectional area (see **Instream Sediment Detention Basin Example Figures 1 through 6** for examples). Long term, instream storage of sediment is less desirable than regularly scheduled removal. Sediment traps function only while they fill. Depending on sediment source conditions, site conditions and trap design, once the basin is full, sediment may pass downstream as before.

Effective design of sediment detention systems is dependent upon prediction of the volume and size gradation of sediment moving through the system. Methods to estimate sediment transport are provided in the *Sediment Transport* appendix. Dredge records are the first source for volume estimates. Sediment size can be determined by sieve analysis of dredge spoils.

Prior to undertaking a sediment detention method, a feasibility assessment is advised to justify that a sediment detention basin is the best solution. Early discussions with regulatory and resource agencies and other stakeholders are encouraged to determine if implementing a sediment detention basin is an acceptable option. Sediment traps should not be employed without first asking the following questions during data collection, assessment and design:

1. Could the sediment deposition problems experienced at the site be solved in a different way than a sediment basin? Make sure there is no alternative before designing the basin.
2. What sort of mitigation will be required for the installation of the sediment basin? Might mitigation obligations offset the benefits of the sediment basin?
3. Would a sediment trap starve downstream spawning habitat of gravel? It has been suggested that loss of spawning habitat cannot be mitigated. If good spawning habitat is limiting in the stream system, then loss of spawning habitat may be a very important consideration.

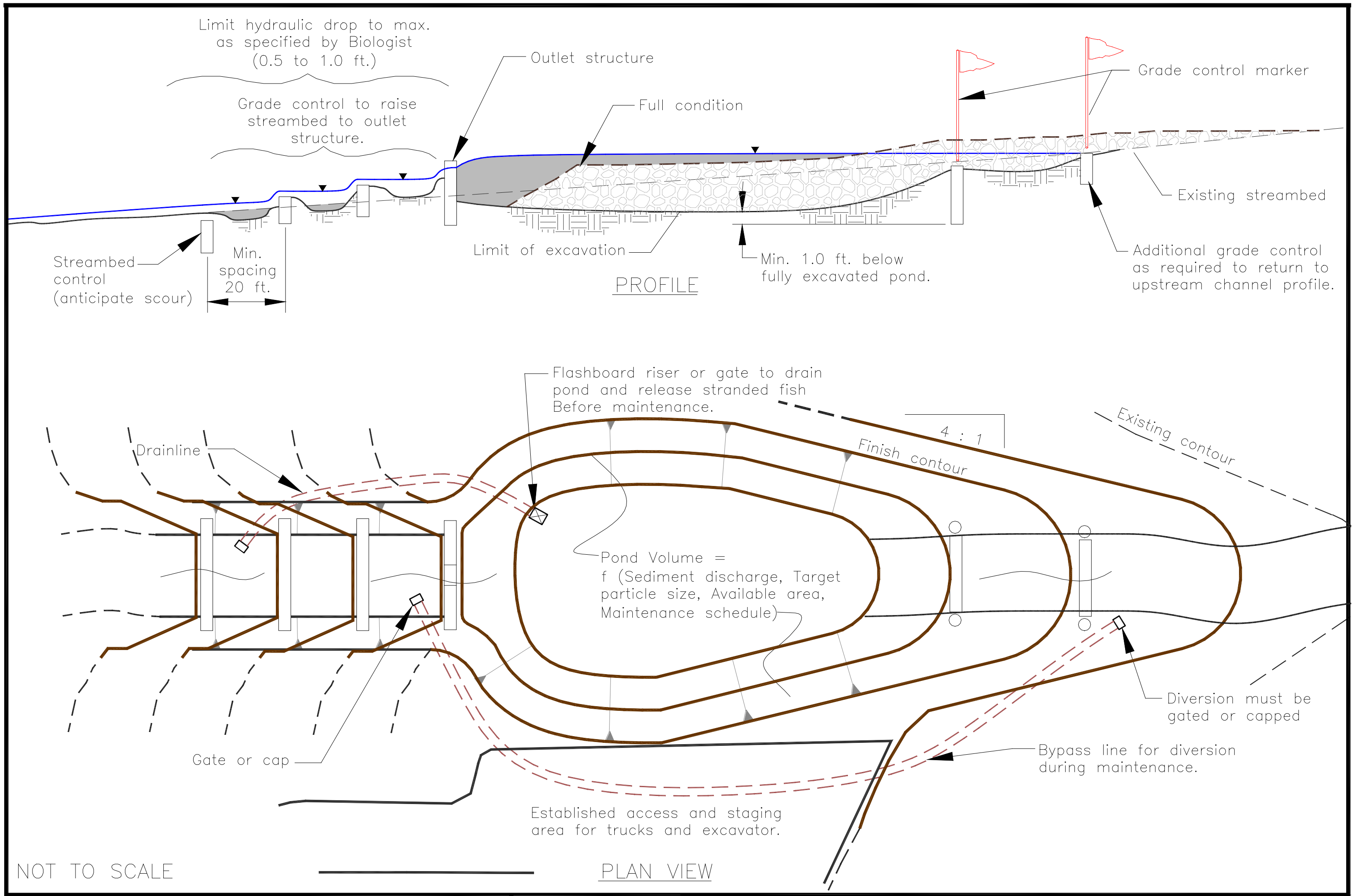

FIGURE 1

SEDIMENT DETENTION BASINS
ONE TYPE OF
CONCEPTUAL DESIGN

STREAM HABITAT
RESTORATION GUIDELINES

4. Would a sediment trap in a given location cause downstream incision or scour? In a metastable stream small changes in external conditions can result in a major change in channel evolution.
5. How often would the sediment trap require inspection, maintenance and cleanout? Identify the individual or organization responsible for maintenance and make sure that funds are budgeted for this purpose for the life of the project.
6. Where will removed sediments be dumped? Will the spoils site be available for the duration of the basin's predicted life? Is the spoils site large enough for the anticipated volume over the life of the project? Could the spoils be used in restoration projects requiring gravel?
7. How and when will the trap be decommissioned and natural stream function restored? A set date for decommissioning is recommended, with clear conditions and consequences for failure to decommission on time. A funding source or responsible party should be identified that will pay for the decommissioning.

5.1 Data Collection and Assessment

Planning and designing instream sediment detention basins should be preceded by careful assessment of sediment conditions within the stream, including evaluation of the natural forces at work and the biological impacts of the sediment.

- *Watershed assessment* Since sediment detention basins exert significant impacts on stream systems they should be considered a "last resort" technique to be used only when other options are not feasible. Prior to implementing instream sediment detention, sediment sources should be identified and alternatives to control these sources should be evaluated.
- *Fluvial Geomorphic Assessment.* A geomorphic analysis of the natural stream processes, human influences affecting the reach, and historic conditions, should be conducted in order to assess the appropriateness of a detention basin in the geomorphic and historic context. Refer to the *Fluvial Geomorphology* appendix for details on geomorphic principles. The effects of channelization are often what drive landowners to feel they need sediment traps. One half of the sediment basins in Western Washington are there because of channelization. Channels that have been straightened and cut off from their floodplains lack the sediment storage and transport characteristics of natural channels that have configured themselves to efficiently handle their sediment discharge. Other naturally depositional stream reaches often have adjacent infrastructure that need sediment traps for protection until a long-term solution can be implemented.
- *Biological habitat Impacts.* Planning for instream sediment detention should include a biological assessment of the impacts of the project. Particularly important in this regard are impacts to downstream spawning and macroinvertebrate habitats and other discontinuity effects associated with dams[8] [10]. Operations and maintenance represent continuing impacts to habitat.
- *Sediment Transport Analysis.* Planning for instream sediment detention will require estimation of sediment volume being transported through the stream. This will typically require hydrologic, hydraulic, and sediment transport assessment and/or analyses that are

detailed in the *Hydrology, Hydraulics*, and *Sediment Transport* Appendices respectively.

- *Hydrology.* In order to estimate sediment volumes using some methods, detailed hydrologic statistics, including a flow duration curve derived from mean daily flows over the period of record, will be needed.
- *Hydraulics.* Additionally, a hydraulic model will have to be developed to determine flow velocity, energy slope, depth, effective width and shear within the channel at varying flows. This typically requires detailed surveying of cross-sections throughout the channel.
- *Sediment supply and volume* The simplest method to estimate the average annual sediment yield is to integrate the stream flow duration curve with the sediment discharge rating curve at the inlet to the trap[24] [25] [26] [27]. The U. S. Army Corps of Engineer's SAM[26] at-a-section sediment transport model can be used for these calculations. Often, this method gives an overestimate of sediment volumes when the bed substrate is armored, as transport does not occur to predicted levels until a flow threshold is reached that breaks the armor layer. The average annual sediment yield can be used for an initial planning level estimate of frequency of maintenance.

  More complex analyses may include the use of the U.S. Army Corps of Engineer's HEC-6[28] one-dimensional sediment transport model. HEC-6 is capable of modeling armoring effects in sediment transport processes. Estimates of sediment volumes transported by a specific event can be estimated with a known flood hydrograph, enabling estimates of event-based deposition.

  Estimates of sediment yield are difficult to make and may have little to do with actual yield in any given year. Sediment flux is episodic due to failure of channel bank and bed features as well as variable colluvial process. Sediment volumes are also highly dependent upon the magnitude and duration of flow; a single low frequency flood may fill the trap. Monitoring and maintenance should include documentation of prior stream flow conditions, sediment yield (volume collected), and size distribution of bedload material collected in the trap. Records of dredge volumes may give an indication of sediment discharge.

5.2 Site Selection for Sediment Basins

If possible, basins should be located where the channel has a natural grade break or constriction that increases the natural tendency for sediment to accumulate. The site should be readily accessible to equipment such as front-end loaders, excavators, and dump trucks. Areas immediately upstream from road culverts may make good sediment basin locations, provided the basin and associated sediment deposits will not impair the function or structural stability of the culvert. If such a culvert is not large enough to pass floodwater, sediment and debris, or is a barrier to fish passage, then it should be replaced before the sediment pond is installed. Don't let an existing culvert determine pond characteristics - design the outlet to accomplish the goals of the project. It is possible that increasing culvert capacity may change the deposition pattern in such a way that a sediment trap is not necessary.

The profile of the entire reach should be considered when designing a sediment basin. Fish passage must be maintained up to the ten percent exceedance flow for periods when fish migrate through the reach, according to the Revised Code of Washington (RCW) 75.20.060. Many organisms move up and down the channel using means that are not often identified. Designing sediment traps to resemble natural channels is the best insurance for maintaining this movement. Transitions between the various elements should be smooth, both horizontally and vertically. No abrupt water surface changes greater than one foot at all flows and pond conditions. Grade control should be established downstream for a smooth transition as well as scour protection at the outlet of the flow control device. At least one grade control should be installed 25 to 50 feet downstream of the basin outlet to maintain the bed elevation. Grade control upstream will be necessary to prevent headcut when the pool is excavated. The first grade control immediately upstream of the pond must extend down to at least 1 foot below the maximum depth of excavation to prevent failure from undermining or sloughing. When the pond is empty, this control acts as a dam supporting the upstream channel.

5.3 Flow Control Structures

Flow control devices are required to create and operate the sedimentation basin. These controls include outlet controls to create a damming effect, inlet controls to divert low or high flows from the stream to the basin and gates to isolate the trap and create a bypass during maintenance operations. Flow control devices include weirs, slots, gates and flashboard risers. For detailed guidance on the design of hydraulic structures, refer to these or similar manuals:

- *Handbook of Hydraulics,* E. R. Brater and H. W. King[29],
- *Fluid Mechanics,* J. A. Roberson, J. J. Cassidy, and M. H. Chaudhry[30].

5.3.1 Weirs

Discharge through a weir is controlled by the shape, elevation and length of the weir crest. Flow passes over the crest of the weir. A weir used as an outlet structure to backwater a basin, collect gravel, and provide grade control may be constructed out of a variety of materials, including rock, wood, or concrete. See **Instream Sediment Detention Basins Figure 5**.

5.3.2 Slots

Slots are configured in a vertical orientation with flow passing through the slot. They are used as an outlet structure. Flow through a slot is conveyed less efficiently than over a weir, increasing water levels in the upstream pool higher than a weir. Slots form a more concentrated jet that may scour the downstream channel. Slots are susceptible to accumulations of debris and the design must account for this. See **Instream Sediment Detention Basins Figure 3**.

5.3.3 Flashboard Risers and gates

A flashboard riser is one method to drain and allow fish to escape the trap during cleanout operations. Gates allow isolation of the active working area from the stream while the stream is shunted to a bypass.

It is important to consider the hydraulic conditions for each component of the structure. The stage-discharge relationships for the various flow control structures involved in the project (e.g. slots and weirs) and channels may all have different flow depths for a given flow. Changes in flow depths through the various components of the structure will result in changes in water surface elevations. Changes in water surface elevations between these structures should not be greater than one foot to provide fish passage and discourage deep scour.

5.4 Detention Basin Design

Detention basins function by providing a lower energy zone that enables sediment to deposit within a constructed basin. The size and shape of a sediment detention basin depends on the stream size, stream hydrology, sediment load, available site area, access, and impacts to upstream and downstream reaches. As sediment is deposited in the basin, trapping efficiencies for the range of sizes of particles changes. This is particularly important for trapping smaller sized particles since the settling velocity is slower and residence time in the basin decreases as it fills[30]. Design typically focus on providing trapping of critical particle sizes at the pool volumes expected under normal circumstances. Other design factors may prove to be important including: pool length, expansion rate, depth and shape. Methods to calculate sediment deposition and trapping in reservoir-type conditions can be found in Hann[31], Lopez[32], and Raudkivi[33] and primarily consider settling velocity and residence time.

Sediment detention basins are typically located on the mainstream channel. Width, depth, length and shape of the basin should work with existing site constraints and allow for efficient gravel removal. An example of one type of sediment basin is shown in **Instream Sediment Detention Basins Figure 5** where the effects of expansion of the channel width and backwater by the downstream hydraulic control combine to promote the deposition of streambed material. Expansion rates of 1:2.6 to 1:4 have been tried. These traps are successful, although expansion as an independent variable has not been thoroughly evaluated. Another trap has been designed to take advantage of the hydraulic characteristics of a meander bend. The trap is configured to look like a bend; sediment is deposited on the “point bar” of the trap and a pool is maintained around the outside of the bend (the pool drain is located along the outside and is not buried by errant deposits). Aesthetic and habitat concerns are less important since the basin is temporary. Habitat enhancement should not be a part of trap design and features that attract fish or encourage spawning should be eliminated. Since the pool is deep after cleaning, many fish are attracted to it.

Uncertainties in design primarily include the structural stability of the weir, and the sediment trapping capability of the basin. The weir should be relatively low and simple. The areas backwatered by the weir should be large and low gradient enough to effectively trap the desired quantity of sediment. In all but the simplest cases, a hydraulic engineer with experience in sediment transport should conduct the hydraulic design. A civil or structural engineer should design the supporting infrastructure. A geotechnical engineer may be required for design of the foundations and mass stability of the structure.

5.5 Fish Passage through Basins

Large drops between the pool exit and the downstream bed elevation may require structures to provide fish passage, sometimes-involving concrete dams and fishways. A guidance document on design of fishways is available from the WDFW at www.wa.gov/wdfw/hab/engineer/habeng.htm. A hydraulic engineer with experience in design of fishways and a civil or structural engineer may be required for design. A geotechnical engineer may be required for design of the foundations and mass stability of the structure.

5.6 Sediment Removal

Basin design should include a bypass ditch or pipe for diverting stream flow during basin maintenance and sediment removal. Both ends of the bypass should be blocked when it is not in use to prevent fish stranding. It the bypass is a channel it can be designed to function as off channel habitat. One such design has been developed for a sedimentation basin in Whatcom County[34]. This same design configured the sediment trap to divert all low stream flows along a habitat bypass channel. Above a threshold stream flow, flow control devices limit the flow diverted into the bypass channel and the bulk of the flow and sediment is conveyed into the sediment trap. This facilitates isolating the trap for cleanout and limits increases in summer time stream temperatures.

A sluice gate or flashboard riser should be included in the bottom of the sediment basin to allow its drainage (in conjunction with fish removal) prior to sediment removal. Locate this drain in a place that is not likely to become overwhelmed with sediment and remains clear prior to excavation. When repeated sediment removal is expected, an access road and work pad should be provided for excavation equipment and truck access.

The Freshwater Gravel Mining and Dredging Issues white paper[1] provides additional information on sediment detention.

5.7 Decommissioning Sediment Basins

Once the sediment basin is no longer required it should be decommissioned to restore continuity of stream processes including flow, sediment, biologic function and riparian function. Decommissioning for smaller basins may be as simple as removing the flow control device. Larger basins will require removal of infrastructure to allow stream flow to pass unimpeded. The stream channel may need to be reconstructed through the pool of the basin by grading trapped sediments and reconstructing streambanks. Refer to the *Channel Modification* technique for guidance on channel reconstruction and the Integrated Streambank Protection Guidelines[35] for design of reconstructed streambanks.

6 PERMITTING

Permitting sediment basins is likely to require a considerable effort in justification and a discussion of the operations and maintenance throughout the life of project as well as decommissioning (nearly all sediment traps are temporary).

As construction and maintenance of instream sediment detention basins involves in-channel work, excavation, and the placement of fill within the channel, required permits and checklists may include, but are not limited to, State Environmental Policy Act (SEPA) and a Joint Aquatic Resource Permits Application (JARPA) (including a Hydraulic Project Approval and possibly a Shoreline Management Act Permit, Section 401 Certification, and Section 404 Permit). A Washington Department of Natural Resources Use Authorization and an Endangered Species Act Section 7 or 10 Consultation may also be required. Refer to the *Permitting Considerations for Work In and Around Water* appendix for more information regarding each of these permits and checklists.

7 CONSTRUCTION

A complete discussion of construction considerations for in-channel projects is presented in the *Construction Considerations* appendix. In addition, it is recommended that all weirs and structural elements that can be buried by deposited sediment be marked to avoid damage during sediment removal.

There are two major components of sediment detention construction – excavation of the basin and construction of control structures. Control structures may be constructed from a wide variety of materials and methods. Depending on their size and complexity, they may be constructed in place or may be constructed off-site as units to be installed. The advantage of off-site assembly is that it reduces the amount of time that a stream must be impacted by dewatering. A structural engineer should be consulted for further details on construction considerations for the structural components of the basin.

The excavation of sediment detention basins is typically a very intrusive endeavor and requires the movement of large volumes of material. To reduce impacts and facilitate construction, all construction activity should be conducted in a dewatered environment - the stream should be routed around the basin site during construction to minimize water quality impacts. Dewatering methods are further described in the *Construction Considerations* appendix will be essential for construction of sediment detention systems. As with any channel disturbance, construction should be conducted during a period where impacts to critical life stages of fish and wildlife are avoided and when dewatering for construction is possible (if necessary). Instream work windows vary among fish species, other aquatic organisms, and streams. Contact the Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows.

Excavation within stream systems is best accomplished using either a tracked hydraulic excavator or a dragline. The size of equipment will be dictated by the size of the basin, materials to be excavated, and site constraints. Excavated material may need to be hauled off-site in dump trucks. Site conditions will dictate whether these trucks can be loaded directly at the site, if other loading equipment will be necessary, and whether a haul road is necessary. Because most sediment detention basins require maintenance and cleaning out, a haul road constructed for excavation may also be useful for long-term maintenance. Disturbance limits for excavation can be limited by having the majority of operations conducted within the basin's footprint.

Sediment detention basins are well suited for unit cost or lump sum contracting because excavation quantities, structural components, and dewatering systems, and other construction components can be readily estimated prior to construction.

7.1 Cost Estimation

Costs to construct a sediment basin will include excavation and hauling to construct the basin, construction of infrastructure and flow control devices, and, potentially, construction of any bypass channels. Dewatering, sedimentation and erosion control and restoration of disturbed surfaces will have costs similar to those discussed in *Channel Modification* technique.

Maintenance costs for sediment removal from the sediment trap and removal of debris accumulated on the trap will include labor, excavation and hauling. Rates for these tasks vary by region and by haul distance. Local rates can generally be estimated based on conversations with a few local contractors. The circumstances and location of the work can also affect cost significantly. When working in difficult-to-access sites and/or space-constrained conditions, construction crews and equipment may require twice (or more) as much time as they would to complete tasks under ideal conditions.

Maintenance, operation, and decommissioning costs should be included in cost estimating. Operational costs will include routine inspections. Costs will be dependent on hourly billing rates and expenses for inspection staff to visit, inspect and document site conditions.

8 MONITORING

Sediment detention basin volume requires monitoring to determine when sediment removal is necessary. In addition, structural integrity of basin components, basin effects on local streambanks, and downstream effects (such as increased erosion) should be monitored. Monitoring may include any or all of the following elements:

- Visual inspections (periodic, and after storm events);
- Section and profile data (upstream, through the basin and downstream);
- Document stream flows between maintenance/monitoring operations;
- Record the volume of sediment taken out the trap;
- Record the bed substrate data (e.g. grain size distribution) of sediment removed from the trap. Note any variation in size and relative location in the trap (coarser materials are expected near the inlet with finer materials further from the inlet);
- Photo Points;
- Reach based fish snorkeling to identify impacts to habitat; and
- Spawning surveys, document location of redds (this is often not a part of spawning surveys) to detect impacts to downstream reach.

Visual reference points may simplify monitoring. For instance, a staff gage or pin driven into the bed can indicate maintenance is needed. Scour chains with floating balls downstream can show threat or injury to spawning redds.

9 MAINTENANCE

Operation and maintenance play a major role in successful sediment detention basin application. With the exception of structures intended to be permanent and naturally maintained (e.g., large wood placed in low-order streams to enhance sediment retention), the majority of sediment detention structures will require operation and maintenance efforts. As mentioned previously, detention basin volume should be monitored so that sediment removal can be initiated as they near operating capacity. In addition, structural integrity of basin components, basin effects on local streambanks, and downstream effects (such as increased erosion) should be monitored.

A maintenance schedule and procedures should be a part of the design and contracting documents, and as a provision in the original HPA (the Hydraulic Project Approval permit). The schedule should require the use of a checklist to insure that all procedures are followed, specifically stating who is to perform the maintenance and the details of that activity.

Modifications to that schedule should be made in cooperation with all the interested parties. Check at least after each flood since sediment flux is episodic and may vary dramatically from storm to storm and year to year.

In addition to monitoring, repair, and removal of sediment, removal of the basin and associated structures should be included as operation and maintenance duties. Additionally, cleanout operations require careful transplanting of fish from within the basin to upstream or downstream reaches.

10 EXAMPLES

Instream Sediment Detention Basins Figure 2: Coal Creek sediment basin, Skagit County. Looking downstream from basin to slot-type outlet structure. Stream enters on left, deposition shoaling in middle left.

Instream Sediment Detention Basins Figure 3: Coal Creek sediment basin, detail of outlet structure. Downstream weir prevents erosion of channel. A more fish-friendly structure downstream of the slot might be a porous weir. Fish passage is an important consideration in the design of outlet structures.

Instream Sediment Detention Basins Figure 4: Hansen Creek sediment basin, Skagit County. Looking downstream at outlet structure. Outlet is more ad hoc than other basins and can be a passage problem at some flows. Basin is actually many acres with only the outlet shown here.

(a)

(b)

(c)

Instream Sediment Detention Basins Figure 5: Chimacum Creek sediment basin, Jefferson County. (a) Pre-construction, (b) Post-construction, and (c) Looking upstream at control weir and nearly full sediment basin. Log control used as the outlet structure. Machinery pad and access road is off the picture to the right. Bypass pipe starts above the basin and outfalls just below picture.

Instream Sediment Detention Basins Figure 6: Maplewood Creek sediment basin, King County. Looking upstream at sediment basin. High flow overflow structure in on right, inlet stream on right. Low flow outlet structure is a fishway off the picture on the left.

11 GLOSSARY

Colluvial – Material supplied to a river that is not derived from river transport and deposition.

Mass wasting – Geotechnical failure of a bank in response to gravity forces resulting in deposition of a wedge of bank material in the channel bed.

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APPENDIX A

CLIMATE CHANGE

Climate Change Appendix

1 INTRODUCTION

Climate change is projected to continue to affect many of the fundamental drivers of stream ecosystems and stream habitat. In particular, climate change is likely to dramatically alter the hydrologic regimes within most watersheds across Washington State. While predictions of specific impacts are variable and uncertainty around those predictions is considerable, little argument exists that significant changes and impacts will be manifest. In the coming decades, climate change will affect virtually all variables influencing hydrologic parameters that govern stream habitat, from upland watershed inputs to stream channel dynamics. Climate change will likely impact:[1]

- Precipitation
    - Annual average and inter-annual variability
    - Seasonality
    - Event intensity and duration
    - Rain-snow partitioning
- Vegetation and land use
- Evapotranspiration
- Rainfall-runoff relationships
- Groundwater and stream baseflow
- Sediment sources and transport
- Base level (sea level)

This Climate Change Appendix is provided to synthesize and summarize contemporary science regarding impacts of climate change on stream systems and stream habitat in Washington and to provide references for further information. The primary sources of information for this appendix have been derived from the Climate Impacts Group (http://cses.washington.edu/cig/) publications, an unpublished report developed by Paul Bakke,[2] and unpublished and internal documents from the Washington Department of Fish and Wildlife (WDFW) and National Wildlife Federation (NWF) developed for the Ecosystems, Species, and Habitats Topic Advisory Group (TAG).

Efforts to restore stream habitat will be inadequate without consideration of climate change – restoration efforts must account for climate change in planning and design in order to increase the likelihood that they will be effective. This appendix provides a summary of recommended appropriate strategies for planning and design of stream habitat restoration efforts in the face of certain climate change. Strategies emphasize accommodating changing processes and uncertainty.

2 OBSERVED AND PREDICTED CLIMATE CHANGE PATTERNS IN WASHINGTON

Climate change is unambiguously well documented.[3,4,5,6] Globally and regionally, climate change is being driven in large part by increased atmospheric CO_2 concentrations, which are approximately 30% higher today than in any time during the previous 800,000 years.[7] This has resulted in both changes to temperature and changes to precipitation. The Climate Impact Group (http://cses.washington.edu/cig/) has documented observations and developed extensive climate change and impact scenarios for the Pacific Northwest (PNW) and Washington State.[8] Temperature and precipitation are the major drivers of projected changes in stream ecosystem and habitat variables. Observed and projected changes in temperature and precipitation include:[9]

Temperature: Average global and regional temperature have increased over the past century, and a high degree of agreement exists among model projection scenarios for continued increases through this 21st century, as indicated in Figure 1.

- Pacific Northwest temperatures have increased about 1.5°F (0.8°C) since 1920.
- Most models project increases of 2.0°F (1.1°C) by 2020s, 3.2°F (1. 8°C) by the 2040s, and 5.3°F (2.9°C) by the 2080s, averaged across all climate projection models, and compared to the period between 1970 and 1999.
- Warming is projected to vary by season, with the most pronounced increases anticipated for summer temperatures.
- Additional details of projected temperature change are provided in Table 1.

Figure 1. Smoothed traces in temperature model simulations for the Pacific Northwest, relative to the 1970-1999 mean. The top and bottom bounds of the shaded area are the 5th and 95th percentiles of the annual values from roughly 20 model simulations. B1 and A1B emissions scenarios are selected by authors of the source report as representative of upper and lower scenarios (adapted from Mote and Salathé[10])

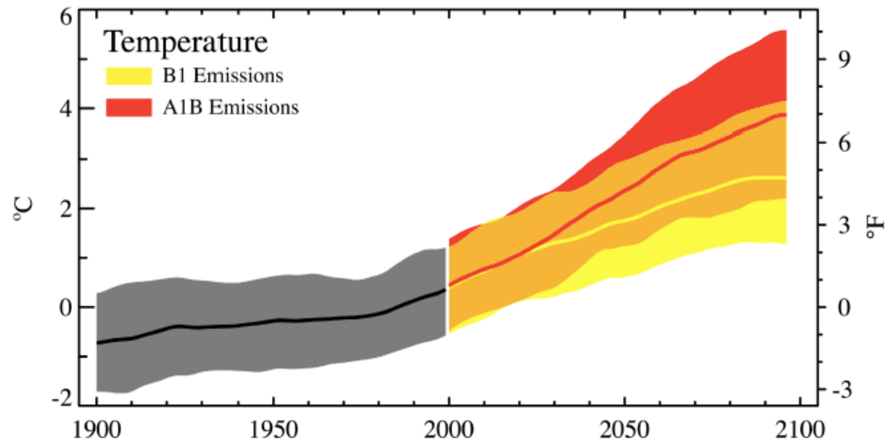


Table 1. Summary of projected temperature change for Washington (adapted from Summary of Projected Changes in Major Drivers of Pacific Northwest Climate Change Impacts prepared by the University of Washington Climate Impacts Group for the Washington Department of Ecology, 21 March 2012 version; http://cses.washington.edu/cig/pnwc/pnwc.shtml). Note: The information provided in the table is largely assembled from work completed for the 2009 Washington Climate Change Impacts Assessment. Other sources have been used where relevant but this summary should not be viewed as a comprehensive literature review of the Pacific Northwest (PNW) climate change impacts. Confidential statements are strictly qualitative with the exception of IPCC text regarding rates of 20th century global sea level rise. Note that multi-month intervals are abbreviated by each month's first letter, e.g., DJF-Dec, Jan, Feb.

Climate Variable	General Change Expected	Specific Change Expected	Size of Projected Change Compared to Recent Changes	Information About Seasonal Patterns of Change	Confidence	Sources and Context
Temperature	Increasing temperature expected through the 21st century Variations in season and annual temperature associated with natural variability (e.g. El Niño and La Niña) might be affected by climate change.	Projected multi-model change in average annual temperature (with range) for specific benchmark periods: • 2020s: +2F (1.1-3.4° F)** • 2040s: +3.2°F (1.6-5.2°F) • 2080s: +5.3°F (2.8-9.7°F) These changes are relative to the average annual temperature for 1970-1999: The projected *rate* of warming is an average of 0.5°F per decade (range: 0.2-1.0°F) --------------------------------- *** Mean values are the weighted (REA) average of all 39 scenarios. All range values are the lowest and highest of any individual global climate model and greenhouse gas emissions scenario coupling (e.g., the PCM1 model run with the B1 emissions scenario).*	Projected warming by the end of this century is much larger than the regional warming observed during the 20th century (+15°F) even for the lowest scenarios.	Warming expected across all seasons with the largest warming in summer months (JJA). Mean Change (with range) in winter (DJF) temperature for specific benchmark periods, relative to 1970-1999: • 2020s: +2.1°F (0.7-3.6°F) • 2040s: +3.2°F (1.0-5.1°F) • 2080s: +5.4°F (1.3-9.1°F) Mean change (with range) in summer (JJA) temperature for specific benchmark periods relative to 1970-1999: • 2020s: +2.7°F (1.0-5.3°F) • 2040s: +4.1°F (1.5-7.9°F) • 2080s: +6.8°F (2.6-12.5°F)	High confidence that the PNW will warm as a result of increasing greenhouse gas emissions. All models project warming in all scenarios (39 scenarios total) and the projected change in temperature is statistically significant.	Mote and Salathè 2010

Precipitation: Precipitation projections are both more variable and more uncertain than temperature predictions, with pronounced regional variation. The major patterns include:

- Inter-annual and cyclical variations (i.e., the El Niño Southern Oscillation and Pacific Decadal Oscillation, ENSO and PDO, respectively) in the past century were large relative to any regional or global trends associated with global warming.

- Projected changes in annual precipitation for the Pacific Northwest, averaged across all projection models, are for modest 1% to 2% increases. Inter-annual and cyclical variations will likely continue to drive more significant variation than multi-decadal trends, at least in the relatively near future.

- Precipitation changes are expected to trend toward greater seasonal and inter-annual variation with wetter fall/winter seasons and drier summers. Most models project a weighted average decrease in summer precipitation of 16% by the 2080s. Some models predict reductions in summer precipitation of 20-40% (3-6 cm [1.2-2.4 inches]). Projected increases in winter precipitation are for a weighted average value of 9% increase (3 cm [1.2 inches]) by the 2080s. Variations among models include modest reductions to fall/winter precipitation and increases of up to 42%.

Table 2 provides further details of projected precipitation changes.

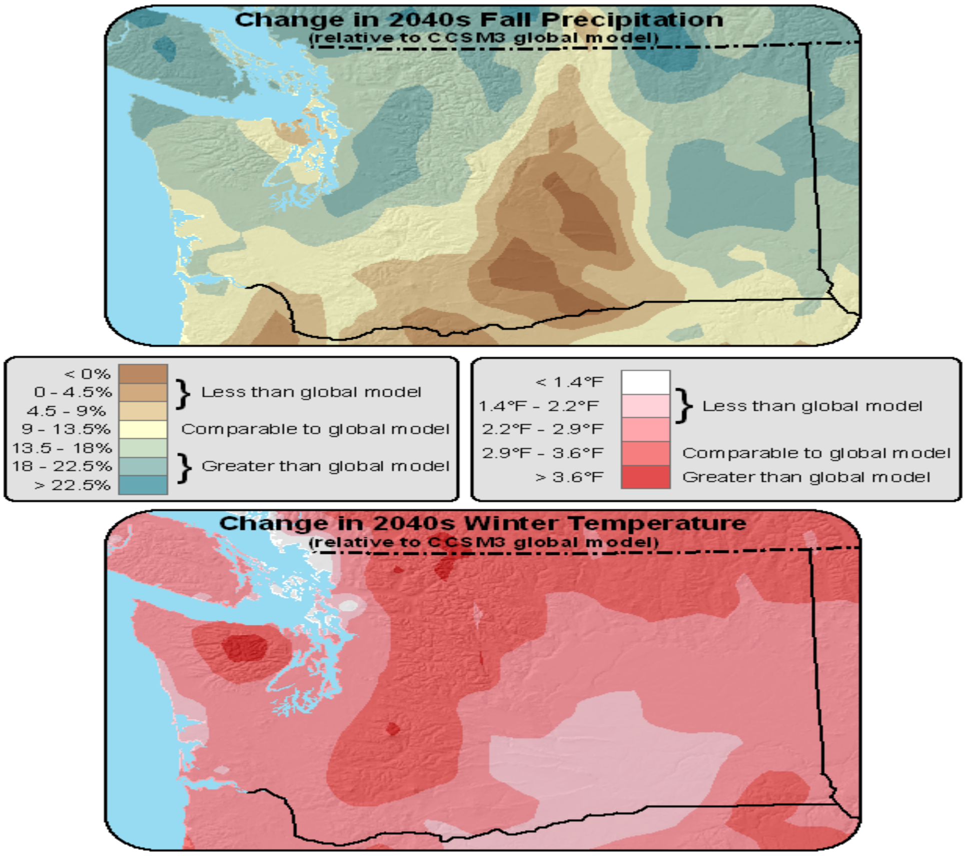
Table 2. Summary of projected precipitation change for Washington (adapted from Summary of Projected Changes in Major Drivers of Pacific Northwest Climate Change Impacts prepared by the University of Washington Climate Impacts Group for the Washington Department of Ecology, 21 March 2012 version; http://cses.washington.edu/cig/pnwc/pnwc.shtml). Note: The information provided in the table is largely assembled from work completed for the 2009 Washington Climate Change Impacts Assessment. Other sources have been used where relevant but this summary should not be viewed as a comprehensive literature review of the Pacific Northwest (PNW) climate change impacts. Confidential statements are strictly qualitative with the exception of IPCC text regarding rates of 20th century global sea level rise. Note that multi-month intervals are abbreviated by each month's first letter, e.g., DJF-Dec, Jan, Feb.

Climate Variable	General Change Expected	Specific Change Expected	Size of Projected Change Compared to Recent Changes	Information About Seasonal Patterns of Change	Confidence	Sources and Context
Precipitation	A small increase in average annual precipitation is projected (based on the multimodel average, Mote and Salathè), although model-to-model differences in projected precipitation are large (see "Confidence"). Potentially large seasonal changes are expected.	Projected change in average annual precipitation (with range) for specific benchmark periods: • 2020s: +1% (-9 to 12%)** • 2040s: +2% (-11 to +12%) • 2080s: +4% (-10 to +20%) These changes are relative to the average annual precipitation for 1970-1999. --------------------------------- _** Mean values are the weighted (REA) average of all 39 scenarios. All range values are the lowest and highest of any individual global climate model and greenhouse gas emissions scenario coupling (e.g., the PCM1 model run with the B1 emissions scenario)._	Projected increase in average annual precipitation is small relative to the range of natural variability observed during the 20th century and the model-to model differences in projected changes for the 21st century	*Summer:* Majority of global climate models (68-90% depending on the decade and emissions scenario) project decreases in summer (JJA) precipitation. Mean change (with range) in JJA precipitation for specific benchmark periods, relative to 1970-1999: • 2020s: -6% (-30% to +12%) • 2040s: -8% (-30% to +17%) • 2080s: -13% (-38% to +14%) *Winter:* Majority of global climate models (50-80% depending on the decade and emissions scenario) project increases in winter (DJF) precipitation. Mean change (with range) in DJF precipitation for specific benchmark periods, relative to 1970-1999: • 2020s: +2% (-14% to +23%) • 2040s: +3% (-13% to +27%) • 2080s: +8% (-11% to +42%)	Low confidence. The uncertainty in future precipitation changes is large given the wide range of natural variability in the PNW and uncertainties regarding if and how dominant modes of natural variability may be affected by climate change. Additional uncertainties are derived from the challenges of modeling precipitation globally. Model to model differences are quite large, with some models projecting decreases in winter and annual total precipitation and others producing large increases. Expect that region will continue to see years that are wetter than average and drier than average even as the average changes over the long term.	Mote and Salathè 2010 Salathè et al. 2010

Extreme Precipitation	Precipitation intensity may increase but the spatial pattern of this change and changes in intensity is highly variable across the state.	State-wide (*Salathè et al. 2010*): More intense precipitation projected by regional climate model but distribution is highly variable; substantial changes (increases of 5-10% in precipitation intensity) are simulated over the North Cascades and northeastern Washington. Across most of the state, increases are not significant. For sub-regions (*Rosenberg et al. 2010*): Projected increases in the magnitude (i.e., the amount of precipitation) of 24-hour storm events in the Seattle-Tacoma area over the next 50 years are 14.1%-28.7%, depending upon the data employed. Increases for Vancouver and Spokane are not statistically significant and therefore cannot be distinguished from natural variability. An increase in the intensity of the winter season midlatitude storm track in the Northern Hemisphere is expected globally, however there is considerable variation in model results at the regional scale (O'Gorman 2010, Ulbrich et al. 2008).	Projected increases in the magnitude of the 24-hour precipitation events for the period 2020-2050 for the Seattle-Tacoma area (14.1-28.7%) is comparable to the observed increases for the 24-hour events over the past 50 years (24.7%) (*Rosenberg et al. 2009*).	The ECHAM5 simulation produces significant increases in precipitation intensity during winter months (Dec-Feb), although with some spatial variability. The CCSM3 simulation also produces more intense precipitation during winter months despite the reductions in total winter and spring precipitation (*Salathè et al. 2010*). Projections for increases in coastal precipitation intensity are for the winter season. There is little information on how summer precipitation intensity may change along the coast or in the interior PNW.	Low confidence for increase4s in precipitation intensity. Anthropogenic changes in extreme precipitation are difficult to detect given wide range of natural precipitation variability in the PNW. Computational requirements limit the analysis of sub-regional impacts within Washington to two scenarios, reducing the robustness of possible results. Simulated changes from these two scenarios are statistically significant only over northern Washington. Low confidence for increasing coastal storm track intensity. While there is good agreement across models at the global scale that the intensity of midlatitude storm tracks is likely to increase, there is considerable variation in model results (and therefore considerable uncertainty) as you move to the regional scale.	Salathè et al. 2010 Rosenberg et al. 2009 Rosenberg et al. 2010 O'Gorman 2010 Ulbrich, U et al. 2008

Projected changes in temperature and precipitation are strongly influenced by regional terrain, topography and other climate variables. Figure 2 depicts regional projections for changes in temperature and precipitation relative to global projections, and illustrates the anticipated variability.

Figure 2. Differences between a regional climate model (WRF) and a global climate model (CCSM3) for projected changes in fall precipitation (September to November top) and winter temperature (December to February, bottom) for the 2040s. The global model produces a regionally averaged 11.7% increase in precipitation, but the regional model provides more detail (top), projecting some areas of increase (green) and some of decrease (brown) compared to the global model. Note that large increases are seen on windward (west and southwest) slopes and smaller increases on leeward (east and northeast) slopes. The global model produces a 3.6°F (2.0°C) statewide averaged increase in winter temperature, while the regional model produces a statewide average 2.6°F (1.4°C) warming. Greater increases (darker red) occur at higher elevations and windward slopes, particularly the Olympic Mountains, North Cascades, and central Cascades. These differences illustrate the value of regional climate models for identifying sub-regional patterns and differences. The patterns of climate change differ depending on the global model being downscaled (we present only one here); nevertheless, the local terrain has a consistent influence on the results (Figure and caption used with permission from Littell et al.[11])



2.1 Climate Change Modeling

Climate change is an observed phenomenon strongly supported by regional and international investigations. Predicting the future resulting from climate change requires modeling of future scenarios that vary based on assumptions and inputs to the model, and which compensate for cyclical variations such as those generated by the ENSO and PDO, respectively. Except for historical studies, virtually all of the climate change literature relies on modeling. *Physical modeling* uses a simplified representation of the earth as a series of spatial elements or "cells," and uses the equations of mass transfer, energy transfer, and fluid dynamics to link these cells into a dynamic model that can then be solved numerically on a computer. Model output will depend on not only the laws of physics, but the choice of values for input parameters, some of which are known more accurately than others. *Statistical modeling*, by contrast, uses the existing data on climate and/or hydrology, without regard to the physics of how "climate" or "hydrology" comes about, and involves adjustments to these data in ways that match certain expectations or assumptions about how the climate will change.

Most projections and implications summarized in this appendix are drawn from modeling performed by the Climate Impacts Group (CIG) at the University of Washington (http://cses.washington.edu/cig/). For more information on the CIG approach to regional modeling, and details of models and applications, refer to http://cses.washington.edu/db/pdf/wacciach2rcm643.pdf.

Selected limitations exist to modeling that need to be understood in order to interpret climate change literature. First is the issue of probable range of future conditions, such as a future average annual temperature. Diverse physical climate models are now in use, each based on somewhat different assumptions, numerical techniques, or representation of the Earth's surface and atmosphere. Output from many models is often averaged, while the differences between the various model outputs are treated as a measure of the variability in the probable range of future condition (the *ensemble approach*; e.g. CSSP, 2008). Strictly speaking, this is an incorrect approach because it assumes that each of the model outputs are equally likely, ignoring the issue of which models work better, or are better suited for a particular region or application. For non-experts, multi-model comparisons are more appropriately interpreted as a way to describe the overall range of conditions treated in the literature, or the collective state of climate change prediction science.

The second issue that arises in modeling is termed *downscaling* (Wood et al,[12] Salathé,[13]Salathé et al.,[14] Maurer et al.[15]). Generally, the physical climate models (called Global Climate Models or GCMs) used to study global warming divide the earth into cells that are about 2.5 degrees of latitude (~300 km) on each side. For use in regional studies, these results must be interpolated to a grid that is a maximum of 1/8 degree (~15 km) or finer. This represents an artificial enhancement of spatial resolution, which gives the appearance of greater accuracy than actually exists.

A more serious issue is downscaling of temporal resolution, more properly termed *disaggregation*. The global climate models provide output in the form of monthly and annual averages, yet what is needed for assessment of geomorphic change, flood magnitudes, and hydraulic aspects of habitat are instantaneous water discharges. No scientifically tenable way exists of bridging that gap in resolution. Currently, the best approach available is to examine relative changes to the extreme values predicted and assume that these levels of relative changes are preserved at all timescales (Hamlet and Lettenmaier[16]). This almost certainly underestimates the changes to magnitudes observed over short time scales due to loss of variance that averaging produces. Statistical models avoid this problem by using an actual time series of climatic or hydrological measurements, usually daily mean values, and adjusting these in ways predicted by the GCMs for larger timescales, or in ways that isolate precipitation from temperature, for example. In this manner, the total variance of the data is retained. Yet for selected studies, such as flood magnitude predictions, this approach remains inadequate because of the use of daily mean values in lieu of instantaneous values. The latter is expected to display higher variances than the former. Furthermore, the variance of future temperature or precipitation records is anticipated to increase.

While modeling is valuable for assessment of regional climate impacts, multi-model ensembles of global climate projections and statistical methods may under-represent the local severity of climate change.[17] Best professional judgment of climate change scenarios is a combination GCM predictions tempered by careful scrutiny of the statistics of recent historical records and physical reasoning. Conclusions based solely on downscaled GCM results are incomplete with a large uncertainty component.

For more information on downscaling of models in the PNW, refer to:

- Salathé, E.P., P.W. Mote, and M.W. Wiley. 2007. Review of scenario selection and downscaling methods for the assessment of climate change impacts on hydrology in the United States Pacific Northwest. *International Journal of Climatology* 27:1611-1621.

- Hamlet, A.F., E.P. Salathé, and P Carrasco. 2010. Chapter 4, Statistical downscaling techniques for global climate model simulations of temperature and precipitation with application to water resources planning studies. The Columbia Basin Climate Change Scenarios. Climate Impacts Group, University of Washington. Available: http://www.hydro.washington.edu/2860/products/sites/r7climate/study_report/CBCCSP_chap4_gcm_final.pdf

3 IMPLICATIONS OF CLIMATE CHANGE

Climate change has the potential to impact stream ecosystems through many direct and indirect ways: temperature increases will lead to increased water temperature; drier hotter summers will likely exacerbate the incidence and intensity of forest fires, leading to changes to water chemistry, sedimentation, and shading of streams; drought that can affect soil moisture and runoff balances; increased storm intensity that may lead to increases in soil saturation and landslide incidence; and seasonal variations in precipitation and temperature will affect the balance between runoff from rainfall and that from snowfall, thereby altering hydrologic regimes. When considering the myriad variables and potential scenarios, particularly as stratified among regions within Washington, the potential impacts are virtually impossible to predict with a high level of precision at a basin scale. However, from the perspective of stream habitat, generalizations about probable stream outcomes exist that need to be considered in developing restoration strategies and selecting restoration techniques. SHRG chapters 2 and 4 and the Geomorphology and Hydrology Appendices note the important relation between geomorphic processes, the key variables that drive these processes (hydrologic regime, sediment regime, distribution of large wood), and the character of habitat in stream systems. Climate change necessarily will affect these relations primarily and most immediately by impacting the hydrologic regime (refer to *Hydrology* Appendix for further discussion of hydrologic regimes and the *Geomorphology* Appendix for further discussion of its relevance to stream processes).

A useful summary of climate change projections for Washington, is available from: http://cses.washington/cig/res/ia/waccia.shtml.

3.1 *Projected impacts to Washington hydrologic variables and systems*

Washington can be generally partitioned into two geographic climatic regimes, separated by the Cascades divide: the western region receives an average of 1250 mm (4 ft) of precipitation annually; the eastern region of the state receives slightly more than 300 mm (1 ft), or roughly one quarter of the western portion of the state.[18] The precipitation characteristics between the two regions exert fundamental influences on the formation and character of stream habitat by influencing the distribution of large wood controls on streams (historically, predominantly western Washington) and the hydrologic regime driving geomorphic and ecological processes. Flow within a given stream typically exhibits a seasonal pattern, or flow regime, from year to year that reflects watershed characteristics and the general timing, intensity and form of precipitation. Within the two climatic regions of Washington, the character of flow regimes is influenced primarily by watershed elevation, basin geology, and climate. The magnitude, duration, frequency, and sequencing of variable flows can influence the physical and biological characteristics of a stream in several ways. The hydrologic regime of a stream is a key element in planning, design, and evaluation of stream habitat restoration and stream bank protection projects. Hydrology regimes in Washington are categorized as rain-dominated, snowmelt-dominated, transient or bi-modal with rain-dominated and glacier or snowmelt components, or groundwater controlled (refer to *Hydrology* Appendix for a detailed discussion of hydrologic regimes). All four hydrologic regimes may be present in eastern or western Washington climatic regimes, but will exhibit differing regime characteristics.

The key projected climate change drivers of impacts to Washington's hydrologic regimes include:[19,20,21]

- Increase in precipitation
- Decline in April 1 snowpack
- Increase in intensity of precipitation
- Change in soil moisture and vegetation
- Increase in water temperature
- Sea level rise

Each of these climate change-induced changes may result in cascading and complex indirect impacts to hydrologic regimes and habitat. Explanations of the causes of these impacts and potential indirect impacts to stream habitat are summarized in the following sections. Additionally, section 3.2 of this appendix presents a table (Table 4) that provides a comprehensive listing of probable climate change-induced changes to physical processes and the potential physical and biological impacts of these changes.

Note to readers regarding specific values representing projected changes: Projected changes resulting from global warming presented in this appendix are derived primarily from ongoing research at the Climate Impacts Group (CIG, University of Washington, http://cses.washington.edu/cig/). The CIG offers comprehensive and regularly updated documentation of their research. A careful reader may note that values derived from these varying documents occasionally present apparent inconsistencies that are difficult to reconcile because they may be derived from analyses that use varying periods of record or varying sets of simulations. Nonetheless, the values presented in this appendix are generally in agreement insofar as that they support with trends reported by the CIG and do not contradict these trends.

3.1.1 Increase in precipitation

Statewide average cool season (October to March) runoff is projected to increase by 16-21% by the 2040s and 26-35% by the 2080s as a result of increases in fall/winter rainfall and reduced snowpack. Conversely, warm season runoff (April to September) is expected to decrease dramatically, as much as 2-28% by the 2040s and 34-43% by the 2080s. However, the magnitude of statewide change is smaller for warm season runoff, and total annual runoff, or the total streamflow from a watershed, is expected to increase on average across the state by 2-3% by 2040s and 4-6% by 2080s.[22]

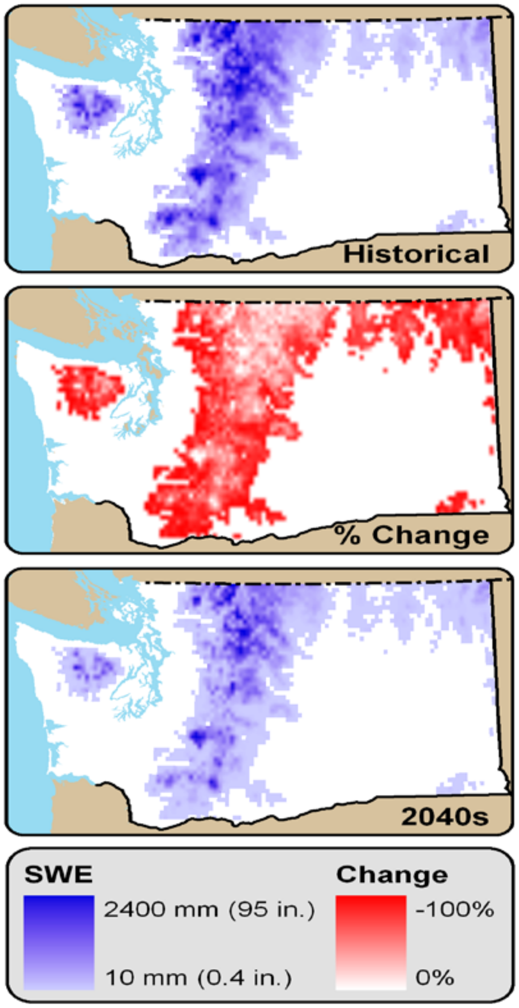
The habitat implications of projected changes in precipitation and resulting runoff include the potential for increased summer drought conditions and diminished summer habitat quality and quantity due to reduced flow. This may limit the availability of important rearing habitats and exacerbate any summer water temperature-related stresses.

Conversely, increases in cool season runoff may lead to increases in effective discharge flow durations (refer to *Hydrology* Appendix and *Geomorphology* Appendix for discussion of 'effective discharge') and associated changes to geomorphic processes that create and maintain habitat, and may aggravate erosion or deposition and associated channel instability.

3.1.2 Decline in April 1 Snowpack

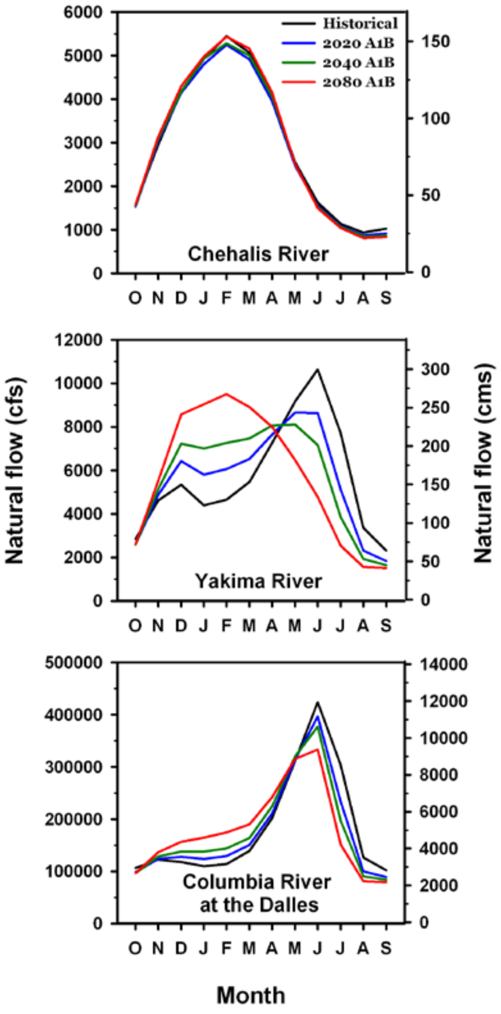
Many of the flow regimes in Washington's watersheds are influenced by snowpack, and past studies have shown that snowpack is a primary impact pathway of regional warming in the PNW.[23,24] A common metric for snowpack is the April 1 Snow Water Equivalent (SWE), which is strongly correlated with summer water supply.[25] Changes in snowpack are driven by both temperature and precipitation, though temperature appears to be a dominant driver in Washington due to the fact that large portions of the area comprising the snowpack are only slightly below freezing temperature during winter months.[26,27] Observations indicate that April 1 SWE has declined almost everywhere in the Cascades since 1930.[28,29] Declines at lower elevations occurred at a rate of approximately 2% per decade. Future projections indicate a decrease in April 1 SWE across the state (but with significant regional and elevation variation) of 53-65% by the 2080s.[30] For projections specific to watershed elevation, refer to Elsner et al..[31] Projections for near-term (up to 2025) loss of snowpack vary markedly among studies previously referenced. Figure 3 portrays historic and projected change to SWE across Washington.

Figure 3 - Summary of projected April 1 snow pack (measured as snow water equivalent, or SWE) and changes in April 1 snow pack for the 2040s, medium emissions scenario (A1B). Projected statewide decline relative to 1916-2006 is 37% to 44%. Snow water equivalent is simply the amount of water the snowpack would yield if it were melted. (Figure and caption used with permission from Littell et al.[32])



Watersheds that were historically characterized by significant winter snowpack and a snowmelt runoff regime are likely to shift toward earlier onset of snowmelt and associated change in timing of runoff, spring freshets and scouring flows. This may affect seasonality of habitat availability and quality and ecological processes dependent upon timing (migration cues, riparian seed germination, etc.). Figure 4 portrays projected changes to timing of runoff for three major river systems in Washington. Note that changes to timing for lower elevation watersheds with minimal snowpack (i.e. the Chehalis) are less likely to change than watersheds historically characterized by snowmelt runoff. Even if the volume of snowpack does not change, the timing of snowmelt runoff is likely to change.[33,34]

Figure 4 – Historical and projected future hydrographs for three rivers under the medium emissions scenario (A1B). The Chehalis River represents a rain-dominated watershed, the Yakima River represents a transient watershed (mixed rain and snow), and the Columbia River represents a snowmelt-dominated watershed. Projected climate changes will influence the timing of peak streamflow differently in different types of hydrologic basins. The timing of peak streamflow does not change in rain-dominated basins because most of the precipitation falls as rain, both currently and in the future, and is therefore available for runoff as it falls. Timing of peak flow shifts earlier as climate warms in the transient and snowmelt-dominated basins because precipitation that historically fell as snow later falls as rain – snowpack melting ceases to dominate the timing of peak flow as the snowpack declines (Figure and caption used with permission from Littell et al.[35]).



A related phenomenon to change in snowpack is the change in high altitude glaciers. Loss of snow and ice will alter spatial and temporal dynamics of runoff, affecting the relative contribution of snowmelt, glacier melt, runoff, and groundwater to streamflow.[36] While changes in hydrologic conditions can affect the quality and availability of existing stream habitat, altered sediment loads in glacial rivers can fundamentally alter the geomorphic processes and channel stability characteristics that strongly influence the character and distribution of stream habitat. Retreating glaciers in Washington are contributing to changes in summer hydrologic conditions, the sediment and thermal regimes of glacial rivers, altered coarse sediment loads and reduction in summer suspended sediment load. Stream habitat within glacially-fed river systems may experience the most dramatic change in stream processes and associated habitat, adding significant challenges to restoration planning in these basins.

3.1.3 Increase in intensity of precipitation

The intensity of precipitation, defined as the annual total precipitation divided by the number of wet days, is an additional hydrologic variable that can affect stream habitat. Precipitation projections indicate that extreme precipitation increases over the North Cascades and eastern Washington.[37] Geographical variation in projected changes follows terrain, indicating the role of elevation and topography in predicting impacts of climate change. Increases in the intensity of rainfall may be associated with:

- Increased incidence and magnitude of peak flows: may lead to increased scouring and erosion of streambanks or streambed, which, depending on timing, may also scour spawning habitat or eggs. Erosion may lead to widened or incised channels and associated habitat impacts including greater separation between summer wetted habitat and bank cover, including wood and undercut banks, and shade.
- Increased flashiness of hydrograph: flashiness refers to the rates of change in storm hydrographs (refer to *Hydrology* Appendix for further discussion of storm hydrographs). Rapid rates of change in stream flow can exacerbate stranding of fishes in off-channel habitats and changes in the availability and quality of habitat, particularly that which may be available or functional only during high flows.
- Change in timing and volume of runoff: changes in the intensity of storms may lead to changes in the character of runoff (timing and volume), resulting in impacts to ecological processes dependent on runoff character, such as seed germination and life history cues for migration or spawning that are keyed to runoff.

These changes are relevant to stream habitat and restoration strategies because they affect both watershed controls and stream processes. Current research indicates that alluvial stream types common throughout the Pacific Northwest are particularly sensitive to changes in the frequency of high intensity storms that are expected under climate change scenarios.[38,39] For further discussion regarding the implications of changes to hydrologic inputs, refer to Chapter 2 and the *Geomorphology* Appendix.

3.1.4 Change in soil moisture and vegetation

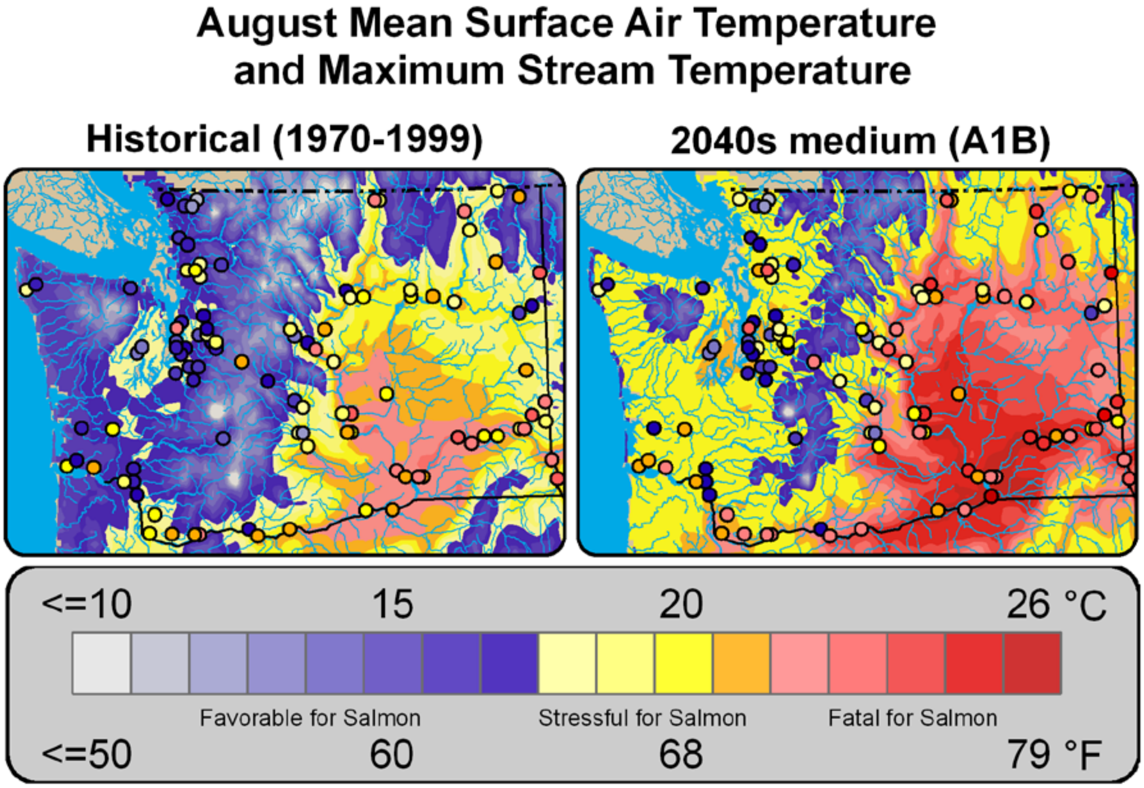
The hydrologic character of a watershed, which influences stream habitat processes as well as habitat quality, is strongly influenced by soils and vegetation, which are in turn highly correlated and influenced by climate. Climate change will necessarily affect vegetation and soils at a watershed scale, and impacts will vary geographically depending on elevation, terrain, underlying geology, and other variables. Changes in vegetation and soil moisture may be associated with:

- Change in timing and volume of runoff. Vegetation and soils, including soil moisture characteristics, influence the infiltration of precipitation and its movement to streams (refer to Hydrology Appendix). Soil moisture projections indicate reductions in summer soil moisture throughout the mountainous regions of Washington, and modest increases in soil moisture in the central lowland areas.[40] Changes in vegetation and soils resulting from climate change will affect the timing and volume of runoff, which are critical stream habitat variables and to the processes that support stream habitat. Changes in infiltration rates can affect groundwater and streamflow interaction and associated baseflows, which are critical to summer habitat.
- Increase in forest fires. The area burned by fire within the U.S. Columbia River basin is projected to double or triple by the 2040s, with far larger increases projected for the 2080s.[41] Forest fire can significantly affect stream habitat by causing sedimentation, bank erosion and gullying, reducing shading, increasing stream temperature, as well as increasing runoff volume and flashiness. Fire also leads to increased mass wasting by reducing root strength and increasing the time during which soils remain saturated.[42]

3.1.5 Increase in water temperature

Water temperature is of critical importance to coldwater fishes (including all species of salmonids), cool-water adapted stream-breeding amphibians, and is generally projected to increase. For coldwater fish species, water temperature can create biological stress, can create a passage barrier to movement within a watershed, and can be fatal when critical thresholds are exceeded. Conversely, warmwater fish species may benefit from regional increasing water temperature trends. Change in water temperature is a result of numerous variables including summer baseflow volume, surface air temperature, shading, season, timing of precipitation, and runoff timing and pathways. Figure 5 portrays projected change in air and water temperature, implying a significant increase in the potential to reach stressful or fatal thresholds, and a significant increase in the duration of those areas already at or above those thresholds. Impacts are greatest throughout the Columbia River basin; lowland rivers of western Washington may also reach these thresholds, though incidences are expected to be rare.[43] While increasing water temperatures will stress salmonids and other coldwater fishes in some rivers, the effects of these stresses will be most profound in river systems that are already at or near threshold temperature conditions.[44,45]

Figure 5. August mean surface air temperature (colored patches) and maximum stream temperature (dots) for 1970-1999 (left) and the 2040s (right, medium emissions scenario, (A1B)). The area of favorable thermal habitat for salmon declines by the 2040s in western Washington, and in eastern Washington many areas transition from stressful to fatal for salmon. Circles represent selected stream temperature monitoring stations used for modeling stream temperatures (figure and caption used with permission from Littell et al.[46])



3.1.6 Sea level rise

Sea levels are largely influenced by thermal expansion of the oceans, changes to the global balance of freshwater storage in glaciers and local land subsidence and tectonic uplift. Changes in sea level will affect the approximate 3000 miles of Washington coastline, though these effects will vary considerably depending on local variables such as substrate, slope, and exposure to storms. Impacts to stream habitat will be felt primarily where stream habitat is inundated by tides – as sea level rises the reach of tidal influence will increase inland, the potential for flooding of lowland and coastal habitats will increase as tides backwater rivers and are compounded by storm surges, and the effects of saltwater intrusion will increase. Sea level change will affect the location and distribution of tidally influenced habitat. Medium projections for sea level rise within Washington State for 2100 are from 2 to 13 inches (5-33 cm).[47] Projected sea level rise by region and for low and high estimates are presented in Table 3. Sea level rise will also affect the base level of stream systems, thereby causing changes in stream dynamics in an upstream direction.

Table 3. Relative sea level rise projections for the major geographic areas of Washington State (adapted from Mote et al.[48]). Source: http://cses.washington.edu/db/pdf/wacciach8coasts651.pdf)

SLR	**By the Year 2050**			**By the Year 2100**		
	NW Olympic Peninsula	Central & Southern Coast	Puget Sound	NW Olympia Peninsula	Central & Southern Coast	Puget Sound
Very Low	-5" (-12 cm)	1" (3 cm)	3" (8 cm)	-9" (-24 cm)	2" (6 cm)	6" (16 cm)
Medium	0" (0 cm)	5" (12.5 cm)	6" (15 cm)	2" (4 cm)	11" (29 cm)	13" (34 cm)
Very High	14" (35 cm)	18" (45 cm)	22" (55 cm)	35" (88 cm)	43" (108 cm)	50" (128 cm)

3.2 Link between physical processes and potential impacts

The previous sections provide a concise overview of the real and projected impacts of climate change. With any natural system, the full suite of inter-related stream habitat variables and feedback and responses to change in those variables is extremely complex. Refer to the *Geomorphology* Appendix and Chapter 2 for further discussion of these linkages and their relation to channel habitat.

Two general global warming responses we can expect are:

1. *A prolonged period of adjustment of stream morphology in response to new patterns of flooding and sediment load. Depositional or 'response' reaches will be most severely impacted.* Evolution of channel morphology generally lags a change in climate, land use, or sediment by many years or decades.[49] Adjustment of rivers to changes in climate will occur slowly, and we can expect a protracted period of adjustment. Furthermore, streams will exhibit varying degrees of sensitivity to climate change-induced changes in hydrology or sediment. The most sensitive stream types are typically *response reaches* - those where sediment tends to deposit over long periods of time. Common locations of response reaches include alluvial fans, transitional areas from confined to unconfined valleys, and places where channel slope flattens. Table 4 indicates common geomorphic or hydrologic settings that are more likely to be sensitive to climate change; Table 5 indicates common settings that may be more resilient in the face of climate change, or otherwise less likely to lead to impacts to available habitat. Table 4 and 5 are presented to illustrate examples of sensitive and resilient hydrologic or geomorphic settings, but should not be viewed as comprehensive or all encompassing.

Table 4. Geomorphic or hydrologic settings that are likely to be sensitive to climate change impacts, and consequently where stream habitat is likely to be more significantly impacted (adapted from Paul Bakke's unpublished Climate Change Screening Matrix).

Landform or Geomorphic Setting	Identification, Description	Response to climate change	Implications
Response reach	• High volumes of bedload sediment • High unit stream power > 25 w/m^2 • High channel migration rates • Channel avulsions common	• Period of reduced stability • Increased channel migration • Aggradation • Increased scour • Reoccupation of dormant terraces	• Burial by sediment likely • Channel abandonment due to avulsion • Erosion or flooding of recently inactive terraces
Alluvial fan	• Confluence of tributary with lower gradient mainstem • Fluvial gravel or sandy soil • Active fan: water can access top of bank • Dormant fan: channel incised	• Reactivation of dormant alluvial fans • Channel avulsions	• Channel migration & abandonment due to avulsion • Flooding/erosion of historically dry areas
Debris fan	• Confluence of tributary with lower gradient mainstem • Mixed soil: silt/clay to large boulders • Fan "large" relative to stream channel	• Potential increased rate of debris flows	• Increased or high debris flow risk • Increased channel migration due to avulsion
River delta	• Depositional landform where river enters Puget Sound, the Pacific Ocean, or a major lake	• Inundation by rising sea level • Altered (possibly increased) sediment deposition rate • Upstream migration of deltaic zone	• Increased flooding • Increased channel avulsion rate • Loss of floodplain area • Shift in floodplain boundaries to include new areas
Glacial hydrology, source < 2500 m elev.	• Small, lower-elevation glaciers in headwaters (*cirque* glaciers) • Glaciers without extreme precipitation in accumulation zone	• Complete disappearance of glacial ice	• Reduced summer baseflow • Increased summer temp. • Floods shift from spring to fall, winter
Snowmelt hydrology, source < 2500 m elev.	• Headwaters in transient snow zone	• Shift from season-long to transient snowpack • Degradation, increased scour	• Reduced summer baseflow • Increased summer temp. • Floods shift from spring to fall, winter

Table 5. Geomorphic or hydrologic settings that are likely to be resilient to climate change impacts, and consequently where stream habitat is less likely to be impacted. (adapted from Paul Bakke's unpublished Climate Change Screening Matrix).

Landform or Geomorphic Setting	**Identification, Description**	**Resilient factors**	**Implications**
Transport reach	• Low channel migration rates • Channel avulsions rare • Bank vegetation typically stable	• Channel form and associated habitat •	• Consistent habitat character and availability • May be sensitive to general temperature change • May become sensitive if near threshold conditions for transport of bed materials
High-groundwater river segment	• August baseflow > 2 $ft^3/s/mi^2$ • Low ratio of peak flow to baseflow • Low channel density • Recent basalt volcanic lithology • Glacial drift lithology	• Late summer baseflow volume • Temperatures • Flood hydrology	• Cold water refugia • Low velocity refugia during floods • Sensitive to groundwater withdrawals • Sensitive to impervious surfaces or other reduction in infiltration in recharge zone
Glacial hydrology, source > 2500 m elev. or accumulation zone has extreme precipitation	• Rivers originating on high elev. volcanoes • High elevation glaciers survive climate change • Glaciers with extreme precipitation may survive • May harbor unstable recently-exposed sediment sources	• Late summer baseflow volume • Temperatures • Flood hydrology	• Cold water refugia • Increased debris flow – Lahar mudflow potential • Problems related to increased sediment load (aggradation, channel avulsion, embeddedness, etc.) may increase • Shift in proportion of glacial melt may affect some organisms
Snowmelt hydrology, source > 2500 m elev.	• Headwater streams in North Cascades • Long-term snowpack survives climate change at high elevations	• Temperatures • Flood hydrology	• Cold water refugia • May have some reduction in summer baseflow volume due to smaller snowpack

2. *Mass wasting frequencies will probably increase as climate change proceeds*. Global warming increases the rate of mineral weathering and organic material decomposition, thus speeding up this cycle of erosion. Increasing the intensity of winter storms also speeds up the cycle, by reducing the interval between episodes of saturated soil and increasing the magnitude of the soil water buildup (pore water pressure). The slow movement of deep-seated landslides thus becomes more frequent, as does the incidence of shallow rapid landslides. Increases in the frequency or intensity of wildfires can lead to increased occurrence of times when root strength (and hence, soil strength) is at a minimum, making upslope systems more prone to mass wasting.

While some overlap with previous sections exists, Table 6 provides a table illustrating the myriad potential responses to changes in physical processes brought about by climate change.

Table 6. Outline of effects expected due to specific physical processes documented in the literature (drawn from Bakke[50]).

Physical Process	**Potential physical and biological impacts:**
Change in balance between snow and rain	a. Reduction in long-term snowpack b. Earlier snowpack melt c. Conversion of permanent snow zone to transient snow zone d. Altered flood mechanism & timing (snowmelt to rain-on-snow) -Shift from spring flood maxima to fall-winter flood maxima e. Reduced summer base flows, loss of headwater perennial habitat -Impact dependent on geological structure, soil thickness
Increased storm intensity, including intensity of precipitation	a. Surface erosion increase b. Possible long-term increase in mass-wasting frequency -Era of increased mass wasting as landscape adjusts to new hydrological conditions -Altered long-term pattern of mass wasting dependent on geological structure, specific changes to hydrology and vegetation c. Shifting of moderate landslide hazard areas into high hazard category d. Increased magnitudes and variability of peak flows, even in rain-dominated flood hydrology e. Era of increased sediment load to rivers f. Aggradation, channel morphological adjustments -Influence of geomorphic setting: response reaches affected, conversion of some transport reaches to response reaches g. Translation (longitudinal movement) or expansion of geomorphic process zones including response reaches to different positions on landscape
Changes to total annual precipitation amount and seasonal distribution	a. Moderate increase in winter precipitation b. Moderate decrease in summer precipitation c. Increased average runoff in winter and spring months d. Decreased summer baseflow
Increased flood risk and resultant channel instability	a. Increased flood risk in response to increased peak flow magnitudes b. Increased flood risk in response to aggradation c. Shifts in location of channel migration zone and 100 year floodplain boundaries d. Increased rates of channel migration and associated streambank erosion
Melting of glacier ice	a. Altered summer hydrology, sediment and thermal regime of glacial rivers b. Altered sediment load: period of high sediment loading due to recently exposed or destabilized glacial deposits c. Reduction in summertime suspended sediment load
Increase in average water temperature	a. Shifts in habitat type and shrinkage of useable habitat for cold water species, including loss of mid-elevation habitat b. Disproportionate importance of groundwater-fed systems to cold water obligate species. High groundwater-influence sites include: o Recent volcanic lithology o Wall-based tributaries in glacial terraces o Streams originating in glacial drift lithology c. Lower dissolved oxygen d. Higher surface water salinities in summer and decreased salinities in winter, especially in estuaries and salt marshes e. Altered density stratification patterns in lakes (longer summer stratification period), and Puget Sound (stronger winter-time stratification) f. Increased algal blooms, including toxic (“red tide”) species

Increased evapotranspiration & loss of soil moisture	a. Reduced summer baseflow in rivers b. Reduced groundwater recharge c. Loss of wetland area d. Conversion of perennial to seasonal wetlands
Sea level rise	a. Altered coastal sediment recruitment and transport b. Upstream translation of deltaic areas, depositional/response zones c. Increased tidal prisms resulting in increased energy in estuaries and tidal marshes d. Morphological and substrate changes in beaches and nearshore zones e. Altered coastal upwelling patterns f. Altered patterns of water circulation g. Loss of some beaches, potential formation of new beaches in other areas
Increase in fire frequency, intensity (due to drought, type vegetation conversion)	a. New disturbance regime: disturbance-dominated channel morphology (unstable channel types), in systems where fire interval is less than recovery time b. Sediment load increase due to increased surface erosion and mass wasting, leading to aggradation of river channels
Changes in vegetation cover and species composition brought about by temperature and precipitation change	a. Potential expansion of invasive riparian species b. Altered erosion rates c. Changes to long-term large wood dynamics (input, persistence)
Effects of elevated levels of carbon dioxide on plant physiology, transpiration and water use	a. Altered competitive relationships among plants, leading to altered recovery form floods, fire, human disturbance b. Increased growth rates
Changes to human management of land and natural resources in response to climate change	a. Increased demand for structural streambank protection b. Increased demand for structural shoreline protection c. Increased groundwater withdrawals in response to declining surface water resources d. Increased demand for irrigation water e. Increased demand for surface water storage reservoirs (e.g. dams) f. Increased renewable energy development, impacting new areas on landscape

4 STRATEGIES TO ACCOUNT FOR CLIMATE CHANGE IN HABITAT RESTORATION

No single best approach exists to accounting for climate change in stream habitat restoration. Strategies for addressing climate change are similar in many respects to generalized restoration strategies presented in Chapter 4, though they require the additional acknowledgment that climate will continue to change, even though uncertainty exists around how those changes will express themselves in the stream ecosystem and habitat realm. Strategies for accounting for climate change will require consideration at multiple scales, from planning at regional and watershed scales to reach-scale design considerations. Strategies have been grouped conceptually into three Rs: Resistance, Resilience, and Response[51].

- *Resistance* to change focuses on minimizing the impact of climate change and can require extensive investment of time, money, and resources. Examples of 'resistance' approaches include installation of channel bed grade control where channel incision is anticipated or the installation of streamflow impoundments to capture and manage streamflow. While it may be justified if resources are highly valuable, the risk of loss is great, and need for action is urgent, it should be considered a temporary or interim measure.

- *Resilience* to change implies the capacity to bounce back to a previous condition or value following disturbance or change and is one of the most commonly promoted adaptation strategies.[52] It is commonly assumed that relatively healthy (mature and functional floodplain and riparian systems) and unconstrained systems will be more resilient. Resilience may provide for recovery from projected increases in inter-annual variation, but may not necessarily provide for longer-term shifts in background climate. Dominant resilience strategies include restoration of riparian health and restoration of natural flood retention capacities through re-introduction of beavers.

- *Response* refers to facilitating system response to climate change and provides a longer-term approach. It recognizes that systems as they are may not be able to respond, and instead focuses on maximizing the capacity for response over time. In stream management, recognizing inherent sensitivities to change, providing room for a stream (i.e. full floodplain) and removing constraints to transition, and managing upland watershed land use to reverse or minimize changes that exacerbate those anticipated from climate change are suggested as primary mechanisms for facilitating response.

4.1 Addressing Climate Change Projections in Restoration Project Development

Throughout this appendix on climate change, as well as through Chapter 4, uncertainty is presented as a critical consideration for project planning and development. Uncertainty about climate change impacts is a fundamental consideration in strategic thinking about stream habitat restoration. Uncertainty stems from limitations of data inputs upon which to develop models, model scale constraints (issues with downscaling), and temporal resolution constraints (models use averages, whereas streams are sensitive to finer resolution event durations). And uncertainty about future change implies that historic or reference conditions are likely no longer valid bases for project design. In contrast to traditional restoration design thinking, the past is no longer a guide to the future. Consequently, restoration planning and design in the face of the certainty of change and the uncertainty of the form or degree of that change, can best be accommodated through scenario modeling of probable future outcomes, relying on the best available climate predictions.

> “To the extent that it can be identified, quantified, and mitigated, uncertainty is a component of planning, not a reason to avoid planning. Many sectors report different impacts in different systems (e.g., snowpack response in low vs. high elevations, fire response in the western Cascades vs. Blue Mountains, different salmon populations and different crops etc.), but the natural complexity (variability in geographic space and in time, such as decadal climate variability) of these systems is a key part of planning for the future. Better climate information, better monitoring, and better awareness of complexity are all required to anticipate future impacts and to develop adaptation strategies that are likely to be successful.”

Key strategies presented above include fostering resilience and facilitating response to changing conditions. Providing refuge, and connectivity with that refuge, is a core principle of resiliency. Facilitating response to change requires consideration of potential future scenarios and providing opportunity for response in both time and space. The following sections discuss *resilience* (Section 4.1.1) and *response* (Section 4.1.2) in greater detail.

4.1.1 Resilience

In the physical sciences and engineering, resiliency refers to the ability of a system to quickly and completely return to its original condition after being disturbed. In the ecological literature, resiliency carries the additional meaning of how much disturbance a system can "absorb" without crossing a threshold and entering an entirely different state of equilibrium (e.g. distinctly different physical habitat structure or conditions)**.** In regard to recovery, habitat restoration, and conservation of at-risk aquatic species, resiliency also requires that certain key habitat characteristics or processes will change little, or not at all, in response to climate change. When it comes to aquatic fluvial habitat, the most important elements to remain steady are *temperature* and *disturbance regime*.

Rivers and streams resilient to *temperature* change include those dominated by groundwater input. Important requisite geological conditions include a highly permeable surface layer with a low density of stream channels, and an aquifer with great storage volume but intermediate hydraulic conductivity, such that the stored water does not rapidly drain. These characteristics occur in terrains dominated by extensive recent volcanic processes, such as the high Cascades region, which includes the eastern portion of the Cascade Range in Oregon and Northern California, and extends northward into Washington between the Columbia River and the Mount Adams/Mount Saint Helens area.[53] Unfortunately, other physiographic provinces have not been investigated for these properties within Washington State. However, likely candidates include streams originating entirely within the glacial drift comprising the Puget Sound lowlands and the rim of the Olympic Peninsula. This area is likely to be intermediate in character between the extreme groundwater dominance of high Cascades streams and runoff-dominated streams elsewhere.

A resilient *disturbance regime* would be one in which the peak flow (flood) mechanism and available sediment sources do not become altered. Rivers and streams likely to be resilient to changes in disturbance regime would include those with flow dominated by groundwater. This is because large groundwater aquifers tend to buffer the movement of water, averaging out the extremes in precipitation, and producing a hydrological pattern characterized by fairly constant flows and much smaller differences between peak flows and baseflow than streams dominated by runoff. For runoff-dominated streams, from most to least severe, changes to disturbance regime would occur in:

1. Glacial streams that entirely lose their glacial ice, becoming snowmelt streams or rain-on-snow streams (large portions of the non-volcanic North Cascades);
2. Glacial streams experiencing ice retreat that rejuvenates or exposes large volumes of unstable sediments (streams on major volcanoes, especially Mt Rainier);
3. Snowmelt streams that transition to rain or rain-on-snow hydrology (streams with significant headwater areas currently above the transient snow zone);
4. Rain-dominated streams in landscapes prone to mass wasting;
5. Rain dominated streams in relatively stable landforms; and,
6. Rain-dominated stream reaches downstream from lakes.[54]

Even in rain-dominated streams, potential increases in storm intensity may bring about larger, more frequent floods, but without the changes in timing of flood and baseflow hydrology that will occur in the other three types.

It should be noted that resiliency is temporally dependent. To address this, *the strategy suggested here is to provide multiple interconnected refugia that undergo severe disturbances at differing periods of time*. Given enough time, large disturbances are virtually certain to occur on the landscape and to the climate. Thus, resiliency can only function on a landscape scale - enough individual rivers available with the appropriate habitat and connectivity must exist so that a disturbance to one system allows the others to support the sensitive populations through the recovery and recolonization period. In the long term, no substitute exists for a landscape that offers redundancy of habitat opportunities. Many of the features that make up high-quality salmonid habitat, such as buried organic matter, large gravel deposits, side channels and logjams, for example, are relics of the legacy of past disturbances. The issue is not to shun stream reaches that are more prone to disturbance, but to identify and work with stream reaches that are likely to have a consistent disturbance regime as opposed to ones that will drastically change as the climate continues to change. This will assure that the habitat identified retains its physical morphology and patterns of cyclic evolution rather than shifting to some different, and presumably less stable, habitat type.

Refugia are places in the landscape where organisms can go to escape extreme conditions; usually, this refers to short-term conditions such as floods or high water temperatures. The term refugia also may refer to safe havens when the majority of historic habitat is impacted and stressful. In the context of climate change, *refugia* can also be places where a population may persist through decades and centuries of unfavorable climate conditions and instability.

Some researchers (e.g. Battin et al.[55]) have suggested that headwater reaches of rivers, traditionally considered the best possible refuges due to their colder temperatures, will become less available due to reduction in the summer baseflow as the hydrologic pattern changes from snowmelt- to rain-dominated. This would appear to push the emphasis on identification of refugia and restoration efforts to lower elevation reaches where summertime hydrology is expected to be less affected.

However, for coldwater obligate fish species, refugia will continue to be areas where groundwater emergence influences water temperature and volume. *Connectivity of these watersheds to other refugia and to the downstream migration corridors will be crucial for them to adequately serve as refugia*. These refugia will exist on several scales: local areas of cool water emergence within a reach otherwise insufficiently cool, and entire streams or reaches where groundwater hydrology is dominant. Local zones of groundwater emergence include springs in settings where springs occur adjacent to streams. Two of the most important settings have already been mentioned, namely, streams running through Pleistocene glacial deposits in the Puget Sound lowlands and rim of the Olympic Peninsula, and the recent volcanic terranes of the Southern Cascades. In addition, watersheds with considerable percentages of high elevation sites that retain their permanent snowpack in the face of global climate change will continue to serve as important refugia. Some watersheds of the North Cascades, streams draining the large glaciers on Mount Rainier and other highest peaks, and high elevation parts of the Interior Columbia Basin (see Martin and Glick[56], Rieman and Isaak[57]), are expected to retain late-season cold water flow.

Rivers that have floodplains will also have emergence zones for subsurface water, which form cool water refugia. This will include hyporheic water, or mixtures of hyporheic and groundwater that may be flowing through subsurface pathways such as relic, buried channels.[58,59,60] Hyporheic water flows through the shallow sediments beneath or near a river channel and exchanges with the streamflow. Tributaries flowing across the floodplain may go partially or entirely subsurface, emerging as cooler water in the side or bottom of the main channel. Alluvial fans associated with tributaries are generally places where surface water is lost into the ground, emerging down gradient where the main channel abuts against the alluvial fan. The degree of cooling depends on the amount of time the water spends flowing through the subsurface, and the degree to which it mixes with cold groundwater. Finally, some geomorphic settings produce upwelling of cool subsurface water, which may be a mixture of hyporheic and groundwater. For example, if the river enters a valley that initially widens, and then constricts in the downstream direction, the constriction zone will be a zone of upwelling. Water that entered the subsurface in the upper portions of the valley, which has been flowing as hyporheic water and mixing with groundwater, must reemerge as the cross-section of shallow alluvial deposits constricts.[61] Thus, the same set of circumstances producing cool water conditions in the current landscape may to varying degrees produce thermal refugia against global warming. *Maintaining connectivity amongst these refugia will be a critical element of refugia strategies.*

4.1.2 Response

In planning restoration actions, facilitating system response to climate change provides a more defensible, longer-term approach than near-term strategies associated with either resistance or resilience. Facilitating response to climate change includes establishing conditions that allow for the greatest range of likely future conditions and fewest constraints to probable channel evolution. Assessing the potential to facilitate system response requires the following considerations:

1. *Sensitivity*: The inherent sensitivity of certain stream types to change is a critical consideration. Sensitive streams or reaches may be impractical for active restoration, since the pace and magnitude of physical changes they will undergo may overwhelm human manipulations, even those designed to be redundant in terms of robustness and spatial extent. However, passive restoration, such as buffering to give the stream room to respond, may be effective. Inherently sensitive stream types or reach types include: response reaches, alluvial fans, transitional hydrologic regimes, and systems that are at or near threshold temperatures for coldwater species of concern (for further discussion of sensitive reach types, refer to Table 4).

2. *Uncertainty*. Uncertainty is an unavoidable consideration for stream restoration, and is exacerbated by future climate change. While uncertainty should not constrain efforts to restore systems or facilitate response, the extent of uncertainty should be considered by estimating the degree of variation among projected change and future scenarios. For any given system, comparison of multiple future scenarios will allow for a sensitivity analysis of uncertainty, and those with greater uncertainty may not be good candidates for project development. Ideally, projects will adopt techniques and designs that accommodate multiple future scenarios - the more those scenarios diverge, the harder this is to accomplish.

3. *Projected change*. Climate change modeling, and subsequent modeling of the implications of climate change on fundamental stream processes and drivers, may indicate considerable variation in the extent of future change. Where projected change is significant, it becomes challenging if not impossible to design for both near-term and projected future. While adaptive management strategies may provide a means to accommodate change, generally, such strategies may be unable to accommodate dramatic change.

4.1.3 Project development and design considerations

Restoration of stream habitat in the face of future climate change will benefit from the following design considerations and principles.[62]

1. *Design for future condition*. Accounting for climate change in planning and designing a restoration project generally requires that designs accommodate the range of projected future conditions, rather than historic or past conditions. Projections for 10 years and 50 years into the future will provide both near-term and

long-term perspectives. Much of the available modeling research from CIG, however, projects changes for the 2020s and 2040s decades; where robust climate modeling already provides projections at relevant geographic scales on timescales of one to many decades, these should be used for convenience and defensibility. In particular, the fundamental inputs to design of hydrologic and sediment variables should be based on the range of future projections, rather than solely on empirical, past data and observations. This necessarily requires multiple-scenario modeling, which is susceptible to the quality of inputs and assumptions. Planning a restoration project that is able to successfully adapt to hydrologic, sediment, and environmental impacts of climate change may require the abandonment of routine design approaches and assumptions. Analog design approaches that rely on reference reaches (refer to Chapter 5 Design Approach), in particular, may be inappropriate as references selected will likely reflect past hydrologic, sediment, and vegetation regimes rather than future and uncertain regimes. Similarly, planting a wider variety of native riparian plant species will improve the chance that some species present will respond favorably to climate change impacts.

2. *Minimize constraints imposed on physical or ecological processes*. Many traditional approaches to stream habitat restoration rely heavily on the semi-permanence of channel form or installed structures. However, these often pose constraints on stream processes. Restoration designs should maximize the number of degrees of freedom (channel form variables) kept open to the river so that the fluvial system can accommodate climate-induced changes through mutual adjustment of multiple channel-form parameters. In particular, because more sensitive stream types (Table 4) are more likely to exhibit significant or dramatic change, these stream types warrant greater emphasis on minimizing constraints and often expensive structures that are likely to have only short functional lives.

3. *Give the stream and floodplain room*. Additional stream corridor space provided to allow for anticipated or unexpected morphological adjustments may lower the risk of adverse impacts. Stream habitat restoration projects will provide greater opportunity for response to climate change if they are given greater floodplain capacity to accommodate larger floods, allow avulsions. Table 4 provides a listing of stream types that are more likely to exhibit significant responses and change in the face of climate change. These stream types in particular warrant planning and design that emphasizes adequate stream corridor and minimization of project elements that constrain stream change.

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- The CIG report presents a summary and detailed methods for assessing projected impacts resulting from climate change to a variety of industries and interests specific to Washington State.

EPA, State and Local Climate and Energy Program. A variety of information, webcasts, and podcasts available: http://www.epa.gov/statelocalclimate/web-podcasts/index.html

- This website provides a range of technical information about climate change, presented as webcasts and podcasts, and developed expressly to educate local governments as they explore the implications of climate change.

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- PAWGS are established by the Governor and formed to examine the impacts of climate change and recommend to the Director of Ecology specific steps to prepare for its impacts and policy recommendations.

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APPENDIX B

FLUVIAL GEOMORPHOLOGY

Fluvial Geomorphology Appendix

1 GEOMORPHOLOGY: WHY DO WE NEED IT?

Geomorphology means, literally, the study of the form or shape of the earth. More specifically, it is the science of the shape of the earth's surface, the processes that mold this surface, and consequently, how the surface will change its shape or evolve over time. *Fluvial geomorphology* is the study of how rivers form and evolve, and how they interact with adjacent landforms. Rivers, of course, are distinguished by movement of water. But rivers are equally important as pathways for the movement and storage of sediment and of organic material, especially large wood. Alteration or disruption of any of these material flows (water, sediment and large wood) will, sooner or later, alter the river channel and its rate and trajectory of change. The task of the applied fluvial geomorphologist is to recognize when such disruption will occur, and to estimate the magnitude, direction, and timescale for alteration of the river's form (i.e. its morphology). This, in turn, demands understanding of certain geomorphic processes, namely, the erosion transport and deposition of fine and coarse sediment, the mass wasting of hillslopes and streambanks, and the recruitment, retention and transport of large wood. Ultimately, the fundamental goal is to determine whether a channel is "stable" or "unstable" (to be defined below), and if the latter, to determine the causes and degrees of instability, both under current conditions and under any newly-proposed human management or tinkering with the river morphology.

Note that in geomorphology, "stable" has a different meaning than in common usage. This is because geomorphologists are trained to consider processes that occur over long timescales. On long timescales, river channels migrate across the landscape, which requires that streambanks often erode. Landslides occur. Floods deposit fine sediment across the floodplain, which gradually fills in valleys, and becomes the raw material of new soils. Logjams form or break up and the river channel moves in response. All of these things happen in a "stable" river. The river is *unstable* if these processes are happening faster than they historically have, forcing the river to evolve rapidly into a new and perhaps unprecedented morphology. Fluvial geomorphology is about learning the natural or expected rates, styles, and trajectory of change, and is about understanding what timescales best describe the processes at work, and which processes are relevant to a given management problem.

To the non-geomorphologist, and particularly to the non-scientist, the need for a geomorphic analysis, or even a geomorphic perspective, is often unclear. What knowledge does the fluvial geomorphologist bring to bear in the discussion of river management, and why do we need this knowledge? Here, in a nutshell, is the role of the geomorphologist:

· *Quantification and/or description of historical or equilibrium conditions and processes.* This is different than just establishing current or "baseline" conditions. It is a thorough look at what processes were active in the past and what were their approximate magnitudes. It is also a look upstream and downstream, to see how the site of interest fits in with the rest of the watershed, as a physical system. For example, what were the streambank erosion rates, and channel migration rates, historically? If these rates are high, are they high everywhere, or only here, locally? The geomorphologist can help establish the proper spatial scale and proper time period over which to focus this sort of evaluation, and advise on which types of stream channels in which valley settings are expected to have low, medium, or high channel migration rates. Simply attempting to control streambank erosion in the absence of this perspective could lead to a futile effort, or one with disproportionate cost or impact to downstream resources.

· *Recognition and quantification of departure from historical or equilibrium conditions and processes.* This is particularly important if the processes at work shaping the stream channel have changed. For example, urbanization leads to profound differences in hydrologic patterns and sediment load, meaning that historically stable channel morphologies may no longer be relevant. Or, if addition of large wood is desirable for habitat enhancement, and large wood was historically present, are the processes which recruit and retain large wood still intact?

· *Understanding the causes of departure from historical conditions.* Such departure may or may not indicate geomorphic instability. If it does indicate instability, it is important to know whether this is due to local causes, acting at the site scale, or due to changes to processes acting on the entire reach, or the entire watershed. For example, accelerated streambank erosion can be caused by poor management of local riparian vegetation, or, it can be due to reach-scale channel incision (downcutting). Each case suggests different management approaches.

· *Evaluation of potential response to management alternatives.* Geomorphologists, through knowledge of river processes, can help predict the probable response (trajectory) of the river system to management actions (including no-action scenarios) at multiple timescales, provided they are armed with the proper geomorphic analyses. For example, will the river bury a new in-stream structure in gravel? Will the logs meant to enhance habitat be left suspended above the water surface as the channel downcuts? How far will the streambank of an unstable reach erode before it slows or stops naturally? Will a log structure function only to create local habitat, or will it have a geomorphic function, acting to retain other logs and affect channel migration or side channel development?

Now that the need for fluvial geomorphology has been established, the remainder of this chapter will be devoted to an introduction to the science, followed by discussion of how a geomorphic analysis is conducted. Finally, there will be recommendations for further reading. Throughout this chapter there will be periodic reminders of the rationale for considering geomorphic information and for conducting geomorphic analysis.

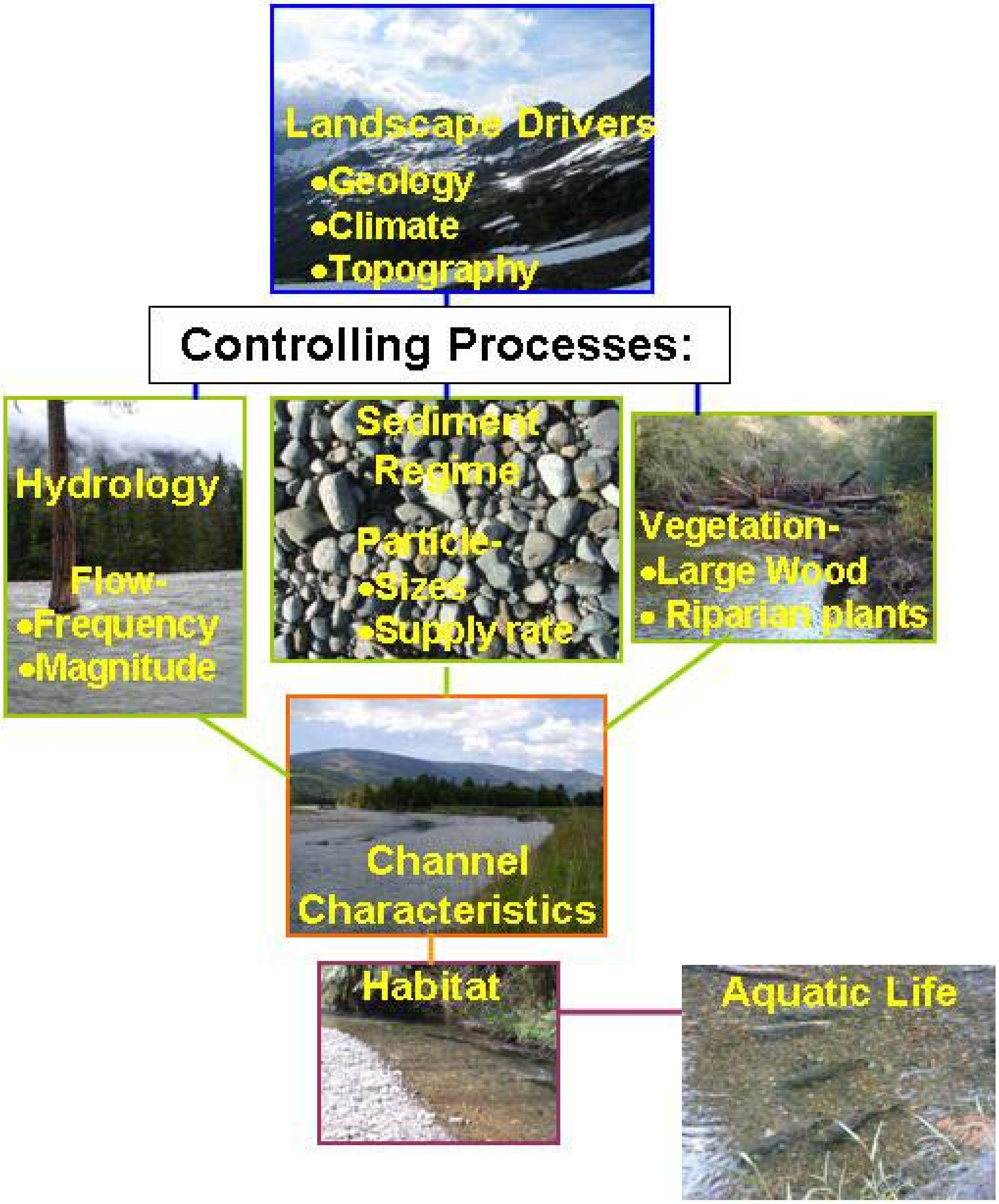
2 THE RIVER AS A GEOMORPHIC SYSTEM

In its broad-brush characteristics, the geomorphic description of the Earth's surface is very simple (Leopold et al., 1964). Volcanism and tectonic forces create uplift. The rocks brought to the surface by these processes were formed at very different temperatures and pressures than they encounter at the surface, and so are no longer in chemical equilibrium with their environment, and begin to decompose. Meanwhile, these mountains and highlands intercept moisture from the atmospheric circulation, creating runoff from rain and melting snow and ice. This runoff, in conjunction with the gravitational forces acting on steep slopes, erodes the sediment produced by weathering of rocks, carving a river network. In parts of that network, particularly its lower reaches, sediments are deposited, entering long-term storage as valley fill (to be exchanged during subsequent events), or short-term storage within the stream channel.

Eventually, this sediment, broken down into finer and finer particles, enters and is deposited on floodplains, and estuaries and deltas on the ocean margins.

Thus, broadly, the geomorphic system which comprises the landscape is driven by its geological characteristics (tectonic setting, rock types, etc.) and its climate, both of which may encompass multiple watersheds and time frames of thousands of years or more (seeFigure 1). These *landscape drivers* in turn determine the principal triad of controlling watershed-scale processes that affect stream channels, namely, hydrology, sediment supply, and vegetation. It is through acting on these three processes that humans alter the river system, and in many cases, have become as significant an influence as geology and climate. It is also through the predictable variation in the way sediment sources, sediment transport processes, runoff volumes and patterns, and interactions with vegetation change spatially within the watershed that we encounter a predictable series of channel types and valley settings along the way.

Figure 1. Hierarchy of factors controlling the river as a geomorphic system. Landscape drivers, comprised of climate, geologic setting, give rise to river processes of hydrology, sediment regime, and interactions with riparian vegetation, most notably, recruitment and transport of large wood. These controlling processes, in turn, create the channel characteristics, which gives rise to habitat for aquatic life.



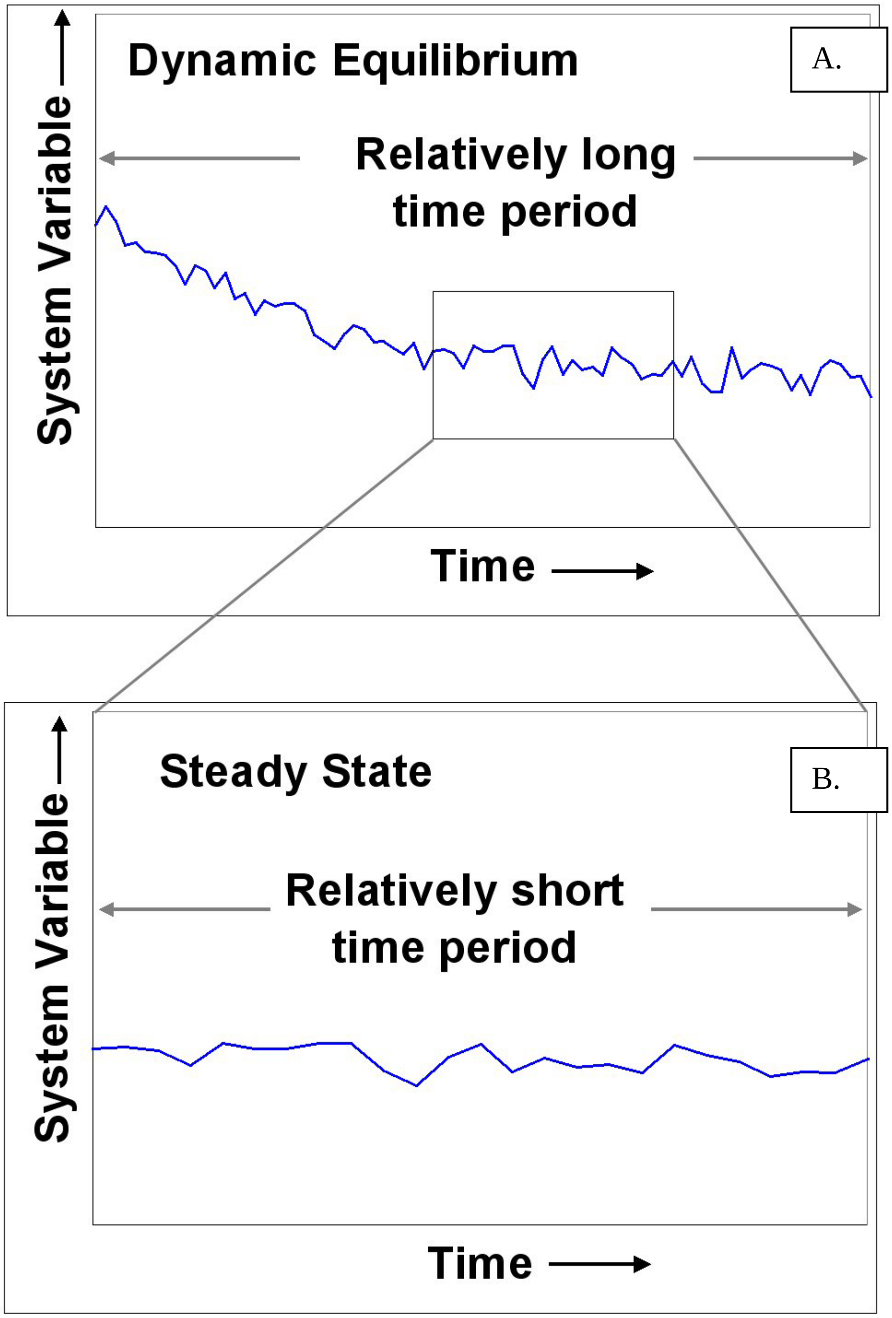
Habitat is an outcome of geomorphic processes, and can only be sustained or restored by allowing or fostering these processes – either by removing constraints on process or by restoration of variables that influence the processes.

Although punctuated by disturbances (to be defined later), we tend to think of the average hydrology, sediment supply and natural vegetation as being relatively constant, at least on the scale of the human lifetime. Thus, it is possible to understand stream channel morphology (width, depth, slope, planform pattern) and stream channel behavior in terms of an approximate state of *equilibrium*, in which the input and output of sediment, organic material, and hydraulic energy are in balance. This equilibrium is not exact, of course, because variations in water discharge and sediment input occur on short time scales, over seasons, days, and even hours. However, it is useful to conceive that this "quasi-equilibrium," as it is sometimes called[1], implies an characteristic channel morphology in response to an annual average sediment supply and input of hydraulic energy. This channel morphology accommodates inputs that fluctuate about some average value. Note that an characteristic channel morphology does not imply that the channel is static, or that it never changes its location, but merely that changes in form oscillate about some average value, and changes in location occur while maintaining the same average form. *The destabilization of streams typically occurs when the balance between sediment input and sediment output from a reach becomes altered, eliminating the equilibrium, and triggering rapid channel adjustments.*

Existence of equilibrium is dependent upon the time scale under which equilibrium is scrutinized. If the time scale is too short, the mean value of the variable in flux will not be accurately determined. On the other hand, the same channel process may be defined as differing forms of equilibrium, or even as non-equilibrium, simply by virtue of differing periods of observation. The equilibrium concept we have just discussed is referred to by some geomorphologists as *steady state* (see Figure 2). Steady state, which in the case of Figure 2B means an average annual sediment yield, may exist on the time scale of 10 to 100 years or so. Over longer time spans, say, 100 to 1,000 years, the same river may display a pattern such as that shown in Figure 2A, which is called *dynamic equilibrium*. Note that numerous shorter periods of approximate steady-state equilibrium exist within this dynamic equilibrium. The dynamic equilibrium might apply, for example, to the long period of time following a stand replacement fire, or the period following an infrequent severe storm that triggered numerous landslides, or the period of adjustment in channel longitudinal profile after building a reservoir, or even to the first few thousand years after the Pleistocene glaciers melted, exposing massive amounts of unstable sediments.

It is important to distinguish between disequilibrium, altered equilibrium, and disturbances. *Disequilibrium* describes a case where the stream channel has changed its form, such that it is no longer able to achieve the balance between input and output of material and energy, even though the average hydrologic patterns and sediment input may not have changed significantly. The stream channel becomes unstable (that is, undergoes rapid changes in form or location) because much material needs to be moved and rearranged in order to reestablish an equilibrium channel form. Disequilibrium is often a response to anthropogenic modifications of the stream channel, its floodplain, or the riparian zone. Straightening a stream channel would be a typical example. When the stream channel is straightened, its length is shortened, which increases the channel slope. A steeper slope means greater hydraulic force on the streambed, which typically results in erosion, disturbing the balance between sediment input and output from the reach. Removal of large wood from the channel has also been a common source of disequilibrium, and can have significant impacts on channel processes and habitat. Large wood is important for dissipating hydraulic energy, so its removal can lead to streambed erosion, reduction in the amount or complexity of in stream gravel bars, or even conversion of a gravel bedded channel to a bedrock channel. Recovery to pre-removal large wood conditions is exceedingly slow, especially if the riparian forest has been removed or converted to an earlier seral stage by forest harvest.

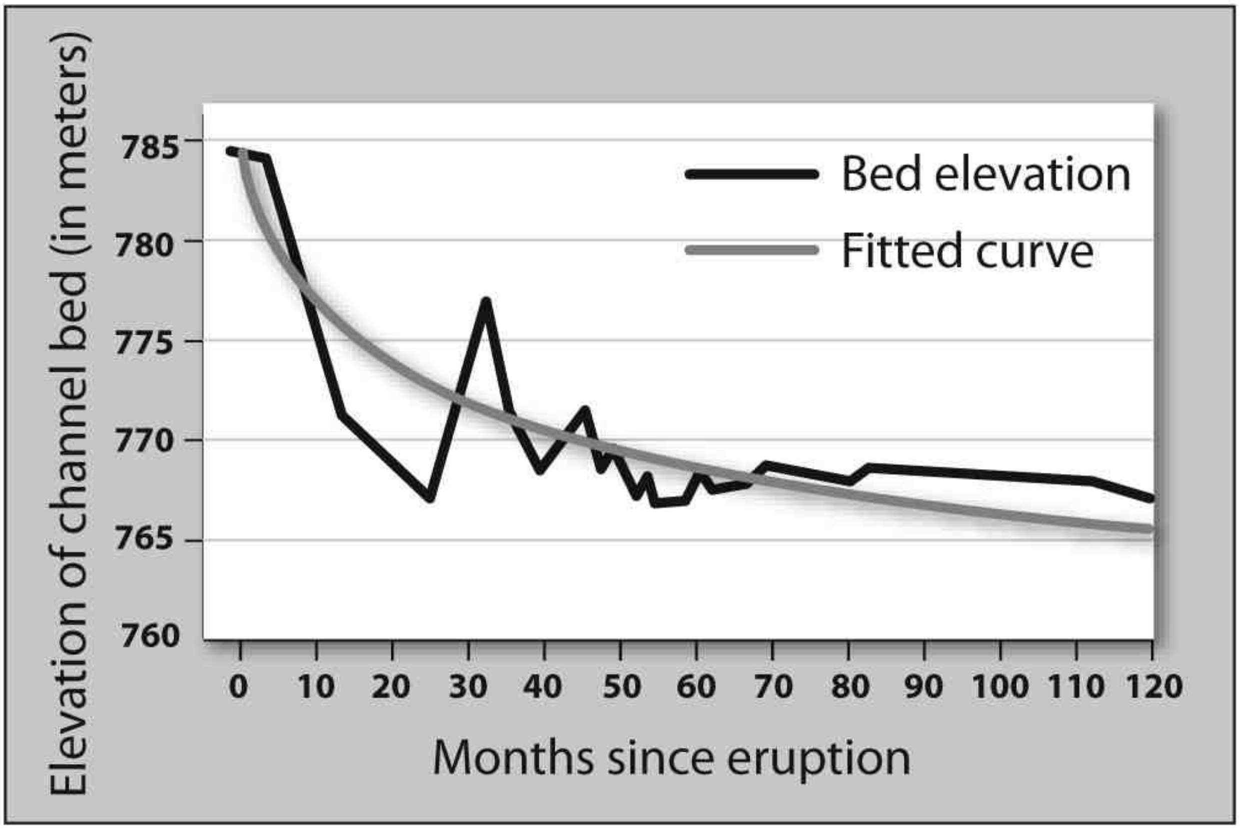
Figure 2. Concepts of A) dynamic equilibrium and B) steady state. System variable could be any number of things, such as sediment yield, streambed elevation, or channel width.



Altered equilibrium refers to the case where inputs of sediment and/or energy have changed, such that the pre-existing channel morphology is no longer appropriate to the new sediment and hydrologic regime. Inputs and outputs are no longer equal. Like disequilibrium, this condition can also be the result of anthropogenic modification, but on a larger scale, and will also destabilize a stream. For example, building a flood control dam drastically alters the sediment input, as well as the temporal pattern of hydraulic energy dissipation. Short, intense peak discharges are replaced by longer periods of intermediate discharge. Starvation of sediment input due to cutting off of upstream reaches will cause streambed erosion, because input and output of sediment are no longer in balance. Longer periods of intermediate discharge will alter the streambed sediment size distribution in reaches where sediment supplies exist. The stream channel is destabilized as it rearranges its morphology to come into balance with the new, altered, pattern of sediment input and hydraulic energy. The most common and drastic human influences are related to urbanization, and include severe changes to the hydrologic patterns and sediment input. Imposing constraints on the channel, such as levees, revetments or culverts, will also change the equilibrium by altering the distribution of hydraulic energy and the stream's ability to transport and store, or exchange, its sediment and large wood.

Disturbances are perturbations to an existing equilibrium, which go beyond the kind of short-term fluctuations that the channel can accommodate without significant change in morphology. A rare, large flood, for example, might cause downcutting of the streambed and bank erosion in some reaches, sediment deposition in other locations, or abandonment of one channel in favor of another. Immediately after such a flood, the channel will not appear to be exhibiting equilibrium conditions. However, in subsequent years, the bed and banks may recover to previous channel dimensions. The length of this recovery period depends on the scale of the disturbance and the amount of material that needs to be moved in order to reestablish an equilibrium condition, in relation to the energy available in the stream to move that material. The rate of recovery is generally more rapid at first, slowing asymptotically as equilibrium is approached (see Figure 3). Depending on the sediment and hydrologic regime, this could be a few years, a decade, or a century.

Figure 3. Toutle River channel response to a disturbance consisting of the impulse of massive sediment deposition as a result of the eruption of Mount St. Helens, May 1980 (Adapted from Skidmore et al.[2] after Simon[3]). Graph shows only response following impulse, does not show pre-disturbance bed elevation.



Habitat form and function is also significantly influenced by and dependent upon disturbance to the channel system. Major disturbances are important for input of certain habitat elements, most notably coarse sediment and large wood. A disturbance can also "reset the clock", that is, bring parts of the stream channel back to an earlier stage in their evolution towards steady-state equilibrium. For example, a flood which scours gravel bars can remove encroaching herbaceous or small woody vegetation, and clean gravel deposits from infilling by fine sediment. Landslides can create deposits of large wood which become important structural elements and nutrient sources as the stream cuts into them. The superposition of short-term variability in inputs (such as seasonal variations in hydrology) and longer-term disturbance regimes (e.g. patterns of major disturbances, such as landslides and fire), which are characterized by even greater variability in magnitude and timing of inputs, results in unique suites of geomorphic processes that dictate physical habitat structure, dynamics and evolution. Disturbance is most important to geomorphic form and process when this recovery time is greater than the time between significant disturbances, leading to unique channel morphologies in which steady-state equilibrium never actually exists.

3 COLLUVIAL AND ALLUVIAL CHANNELS

Within a watershed, a predictable series of channel types and valley settings are encountered in moving from the small, numerous, steep, headwater channels, to the larger, gentler gradient channels at the lower end of the network. These channel types reflect the way sediment sources, sediment transport, hydrologic patterns and the function of large wood change in a downstream direction. A detailed discussion of channel types will be given later. However, a more fundamental distinction is between *colluvial* and *alluvial* channels, and the implications of this to channel-forming processes. Figure 4 summarizes this distinction.

Figure 4. Comparison of attributes of alluvial and colluvial channels

Attribute:	Alluvial Channel	Colluvial Channel
Streambed	Mobile	Mostly immobile
Banks	Alluvium	Colluvium
Floodplain	Yes	None, or only small rudiments
Equilibrium	Sediment Deposition≈Erosion	Resistance to erosion≈Hydraulic force
Sediment storage	Large amounts in bars, floodplain	Small amounts behind obstructions
Sediment load	Moderate to high	Relatively low
Hillslope linkages	Usu. low (isolated by floodplain)	High
Hydraulic energy	Low	High

Basically, a *colluvial channel*[A] is one in which the channel boundaries (streambanks, and most of the material comprising the streambed) consists of colluvium, that is, of material derived from the local hillslope. Colluvial channels create their morphology through erosional processes acting on material made available by hillslope processes such as soil creep (the gradual, downslope slumping of a soil mass), mass wasting (landslides and debris flows) and weathering of bedrock. As such, their morphology and the characteristics of the material comprising their banks and streambed are largely inherited from the properties of the materials making up the valley walls. Another way of stating it is that these channels are strongly linked to what happens on the valley hillsides.[4] The channel size and shape represents a balance between the available hydraulic energy and the resistance of the bed and banks to erosion.

By contrast, an *alluvial channel* has channel boundaries consisting of alluvium, which is material transported and deposited by moving water. An alluvial channel can be said to be "self-constructed," and its characteristics are determined by the processes of fluvial (flow-mediated) erosion, transport, and deposition of sediment. In building themselves, alluvial channels also build their own floodplain. Though the way an alluvial channel builds itself depends on its valley setting, hillslope processes occurring on the valley walls have much smaller relative influence on the form of an alluvial channel. Essentially, the floodplain and other alluvial valley fill work to insulate or de-couple the channel from the valley walls. Channel form and size represents a balance between erosion and deposition of alluvial sediment.

Sometimes the terms *supply limited* and *transport limited* are used to describe colluvial and alluvial channels, respectively. Supply limited, in this sense, means that the amount of sediment transported is small relative to the amount of hydraulic energy available to transport sediment. That is, more sediment would be transported were it accessible. Transport limited implies that most of the hydraulic energy available to transport sediment is being used to do so. These terms must be used cautiously, however, as they are often interpreted too broadly. One misconception is that if the sediment load of a "transport limited" stream is increased, the channel will no longer be able to transport the sediment. In fact, many channels can adjust their boundaries according to sediment load, within reasonable limits, and there is really not a practical upper concentration limit for sediment transported in suspension. For instance, an alluvial channel can develop a finer textured streambed, and thereby increase its sediment transport rate. Another misconception is that the sediment transport rate in a "supply limited" stream is only dependent on the amount of easily accessible sediment, and not on flow hydraulics. However, even in colluvial, "supply limited" channels, a good correlation exists between hydraulic shear stress and sediment transport rate. The amount of sediment transported in colluvial and alluvial streams reflects a balance of the physical forces acting on individual particles, which responds to hydraulic conditions. In many cases, it is more appropriate to use the terms "sediment poor" and "sediment rich," referring to the relative amount of alluvial sediment present in transport and in the streambed, instead of supply or transport limited, respectively.

[A] The concept of "colluvial channel" presented here is broader than the "colluvial" channel type in the Montgomery and Buffington classification system (discussed later), which refers only to headwater channels that are too small to transport their sediment input.

The alluvial/colluvial channel distinction is very important when addressing restoration or management questions, including, for example:

- What degree of response do we expect in this channel to sedimentation impacts? Alluvial channels are much more sensitive to shifts in the balance between sediment input and sediment output, and will adjust their morphology in response to altered equilibrium. Colluvial channels, by contrast, tend to readily transport additional material (up to a certain point) without altering their form, since their form represents a balance between hydraulic energy and resistance of the streambed and banks to erosion rather than a balance between erosion and deposition.
- Can spawning gravel be augmented in this channel? Colluvial channels tend not to accumulate extensive in-stream deposits of gravel.
- How likely is this channel to be destabilized? Colluvial channels naturally have lower streambank erosion rates than alluvial channels, and are thus more difficult to destabilize. However, colluvial channels can be destabilized by altered hillslope processes, such as increased landslide rates, which may overwhelm their ability to erode and transport sediment. Any channel strongly coupled to the valley sides may not be able to move some of the sediment that originates from hillslope processes other than with flowing water.
- Does this channel have an active or extensive hyporheic zone? Subsurface water in colluvial channels tends to be groundwater rather than hyporheic water, which by definition is water flowing in the subsurface which originated as, and exchanges with, the stream surface water. Alluvial channels tend to have more extensive, permeable alluvial deposits bounding the channel, including floodplain deposits that facilitate hyporheic flow in lateral directions and longitudinal flow beneath the channel itself.
- Should I rely on bankfull hydraulic geometry relationships when designing restoration for this channel? The “tops of bank” present in colluvial channels are often debris flow terrace deposits, not true floodplains. The hydraulic geometry concept (to be discussed later), and most of the work on hydraulic geometry equations is theoretically meant for, and best applicable to, equilibrium, self-formed alluvial channels.
- Do I need to develop predictions of sediment load for this channel? Alluvial channels tend to be more sensitive to changes in the balance between input and output of sediment. Thus, it is often important to determine the sediment load. In colluvial channels, by contrast, it is often enough to know which particle sizes will move, and to make sure that the streambed will not be destabilized by increased frequency of movement of its dominant particle sizes.

4 GEOMORPHIC EFFECTIVENESS: HOW RIVERS PERFORM THEIR WORK

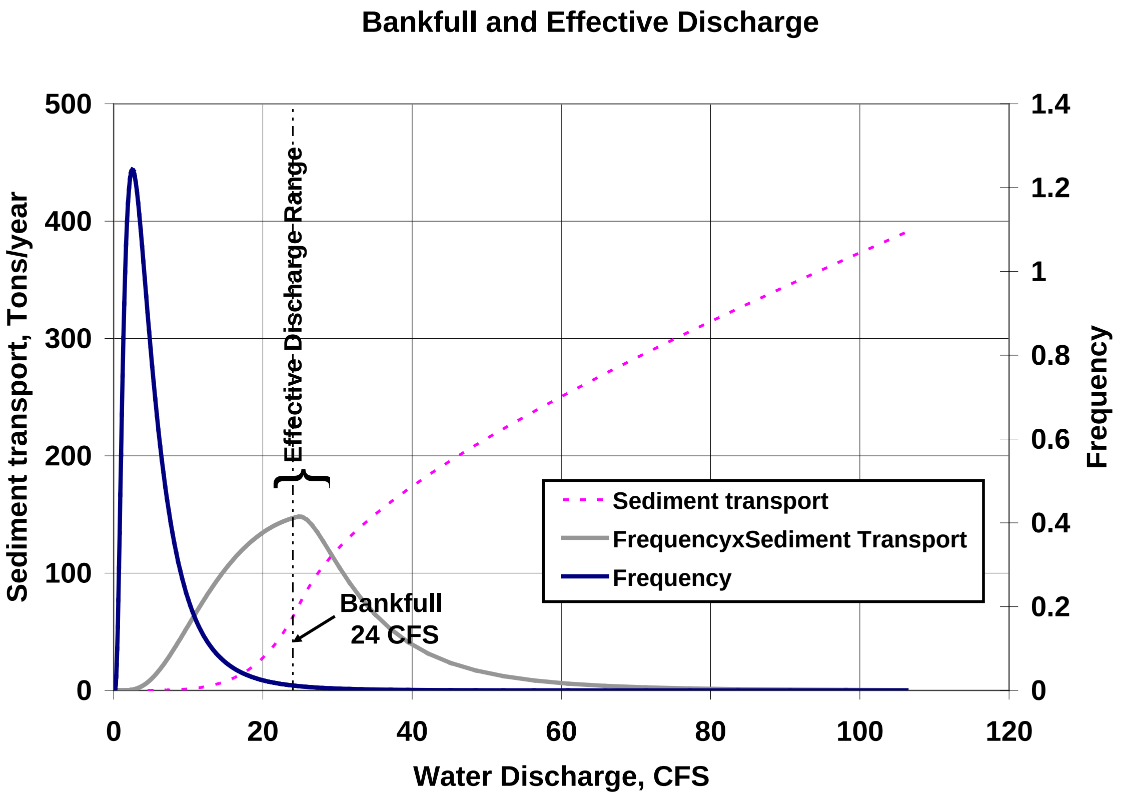
We have already used the term "channel forming processes." As applied to alluvial channels, the channel is largely formed by mobilization, transport and deposition of fluvial sediment, as moderated by living and dead vegetation (e.g. large wood). Moving sediment takes energy, and this energy comes from flowing water. Rivers can be thought of as agents that continually rework the Earth's surface and it is through dissipating the energy of flowing water that rivers perform this work. But the discharge of flowing water, and the sediment transported by this water, varies continuously over time. Intuitively, one might expect that large floods do most of the work of sculpting the river channel. However, such is not the case, because these large floods occupy such a short amount of time relative to more moderate floods that also move sediment.

Figure 5 shows why this is true. On this figure is a line showing the frequency distribution of water discharge, along with another line representing the sediment transport rate at each discharge. Frequency of occurrence can be thought of as the proportion of time that a given discharge occurs, over a long-term average. Note that the frequency distribution is very skewed. Most of the time, the discharge is fairly small, too small to move much, if any, sediment. Conversely, the frequency of occurrence of very large discharges is quite small. Note also that the sediment transport curve contains an inflection point, which occurs at "bankfull discharge" (to be defined later), meaning that sediment transport rates increase less rapidly with increasing discharge once the flow begins to spill out over the floodplain. If the frequency of occurrence is multiplied by the sediment transport rate, one obtains the third line on this diagram, which essentially represents the effectiveness of each incremental discharge in moving sediment. What this effectiveness curve tells us is that the river does most of its work not during large floods, but during moderate floods, centered around the peak of the curve, which also tends to approximate the point where the river begins to spill out onto its floodplain.

The peak of the effectiveness curve is called the *effective discharge*. It represents the range of flows over which the river does most of its geomorphic work. Effective discharge is a useful *index discharge* for analysis of management actions and design of projects which modify the channel morphology. Any action which changes the effective discharge is bound to be expressed by changes in the channel boundaries. Likewise, any action which affects sediment transport at the effective discharge is likely to affect the balance between sediment input and output, thus affecting the equilibrium shape of the channel.

The idea that "process" implies "form" in geomorphology seems to be self-evident, as long as we can properly identify the dominant processes, and as long as those processes act in predictable ways. These are much easier assumptions to make if the river system is in quasi-equilibrium, as was discussed earlier. The reverse of this statement, that "form" implies "process," is not as easy to defend, since it is possible for similar morphology to be produced by differing suites of processes. One place where this equivalence of form and process is commonly used is the concept of a *channel forming discharge*, sometimes called the d*ominant discharge*. Dominant discharge implies that there exists one single, steady discharge which would produce the same cross-sectional morphology, planform geometry and longitudinal profile as those generated by the actual patterns of flow.[5] Since water discharge, and thus sediment transport, in a real stream varies continuously over time, it is impossible to actually measure this dominant discharge. But, it is often assumed in practice that the effective discharge is equivalent to dominant discharge.[6]

Figure 5. Development of the effective discharge relationship from the frequency distribution of discharges and the sediment transport equation.



The concept of a dominant discharge, though still common in applied literature, actually predates the effective discharge concept, and ties back to early applied research on stability of unlined irrigation canals, which did have essentially constant flow of water. When these canals were in equilibrium with their flow of water and sediment, they were said to be “in regime,” and a set of equations and graphical relationships was developed (called “regime equations”) relating channel shape to discharge, sediment load, and bank resistance.[B] Regime theory and its associated equations have largely been supplanted by the literature on regional hydraulic geometry which will be discussed below.

Other forms of index discharge appear in the scientific literature. The most common is the index peak flow, such as the 100-year return period flood, 2-year return period flood or the 1.5 year return period flood. None of these has any geomorphic significance *per se*. That is, no such thing exists as a “surface” corresponding to the 100-year “floodplain.” It is possible to find an average recurrence-interval flood that corresponds to certain geomorphic indices, such as bankfull discharge (see below), but there is no theoretical reason for this correspondence to exist other than that, on the average, each channel is sized to fit some “moderate” flood. The variability about the mean for these geomorphic surrogates is often high, and is dependent on

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[B] The term "regime,” however, in addition to equilibrium, has another meaning in geomorphology, as it is used to describe the average temporal pattern of water or sediment discharge in a river, taken in its entirety. Thus, one can refer to the "sediment regime" or the “hydrologic regime.”

watershed characteristics and climate. Note that in the probability distribution of annual maximum floods, the "2-year return period flood" represents the median value (see *Hydrology* Appendix). Thus, the range from the minimum flood to the 2-year flood is large, spanning half of the distribution!

Finally, the term *ordinary high water* (OHW) is often used in regulatory literature, and sometimes in design. OHW refers to the elevation "where the presence and action of waters are so common and usual, and so long continued in all ordinary years, as to mark upon the soil a character distinct from that of the abutting upland, in respect to vegetation…" (WAC 173-22-030[7]). There is no geomorphic significance to ordinary high water, as it appears to depend as much on soil type and dry-season water availability as it does on the hydrological or sediment regime of the river.

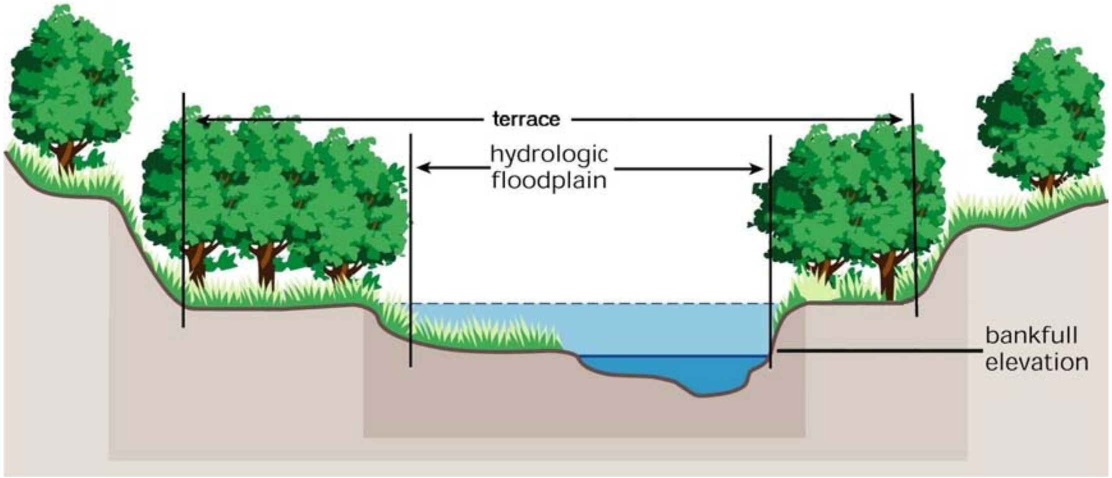
4.1 The Equilibrium Alluvial Channel Concept

It has been said that "rivers construct their own edifice." That is, the shape of the channel (planform, cross-sectional shape, and profile) is sculpted by the river as it erodes and deposits sediment according to the laws of physics. The end result is a quasi-equilibrium channel, having just the right morphology to move the sediment and water carried by the river. One consistent characteristic of a self-formed alluvial channel is the presence of a floodplain. A *floodplain* is a relatively flat, depositional surface adjacent to the channel, formed by the river under its present climate and sediment load, and overflowed during moderate peak flow events.[8]

This definition contains several key points. First, the floodplain is a *depositional* surface, formed by the river, not an erosional surface or a surface formed by other non-fluvial processes that can deposit sediments. The floodplain is thus made of alluvial sediments, not colluvial deposits. Secondly, the floodplain is formed under the current climate and sediment load. Flat surfaces may be present from previous eras of differing climate and/or sediment load, and these surfaces are called *terraces*. Terraces are generally not "geomorphically active," that is, they are not currently being built by river depositional processes[C]. Finally, the floodplain is overflowed, on the average, several times per year, including moderate peak flow events (such as a 1.5-year or 2-year return interval flood). Terraces may be overtopped, but only by larger, less frequent floods (e.g. 50-year or 100-year events). The inner edge of the floodplain, or the point of incipient flooding, is called *bankfull* (see Figure 6). The bankfull channel refers to the channel cross-section below the elevation of the floodplain. Note that this may be different than what appears to be the "top of bank" if a terrace is present.

[C] In some valley settings, such as depositional response reaches, terraces can be active on intermediate time scales (e.g. centuries), where aggradation (filling in) of the main river channel or blockage by large wood causes the river to re-occupy the terrace. This may lead to channel avulsion, which is a common style of channel migration in these river types.

Figure 6. Idealized valley cross section showing floodplain (bankfull) elevation, and a terrace (Adapted from FSRWG[9]).



In theory, the bankfull channel is sized to convey the effective discharge. That is, over the long term, most of the sediment load moves at flows bracketing bankfull. Smaller discharges occur much more frequently, but carry little or no sediment due to lack of sufficient shear stress, thus contributing little to the overall sediment budget. Large discharges have the shear stress to move very high sediment loads, but occur rarely, again contributing little to the yearly sediment budget. Thus, it is the moderate flows, centered about bankfull, which move most of the sediment over the long term, and the channel forms itself into a shape to most efficiently convey these flows. The bankfull channel tends to be stable at higher flows as well, since these flows dissipate their potentially-high shear stress by spreading out over the floodplain. Overbank flow creates a wide, shallow cross-section, reducing velocities and shear stress to the point where sediment carried in suspension is deposited there, contributing to floodplain construction.

Notably, bankfull is a geomorphic concept. Although bankfull may, on the average, correspond to a certain statistically-derived flood (commonly asserted to be the 1.5-year return interval flood), bankfull is defined by the floodplain geomorphic surface, in the field, and not by the 1.5-year flood. If this surface is not present, then bankfull is not defined. Often, secondary indicators such as scour or moss lines on rock surfaces, types or presence of vegetation, changes in substrate texture, etc. are used to delineate bankfull in the absence of a floodplain. Such “surrogate” indicators are only valid if they have been “calibrated” by correlation with a floodplain or incipient floodplain nearby.

4.2 Hydraulic Geometry

If the channel is sized to carry the bankfull discharge, and if bankfull discharge is a natural index of the sediment and hydrologic regime, then, in theory, there exists a *regional hydraulic geometry*, a predictable pattern, profile and shape of an alluvial channel determined by bankfull flow. In other words, alluvial streams situated in the same climate and geologic setting will tend to have a consistent relationship between their physical dimensions (average width, depth, water velocity and cross sectional area) at bankfull discharge. Furthermore, in a given physiographic region (e.g. region with consistent climate, topography and geological substrate, such that the sediment and hydrologic regimes are consistent), bankfull discharge will tend to be highly correlated to drainage area, which means that these channel physical dimensions can be predicted from drainage area alone.

Bankfull hydraulic geometry has formed the basis for a growing literature in quantitative fluvial geomorphology focusing on identifying and defining the geometric properties of equilibrium alluvial channels and their adjustments to discharge and sediment transport regimes. Though many possible combinations of morphological variables exist that could be used to define these relationships, they are traditionally given as empirical equations of the form:

$w = aQ^b, d = cQ^f, v = kQ^m$, and $Q = hD_A^p$

or, alternatively, as $w = gD_A^n, d = jD_A^q, v = rD_A^t$ and $A = uD_A^w$

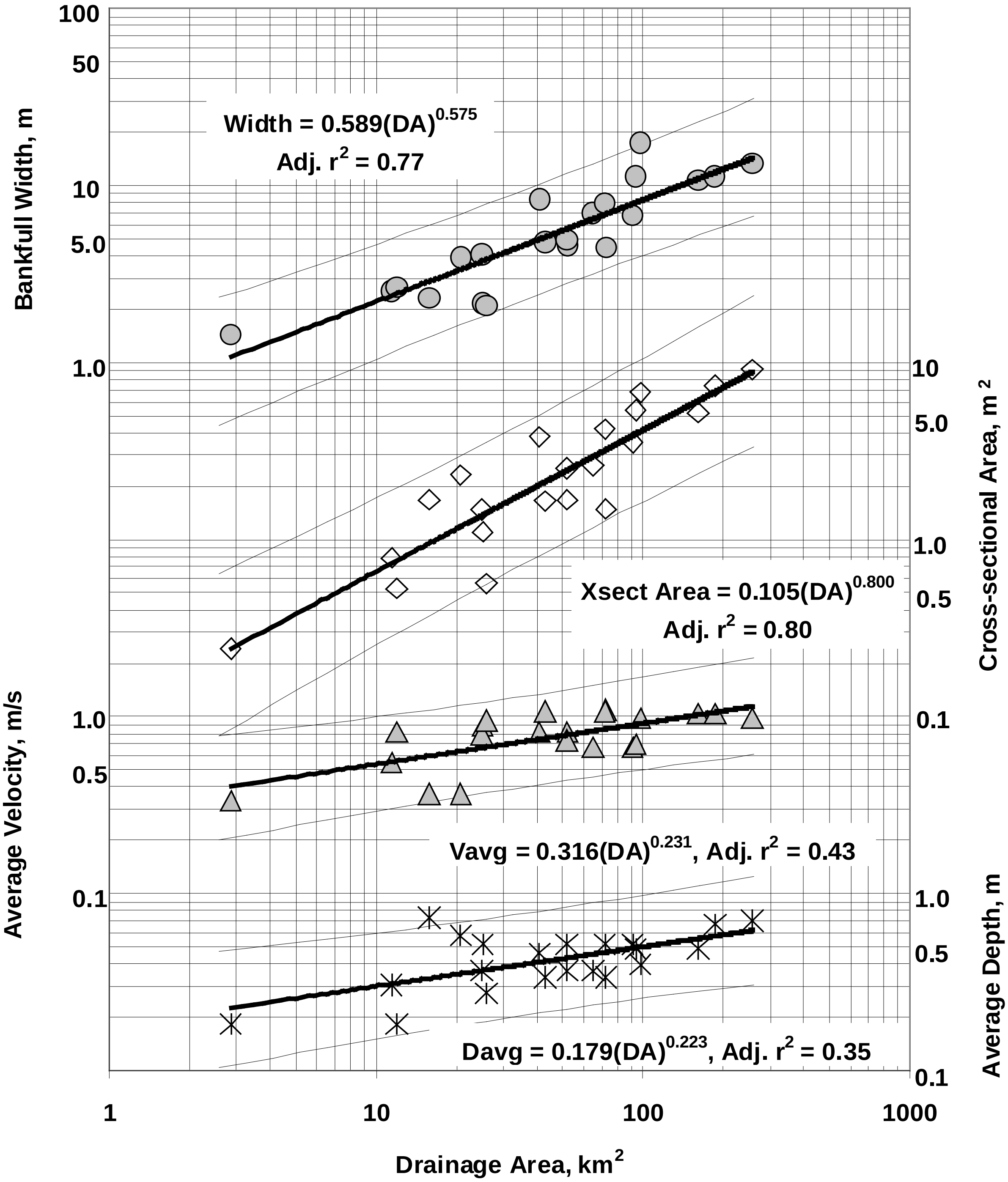
where w = mean width, d = mean depth, v = mean velocity, D_A = drainage area, Q is discharge taken at bankfull, and where the coefficients a, c, h, k, g, j, r and u and the exponents b, f, m, p, n, q, t and w are determined empirically for a given watershed or physiographic region. Other equations can be found to relate planform pattern (see below) properties such as meander spacing or "wavelength", the width or "amplitude" of the meander belt, and the typical radius of curvature of the meander:

$L = 10.9w^{1.01}$, $L = 4.7R_c^{0.98}$

where L = meander length, w = bankfull width, and R_c = mean radius of curvature, all in feet.[10]

Figure 7 shows an example of what these empirical hydraulic geometry relationships, often called "regional curves," typically look like, graphically. It should be noted that hydraulic geometry is only expected to be well defined in quasi-equilibrium *alluvial channels*, that is, channels that are built by the moving water, and is not applicable to colluvial streams or streams located in landscape positions where either erosion or continual deposition is the dominant process, such as alluvial fans, deltas, headwater source areas or confined reaches that inherit their geometry from the valley sides.

Figure 7. Example of regional hydraulic geometry relationships, developed using data from the Upper Klamath Basin of Oregon (Bakke et al.[11]).



In colluvial channels, and even in equilibrium alluvial channels where the morphology is controlled by boundary conditions such as large wood or man-made obstructions, these regional relationships, and the geomorphic bankfull, will be poorly applicable, since the equilibrium between erosion and deposition of alluvial sediment is not the primary determinant of channel form.

As the entire river network evolves over time, reworking the surface of the earth, equilibrium patterns appear on a larger spatial scale as well as the local or reach scale which has been the focus of discussion so far. On this large scale, the equilibrium patterns are best explained by balancing the physical tendencies to evenly spread out the distribution of hydraulic energy dissipation and to minimize the total amount of work performed by the moving water (see Leopold[8])[D]. These patterns arise out of general physics, and are sometimes referred to as "extremal hypotheses." Thus, for example, the overall stream bed longitudinal profile, from mouth to headwaters, takes on a concave shape described by an equation relating channel slope, s, to bankfull discharge, Q (which, itself, varies from mouth to headwaters in a predictable manner; Knighton[12]):

$$s = a^{*} Q^{b}$$

where "a" is a constant which depends on lithology and the units used, while b is an exponent that is usually about -0.3. The longitudinal profile over a whole watershed eventually adjusts to accommodate the drop in elevation between its headwaters and its *base level* (the lowest elevation to which the stream could erode, given enough time) in a form that minimizes total work and evenly distributes energy dissipation. Waterfalls or man-made *knickpoints*, instream gradient-controlling obstacles such as dams, or perched culverts, create local concentrations of energy expenditure which make the equilibrium profile discontinuous and, given enough time, will be eroded out. In general, such profile adjustments occur much more slowly than the local cross section or planform adjustments that occur in response to disequilibrium by altered input or output of sediment. This is because of the large volumes of material that need to be eroded or deposited in order to adjust to a new profile over a whole stream segment. In other words, the amount of *geomorphic work* needed to re-establish equilibrium profile geometry after a disturbance such as valley-altering landslide deposit or the raising of base level elevation by building a dam, is large, and takes time. How much time depends on the type of material and available hydraulic energy to move it.

Similarly, downstream fining, that is, the steady decrease in median streambed surface particle size, can be described by a mathematical relationship that exists due to broad-scale tendencies towards diffusion or spreading out of sediment mass as it is carried downstream. Downstream fining is of particular concern with projects occurring in the zone of transition from a gravel bed to sand bed, because the location of that zone can shift upstream or downstream with changes to the sediment or hydrologic regime, and because the transition can be abrupt. Sand and gravel have different transport and scour properties, implying that the river responds differently to disturbances and to altered boundary conditions when a shift from gravel to sand-bed conditions occurs locally. And ultimately, habitat conditions in sand and gravel-bedded reaches are quite different.

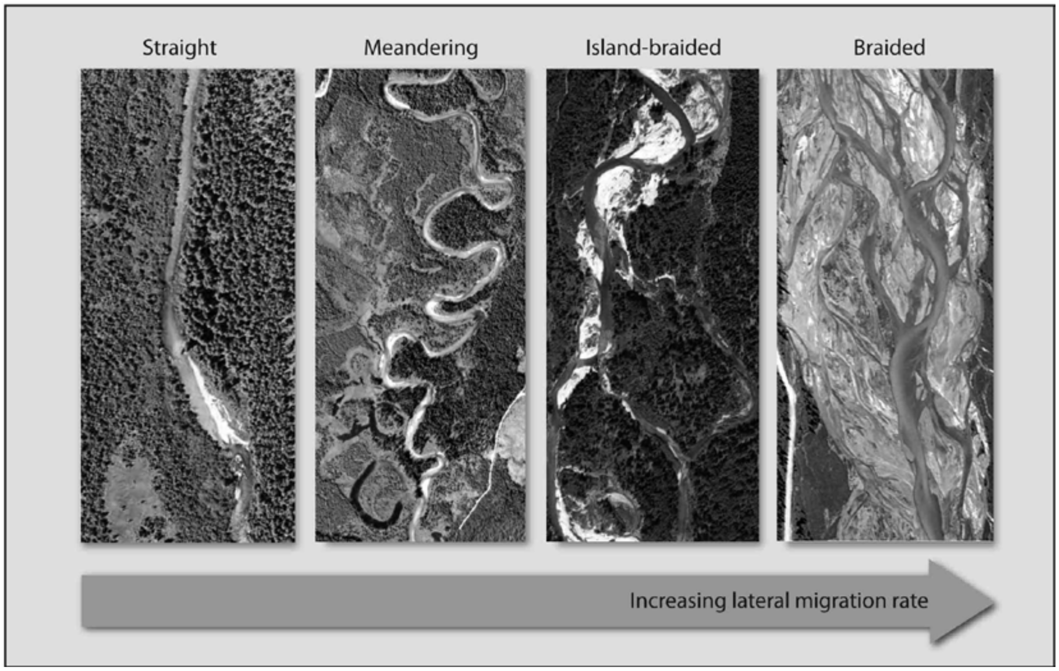
[D] This principle arises out of the universal tendency to minimize the rate of entropy production.

A stream that follows the equilibrium energy dissipation patterns, and thus has a mature, equilibrium slope profile, is said to be "graded" or "in grade[E]." Currently, such large-scale patterns are seldom considered in typical reach-scale geomorphic analysis, or in selection of design dimensions for river engineering. However, they are potentially quite useful considerations in cases where large-scale anthropogenic impacts are anticipated, and for long-term perspectives on sustainability and evolution of channel form, and are incorporated in certain mobile bed sediment transport models (see the *Sediment Transport* Appendix) to provide a basis for adjusting channel cross-section to achieve equilibrium. Interested readers are referred to more detailed sources listed in the Additional Reading section.

4.3 Channel Pattern

Terminology describing channel planform, often referred to as pattern, is a useful form of classification. Channel pattern refers to the two-dimensional character of the stream channel when viewed from above. Various planform categorizations exist. Beechie et al.,[13] building on previous work by Schumm[14] and Leopold and Wolman,[15] define four planform patterns—straight, meandering, braided, and island-braided (Figure 8).

Figure 8. Four common channel planform patterns. Island braided channels are also called anastomosing channels. Sediment load, and channel migration rate, generally increase towards the right (Images from Google Earth, as adapted in Skidmore et al.[16]).



[E] In geomorphology. the term "grade," in addition to signifying an equilibrium slope profile, is used to refer to the streambed elevation, as in the phrase "grade control." Also, a "well graded" sediment is one having a typical distribution of sizes from small to large grains.

Straight and meandering channels are primarily single thread, and are distinguished from each other by the sinuosity or degree of planform meandering. Truly straight channels are rare in nature, as the channel thalweg (deepest portion of channel) typically wanders from bank to bank even within a straight channel, due to the same processes that produce meandering in a less confined valley setting. Straight channels usually exist only in steep narrow valleys where geologic control (narrowness of valley sides or resistant substrate) prevents meandering, and streambank configurations are dominated by colluvial processes of erosion and mass wasting. Hydraulic energy is high and sediment loads generally low, and thus these channels tend to accumulate little alluvial sediment.

Meandering channels, by contrast, wander back and forth across a valley and are typically alluvial in character. The meandering pattern is related to the way longitudinal oscillations in the velocity field of turbulent flow affect the processes of sediment scour and deposition;[12] see Figure 9. That the mathematical regularity of meandering persists over many orders of magnitude in size, and diverse types of substrate is a remarkable demonstration that river channel form and pattern is firmly based in the physics of flowing water,[8] as shown in Figure 10.

Island-braided channels exhibit multiple channels separated by somewhat stable (over years to decades or longer), usually well-vegetated islands. These are also called anastomosing, anabranching, and wandering channels in the literature.[13] The anastomosing pattern of island-braided channels is often regulated by logjams, which control the partitioning of water between channels at branching points, created hydraulic shadows which foster deposition, and protect vegetation on the island from erosion.

Figure 9. Isometric view of flow velocities in a typical meander, showing how centrifugal force causes development of lateral velocity components or "secondary circulation" as the water flows around the bend. On the left, all cross sections are viewed obliquely from above and left of the section. Downstream velocity distributions are shown as open parabolas with arrows proportional to velocity, and lateral velocity is shown as closely-lined areas. To the right is a plan view with surface streamlines (pathways of individual water elements) shown (Adapted from Leopold and Wolman[17]).

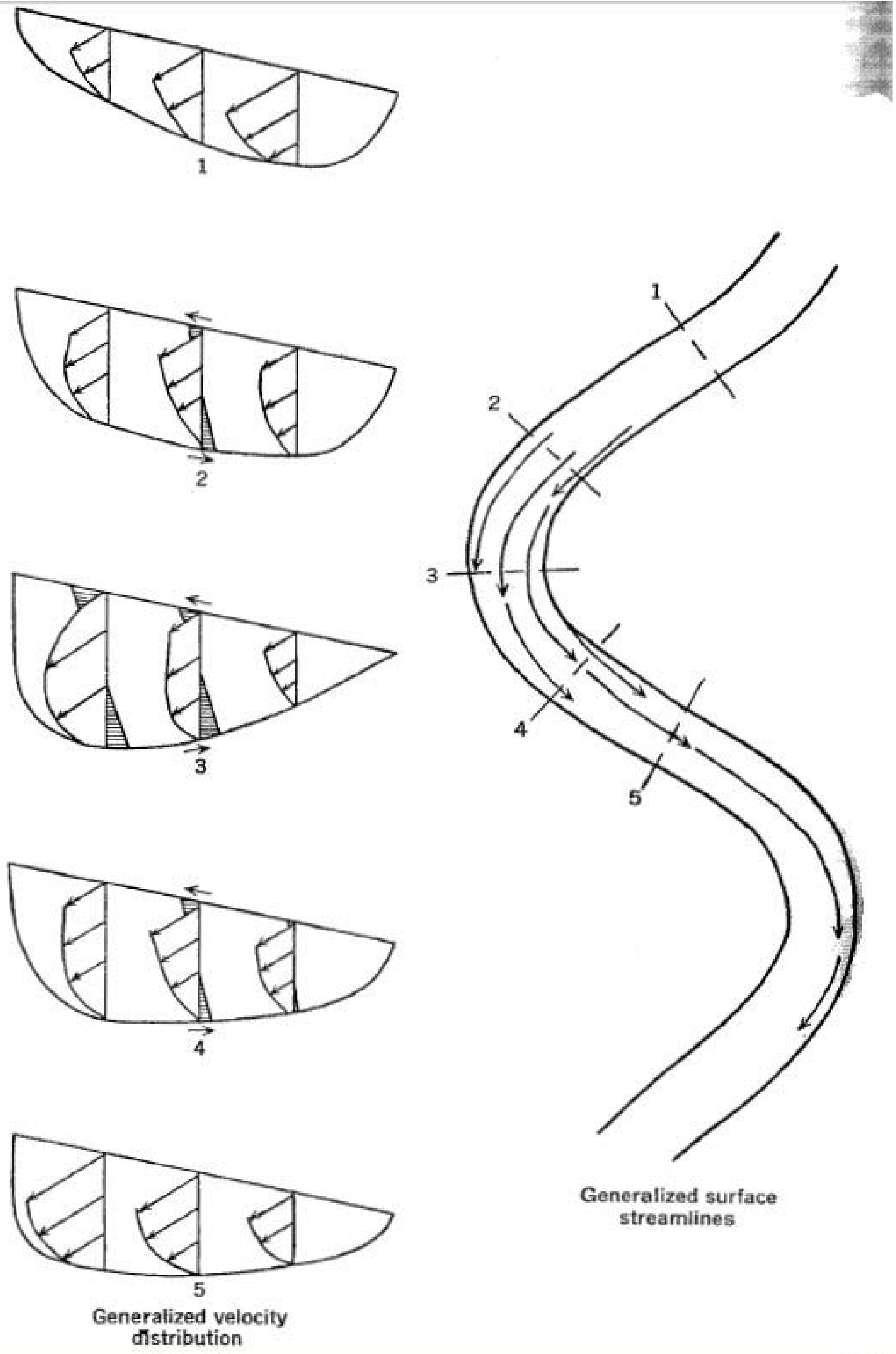
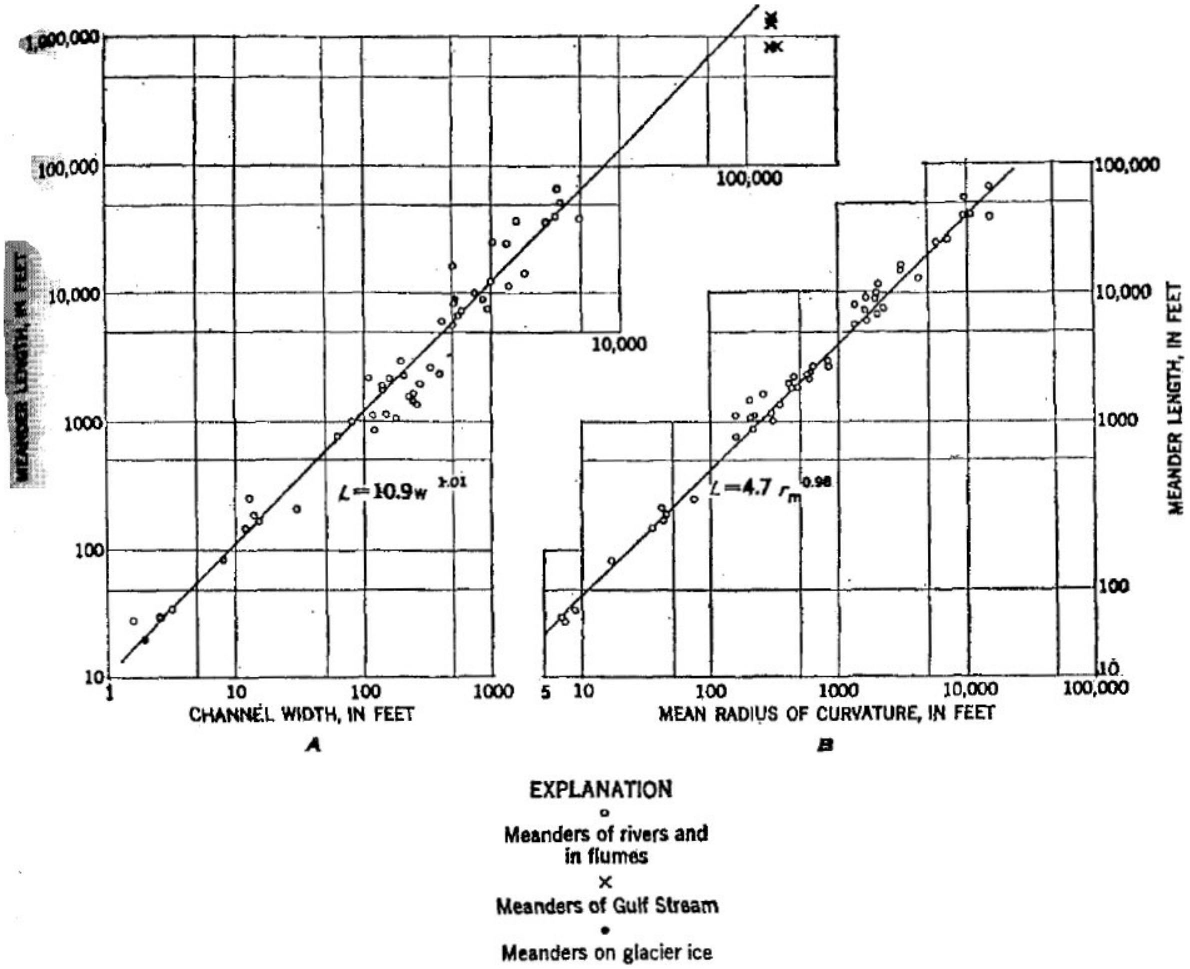


Figure 10. Relations between meander length and channel width (left), and radius of curvature (right) for flows spanning five orders of magnitude in spatial scale (from Leopold and Wolman[17]).

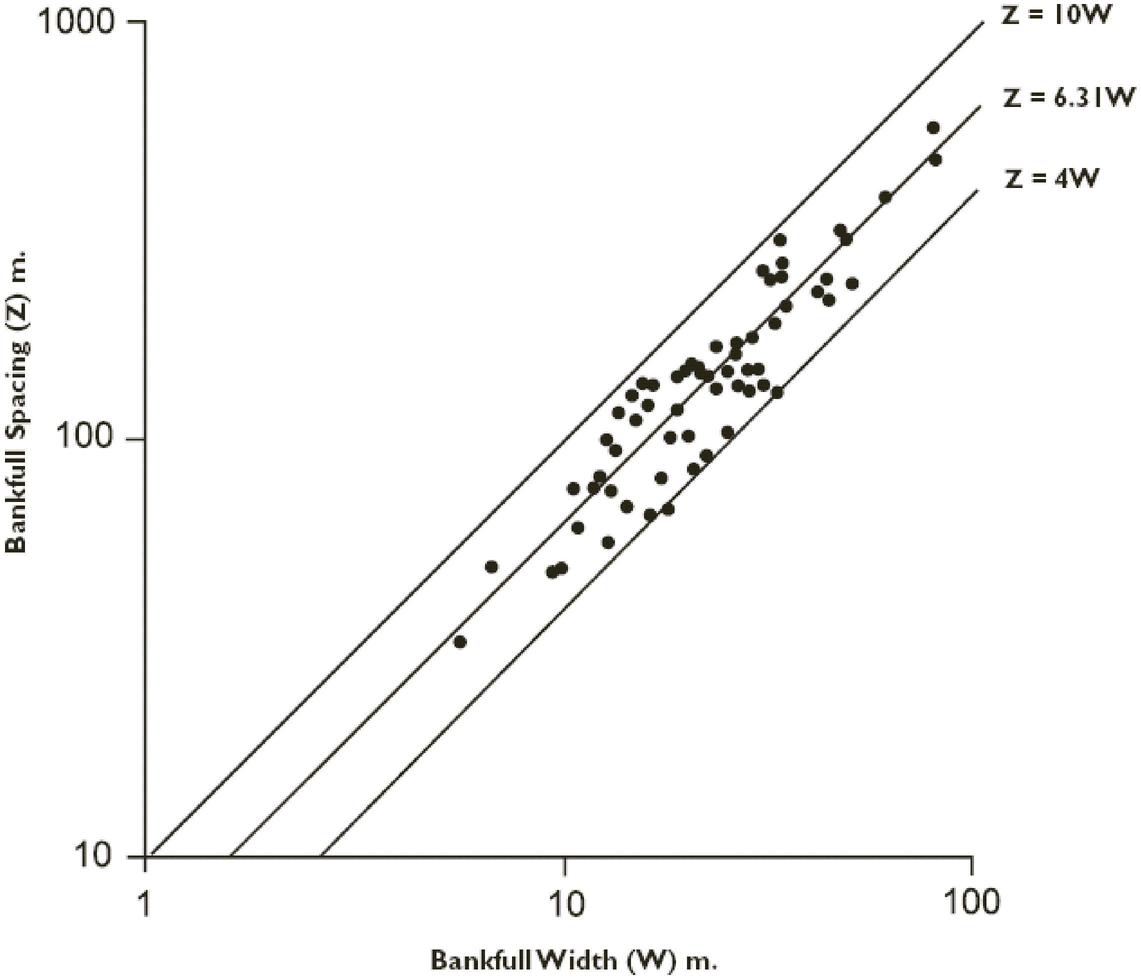


Braided channels consist of multiple sub-channels separated by unvegetated gravel or sand bars which are generally unstable, are often submerged at high flow, and tend to scour, migrate and re-deposit, shifting location and dominance over short (days to months) time scales.

The planform pattern terminology is also associated with a conceptual model of where these channel types are sequenced in the watershed. Braided channels are typically found downstream of glaciated or alpine terrain where bedload volume is particularly high.[13] The braided channels transition downstream to an island-braided system as the volume of bedload relative to the volume of water decreases. Bank vegetation and debris jams maintain a narrower, deeper active channel, and large wood in the form of logjams act as anchors for island deposition. Further downstream, as slope decreases and relative bedload volume decreases, the channel may transition into a single threaded meandering type. Again, it should be emphasized that this conceptual model is just an assumed description of process, and does not substitute for real geomorphic analysis.

Pools and riffles generally occur at relatively constant spacing in meandering alluvial streams. Leopold and others[18] determined that riffle spacings were consistently on the order of five to seven times the channel width (Figure 11). This empirical deduction is consistent with a theoretically predicted spacing of 2π (6.28) times the channel width determined by Hey.[19]

Figure 11. Riffle spacing as a function of bankfull width (Adapted from Leopold et al.[18])



It should be noted that channel patterns can exhibit similar forms in either equilibrium condition or in a condition of disequilibrium. For example, a braided channel may be considered an equilibrium condition across an alluvial fan or in a zone of consistently high sediment load, but may indicate instability when it occurs in a lower gradient alluvial valley. As such, channel pattern can be a clue to identifying disequilibrium, or altered equilibrium, but is not proof of either. Such changes are best determined through concurrently reviewing evidence of historical channel pattern and migration rates along with watershed management and disturbance history.

The special role of large wood in determining channel morphology, particularly channel pattern, in forested landscapes has been the subject of much recent investigation in the Pacific Northwest. Wood jams, historically, were integral to creating and maintaining a dynamic, anastomosing river pattern with numerous floodplain channels and abundant edge habitat.[20] Wood jams affected floodplain development by routing floodwaters and sediment onto floodplains, creating a diverse topography and habitat mosaic (see Figure 12). The specific manner in which wood affects geomorphic processes changes according to the valley setting, and the size of wood pieces relative to the channel width (see Figure 13), which influences the mobility of large wood pieces and their ability to form stable wood jams. In the Puget Sound lowlands, river channels situated in the broader, low gradient valleys created by Pleistocene glaciation generally had a single-thread meandering pattern, with oxbow lakes, infrequent meander cutoff avulsions, and vast floodplain wetlands. By contrast, river channels that created their own valleys during Holocene times by incising into deep Pleistocene glacial deposits typically had an anastomosing pattern with multiple channels, floodplain sloughs, and frequent channel switching avulsions, due to wood jam dynamics (see Figure 14). Although this latter work is specific to Western Washington, similar interactions of large wood with river channels and even valley-forming geomorphic processes occurred in most forested landscapes worldwide.[21] In fact, it can be safely stated that large wood, historically, had as much influence on channel form as sediment load and hydrologic pattern in most forested landscapes.[22]

Figure 12. Topographic cross-sections across the floodplain of the Nisqually River, Washington, showing the multi-elevation nature of the active floodplain surface due to flow splitting and deposition associated with logjams (Adapted from Montgomery et al.[21])

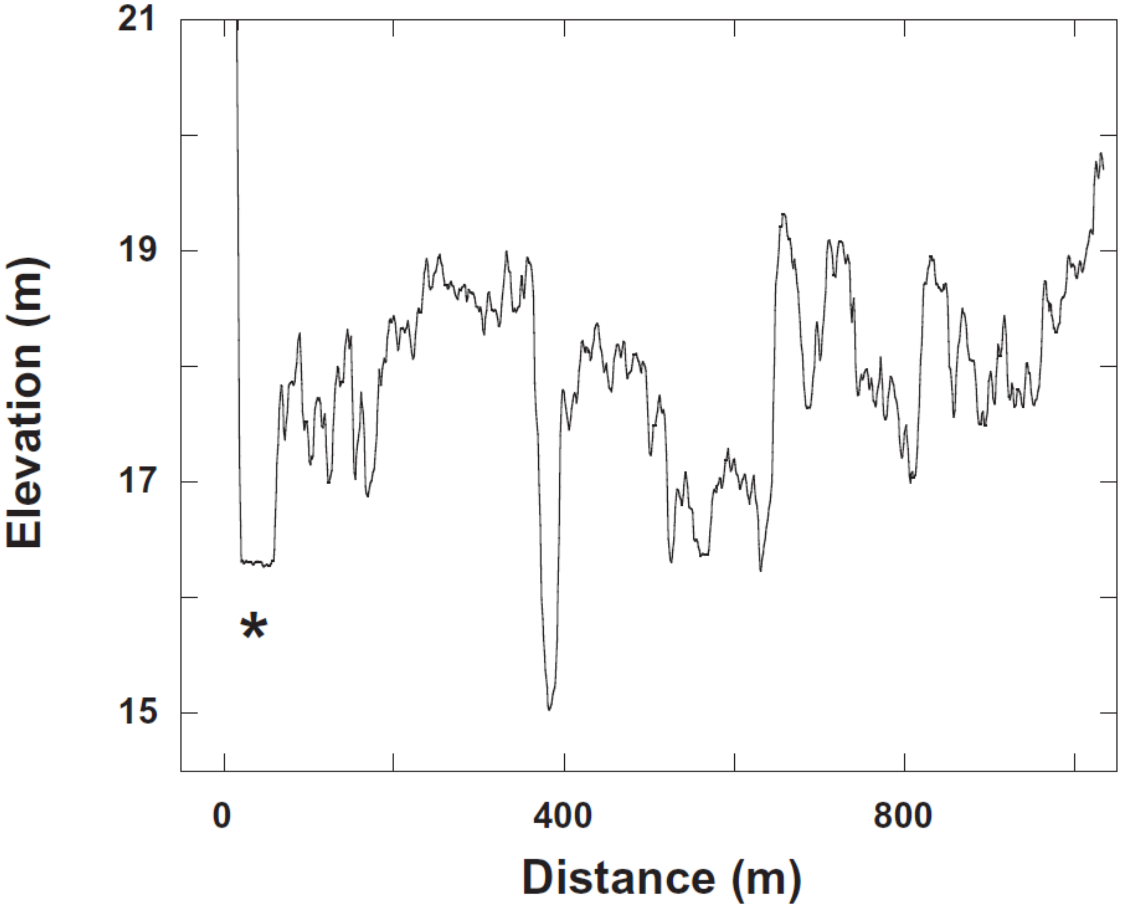


Figure 13. Downstream variations in the style of log accumulations in the Queets River, Washington. Open symbols represent in situ jams that remain close to where they were introduced to the channel; gray symbols represent combination jams composed of transported wood racked onto in situ key pieces; and black symbols represent transport jams in which key pieces of wood were transported within the channel (Adapted from Montgomery et al.[21]).

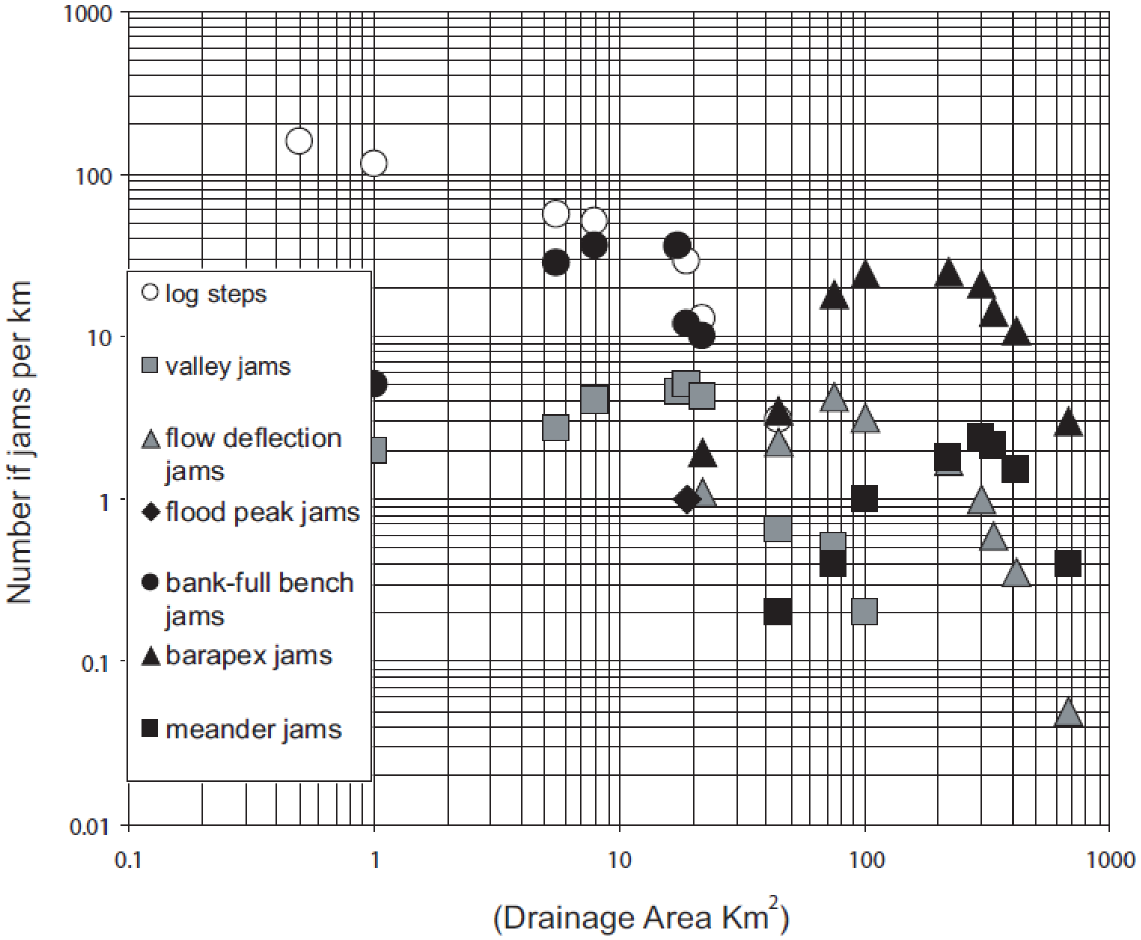
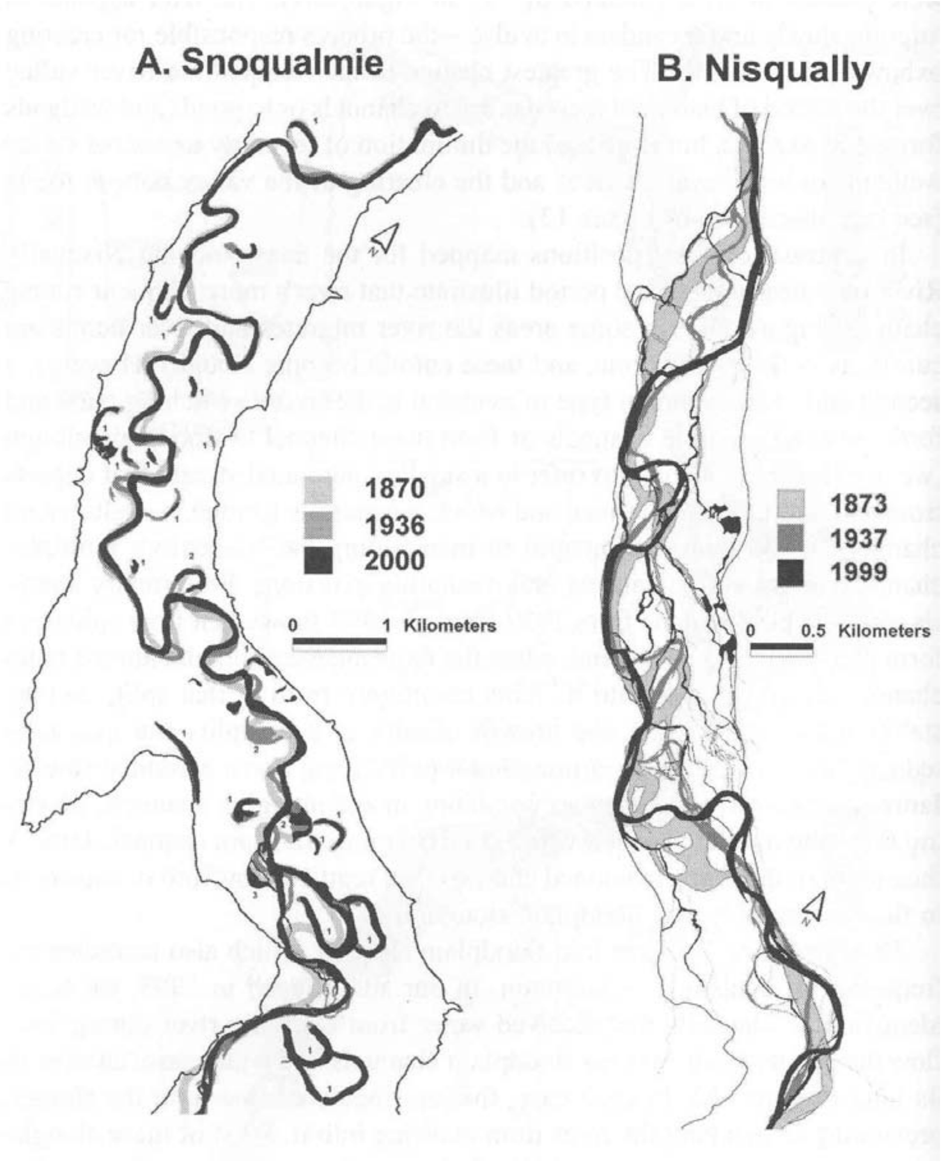


Figure 14. Contrast between channel pattern over time in the Snoqualmie and Nisqually Rivers, Washington. The Snoqualmie represents an aggrading, meandering river within a Pleistocene valley created by subglacial drainage. The Nisqually represents an anastomosing river situated in a Holocene valley created by fluvial erosion. Both are similar in size, and presumably were similarly forested, historically (Adapted from Collins et al.[23]).



4.4 Channel Classification

The basic idea of channel classification has already been introduced in the discussion of channel pattern, and in the colluvial/alluvial channel distinction. In the late twentieth century, several more-sophisticated schemes for describing river channel morphology were developed, a few of which will be discussed below. In this discussion, it is important to keep in mind that with respect to river channels, nature presents us with a continuum, and the thresholds used for separating rivers into different classes all contain a heavy dose of professional discretion. Thus, as useful as classification is for communication and for organizing our observations, it can blind us to important distinctions, similarities, differences, and channel-forming processes by the particular way that a given classification system is crafted and which factors it emphasizes. Classification alone is not a recipe for design or for management. It is wise to become familiar with more than one classification system in order to see through the shortfalls of any one system, and to be suspicious of assumptions about geomorphic process based on classification alone, in the absence of corroborating geomorphic analysis.

Ideally, a channel classification system would be based on geomorphic process. Processes, however, are inherently difficult to observe, much less quantify, and results will vary according to the time scale considered. Thus, most classification systems are ultimately based on the channel morphology or "form," and can only suggest "process" by inference. In the Pacific Northwest, the systems of Montgomery and Buffington[24] and that of Rosgen[25] are by far the most widely known.

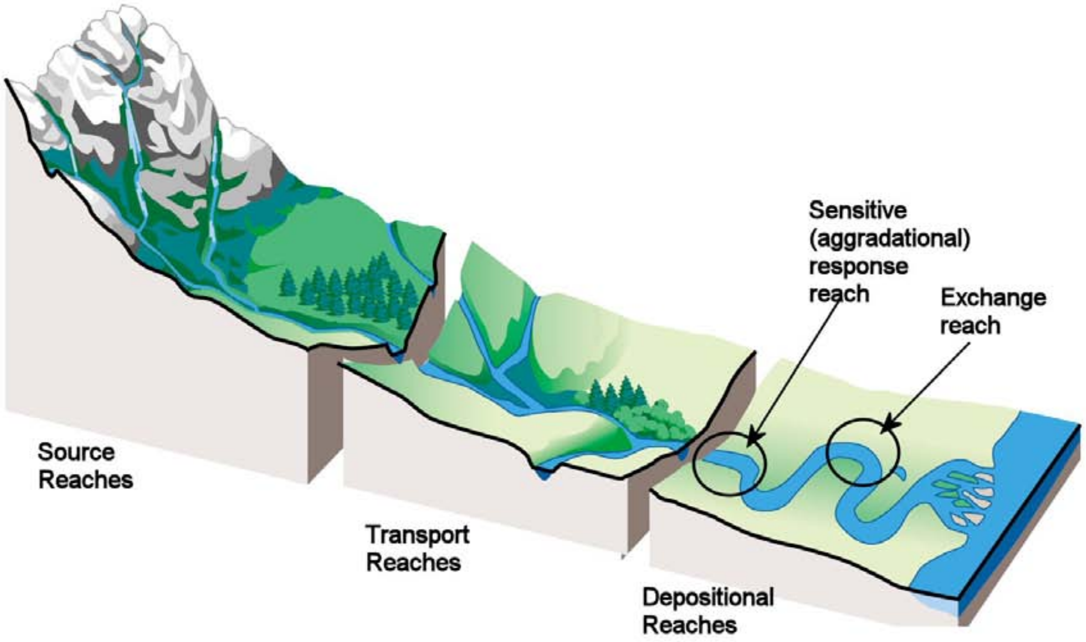
Montgomery and Buffington's classification is based on a hierarchy of spatial scales that are unified by a conceptual model describing how key geomorphic processes vary within the watershed, controling channel morphology. At its largest spatial scale, Montgomery and Buffington depict the river landscape as a continuum from "source reaches" to "transport reaches," and then to "response reaches" (Figure 15).

Source reaches are headwater areas where long-term average erosion rates (tonnes/ha/year) are high, and consequently, sediment in transport tends to be locally derived rather than routed in from upstream. Much of this locally-derived sediment comes from mass-wasting or other hillslope processes, and consists of particles too large to be moved by the available hydraulic forces in these headwater channels. These stream channels are said to be strongly coupled to the adjacent hillslopes. Although channel slopes are steep, water volumes are relatively small, and most of the hydraulic energy is dissipated by large wood and/or rocks. Sediment accumulates in source reaches, but this is largely not alluvial sediment, and depends instead on non-fluvial processes such as debris flows to be, ultimately, transported downstream.

Transport reaches function to efficiently route alluvial sediment delivered from upstream, and, like source reaches, experience flow energy that precludes extensive alluvial deposit formation. But in contrast to source reaches, these channels receive most of their sediment load from upstream fluvial input rather than local erosion and hillslope processes.

Response reaches are areas where alluvial deposits such as active point bars (those frequently experiencing deposition and scour) are common. Over long time scales (centuries to millennia), sediment has accumulated and been stored as alluvial valley fill (e.g. extensive floodplains or terraces). Since these are alluvial channels, built from river deposits, they are expected to more readily adjust their form ("respond") to changes in sediment input or flow intensity. The most sensitive response reaches are zones where high sediment loads or transition in valley setting (decreasing slope and confinement) are driving measurable deposition on short (decades to centuries) time scales. Alluvial reaches where deposition is more evenly balanced by erosion on decadal time scales (the quasi-equilibrium mentioned earlier) are sometimes labeled *exchange reaches* instead of response reaches, since sediment transported away from the reach, which may have been in storage for long periods of time, is exchanged for new deposition. The floodplain often isolates or de-couples these stream channels from the nearby hillslopes.

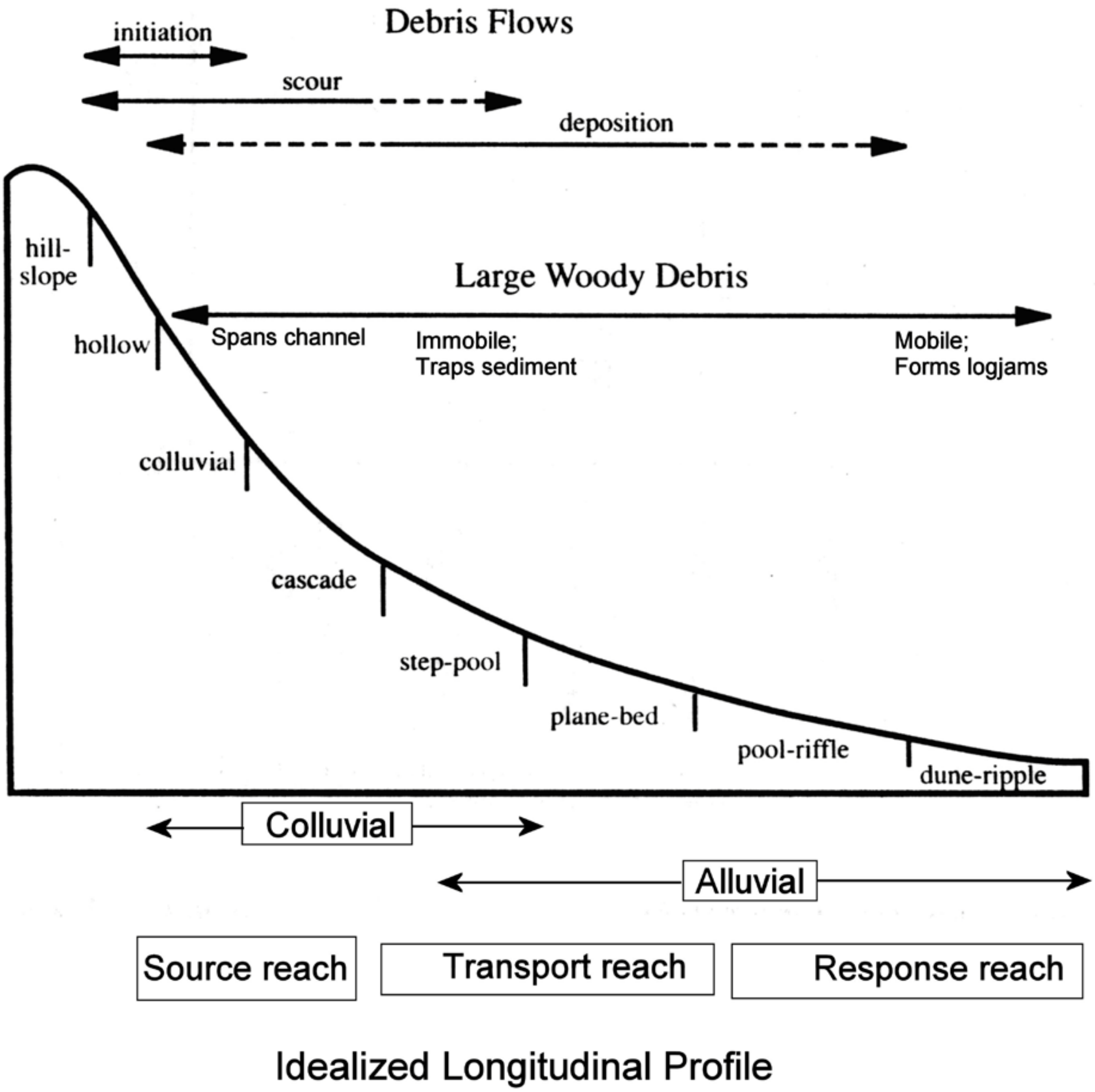
Figure 15. Idealized river landscape, showing source, transport and response or depositional zones. Response reaches at transitions in slope or confinement are the most sensitive, aggrading naturally over time. Exchange reaches have nearly balanced deposition and erosion, and appear in sediment equilibrium over decadal time scales (Adapted from Miller[26]).



Moving down in the spatial hierarchy, Montgomery and Buffington then describe a conceptual longitudinal view of the river channel from headwaters to lowlands (see Figure 16), in which a predictable sequence of reach-scale channel morphologies is linked to changes in dominant sediment sources and transport processes. Progressing from top to bottom in the stream network, one encounters *hollows*, *colluvial channels*, *cascades*, *step-pool*, *plane-bed*, *pool-riffle*, *and dune-ripple* morphologies. In this progression from top to bottom, sediment sources shift from hillslope surface erosion and mass wasting to hydraulic erosion of colluvial material to erosion of alluvial material and influx from upstream of fluvial sediment. Mass wasting (debris flow) processes shift from initiation to scour to deposition. Large wood shifts from being largely immobile and trapping sediment to being mobile and acting as sediment. Slope decreases. Sediment size decreases from large clasts seldom moved by hydraulic forces, to cobble, then gravel, then sand-bed systems, in which bed forms (dunes, ripples, etc.) rather than individual grains characterize sediment movement. Channels shift from being physically bounded by the valley sides and strongly influenced by hillslope processes to being insulated from hillslope processes by an intervening floodplain.

The seven basic channel morphologies (see Figure 17) are arrayed in a way that reflects this continuum of processes. These channel types are defined by qualitative morphological descriptions and sketches rather than physical measurements. An eighth channel type, the *bedrock channel*, is also included, but is more irregular in its spatial occurrence. Bedrock channels occur in relatively confined valley settings where channel slope is steep enough to drive high sediment transport capacity, and scarcity of in-channel roughness (such as large wood or boulders) precludes development of alluvial deposits.

Figure 16. Montgomery and Buffington stream classification. Longitudinal view and watershed-scale process perspective (Adapted from Montgomery and Buffington.[24] Reproduced with permission of the publisher, the Geological Society of America, Boulder, Colorado, USA. Copyright ©1997).



Rosgen’s classification system (see Figure 18) is comprised of eight basic channel types (A, B, C, D, E, F, G and DA), defined according to a dichotomous key, based on bankfull channel measurements. The variables used to classify the channel are multiplicity (single thread, multiple thread), entrenchment ratio (ratio between bankfull width and the width of the channel or valley bottom at an elevation corresponding to twice the riffle bankfull depth, basically serving as a measure of confinement), the bankfull width/depth ratio, and sinuosity. Within each of the eight basic types, the channel is further classified with a number that ranges from 1 to 6 which represents the dominant substrate (bedrock, boulder, cobble, gravel, sand, and silt/clay, respectively), and channel slope. To put the system in a landscape geomorphic perspective, Rosgen also describes 11 different “valley types,” each of which tends to harbor certain stream types by virtue of how the “valley” formed and its typical slope and sediment regime.[27]

Figure 17. Montgomery and Buffington stream classification. Sketches of selected stream types (Adapted from Montgomery and Buffington.[24] Modified with permission of the publisher, the Geological Society of America, Boulder, Colorado, USA. Copyright ©1997 Geological Society of America).

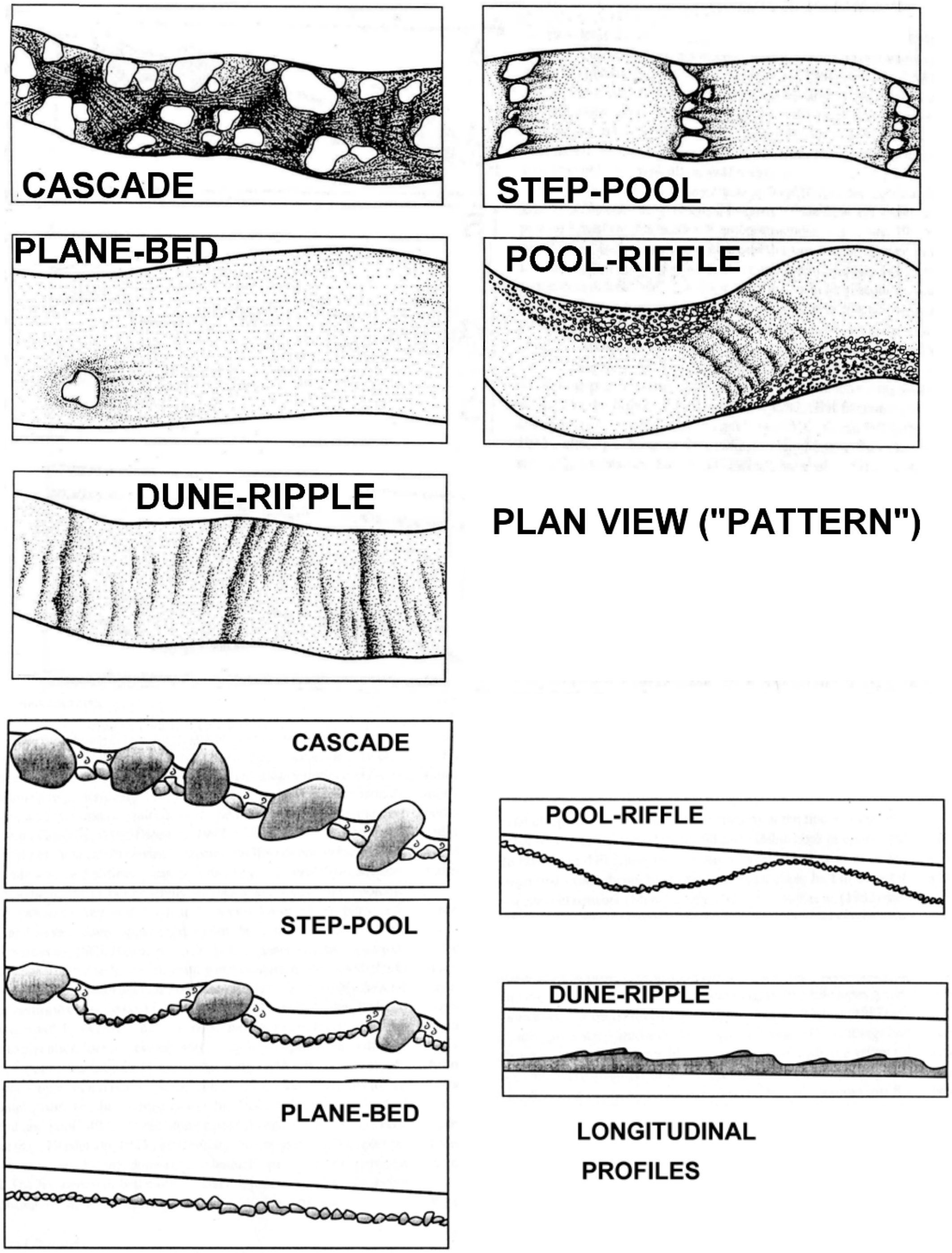
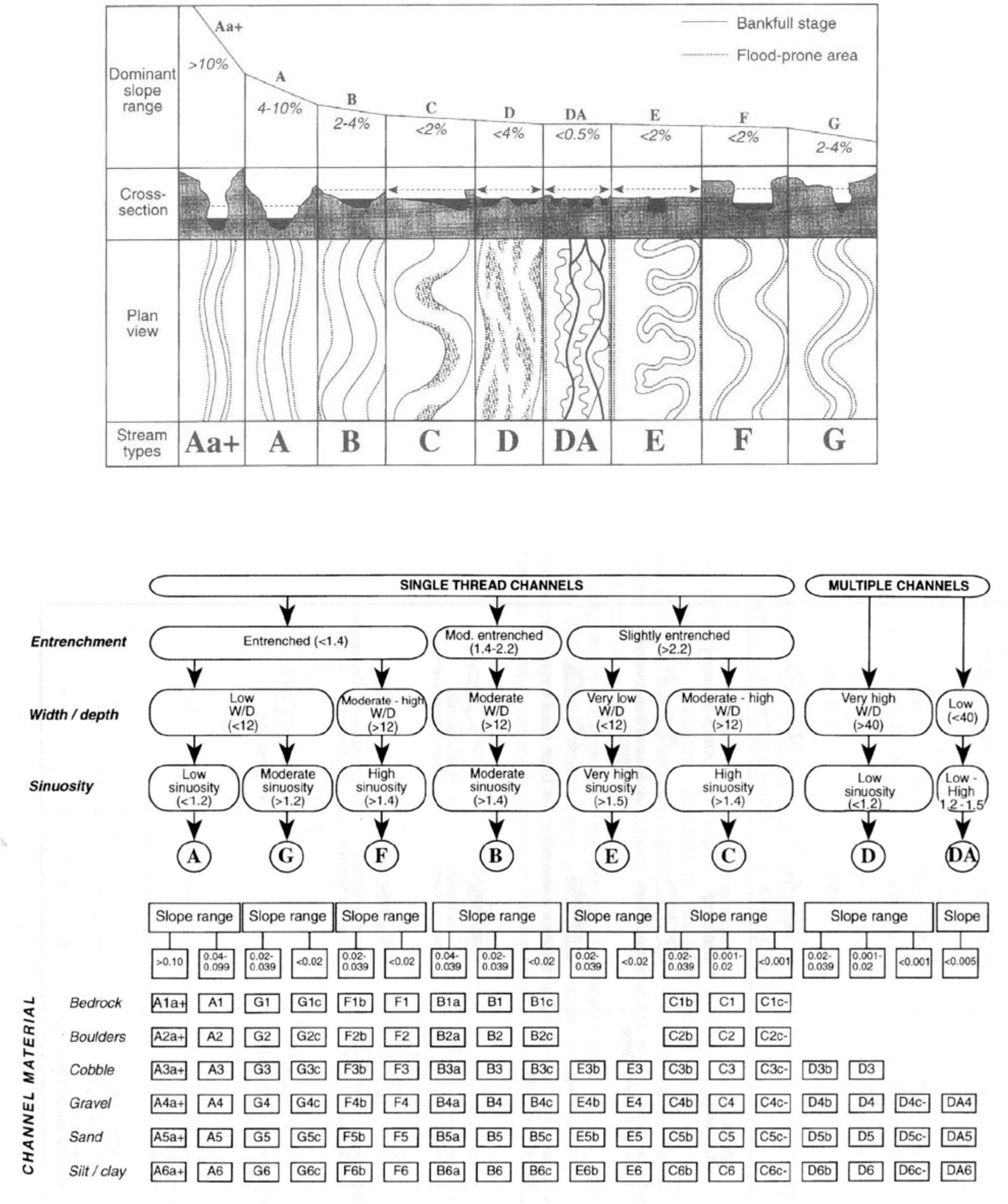


Figure 18. Rosgen stream classification (Adapted from Thorne.[28] Copyright 1997. © John Wiley & Sons Limited. Modified with permission).



To use Rosgen classification, determination of geomorphic bankfull is required, which can be problematic in systems that lack depositional features, have depositional features at multiple levels, or are heavily influenced by disturbance. This has lead to widespread use of surrogate "indicators" of bankfull elevation, such as vegetation lines or "index" discharges, such as the 1.5-year return interval flood, which have been shown to correspond roughly to bankfull in some (but by no means all) places. As mentioned previously, surrogate indicators should be locally calibrated to true floodplain elevation or to effective discharge in order to be consistent with geomorphic theory. Nevertheless, differences in bankfull identification can lead to ambiguous classification (e.g. Roper et al.[29]). The Rosgen classification system is in more widespread use nationwide than that of Montgomery and Buffington.

Although Rosgen's system is strictly defined according to morphology, the temptation exists to use it to infer dominant process characteristics since form and process in river systems are interdependent, at least as they relate to sediment dynamics. For example, the "C4 channel," a typical meandering, pool-riffle, gravel-bed morphology, might be assumed to be the steady-state equilibrium endpoint of channel evolution in floodplain valley settings. Meander migration is assumed to occur by gradual erosion at outer bends (pools), balanced by growth (deposition) on point bars. Bank erosion rates are thus assumed to be small in such a "stable" channel type. However, in many floodplain valley settings, these assumptions do not apply. Naturally high bedload input rates can make the steady-state endpoint or "stable" morphology a "D4" (braided) channel type rather than the "C4" type. And as was discussed earlier, a multi-thread "island braided" channel pattern is the stable evolutionary endpoint in many systems where large wood dynamics plays a dominant role in channel morphology. Island braided systems tend to have naturally high channel migration rates due to channel avulsion processes mediated by logjams, rather than sediment equilibrium. An island braided system might classify as a C4 or a D4 channel type, depending on choice of bankfull elevation, which tends to be ambiguous in such systems due to the variable hydraulic influence of large wood pieces and log complexes on depositional surfaces. Unfortunately, the Rosgen system of classification does not emphasize the intrinsic geomorphic role that large wood dynamics plays in some systems. The reader is therefore cautioned not to jump to conclusions about geomorphic processes or channel stability based on channel classification alone.

The various morphological stages of the Channel Evolution Model for incised channels, described below, serve as a way to classify channels as well, in the context of channels which are actively incising.

To be useful to applied geomorphologists, any classification system should be based on a selection of the most important features that characterize physical processes. Certainly, energy (slope and confinement), and substrate characteristics (particle size, as related to ease of transport and hydraulic roughness) could be considered a minimum list of factors. In rivers where large wood plays a dominant role in channel morphology and migration processes, it should be a key element in classification as well. To avoid unnecessary bias, it is advantageous to become fluent in more than one system. Use of the Rosgen system, Montgomery and Buffington, or other existing or *ad hoc* classification schemes should be done with the objective of learning as much as possible about river processes, and should never be seen as a shortcut around the need for geomorphic analysis. Each classification system comes with a set of assumptions about which morphological features are most important and how these relate to channel-forming processes. It is wise to be aware that how we classify rivers determines the language we use, which in turn strongly influences how we perceive the world of rivers.

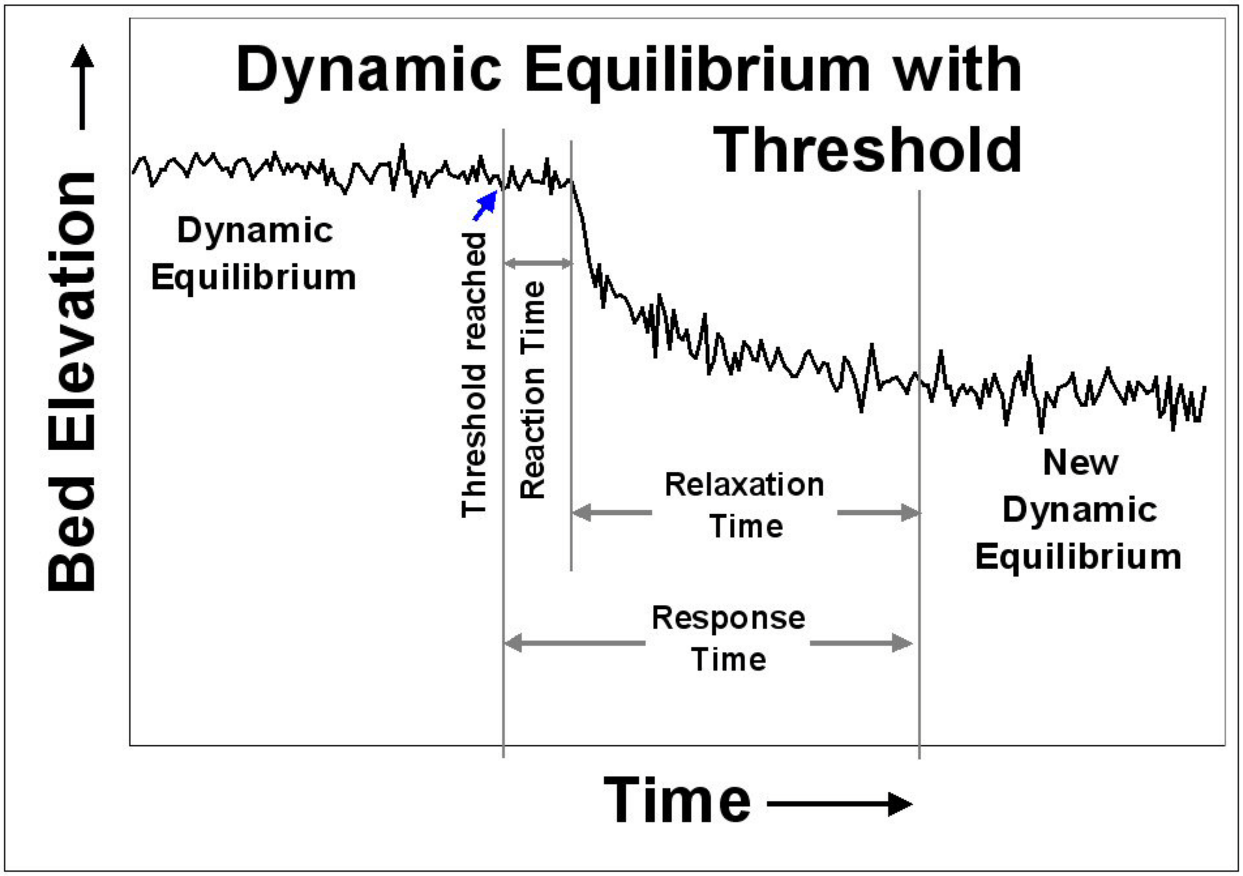
4.5 Geomorphic Thresholds

A threshold is a combination of conditions that results in a sudden shift from one state of stability to another. This shift is initiated at the moment in time and space at which forces and resistance to those forces are equal. The classic example of a physical threshold is the attainment of critical shear stress in a channel during increasing discharge. In such case, the channel bed remains immobile through increasing discharge until a threshold of shear stress is exceeded, upon which bedload sediment motion is initiated.

Building on this example, a gravel bed river can form a coarsened surface layer on its bed, which allows the channel to respond to changes to its sediment load without aggrading or degrading, at least within certain limits. If the sediment load increases, the surface layer becomes finer, which increases the rate of transport of the streambed sediment to match the increased input. Conversely, if the sediment load decreases, the surface becomes coarsened, which decreases the amount of sediment mobilized from the streambed. This tendency to counteract the destabilizing force is negative feedback, built into the dynamics of the streambed surface to allow a stable channel form to persist despite varying sediment input and hydraulic force (shear stress), again, within certain limits.

However, substantial increases in flood magnitude (such as from climate-induced hydrological changes, or from urbanization) can overwhelm the ability of the streambed to resist massive sediment mobilization. Once this happens, the streambed scours and degrades (incises, or downcuts). As it degrades, the flood water can no longer spread out over a floodplain. Thus, the amount of hydraulic force concentrated on the streambed at a given water discharge increases, resulting in even greater scour and degradation. This tendency to amplify the destabilizing force is positive feedback. The original scour event that mobilizes the coarsened surface layer represents a *geomorphic threshold*. Crossing a geomorphic threshold results in a period of instability followed by altered equilibrium (see Figure 19). The channel morphology and streambed condition must now adjust to the new hydrologic regime to reestablish quasi-equilibrium conditions. This may mean a different channel type, with a different morphology. Or, it may mean the same channel type but at a different elevation and with a coarser streambed sediment texture. The amount of time it takes to reestablish equilibrium after crossing a geomorphic threshold depends on the amount of "geomorphic work", in terms of moving materials, it takes to establish the new morphological conditions.

Figure 19. Geomorphic threshold, as illustrated by channel bed elevation at a cross section during channel incision. Threshold may be increase in hydraulic energy from urbanization, for example.



Both extrinsic and intrinsic geomorphic thresholds exist. An extrinsic threshold is exceeded by application of an external force or process, such as a change in sediment supply or discharge. Progressive change in the external force triggers an abrupt, physical change in the system. Examples of forces relating to extrinsic thresholds are climatic fluctuations, land-use changes, particularly altered vegetation type or amount of impervious surface, and base-level changes. In the example above, urbanization typically increases the frequency and magnitude of peak flows, which can overwhelm the resistance of the streambed and banks to erosion, causing an episode of down-cutting or incision. By contrast, an intrinsic threshold is exceeded when system change occurs without a change in an external variable; the capacity for abrupt change is intrinsic to the system and can be considered within the system's natural variability. For example, an intrinsic threshold might be reached when the structural elements (such as wood, rocks, beaver dams or soil cohesion) holding a growing volume of sediment in storage within the floodplain weaken or lose effectiveness over time, causing an episode of channel incision.[30,31]

As another example, gradual accumulation of sediment through soil creep and surface erosion in a small, headwater channel on a steep hillside, combined with gradual weathering of bedrock, causes a steady increase in weight of unconsolidated material. Then, when heavy rainfall and saturated soil conditions weaken the resisting force of the soil to the point where it can no longer hold back that weight, a landslide can be initiated, quickly excavating the accumulated sediment, scouring the channel downstream to bedrock, and eventually depositing all of the sediment where the slope of the channel flattens and the moving sediment spreads and thins out. Channel type has been altered throughout the path of the landslide.

In some river systems, small woody debris may form unstable dams that accumulate a large wedge of sediment within the channel. As the sediment wedge grows, and as the debris making up the dam decays, a point is reached, usually during a peak flow, where the dam can no longer hold back the load of water and sediment. Dam break up is sudden, and the debris and sediment are washed downstream, often setting up again as a new small debris dam. In this manner, fairly large amounts and sizes of sediment can be transported by fairly small streams, as pulses governed by intrinsic threshold behavior.

The most significant controls on channel stability over a period of years or decades are flow regime, sediment supply, and vegetation. Living vegetation both influences the hydrology on a watershed scale, and influences the resistance of the river banks to fluvial erosion. Dead vegetation in the form of large wood influences numerous fluvial processes including flow hydraulics, sediment transport, and sediment accumulation. If any of these controls change (either progressively or suddenly), the channel may cross a threshold and undergo change. Channel avulsion, the formation of a new channel across the floodplain, and channel incision, the general lowering of channel-bed elevation, are two common types of channel changes involving geomorphic thresholds.

5 CHANNEL RESPONSES TO CHANGE IN HYDROLOGY, SEDIMENT AND BOUNDARY CHARACTERISTICS

Although rivers are complex systems, it is possible to describe and often predict the trajectory or style of channel change in response to altered hydrology, sediment, boundary characteristics, or morphology. These styles of change include aggradation, incision, lateral migration, and avulsion. These are most commonly observed in alluvial systems that are free to adjust their channel boundaries. All of these changes can and do occur naturally, but an important role of the geomorphologist is to predict when such channel response might become more likely, more widespread or more severe. Often, the change occurs in response to crossing some geomorphic threshold. In colluvial channels, where the channelboundaries are more resistant, greater resilience to changes in the sediment and hydrological regime is usually the norm. However, changes to boundary resistance due to altered vegetation or loss of large wood can initiate incision or widening in these streams as well.

5.1 Aggradation

Aggradation is the progressive accumulation of in-channel sediment resulting in increased channel bed elevation (see Figure 20). Generally, aggradation occurs as result of either increased sediment supply (load) or size (gradation), or diminished hydraulic energy (transport capacity).

Aggradation associated with increased sediment supply may occur in response to any of the following conditions:

- Increase in sediment size or volume associated with landslides, debris flows, or other geologic disturbances
- Increase in sediment volume inputs from dispersed soil disturbances including vegetation

removal, fire, and agricultural and other land use impacts

- Increase in sediment volume inputs from excessive bank erosion upstream
- Increase in sediment volume inputs from excessive bed erosion from channel incision upstream

Aggradation associated with decreased hydraulic energy may occur in response to any of the following conditions:

- Increased channel width resulting in decreased hydraulic energy (hydraulic force diminished due to reduced depth, and this force is then spread over a larger surface area)
- Alteration of flow regime by dams which reduce transport capacity
- Diversions reduce discharge
- Split flow within a channel reduces discharge, and thus shear stress, in each split channel
- Reduced channel slope associated with local dams or grade control (resistant structures designed to control streambed elevation) placed above the normal stream bed elevation (beaver dams, log jams, culverts, etc.)

Figure 20. Aggradation, resulting in channel widening via streambank erosion. Sooes River watershed, Washington.

Channel Incision

Channel incision involves the progressive lowering of the channel bed relative to its adjacent land surface. Incised channels (also called entrenched or degraded channels) occur when hydraulic energy exceeds the channel bed's resistance to erosion, or when sediment output exceeds the sediment input to the reach.

Incision associated with decreased sediment supply may occur in response to any of the following conditions:

- Upstream dams may cause sediment "starvation"
- Removal of sediment from the channel, such as by dredging or in-stream gravel mining
- Decrease in sediment delivery to the stream system such as by cutting off access to a source area

Incision associated with increased hydraulic energy stream power or decreased streambed resistance to erosion may occur in response to any of the following conditions:

- Stream channelization and straightening causing a steepening of the channel profile, which increases the hydraulic energy
- Decreased channel roughness due to channelization, stream cleaning, large wood removal, and splash damming, all of which increase available energy to erode
- Lowering of base level, such as the lowering of a lake, removal of grade control (culvert, bedrock, log controls), which increases the slope
- Increase in runoff rates due to land use changes such as impervious surfaces (roofs, parking lots, roads, etc.), soil compaction, vegetation removal, conversion of forest to grass or heavy grazing in areas that experience overland flow during storms
- Concentration of high flows within the channel due to encroachment of walls, structures, or levees
- Channel bed disturbance which disrupts the armor layer (push-up dams or gravel mining), which typically results in smaller bed substrate, and thereby reduces the hydraulic energy necessary to mobilize it

Regardless of the causes, the response pattern of incised channels is remarkably similar throughout a variety of stream environments. Incised-channel evolution models are useful for tracking landform development through time, and predicting the trajectory of channel change. Schumm and others, [31] developed a channel-evolution sequence for a stream in Mississippi. The model assumed that the base level for the channel did not change, and that land use in the watershed remained relatively constant. The model (see Figure 21) described five successive channel reach types whose conditions include Stable (Stage I), Incising (Stage II), Widening (Stage III), Stabilizing (Stage IV), and a new, dynamic equilibrium (Stage V).

This model portrays a very common phenomenon occurring subsequent to channel incision – channel widening. As a stream channel incises, its flow capacity increases and stream energy becomes concentrated within the channel during low-probability flows, rather than dissipating on the floodplain. Additionally, bed erosion can destabilize stream banks by oversteepening the slope. A bank height threshold exists, beyond which the bank soil weight overcomes soil strength, causing the bank to erode by increased mass wasting. Hydraulic action undermines the bank toe, particularly after the level of the active channel incises below the root zone of the riparian vegetation, and/or after the channel erodes down to a more resistant substrate. This prevents buildup of material at the toe of the bank, preventing the bank from reaching a stable slope. Groundwater may discharge higher up on the bank, causing saturation and further destabilization. The combination of increased energy within the channel and reduced bank stability often leads to rapid bank erosion ("bank recession") and channel widening. This process is often coupled with the progressive formation of a new floodplain surface within the incised channel (i.e., channel recovery), unless, as often happens, the banks are artificially hardened to prevent further erosion.

Channel incision can result in a floodplain surface becoming high enough above the channel that it is no longer inundated by the current hydrologic regime (see Figure 22). The formation of such a perched floodplain, or terrace, disconnects that surface from the water table and affects the establishment and survival of riparian vegetation, ends the process of overbank deposition that builds floodplain soil, and leads to loss of wetland/floodplain habitat and backwater areas.

Figure 21. Diagram of a channel evolution model, showing cross sections on top and longitudinal profile at bottom (Adapted from Skidmore et al.[2]).

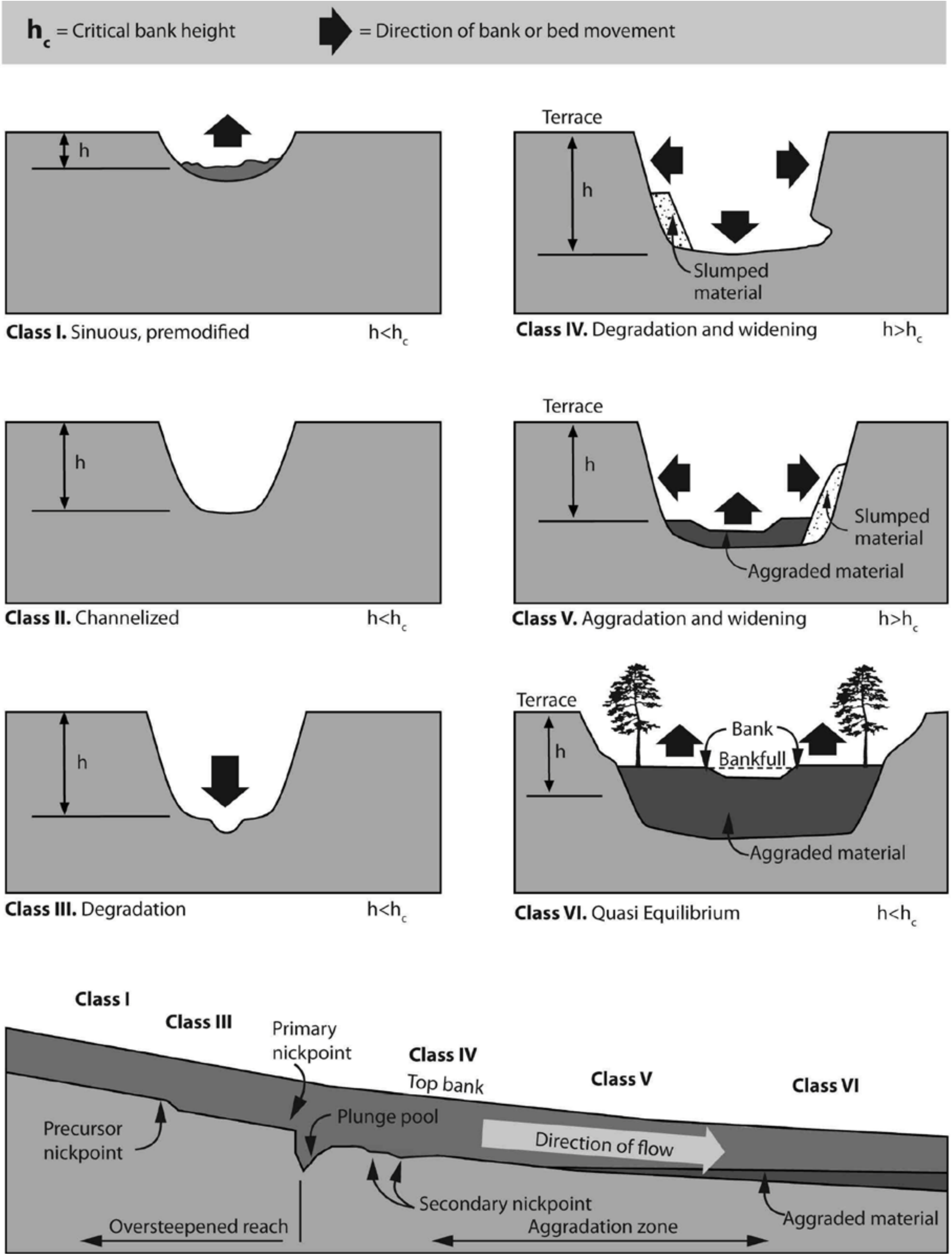


Figure 22. Channel incision. An example of channel instability in an incising channel. Columbia Creek, Oregon. Note undercut banks below rooting zone on left. Photo provided courtesy of Inter Fluve, Inc.

Channel incision will commonly grow in an upstream direction until encountering a grade controlling (i.e. resistant) element in the streambed. This resistant element, which can be natural (log, bedrock sill, coarse riffle) or man-made (culvert, pipeline, etc.), might then become a barrier to fish passage. Extreme caution must be exercised when such a barrier is removed, because this can allow the channel to continue incising upstream, destroying existing habitat and destabilizing the upstream reach (see Figure 23 and Figure 24).

Figure 23. Longitudinal profile through a culvert crossing, in absence of downstream channel incision. Note continuity of stream grade line (red).

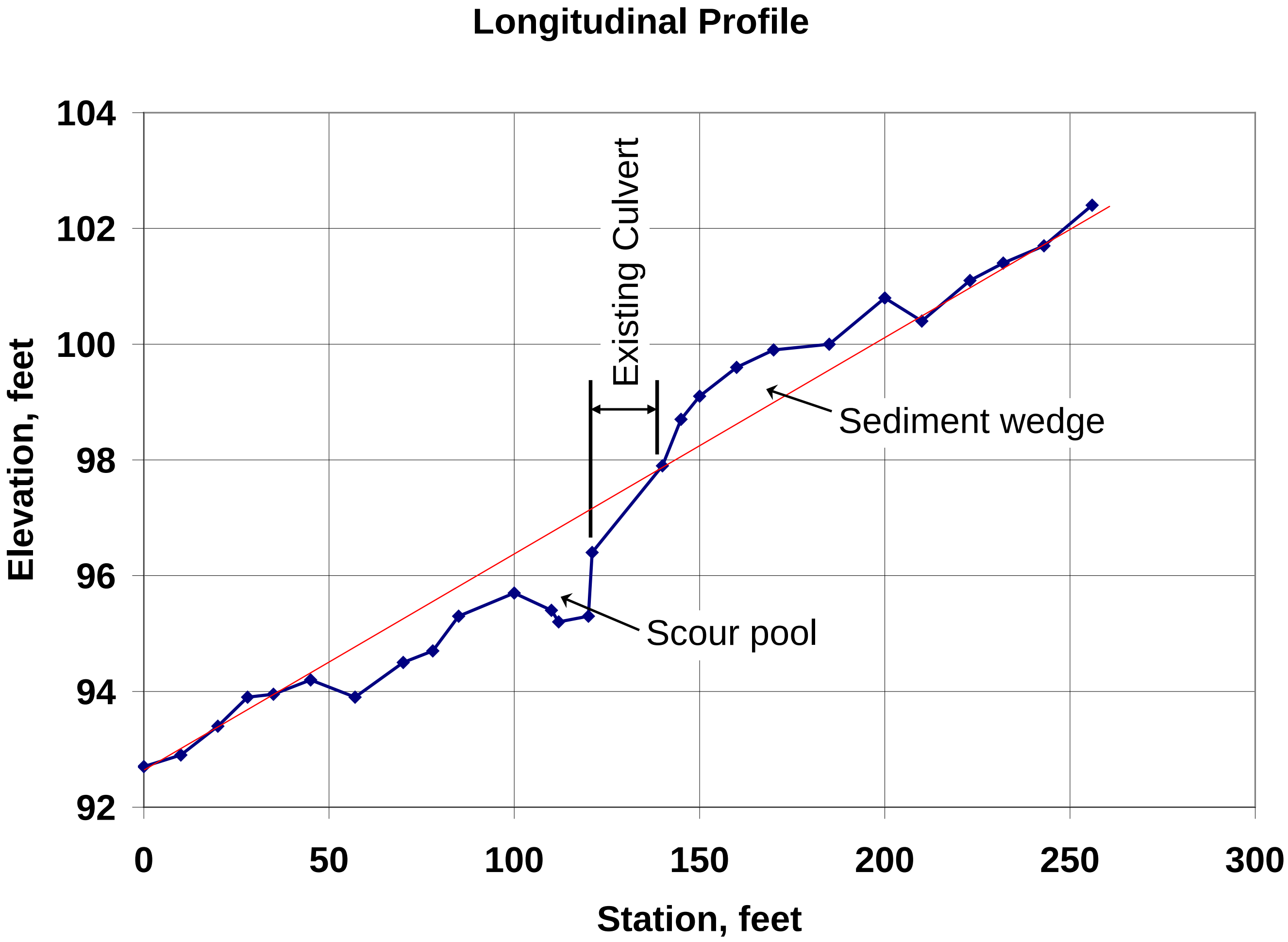
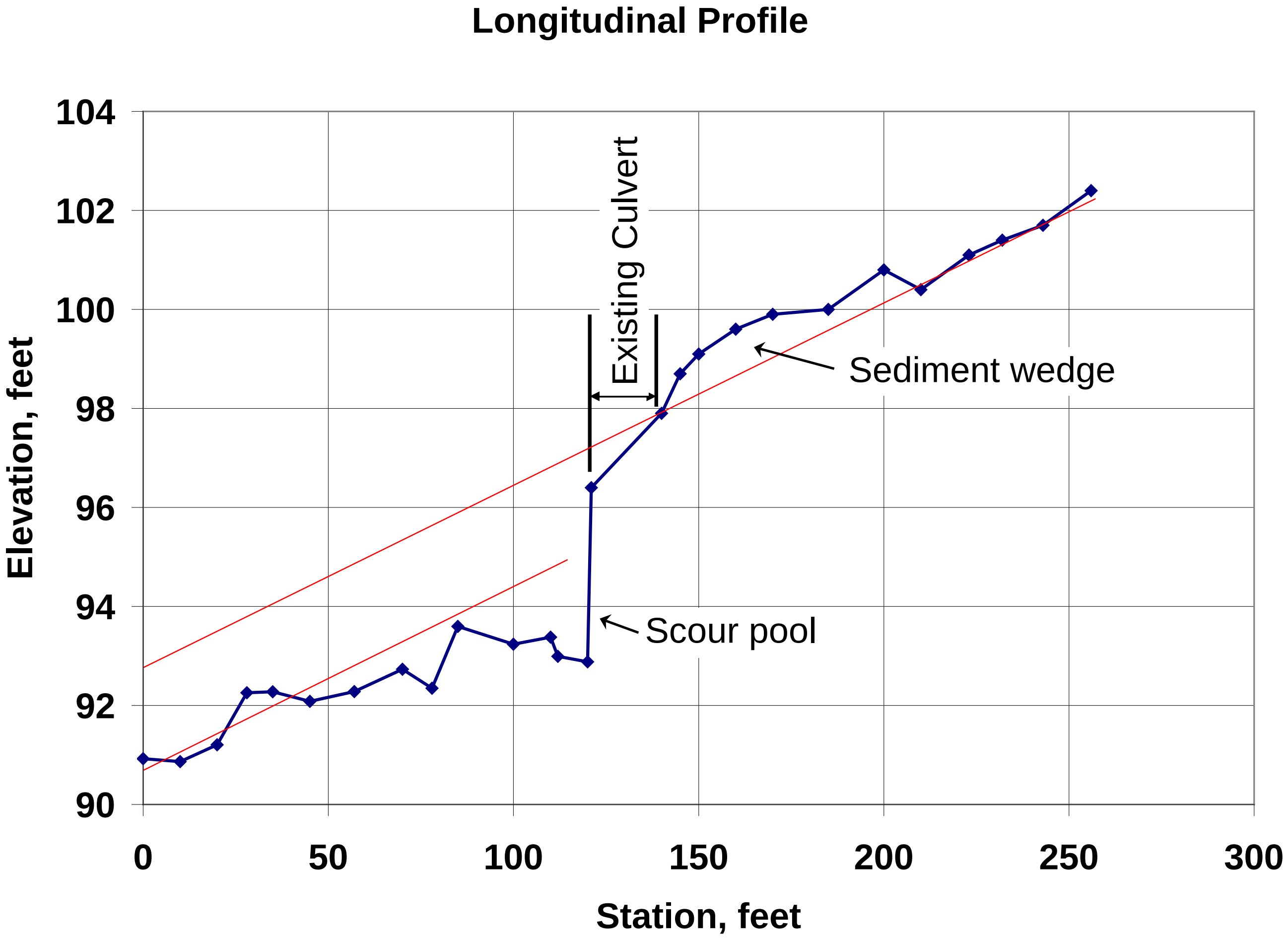


Figure 24. Longitudinal profile through a culvert crossing, in presence of 2 feet of downstream channel incision. Note break in stream grade line (red).



For a complete discussion of channel incision and incised river channels, refer to the Additional Reading section.

5.2 Lateral Channel Migration and Streambank Erosion

Channel migration is the progressive movement of a channel across a valley. It involves bank erosion and transport of eroded materials, and deposition. Lateral channel migration occurs within the context of equilibrium, provided that channel form does not change overall. In such cases, the width of the channel does not change – as a bank erodes laterally, it is balanced by deposition on the point bar across the channel, thereby maintaining channel form. However, increased rates of lateral migration may occur in response to disturbance, to external changes in sediment or hydrological regime, or to altered boundary conditions (such as destruction of streambank vegetation or removal of large wood).

Increased bank erosion rates can result either from increased lateral migration or from channel widening, which can be a symptom of aggradation, incision, downstream channel constriction, or loss of streambank resistance to erosion.

Increased streambank erosion may be initiated or exacerbated by the following conditions:

- Hardening of channel banks upstream or across the channel may reduce the channel's capacity to adjust locally, and may transfer the excess energy to an un-hardened area
- Channel aggradation
- Channel incision
- Riparian and channel bank vegetation removal reducing bank hydraulic resistance and soil resistance to erosion
- Excessive saturation of banks during low flow periods due to irrigation
- Rapid drawdown and saturation failures related to dam releases
- Reduction in local slope due to channel-spanning structures which elevate the grade, or to hydraulic constrictions such as bridge piers or footings downstream

5.3 Channel Avulsion

Channel avulsion is a process whereby a channel shifts its location by cutting across adjacent floodplain. Avulsion occurs naturally in meandering streams, most commonly cutting off a mature meander bend during long-duration or extreme overbank flows. Avulsion is the dominant mechanism for channel migration in some channel types, such as braided and island braided (anastomosing) systems. Avulsion can also be brought about by structures or management practices which interfere with lateral channel migration, inducing hydraulically inefficient channel geometries. Road crossings and streambank hardening has been known to trigger avulsion in this manner.

Avulsion occurs generally through headcutting and scour of a new channel through the floodplain. Floodplain slope is usually greater than channel slope, so for an equal flow depth, velocity and shear stress can be higher on the floodplain than in the channel. This is particularly an issue for wide shallow channels with active floodplains, because flow depth in the channel and on the floodplain can be very similar. This headcutting and scour may be initiated during overbank flows associated with large floods, logjams, beaver dams, or ice jams. Avulsion generally occurs when other channel conditions increase the volume of flow across the floodplain relative to the channel itself, thereby increasing the erosional forces on the floodplain. As the flow reenters the channel from the floodplain, it creates a zone of concentrated turbulence and shear stress acting on the streambank, which can promote head cut migration in an upstream direction across the floodplain. Aggradation within the main channel or a blockage of the main channel are the primary conditions under which flow energy increases on the floodplain. The reentry of floodplain flow to an incised channel will also promote headcutting and channel avulsion to an even greater degree than where incision is not occurring.

On the floodplain, restrictions that concentrate flow or removal of vegetation that slows flow and provides resistance to erosion may result in energy conditions that lead to avulsion during overbank flows. Man-made linear features such as fences, berms, trails, rows of plants, etc., can contribute to concentration of flow.

Avulsion occurs naturally in numerous types of channels.[32] Highly sinuous meandering channels may avulse due to the gradual reduction in sediment transport capacity as the meander loop increases in radius and length through ordinary lateral migration under equilibrium conditions. Increased length results in decreased slope, which causes channel aggradation and further loss of sediment transport capacity. During overbank flows, the differential between the slope of the channel and the slope of the floodplain eventually results in headcutting through the floodplain, causing a meander cutoff. This process creates a variety of habitat, including backwater alcoves, oxbow lakes and wetlands.

Multiple-thread channels with high loads of coarse sediment and debris are prone to blockage at the locations where flows split. This causes frequent shifting of the dominant thread, and less frequently, development of new channels across the floodplain as flows are forced overbank by in-channel aggradation or blockage by large wood complexes. Avulsion is perhaps the most common mechanism for channel migration in anastomosing or island braided channels. Formation of large wood complexes, or sediment deposition in response to large wood can force water onto the floodplain, or even onto terrace surfaces above the floodplain which have not been inundated for long periods of time. This results in a complex, dynamic system of side channels.

Finally, all channels are prone to avulsion if they become perched relative to their floodplain. This is common in alluvial-fan environments, in depositional response reaches or along relocated channel segments.

6 VEGETATION AND LARGE WOOD IN FLUVIAL PROCESS

Vegetation affects the geomorphic process and resultant channel forms by increasing resistance to erosion of channel banks (riparian vegetation) and by slowing and redirecting channel flow (in-channel wood). The type of vegetation that occurs naturally is a function of geological factors (e.g. soil), topography, climate, inundation frequency and the successional state or trajectory of various vegetative communities. Riparian vegetation plays an important role in maintaining a stable channel form by stabilizing streambanks and dissipating energy along the banks in virtually all channel types throughout the Pacific Northwest. The growth of riparian vegetation in or near the channel also facilitates floodplain formation as vegetation increases hydraulic roughness, reduces erosion and promotes sedimentation. Some of the most tortuous meanders occur in streams dominated by sedges in meadow systems. Willows commonly stabilize newly deposited materials in bars and thereby facilitate the creation of new floodplain area. Upland vegetation also plays a role in channel process by controlling hillslope erosion, thereby reducing sediment input to stream channels, and by determining soil hydrologic properties influencing runoff rates.

Vegetative colonization of flood prone surfaces tend to follow somewhat predictive pathways of succession given the inundation frequency of the surface colonized.[33] An understanding of various vegetative community successional trajectories and their change in community composition over time can provide valuable clues to the origins of various geomorphic features or the processes at play over the life span of that community. Dating of vegetation growing in the bottom of an abandoned side channel can to determine when a particular side channel was active or which particular flood disconnected the channel. Vegetative community types are also indicators of specific soil and inundation characteristics. For example, Oregon Ash is a riparian species very tolerant of continuous inundation during its dormant period but requires silty/clay soils and a dry period during the summer months. Vegetation therefore, can provide an independent and direct measure of near term fluvial activity and for long-lived species, an indication of equilibrium status. Vegetation communities and their successional status at a particular site can characterize geomorphic processes in ways no other means can.

Both upland and riparian areas also contribute vegetative debris to the channel. The role of large wood in channels is now recognized as a critical factor affecting geomorphology in forested environments and as a key component of channel design.[34,35] Large wood in streams form large roughness elements that create local turbulence and prevent uniform flow, thereby increasing the complexity of channel form through scour and deposition. Large wood in stream channels results from trees that fall from banks or hill slopes. Processes that initiate tree fall include wind throw, bank erosion, channel avulsion, tree mortality, mass wasting and land-use practices such as logging.[36]

In rivers large enough to float whole logs, large wood may be recruited from areas upstream and exported to areas downstream during peak flows. The ability of a reach to retain large wood becomes an important factor in determining the rates and styles of channel migration processes and streambank erosion. Retention of large wood is influenced by the size and quality of the wood, which is different for each species, and age, of tree.

The introduction of large wood into the channel affects both channel form and process by:

1. Creating steps in the longitudinal profile of the streambed (of steep, confined channels), thus dissipating energy, aiding in formation of both pools and riffles, and increasing sediment storage;[36]
2. Locally reducing channel gradient (i.e., above the log jam), thereby capturing a finer class of sediment than would otherwise deposit in the channel;
3. Initiating/regulating avulsion processes in anastomosing channels;
4. Influencing avulsion and channel migration in meandering channels;
5. Increasing in-channel hydraulic complexity, thereby increasing channel habitat complexity and cover;
6. Improving fish habitat by increasing types and sizes of pools[37] (pools associated with wood may be deeper and have more depth variability than free-formed pools[38]);
7. Inducing hydraulic head differential to promote hyporheic flow;
8. Forming channel bars and creating inducing sorted gravel deposits important to spawning (this influence has not been extensively studied);[39]
9. Promoting sediment deposition along the active channel and floodplain, which provides sites for riparian vegetation colonization, the growth of forested islands in the channel and forest floodplain development;[40]
10. Retaining small wood and organic detritus;
11. Regulating flow in side channels;
12. Promoting floodplain connectivity and periods of inundation by increasing channel roughness; and,
13. Stabilizing backwater and side-channel areas (chute cut-offs and oxbows).

The geomorphic effects of wood vary with the relative scale of stream size to log size. In small, headwater streams, large wood often spans the channel, or, if submerged, induces local sediment storage and steps in the water surface profile. In mid-sized streams, where the trees are similar in length to the channel width, large wood strongly interacts with the flowing water, and plays a significant role in the formation of pools, riffles, grade-controlling steps, and in formation of sediment deposits and sorting of streambed sediment into patches of different sized textures. The larger pieces of wood are generally not very mobile, often forming single-piece structures or structures comprised of a few logs, which influence local channel migration or widening. In larger channels, where the channel width is up to several times the length of a tree, large wood can become mobile. Like sediment, it is mobilized, deposited, and exported during peak flow events. In these channels, retention of large wood in the form of long-duration logjams is a key aspect of geomorphic process, affecting channel migration, avulsions, erosion, transport and retention or storage of sediment. Wood accumulations may increase channel migration through avulsion and the development of secondary channels. Islands formed as a result of large woody deposits may actually be quite stable.[22] Large wood can become the difference between one channel type and another, particularly where braided and anastomosing systems are juxtaposed.

Though standards for target amounts of large wood in streams have existed for many years, only recently have those standards begun to consider the appropriate geomorphic role of large wood besides its function as fish habitat. As important as large wood is to salmonid habitat quality, variations in amount, size, and style of wood accumulation need to take into account the geomorphic setting, forest type, and disturbance regime.[41] Fox and Bolton[41]have developed percentile distributions or numbers and volume of large wood pieces per 100 m, as well as number of key pieces, stratified by bankfull width and forest zone in Washington State.

7 ASSESSMENT METHODOLOGIES

7.1 *Geomorphic Reach Analysis: How to Identify and Characterize Key Processes and Potential Future Trajectories*

The most important components of geomorphic analysis can be summarized in four key points:

- Quantification and/or description of historical or equilibrium conditions and processes
- Recognition and quantification of departure from historical or equilibrium conditions and processes
- Understanding the causes of departure from historical or equilibrium conditions
- Evaluation of potential response (trajectory) to management actions

Habitat restoration, streambank protection, and other instream construction projects will likely be unsustainable or have unforeseen consequences if the driving forces of channel adjustments are not recognized and addressed. Consequently, projects designed to mimic or alter natural channel processes require that those processes be correctly identified and characterized. Characterization of geomorphic processes may involve qualitative description, relative or approximate quantification, or more detailed quantification, depending on the type of stream and its response potential, and degree of risk posed to natural resources by proposed actions.

7.1.1 *Overview of Basic Geomorphic Measurements and Reach Assessment*

Certain fundamental, reach-scale descriptive metrics exist that should be gathered for virtually any project. No matter what the questions are regarding geomorphic processes, this basic morphology information will be needed for a professional scientific evaluation. These basic metrics are summarized in Table 1.

Table 1. Basic channel morphology measurements, to be obtained for all investigations

Metric	Objective	Tools/Tasks
Longitudinal Profile	Channel slope on a reach scale Knickpoint identification for channel incision assessment Grade control (natural or man-made) identification Pool to riffle spacing Average and max pool and riffle depth	Level survey over minimum 300 to 500 ft or 20 channel widths GIS[F] , LIDAR[G], Topographic map (all too coarse for most applications, but can be used to characterize reach)
Cross section	Flow area Presence of a floodplain Floodplain/Bankfull elevation Elevation of terraces, if any Channel confinement	Level survey, to elevation of twice the max riffle depth or greater Topographic survey Bathymetric survey from boat
Planform pattern	Sinuosity Style of channel migration Radius of curvature	Aerial photos, topographic maps, LIDAR, GIS Topographic survey (for the most detail)
Streambed sediment texture (sizes)	Surface D_{50}, D_{84}, D_{100} Silt/Clay, Sand, Gravel, Cobble, Boulder, Bedrock percentage	Surface particle count Bulk sieve sample Streambed photography

Besides the basic measurements, most investigations will require a reconnaissance-level geomorphic assessment. This assessment will include some or all of the metrics summarized in Table 2, depending on the type of channel, its size, and type of proposed management or alteration:

[F] GIS is Geographic Information System

[G] LIDAR, sometimes called laser radar, is a technology for creating detailed surface imagery and using pulsed laser light, usually from aircraft.

Table 2. Reconnaissance-level geomorphic assessment. Which elements are appropriate for a given investigation depends on the type and size of river, its geomorphic setting, and the type of proposed management or restoration.

Investigation	Objective	Tools/Tasks
Geomorphic or valley setting	Characterize setting and associated landforms	Aerial photos, topographic maps, watershed analyses, geology reports or maps, soil survey reports
Geomorphic reconnaissance	Map and characterize channel-adjacent surfaces (floodplain, terraces, erosional surfaces)	Field survey Soil profiles Vegetation survey including age of woody plants and riparian successional status of various communities.
Hydrological assessment	Characterize hydrological regime	USGS[H] or other (state, city, county) stream gage data Peak flow analysis and flood history
Streambank erosion survey	Document streambank condition and erodibility	Field surveys, documenting bank materials, angle of bank surfaces, rooting depth and density, vegetative cover, natural and man-made armor, style of erosion, directly measured erosion rates from cross sections or erosion pins Protocols: BEHI.[I] Link changes observed to flood history if available.
Sediment deposition survey	Document recent deposition history	Field surveys, documenting pool infilling, fresh in-channel and floodplain deposition depths, mid-channel and transverse bar development. Link changes observed to flood history if available.
Channel migration assessment	Document style and rate of channel migration over historical record	Time sequence of aerial photos, old surveys such as the GLO[J] surveys. Link changes observed to flood history if available.

[H] United States Geological Survey

[I] BEHI is the bank erosion hazard index, a protocol developed by Rosgen.[27]

[J] GLO is the General Land Office, a former government agency that conducted land plat and transect surveys in the nineteenth and early twentieth centuries over much of the western United States.

Large wood assessment	Determine large wood recruitment rate, retention or persistence and function	Field surveys, aerial photo sequences
Streambed sediment structure	Determine sediment regime and disturbance history	Field investigation to look for armor/substrate contrast, buried armor layers, matrix vs. framework supported substrate, sand on top of gravel, embedded condition, etc.

The initial characterization of the project reach provides the geomorphologist with basic information about the type and size of stream, and allow preliminary inferences about such things as:

- How sensitive might this channel be to disturbance, or to altered hydrology or sediment regime?
- Might this stream be unstable, that is, out of equilibrium (aggrading, incising, changing from one channel type to another)?
- What sort of channel migration rates and bank erosion rates might be expected for this type of stream under equilibrium conditions? Under current conditions?
- What is the style of channel migration (meander migration, avulsion, or both)?
- Is the sediment load high, medium, or low?
- Are the hydraulic forces high, medium or low?

These inferences are used to suggest further geomorphic reconnaissance (Table 2), to gain certainty in understanding which geomorphic processes are significant, which processes, if any, need to be quantified, and what trajectory the channel is likely to take under various management or restoration scenarios. Reconnaissance-level geomorphic studies provide specific data needed to justify conclusions about what is going on and what sort of management or treatments might be feasible to consider.

If risk to resources is high, and geomorphic reconnaissance identifies the stream as being sensitive as opposed to resilient, more detailed geomorphic investigations or engineering studies, such as those listed in Table 3, might be justified.

Table 3. Detailed geomorphic and engineering investigations. Refer to the *Hydraulics* Appendix and *Sediment Transport* Appendix for detailed explanation of concepts and methods listed herein. Note that some of the models listed under Tools/Tasks are commonly encountered (those marked with an asterisk "*"), while others are rarely used due to cost or lack of familiarity among practitioners. These latter models are mentioned for greater completeness, and to provide context for the state of the art.

Investigation	Objective	Tools/Tasks
1-Dimensional Hydraulic Model	Using hydrological information, estimates: water surface elevations for selected index discharges floodplain connectivity average hydraulic force and shear stress	Hydrological information needed, either flow duration curve or index discharges; channel dimensions from longitudinal profile, cross-sections, or topographic survey; HEC-RAS*[K] MIKE11[L]
2- Dimensional Hydraulic Model	In addition to items listed under 1-D hydraulic model, estimates: Local hydraulic force and shear stress Near-bank shear stress Map zones of potential scour or deposition Assess habitat potential	Detailed topographic reach survey; FESWMS*[M] MD-SWMS*[N] SMS-RMA2[O] River2D MIKE21
Sediment Transport Model	Relative or absolute sediment conveyance under different scenarios Identify high vs. low sediment transport reaches, depositional reaches	BAGS*[P] HEC-RAS* SAM[Q] HEC-RAS or HEC6 K FLUVIAL12 (sand or fine gravel only) Bedload samples for model calibration
Sediment Budget	Estimate relative impacts of specific disturbances (e.g. landslides, bank erosion) Estimate recovery time from disturbances Fate and routing of sediment Reservoir filling rate Estimate relative magnitude of	Aerial photo and GIS analysis with ground-truthing to include: Landslide inventory Road erosion model or inventory Bank erosion inventory Fluvial sediment volume

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[K] Hydrologic Engineering Center – River Analysis System

[L] MIKE11 and MIKE21 are hydraulic models available from DHI (Danish Hydraulics Institute)

[M] Finite Element Surface Water Modeling System

[N] Multi-Dimensional Surface Water Modeling System

[O] Surface water Modeling System – Resource Management Associates

[P] Bedload Assessment for Gravel-bed Streams

[Q] Sediment Analysis Model

	sediment sources for source control	inventory Alluvial fan/delta inventory Surface erosion models (e.g. RUSLE*[R]) Reservoir bathymetric surveys
Geotechnical model	Quantify streambank stability Identify relative influence of stabilizing/destabilizing factors, including plant roots, plant species, fluvial erosion	BSTEM[S]
Effective Discharge Analysis	Identify channel-forming flow for design purposes Estimate total sediment yield, size distribution Predict effects of altered hydrology on sediment transport, yield, and sizes	Flow duration curve Sediment transport model
Channel Migration Zone delineation	Identify probable future channel locations and risk of erosion, avulsion Identify lateral limits to bank erosion Identify future large wood inventory Identify local sedimemt sources Identify lost opportunity due to bank hardening	Aerial photo sequences, LIDAR, field reconnaissance, flood history.

7.2 Basic Geomorphic Measurements

7.2.1 *Channel Longitudinal Profile*

Channel longitudinal profile is a display of the elevation of the streambed versus distance along the channel itself. Besides the streambed, other features might be measured, including the water surface elevation and the bankfull elevation, if evident. The longitudinal profile is used to accurately determine channel slope, which is essential for most modeling, design and assessment. A longitudinal profile is essential for identifying and measuring knickpoints when channel incision is of concern. Knickpoints in coarse-bedded (e.g. gravel-bedded) streams can be subtle and difficult to identify without a profile. Other information can be gleaned from it as indicated in Table 1.

A field survey using either topographic surveying techniques or level surveying techniques is the most accurate way to create a longitudinal profile. A good reference for this is Harrelson et al.[42]

Other techniques exist that are much less accurate, but faster. These techniques may be justified for geomorphic or habitat condition studies that cover large areas, but should never be used for

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[R] Revised Universal Soil Loss Equation

[S] Bank Stability and Toe Erosion Model design purposes, and are not accurate enough to identify knickpoints. For example, it is possible to create a crude longitudinal profile and to measure slope using elevations and distances taken from topographic maps, GIS, or LIDAR data. The EMAP[T] stream survey procedure[43] uses hand-held instruments to measure slope, bearing and distance over short (roughly 10-meter) segments, which are then linked together into an extensive reach profile.

This procedure was developed by EPA[U] for characterizing physical habitat over numerous reaches in a watershed. It also can be applied to estimating pool residual depths and volume, which are metrics of habitat complexity and indicators of aggradation (pool infilling).

A common mistake is to measure the longitudinal profile over too short of a distance, such as, restricting the survey to a road right-of-way. To be representative, the profile must encompass at least several pool riffle cycles above and below the site. Road crossings are often placed at geomorphic transition, such as the toe of a hillslope, the rim of a terrace, etc, and can be sited on top of important transitions in geomorphic processes such as sediment transport. An appropriately long profile will capture this transition. Harrelson et al.[44] recommend a minimum of 20 channel widths.

This factor is particularly important when investigating the presence and magnitude of channel incision, such as for culvert removal or replacement. An explanation of this phenomenon can be found in Castro,[45]

If the profile is to be used for the basis of a hydraulic model, other issues dictate the length necessary. Please review the *Hydraulics* Appendix for more details.

7.2.2 *Channel Planform*

Channel planform is the two-dimensional pattern of a stream as seen in map (aerial) view. It is most efficiently determined from aerial photos, but in some cases field surveying (e.g. topographic survey) may be necessary if, for example, the channel is obscured by vegetation. Elementary channel planform reconnaissance reveals sinuosity, proximity of valley sides, radius of curvature, and style of channel migration. Reviewing a series of sequentially dated aerial photos may also provide clues about recent channel migration or bank erosion that can suggest further geomorphic analysis, such as channel migration zone or bank erosion studies.

Planform is quantitatively described in terms of sinuosity by the equation:

$$P = D_c/D_v$$

Where P = sinuosity, D_c = channel length (feet or meters), D_v = valley length (feet or meters). Other parameters that describe channel planform in streams with meandering patterns are the meander belt width, wavelength, amplitude, and radius of curvature of an individual meander bend (see Figure 25). Collectively, these planform characteristics can be compared to historical conditions along with flood history in order to assess channel behavior over time, and expected ranges of values for channels of the same type in the same physiographic province. Radius of

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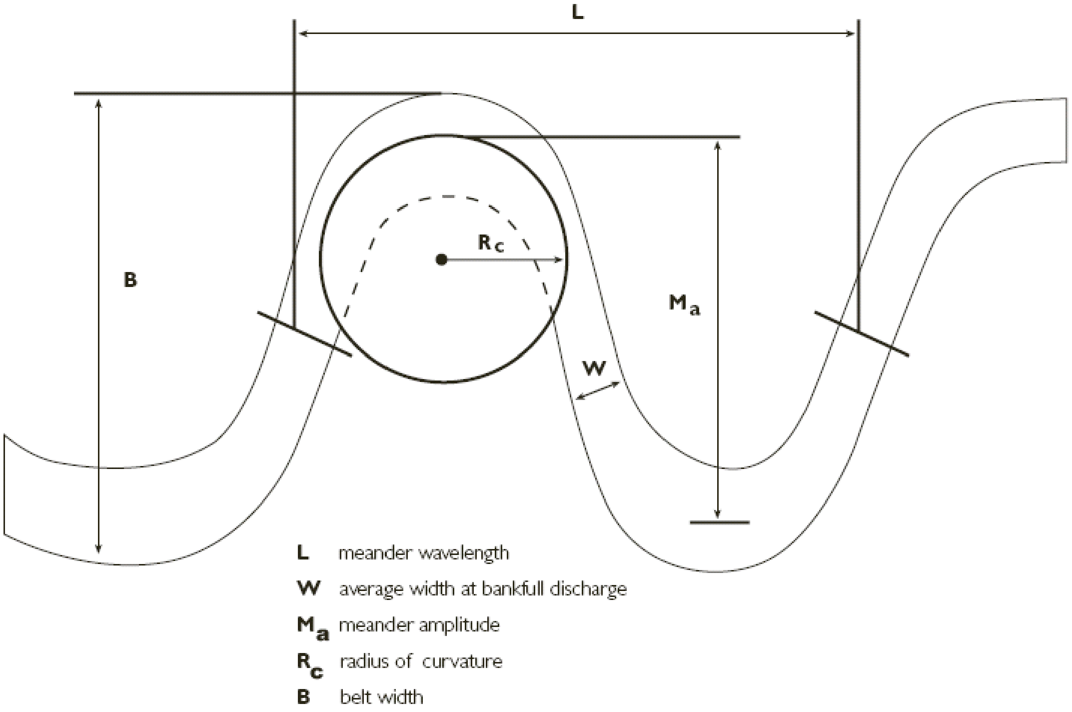
[T] Environmental Monitoring and Assessment Program

[U] U. S. Environmental Protection Agency curvature is particularly important, as overly sharp radii greatly increase the near-bank shear stress and erodibility. Proximity to valley sides indicates a coupling between hillslope processes and the stream channel. Where the meander belt is similar in magnitude to the valley width, or where the stream approaches the valley wall, these sites become actual or potential sediment sources and migration boundaries.

Figure 25. Channel planform characteristics.

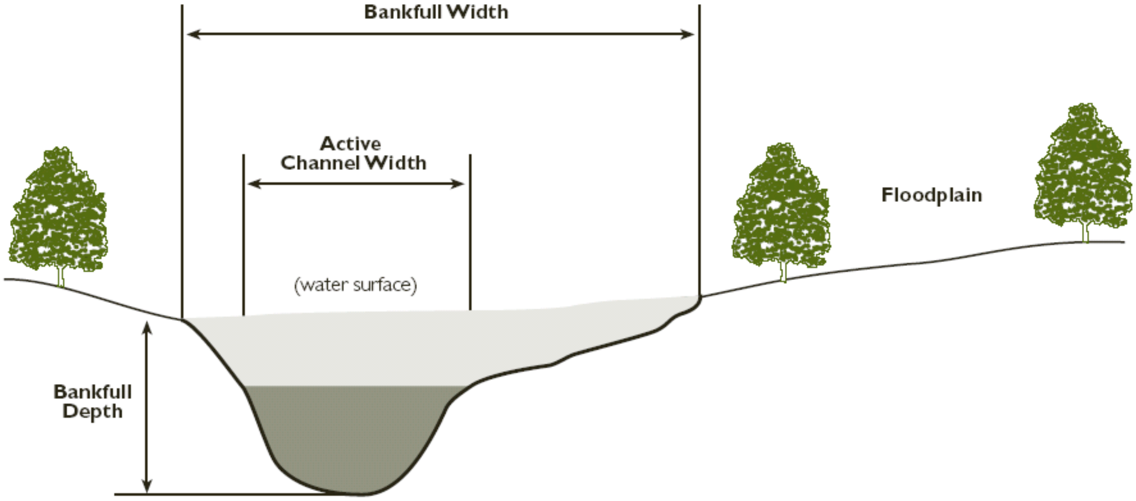


7.2.3 *Channel Cross-Section*

Channel cross-section is a display of elevation versus distance across the channel, perpendicular to the flow, typically viewed in the downstream direction. A set of surveyed cross-section points should include, at a minimum, terrace elevation, floodplain elevation, top of bank, bank toe, lower limit of vegetation, and thalweg, with enough intervening points to define the shape of the channel. The ends of the cross-section should extend far enough up to define at least some of the important peak flows, although the level of detail can be coarser above bankfull. In some geomorphic settings, the elevation at twice the maximum riffle bankfull depth has been shown to encompass the 50-year flood.[46] In the Rosgen classification system, the zone delimited by twice the bankfull depth is called the "flood prone area," and is used to define the entrenchment ratio (W_{fp}/W_{bf}, where W_{fp} = flood prone area width and W_{bf} = bankfull width). Typical dimensions measured from a channel cross-section include bankfull width, bank height, bank slope, and channel maximum and average bankfull depth. By convention, the right and left banks reflect the sides of the channel as viewed in the downstream direction (see Figure 26). The edges of the active channel (typically, the portion of the channel devoid of perennial vegetation) and the ordinary high water mark may be included although these do not have geomorphic significance.

Besides the full cross-sections, width, bank height and thalweg depth should be measured at multiple locations in the reach to characterize the range of variability of pools and riffles. From these locations, a smaller number (minimum: one riffle, one pool, and one pool tail-out zone or other area likely to show response) can be selected that are deemed "typical." More detailed instructions for measuring cross sections can be found in Harrelson et al.[44]

Figure 26. Channel cross-section.



7.2.4 *Streambed Substrate Analysis*

Assessment of sediment transport processes requires quantitative information on streambed substrate. The most accurate way to do this is with a volumetric sample taken from a location judged to be typical of the alluvial materials most recently moved or displaced. Sometimes, this can be obtained from a dry gravel bar, but more often it requires instream sampling of an alluvial bedform. The surface layer is gathered and sieved separately from the subsurface layer, yielding a particle size distribution (percentage in each size class) for each stratum. Size distributions are based on the logarithmic Phi (Φ; powers of two) scale. That is, 1 – 2 mm, 2 – 4 mm, 4 – 8 mm, etc. The size distributions of the surface and subsurface, and their relationship, provides quantitative information about the average sediment load volume and size, the critical shear stress for bed mobility, fine versus coarse sediment sources, hydraulic roughness, spawning habitat quality, and hyporheic flow potential. From these size distributions, sediment benchmark parameters such as the median size (D_{50}), eighty-fourth percentile (D_{84}), percentage of fines and maximum particle size (D_{100}) are determined. Bunte and Abt[47] is an excellent general reference of streambed substrate sampling. Interpretation of sediment structure (layering) is discussed below, and in the *Sediment Transport* Appendix. A practical procedure for collecting a volumetric streambed sample is described in McNamara, M.L. and T. Sullivan.[48]

Some investigators prefer to assess sediment using a pebble count procedure, such as the 100-point Wolman pebble count, which is based on collecting amd measuring a surface particle with each footstep, or the more statistically-defensible 400-point grid sample. Pebble count information is useful for basic channel description (e.g. Table 1), assessing hydraulic roughness, for characterizing the maximum-sized alluvial particle (called the dominant particle), and for channel classification in some systems (e.g. Rosgen classification). For these applications, the pebble count may be superior to the volumetric sample, since a more extensive area on the bed can be sampled. However, for sediment transport assessment (including critical shear stress) or assessment of percentage fine sediment, the pebble count is not recommended, since it is biased against particles smaller than the human fingertip, which can represent a significant portion of the sediment load even in gravel or cobble-bedded streams. Substrate and sediment transport analysis are covered in the *Sediment Transport* Appendix.

7.3 Reconnaissance-level geomorphic assessment

The basic measurements described in Table 1 will give rise to hypotheses and questions about stream condition and geomorphic processes that require further investigation. Table 2 provides a list of reconnaissance level investigations, which are mostly field-based studies or involve a field “ground truthing” component. More specialized investigations, listed in Table 3, may be necessary if the risk to resources or sensitivity to change is high enough to require more quantitative certainty that can be obtained with reconnaissance level study. Some of these items are described in other chapters, and will only be briefly mentioned here.

7.3.1 *Geomorphic or Valley Setting*

Taking an integrative, watershed-scale look at where, and how, a site “fits” into its landscape is helpful. This is sometimes called “geomorphic setting” or “valley setting.” One of the many classification systems available can be used to describe the geomorphic setting. For example, the Montgomery and Buffington[24] stratification of channels into source, transport, and response reaches is useful to describe the context as it relates to sediment dynamics. Likewise, there are classification systems that describe landforms, or that describe valleys according to their morphology and means of formation (e.g. the “Level I assessment” in Rosgen[46], or the U.S. Forest Service Geomorphic Classification System in Haskins, et al.[49]). However, a qualitative description of the reach of interest in the context of its watershed is usually all that is necessary. This description would address, for example:

- synopsis of watershed geology (rock types, topography/relief, disturbance mechanisms, known fault line locations)
- Climatic conditions of the watershed (rainfall, snow, rain on snow patterns)
- overall sediment yield (high, medium, low)
- role of fluvial sediment (colluvial/alluvial, source/transport/response)
- description of the landform or valley in which the channel lies, and its position within, and linkages to, the rest of the watershed
- role of large wood, if any (spans channel, interacts with flow as single, immobile pieces, forms stable jams, forms unstable jams, acts as a channel forming element, acts as mobile sediment, etc.)
- floodplain/channel interaction, if any
- sources of sediment, including local sources and their importance to geomorphology and for habitat
- predominant watershed vegetative cover
- synopsis of watershed management history, including changes to vegetative cover
- landform stability (expected stability of the channel and its valley, as determined by the Earth science literature or actual channel history, if known).

Sources of information for these questions include existing reports or watershed analyses, examination of maps and aerial photos, and most importantly, reconnaissance-level field investigation by a person with training in geomorphic observation.

7.3.1.1 Geomorphic reconnaissance

It is often helpful, and sometimes essential, create a rough map of the channel and its nearby landforms, including the floodplain, terraces, secondary channels and wetlands, etc. The main objective is to characterize these adjacent surfaces with regard to how they interact with, or potentially will interact with, the river, on a reach scale. Factors to document include:

- inundated frequently, infrequently, or never
- depositional (receives sediment from the river) or erosional (acts as a source of fluvial sediment)
- sources of large wood
- evidence for past channel location
- apparent age of the surface (soil development, plant community stage, age of trees)

In many cases, geologic studies or maps, combined with aerial photos, will offer significant insights, which can be field checked. Important clues to site or landform history, disturbances, and historical or currently active processes may only be evident from field study.

7.3.2 *Streambank erosion survey*

As mentioned previously, even stable channels erode. Excessive erosion can be a symptom of local disequilibrium, altered watershed conditions, or reach scale instability, each of which suggests a different management response. Thus, it is very important to quantitatively characterize the rate and extent of streambank erosion, if it is of concern, before proposing corrective management. Relevant metrics include:

- recent flood history
- maximum, and average rate of bank erosion (ft/year or m/year)
- extent of bank erosion (percent of streambank in an actively eroding condition)
- streambank condition, including bank angles, materials (soil and subsoil) comprising streambank, soil stratification, rooting density and depth,
- mechanism of streambank erosion (mass wasting, hydraulic erosion)
- elements providing cover from erosion (vegetation, rocks, logs, etc.)
- factors promoting increased erosion (bank saturation, hydraulic redirection, trampling by cattle, etc.)

Time series of aerial photos are the most reliable method of measuring bank erosion rates over years to decades. Increasingly, LIDAR and other remote sensing technologies are becoming useful as the available period of record becomes longer, encompassing more floods and other disturbances. Direct measurement of streambank erosion at selected sites, using surveyed cross-sections or bank erosion pins (e.g. Harrelson et al.[44]), provides the most accurate evidence of site-specific bank erosion rates, but may be difficult to generalize to reach average. Regardless of how erosion is measured it is important to place that rate of erosion into context with the flood history of the site.

Several field protocols exist for documenting streambank erosion potential. To mention one, Rosgen's Bank Erosion Hazard Index (BEHI)[50] generates rankings based on a mix of seven estimated or measured factors. The Pfankuck Channel Stability Index[51], although still in use, cannot be recommended as it assumes that the presence of large wood increases bank erodability, which is not necessarily the case, and thus tends to assign poorer "channel stability" rankings to sites with large wood, regardless of the geomorphic function of the large wood or the channel type.

It is important that streambank erosion rates and indices be interpreted correctly. A common mistake is to use them for computing volumes of sediment input for sediment budget purposes without considering the counterbalancing effects of deposition within a reach.

7.3.3 *Sediment deposition survey*

Patterns of sediment deposition can indicate channel instability such as aggradation. Reconnaissance-level field surveys are employed to map and describe in-channel sediment deposition and sedimentary structures, such as:

- mid-channel or transverse bars (bars that direct the flow into the bank rather than downstream)
- burial of large wood or boulders
- pool infilling

Floodplain deposition can supplement other diagnostic observations, and suggest studies to quantify aggradation rates. Regardless of how deposition is measured or mapped, it is important to place the episode into context with the flood history of the site. This provides the investigation team with a better understanding of the processes that lead to deposition at the site.

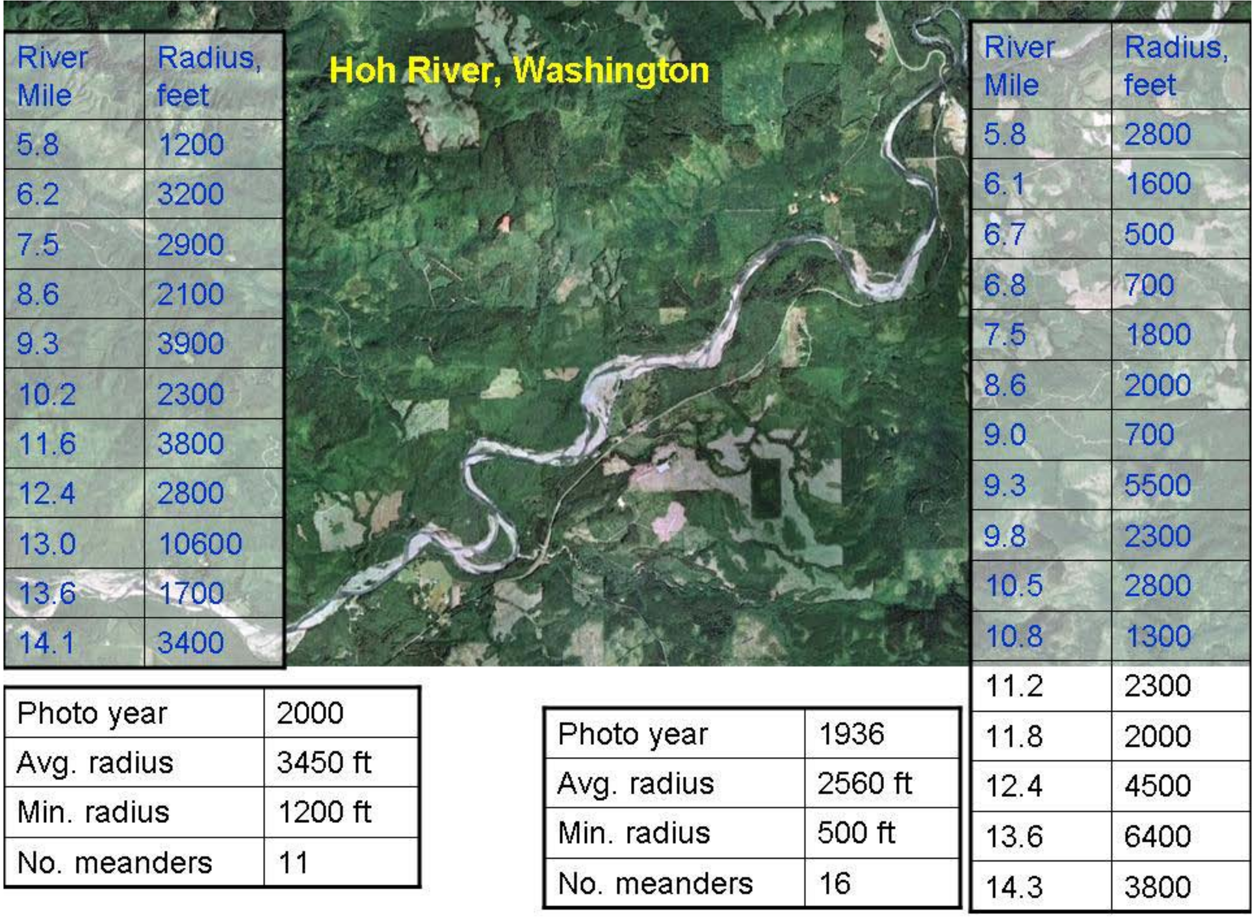
7.3.4 *Channel migration assessment*

Alluvial channels migrate over time. As discussed previously, this migration process is part of the sediment equilibrium that occurs in alluvial streams, and is responsible for creating and maintaining certain types of habitat, such as side channels and backwater alcoves. Documenting the rate of channel migration is essential to provide context for actions based on perceived erosion problems, or actions that may preclude future opportunities for channel migration.

For channel migration assessment, time series of aerial photos are the predominant tool. Changes in channel location from one photo series to another can be converted into average channel migration or bank erosion rates relative to the intervening flood events that occurred between photos. When doing this, it is important to make these computations at numerous points within the reach, selected to represent a balanced stratification of geomorphically distinct positions, such as outer meander bends, pool tail out zones, riffles, straight reaches, etc. It is also desirable (and straightforward) to estimate meander radii of curvature from the photos, so that changes to the distribution of radius of curvature over time can be evaluated.

It is important to bear in mind that the earliest photography available (generally from the 1930s) often represents a time period when significant landscape alteration (grazing, log removal and timber harvest) had already occurred, and that the level of disturbance often exceeds current disturbance levels. No reason exists to assume that a morphology seen in an older photograph would necessarily be stable under current hydrologic and landscape conditions, nor that this older morphology represented equilibrium conditions (see Figure 27).

Figure 27. Comparison of numbers and radius of curvature distribution of meanders for a reach on the Hoh River, Washington, in years 2000 versus 1936. Note that in 1936, there were more frequent meanders, more meanders with very small radius of curvature, and smaller average radius, which is likely an unstable condition (Photo courtesy of Google Earth).



River Mile	Radius, feet
5.8	1200
6.2	3200
7.5	2900
8.6	2100
9.3	3900
10.2	2300
11.6	3800
12.4	2800
13.0	10600
13.6	1700
14.1	3400

Photo year	2000
Avg. radius	3450 ft
Min. radius	1200 ft
No. meanders	11

Photo year	1936
Avg. radius	2560 ft
Min. radius	500 ft
No. meanders	16

River Mile	Radius, feet
5.8	2800
6.1	1600
6.7	500
6.8	700
7.5	1800
8.6	2000
9.0	700
9.3	5500
9.8	2300
10.5	2800
10.8	1300
11.2	2300
11.8	2000
12.4	4500
13.6	6400
14.3	3800

7.3.5 *Large wood assessment*

Field assessments of large wood have traditionally been focused on the number of pieces above certain size thresholds per unit distance within the actively wetted portion of the channel. Although this information can be valuable for habitat quality assessment and assessment of gross change within the stream system over time, what is usually missing is information about the geomorphic function of that large wood. Qualitatively at least, a large wood assessment should include descriptions of the geomorphic role of large wood, and also of smaller sizes of wood if they are playing a geomorphic role. For example:

- Does the wood span the channel without touching the water except during high flows?
- Are the dominant pieces longer than the channel width, making them therefore essentially immobile?
- Do the pieces form stable logjams?
- Do the pieces tend to exist as single logs or small clusters determined by how they fell in?
- Do they form logjams that are not stable (which is common with small wood)?
- Does large wood enter the stream channel mainly by bank erosion, windfall or by rafting at high flows?
- Does large wood appear to be a dominant geomorphic element, either by imposing sediment deposition or by affecting channel avulsion processes?
- What tree species make up the large wood, are these logs long-lasting or not and are they still available for recruitment?
- What is the relative transport rate of wood during flows that raft wood?

Recently, there have been efforts to standardize large wood survey techniques and make them more comparable, as well as more inclusive of geomorphically relevant information. For examples, see Wohl et al.[52]

7.3.6 *Streambed Sediment Structure*

Documentation of streambed particle size distribution or *texture* has become standard in most rivers investigations. However, to a trained observer, the *structure* of streambed sediment carries a wealth of information about the sediment transport regime, the state of equilibrium, and the response potential of the channel to altered sediment equilibrium. Structure refers to the layering of sediment, and the relationships between sediment grains comprising a layer. This is described in greater detail in the *Sediment Transport* Appendix. Field investigations should look for and document the following:

- contrast in size distribution between armor and subsurface layers
- presence of buried armor layers
- matrix- versus framework- supported substrate
- embedded condition of surface layer
- bimodal surface layer
- sand moving on top of a gravel armor layer
- degree of imbrication amongst various particles

Documentation of these factors can assist in the decision of whether to pursue sediment transport modeling in cases where proposed management might affect sediment dynamics, can assist in selection of modeling parameters, and can suggest which model(s) are appropriate to use. More discussion of streambed sediment structure can be found in the *Sediment Transport* Appendix.

7.4 Detailed geomorphic and engineering investigations

When both the risks to resources and the response potential of the stream channel are high, detailed, quantitative geomorphic or engineering investigations such as listed in Table 3 may be justified.

7.4.1 *Hydraulic modeling*

Hydraulic modeling is a tool commonly employed by engineers, but its potential in assessing geomorphic processes is sometimes misused or overlooked. The first of these issues arises when hydraulic models are used as a surrogate for sediment transport modeling. A well calibrated hydraulic model can predict in-stream velocities and streambed shear stress at discharges of interest. This can be highly valuable in designing *threshold channels*, that is, channels where the bed and banks are designed to be immobile under most conditions. However, the predicted ability to move a certain size of particle, such as the D_{84}, at a certain index flow, such as bankfull discharge, is not the same as sediment modeling, and can miss potential imbalances in sediment transport in channels that are fully alluvial. Similarly, the identification of zones of high shear stress (which is a particular benefit of the two-dimensional hydraulic model) in an alluvial streambed can suggest where scour will occur but not its magnitude, since the near bed hydraulics will change as scour proceeds. Another caution is that, currently, the available hydraulic models do not contain state-of-the-art sediment transport models, even though some of these hydraulic models have advertised capability of performing sediment transport computations. Thus, these hydraulic models can give misleading or seriously inaccurate sediment transport results (see the *Sediment Transport* Appendix for further discussion).

However, in their proper context, hydraulic model can answer questions that are sometimes overlooked, such as:

- How frequently is the floodplain inundated under current conditions?
- Where should various plant communities be planted?
- How will site hydraulics change as vegetative communities grow or change?
- What is the distribution of velocities found in a reach under current or proposed conditions?
- What discharge is necessary to mobilize a “typical” log in a stream reach?
- How will site hydraulics change as structural features recruit or shed woody debris?

7.4.2 *Sediment transport models*

Commonly, the concern that drives the choice to use a sediment transport model is whether or not a reach can convey the entire sediment load including all of the sizes delivered to it. However, a sediment model can also be used to compute relative sediment capacity of various reaches within the stream segment, to identify potential depositional reaches, or reaches which stand near the threshold between transport and depositional in character. Sediment transport models can also help estimate fluvial sediment loads, and maximum sediment transport capacities in colluvial reaches. As with any modeling effort, the quality of model results are dependent on the level of effort made to collect accurate calibration data. Use of models to extrapolate data beyond the range of measured conditions may introduce significant errors.

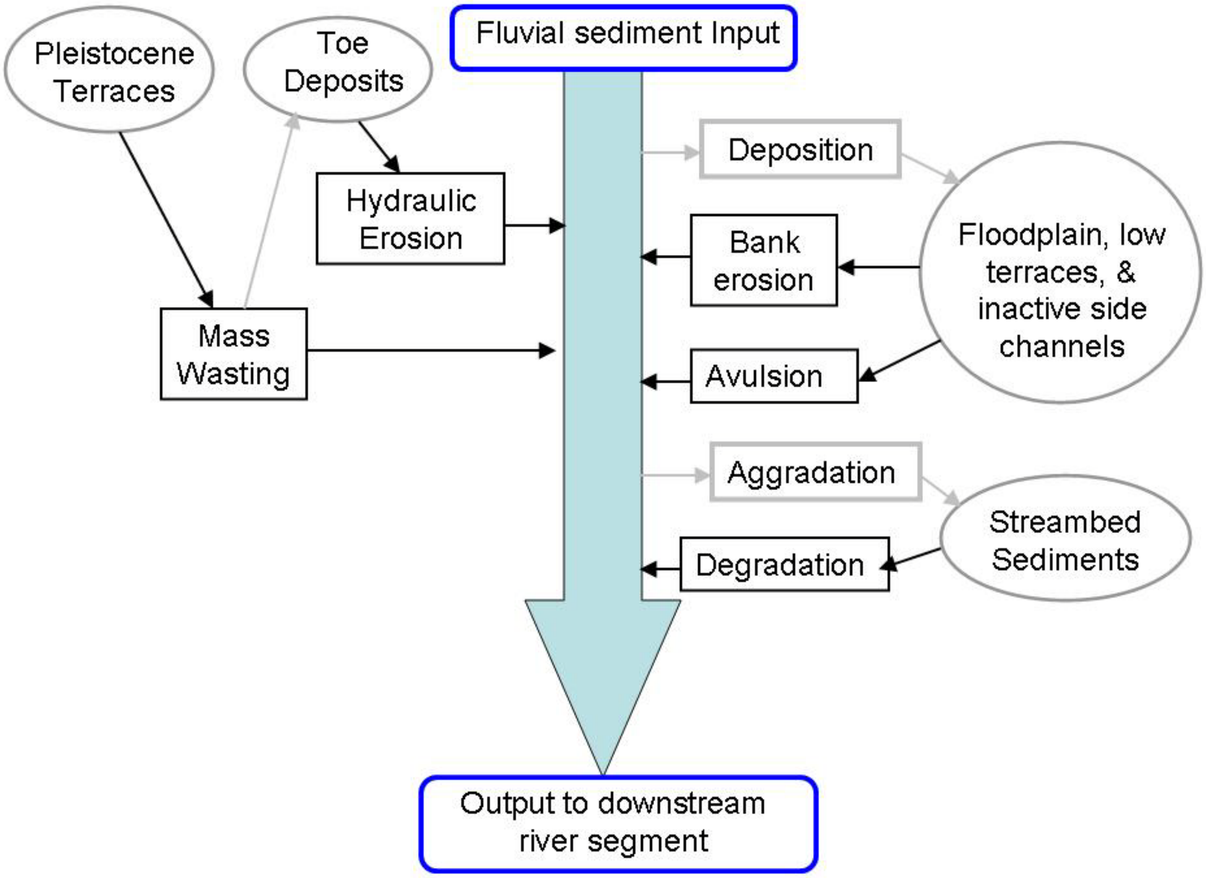
The reader is cautioned that many sediment transport models in common use, especially for gravel bed streams, are obsolete forms inherited by having been built into early (pre-1980) computer software. These older models did not take into account the effect of the coarsened armor layer on particle mobilization thresholds and equilibrium, and in some cases, combined gravel-bed transport equations with sand-bed models even though the respective mechanisms of transport (e.g. single particle versus mass-movement of dunes) were incompatible. For an excellent primer on the current state-of-the-art of sediment transport modeling, see the *Sediment Transport* Appendix in this volume, and also Wilcock et al.[53]

7.4.3 *Sediment budget*

A sediment budget is definitely a watershed-scale endeavor. That said, they do not deserve the reputation they have for being expensive and time consuming. A sediment budget, like any geomorphic investigation, should be designed to address well-defined objectives, and can be conducted at very reasonable cost if well designed. Sediment budgets are used to quantify the various sediment sources, sinks and pathways in the watershed such that attention can be focused on those that are most important. A sediment budget dealing with the routing of sediment through a watershed is useful for estimating recovery times from disturbances, especially in regard to the fate of locations of temporary sediment storage, such as the streambed (see Figure 28). Sediment budgets are very useful for dam removal studies, and for evaluation of expensive, high-impact sediment control measures such as dredging, in-stream gravel mining, engineered sediment traps, etc.

For a thorough and readable summary of sediment budgets and how to conduct them, consult the *Sediment Transport* Appendix, as well as Reid and Dunne.[54]

Figure 28. Flowchart for sediment mobilization, transport and storage in a typical response reach of a river in the Puget Sound lowlands, Washington. Such rivers transition from source and transport reaches in the Cascade Mountains to depositional response reaches just downstream from the mountain front, where gradient decreases as they enter valleys bounded by terraces of Pleistocene glacial origin. A sediment budget would seek to quantify some or all of the pathways shown as black arrows (sediment sources) and gray arrows (sediment sinks).

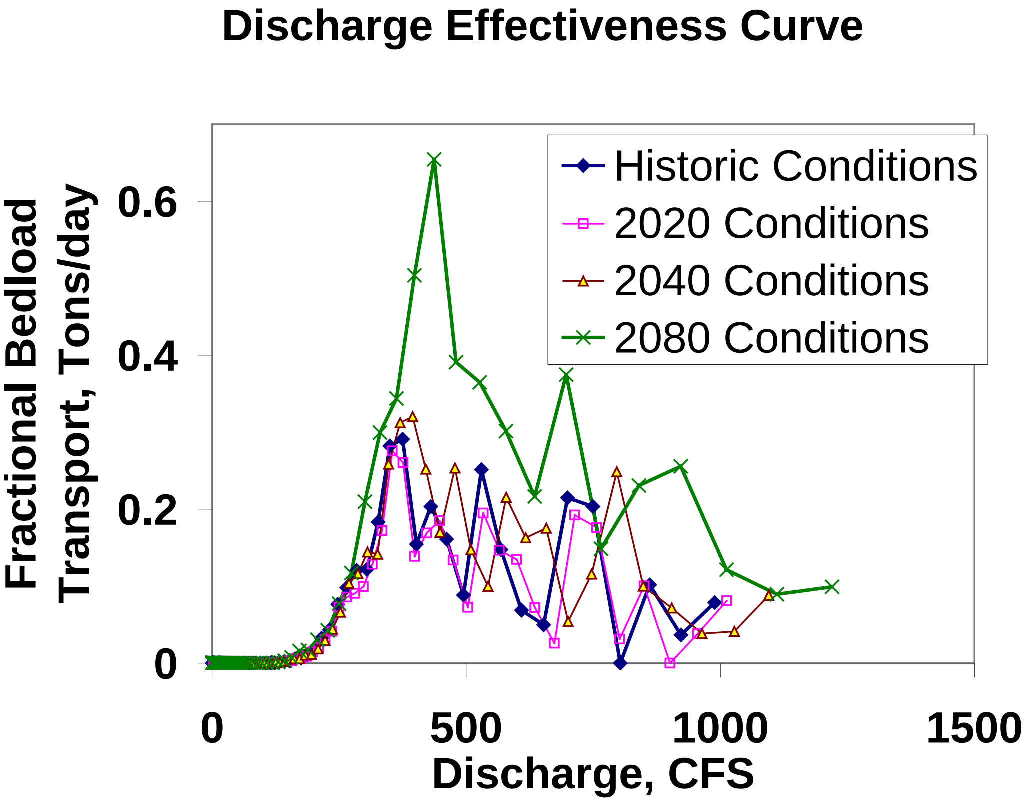


7.4.4 *Effective discharge analysis*

Effective discharge is a very powerful, but underused, analysis tool. Arguably, it is the best tool for selecting a design discharge, particularly in channels subject to altered equilibrium conditions.[55] It is also a powerful tool for investigating the geomorphic effects of altered hydrology, such as from changes to dam operation, from climate change, or from water diversion (see Figure 29).

Instructions on conducting an effective discharge analysis can be found in Biedenharn et al.[56] Insight on objectives and interpretation of effective discharge can be found in Nash[57] and Doyle et al.[55]

Figure 29. Estimated future decade effective discharge curves for the Sycan River, Oregon, based on downscaled regional climate modeling. Flow frequency distributions were generated by adjusting a historic record according to output from a Variable Infiltration Capacity hydrology model, and sediment transport was estimated using a bedload sample-calibrated Parker-Klingeman transport equation (from Bakke 2011[58]).

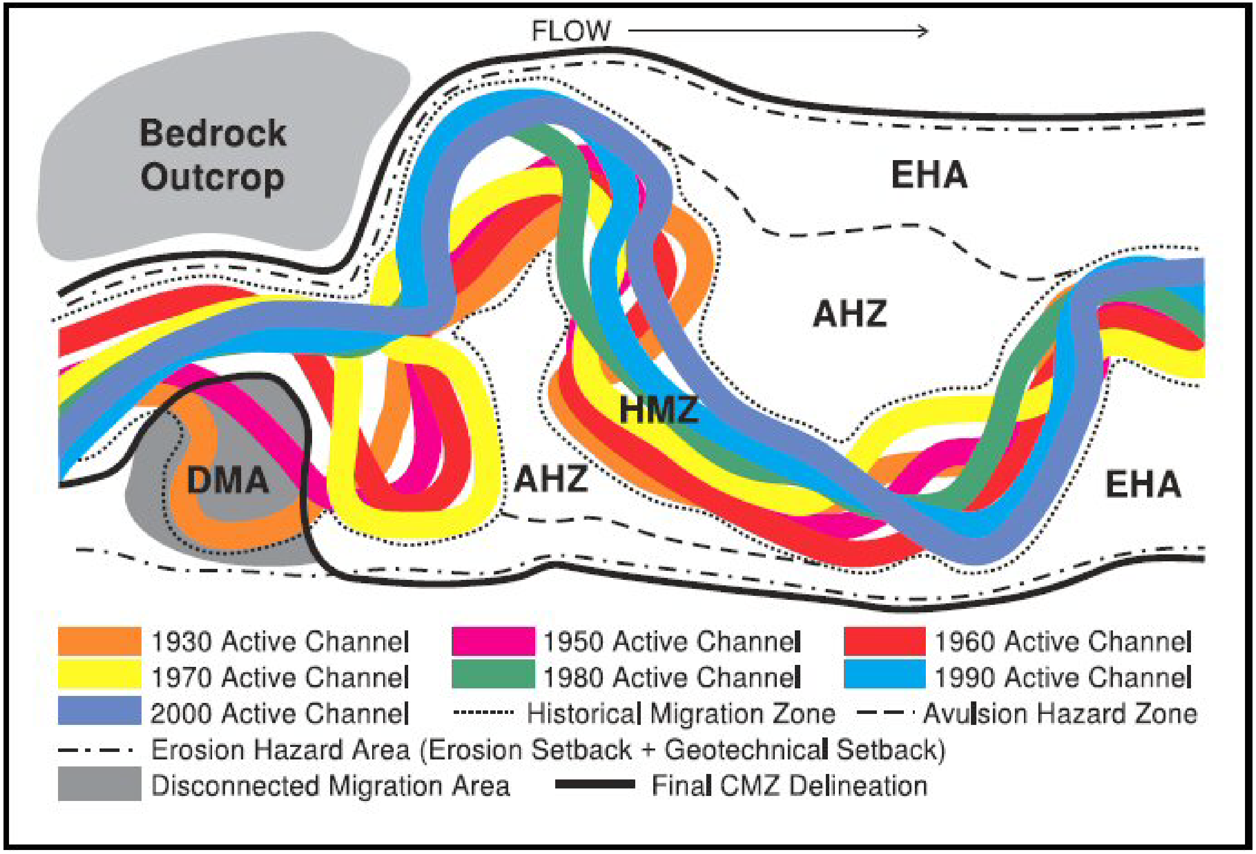


7.4.5 *Channel migration zone (CMZ) delineation*

Although regulatory authorities concern themselves more frequently with artificial constructs such as the “100 year floodplain,” the true natural currency for defining the outer edge of the river domain is the channel migration zone or CMZ. Delineation of the CMZ is useful for identifying conflicts between human infrastructure and river processes, in a way that helps prioritize sites and shows the magnitude of opportunity gained or lost. CMZ delineation can identify key points where small amounts of streambank protection can be substituted for extensive bank armoring. It can identify the extent to which streambank erosion might occur before becoming self-limiting. It can also help identify and prioritize areas to protect in order to keep channel forming processes intact.

The channel migration zone consists of an historical migration zone, an avulsion hazard zone, an erosion hazard zone, and a disconnected migration area (see Figure 30). The latter represents parts of the channel migration zone that have been solidly removed from river access by human structures strong enough to withstand most severe floods. Sometimes, only one of these subunits is of interest. The most comprehensive reference on channel migration zones and their delineation is Rapp and Abbe.[59]

Figure 30. Channel Migration Zone (CMZ) analysis for a hypothetical river (from Rapp and Abbe[59]).



7.4.6 *Geotechnical modeling*

Quantitative modeling of streambank stability is gaining popularity, thanks to easily accessible models such as the Bank-Stability and Toe-Erosion Model or BSTEM.[60] Geotechnical models can be used to assign an actual factor of safety to a streambank, allowing comparison of risk of bank failure for different combinations of management and hydrological conditions. The model can also be used to demonstrate the relative importance of physical factors in streambank stability, including toe erosion, bank geometry, vegetation, and soil properties. Vegetation influences bank stability both by root reinforcement and hydrological effects. Information on the BSTEM model, which includes a succinct primer on the physics of streambank stability, can be obtained from Simon et al.[60]

8 SUMMARY

The role of the geomorphologist in stream habitat restoration planning and design is to bring a large-scale spatial and long-term temporal perspective of the riverine and watershed landscape. Geomorphology includes the suite of processes that create and then maintain the form of the river channel and its habitat over time. By taking a holistic view, geomorphology provides an essential context for the sometimes piecemeal, mechanistic approach used in engineering design and analysis, which can miss crucial linkages and processes inherent to the healthy river system as a whole. Geomorphic analysis allows projects to be designed in such a way as to account for, and work with, naturally occurring processes. This greatly improves the chances for project success, and reduces the need for costly maintenance or unanticipated repairs or retrofits. Finally, accountability to the public that aquatic habitat and river corridors are being managed competently demands a higher degree of certainty in analysis and design than was once the norm, which can only be obtained by collection and analysis of physical process data.

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APPENDIX C

HYDROLOGY

Hydrology Appendix

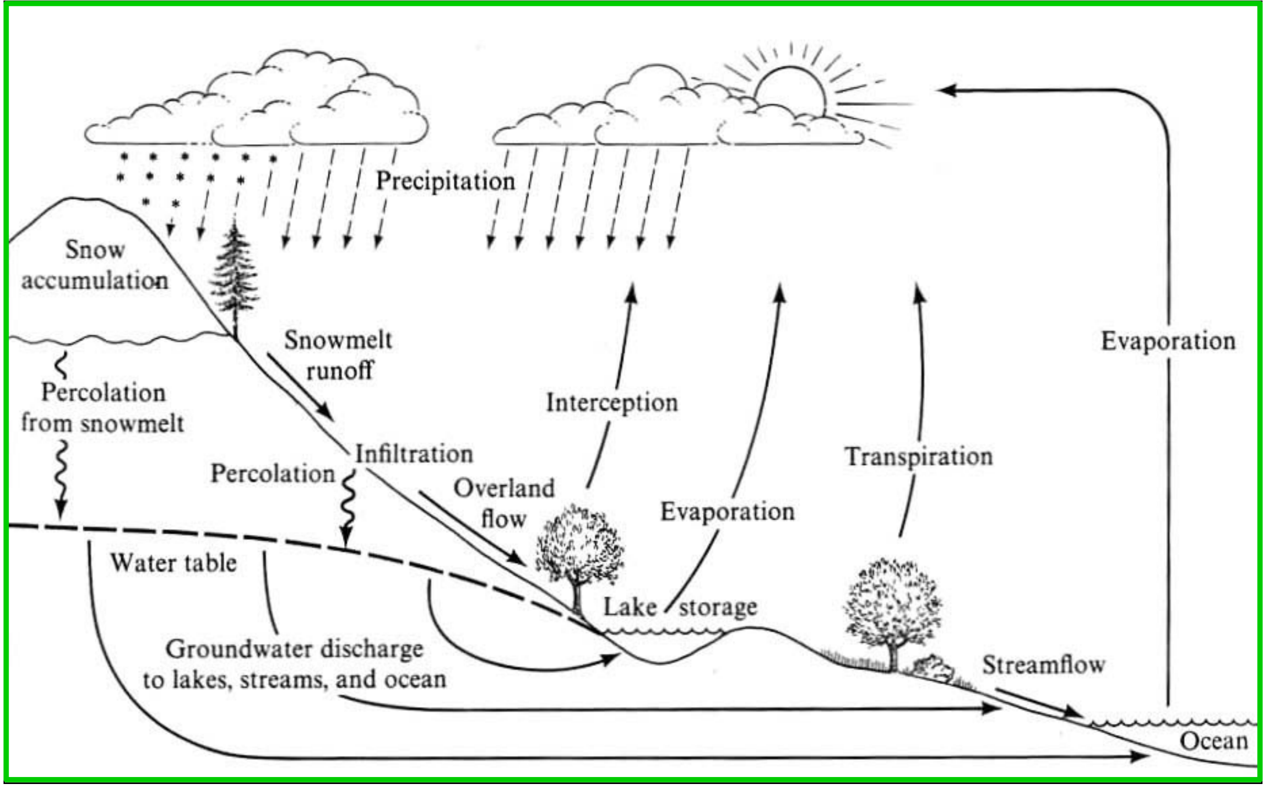
This appendix provides a summary of hydrologic processes and methods for hydrologic analysis as they relate to stream habitat and stream habitat restoration and design. The appendix focuses primarily on streamflow as the primary element of hydrologic sciences of relevance to stream habitat; it also provides background on the relevance of groundwater and hyporheic flow to stream habitat. It is intended to provide a quick reference to hydrologic processes and variables that may be the cause of stream habitat impairment, a reference for methods of analysis to evaluate these impacts, and a reference for methods of analysis for hydrologic variables relevant to stream habitat restoration design. It is not a substitute for research and analysis that may be necessary to understand and evaluate hydrologic processes in a particular project area - readers should seek the advice and analysis of an experienced hydrologist or hydrogeologist for the development and review of hydrologic analyses as they relate to project-specific planning and design. References for sources and citations are listed at the end of this appendix.

Hydrologic inputs to a stream system, together with sediment inputs (see *Sediment Transport* Appendix) (and in some regions large wood), are the fundamental variables of stream ecosystem processes and therefore are fundamental considerations for stream habitat restoration planning. Consideration of past and future impacts to hydrology can make or break a stream habitat restoration plan, and strategies to remedy or mitigate hydrologic impacts may be central to restoration planning.

1 HYDROLOGIC CYCLE

Hydrology is the science of the occurrence, movement, and storage of water in the atmosphere, on land, and in the sea, as characterized in the hydrologic cycle illustrated in Figure 1. Water is stored in clouds (as vapor), in snowpack or in glaciers, as groundwater (in soil or bedrock), or as surface water including streams, lakes, and oceans. The amount of water in storage in each of these ‘reservoirs’ varies daily (e.g. streamflow responding to storms), seasonally (e.g. snowpack), and inter-annually. While regional and global storage and distribution does not vary significantly in timeframes of years to decades, historical climate change has led to significant changes in the distribution of storage over periods of centuries to millennia. And in the past century, accelerated rates of global warming have contributed to more rapid rates of change in storage, particularly for that component of freshwater stored as glacial ice.[1]

Figure 1. Hydrologic cycle. Adapted from Dunne and Leopold[2]



From the perspective of stream habitat and restoration, the primary hydrologic cycle component of interest is streamflow, which drives the geomorphic processes that create and maintain diverse stream habitat types (see Chapter 2 for further discussion of streamflow and geomorphic processes).

The timing and magnitude of streamflow is determined by hydrologic processes that regulate movement of water, including:

Precipitation

Total streamflow is determined largely by precipitation - the water that falls to the ground within a watershed in the form of rain or snow. The amount of precipitation is determined primarily by regional climatic factors, but is also influenced by topography. Climatic and geographic variables also influence the timing, intensity and duration of precipitation events. And the translation of precipitation to streamflow depends on the form of precipitation (snow or rain) and watershed characteristics such as topography, vegetation, soils, geology, and land use. While a strong correlation often exists between precipitation and runoff, the correlation varies regionally under the influence of vegetation, soil, and geologic characteristics of the watershed. Predicting precipitation is critical to modeling runoff and streamflow.

Interception and Evapotranspiration:

Interception refers to the precipitation that never reaches the soil, but rather, is intercepted by vegetation or other surface cover and evaporated back to the atmosphere. The amount of interception may not be a major factor in most hydrologic calculations,[3] but nonetheless affects streamflow. Where precipitation falls as snow, interception may be a more significant influence on the hydrologic balance in a watershed, as forest cover can retain snow for extended periods during which time significant water may be returned to the atmosphere directly, through sublimation (change of state directly from solid to vapor state). Evapotranspiration refers to precipitation that is returned to the atmosphere through either evaporation from lakes, streams, snow or bare soil, or is taken up from the soil and transpired to the atmosphere by plants. It is generally impractical to separate evaporation from transpiration when conducting hydrologic balance analyses, and so these two processes are commonly combined as 'evapotranspiration'.

Infiltration:

Movement of water into the soil is termed infiltration. Precipitation that is not intercepted and returned to the atmosphere through evapotranspiration may infiltrate soils and underlying geologic formations. The infiltration rate is influenced by the character of the soil, soil water content, slope steepness, vegetation characteristics, intensity of rainfall, and land use. Where delivery of water to the soil is less than the infiltration rate, all of that water can be absorbed and infiltrate the soil and underlying geologic formations; where delivery of water exceeds the infiltration rate, water will begin to pond on the surface or run over the ground downslope. Soils provide a filter that determines the path and rate of delivery of water to stream channels, and therefore plays a major role in determining streamflow volume, timing, and peak flow rates.[3] Soils also influence evapotranspiration by influencing infiltration rates, storage of moisture, and transfer rates to underlying geology. Land use can significantly alter infiltration rates through vegetation removal, soil disturbance (agriculture), and urbanization that creates impervious surfaces. Changes to infiltration due to land use significantly affect streamflow by altering pathways from precipitation to stream channels. Identifying infiltration rates is necessary to analyze and model runoff conditions for predicting streamflow in ungaged basins or under varying future land use scenarios.

Groundwater movement:

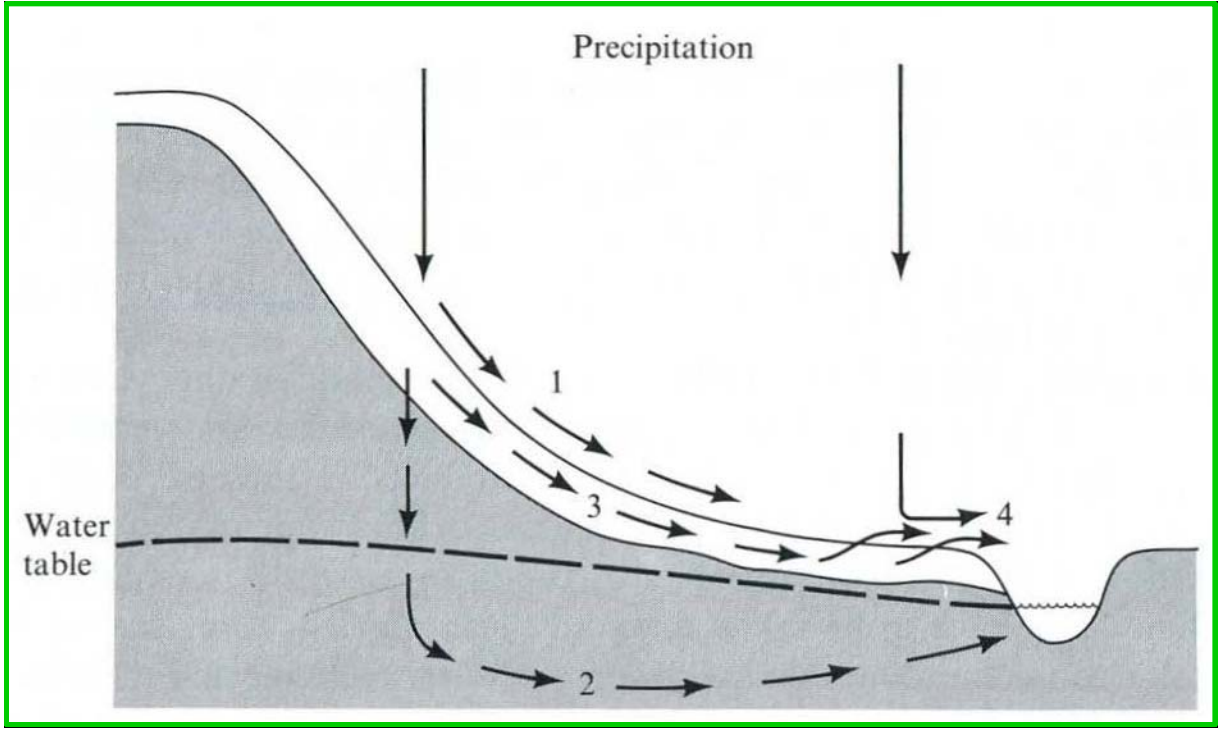
Water that infiltrates soils may move downslope through the soil directly to a stream channel, or infiltrate deeper into geologic formations that store and transfer groundwater through aquifers, which may or may not be connected to a stream channel. Where streambeds are connected to groundwater and groundwater contributes to flow, streams are characterized as gaining (influent); where streamflow is lost to groundwater, streams are characterized as losing (effluent). Gaining and losing conditions for a given stream reach may vary seasonally and annually. Baseflow (i.e. low flows during dry periods) in most streams is supported largely by contributions from groundwater. Where streambeds are not connected to groundwater, they may lose water through infiltration from the streambed. The movement of groundwater is influenced by topography, the seasonal variation in aquifer volume, the porosity and permeability of the aquifer and the connection between the stream and groundwater systems. Modeling of groundwater is extremely complex, uncertain, and typically requires a large amount of data from wells.

Groundwater constitutes more than 20% of all freshwater and is the largest source of non-frozen fresh water in the world; in the United States, 80 to 90 percent of total available freshwater comes from this source.[3]

Runoff:

Runoff refers to the water leaving a drainage basin and may vary from less than 10 percent of annual precipitation in arid regions to greater than 90 percent in the Cascade Mountains of Washington[3]. Total runoff is roughly equivalent to the amount of precipitation less evapotranspiration and less water lost to aquifers that are not connected to stream channels within the watershed. It can be generally classified as overland runoff, interflow, or groundwater runoff (Figure 2). Overland runoff flows in response to storms over saturated or impermeable surfaces directly to stream channels; interflow is water that infiltrates and is transported downslope through the soil directly to streams; and groundwater runoff flows from soil and aquifers to the stream channel. Many factors influence runoff, including precipitation, geology, topography, vegetation, soils, and land use. The seasonality and form of precipitation (rain or snow), in particular, is a dominant variable in determining runoff. Runoff modeling is a common approach to predicting future streamflow and is a complex, intricate modeling process based on many assumptions about the influence of these factors.

Figure 2. Disposition of rainfall on land. Paths of water (numbered) include: 1) Horton overland flow; 2) groundwater flow; 3) shallow subsurface stormflow or interflow; and 4) saturation overland flow (Adapted from Dunne and Leopold[4]).

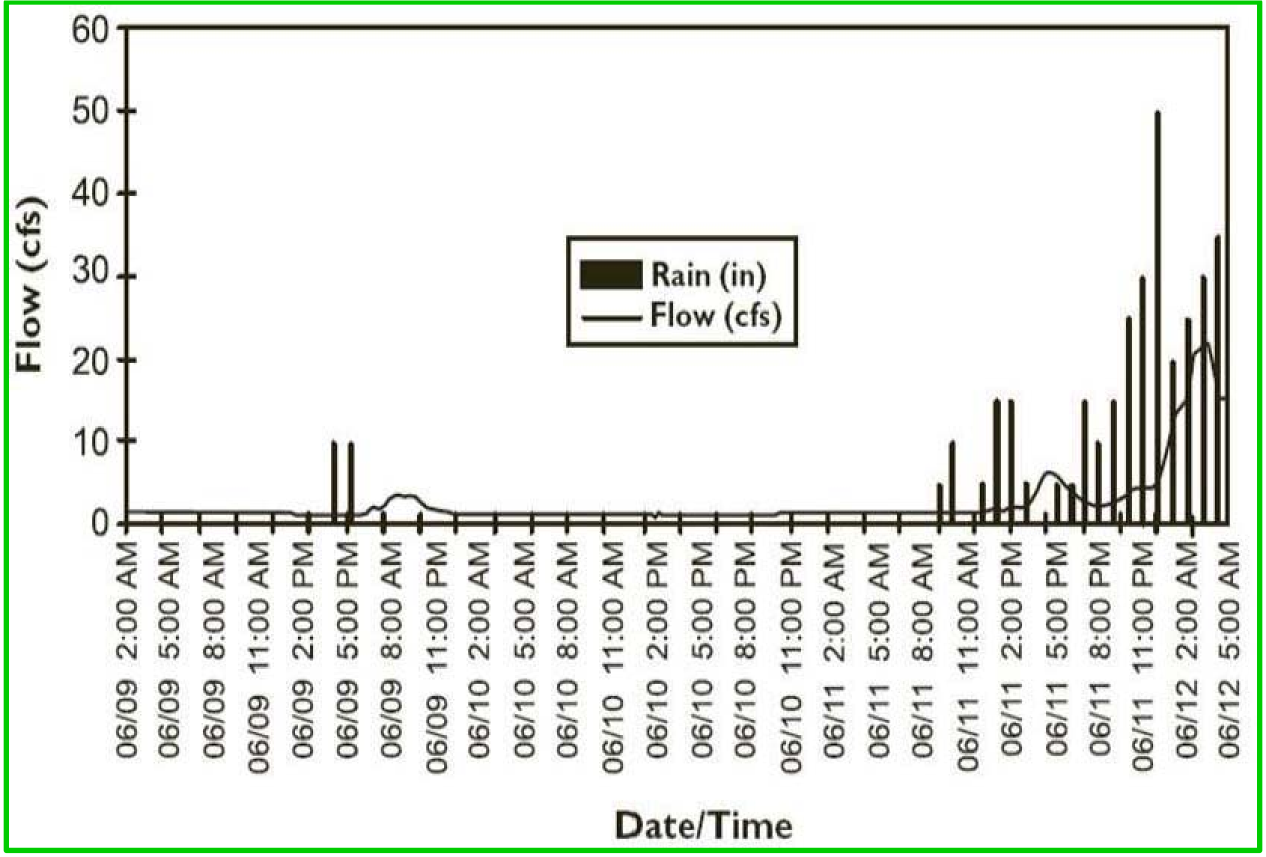


1.1 Streamflow

Water flowing in a stream represents the culmination of runoff processes that transport water from different locations in the watershed by surface and subsurface pathways. The dominant source of runoff is generally precipitation (rain, fog, or snow), although significant amounts of water may be delivered from outside a watershed by inter-basin transfer for municipal water supply and irrigation. A portion of precipitation is lost to evaporation from open water, soil, and other watershed surfaces, transpiration from plants, recharge to deep groundwater aquifers, and diversion for use outside of the watershed. Water from precipitation is also stored in ponds, lakes, reservoirs, floodplains, and wetlands as well as below ground in soil and aquifers. Stored water may drain to a stream or be lost to evapotranspiration or deep groundwater aquifers.

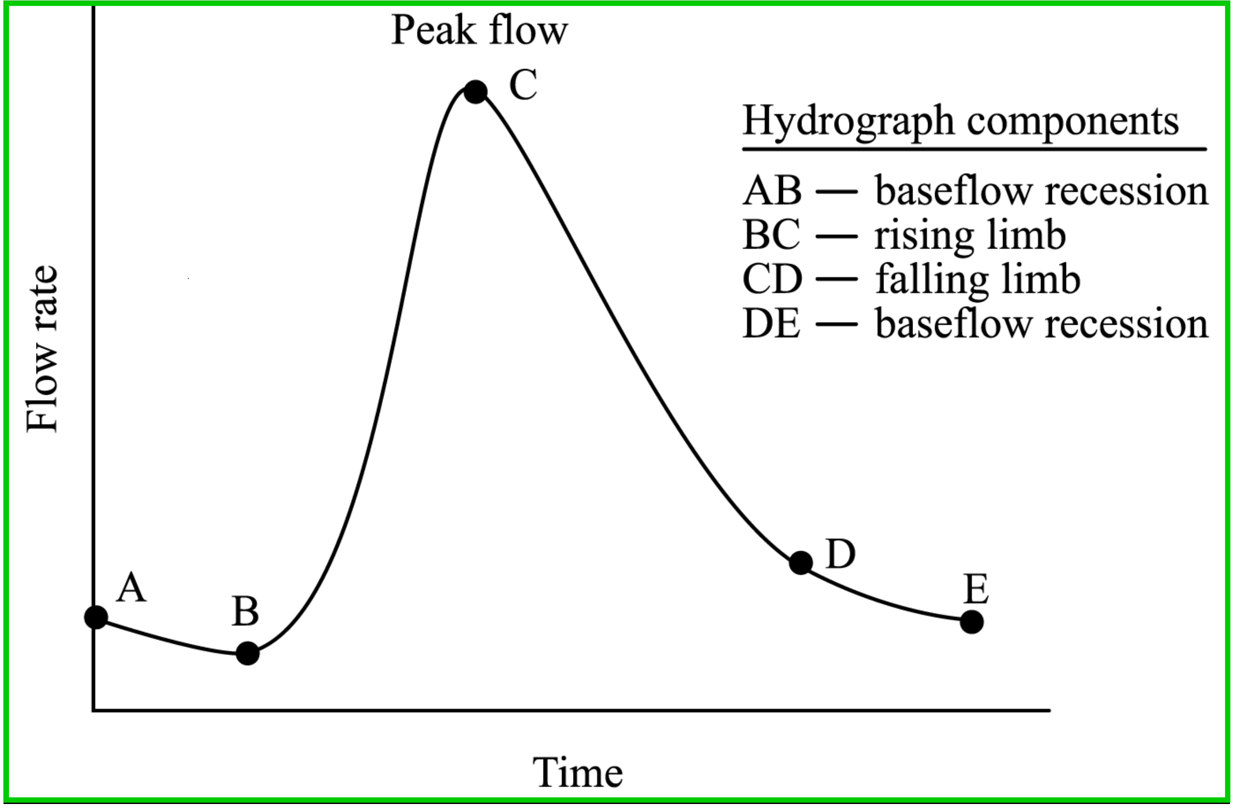
Streamflow, often termed *discharge*, is calculated by measuring flow through an area of channel, typically reported as a volume per unit time (i.e. cfs - cubic feet/second). Changing water levels and stream discharge are plotted over a period time as hydrographs. Hydrographs typically depict annual, seasonal, or single storm periods but may depict other periods as well. A storm ***hydrograph*** depicts the hydrologic response to rainfall or snowmelt in addition to baseflow, as shown in Figure 3. The shape of a hydrograph reflects variable rates of inflow, outflow, and changes in storage. A “narrow” storm hydrograph with a short time-to-peak indicates rapid runoff due to overland flow and limited surface storage. A “broad” storm hydrograph, with a longer time-to-peak, reflects a large storage capacity with possibly large areas of wetlands and floodplains.

Figure 3. A three-day hydrograph with a storm at its tail. Adapted from Dunne and Leopold[5]



Specific components of a storm hydrograph are shown in Figure 4. The curve AB is a period of declining baseflow, or groundwater discharge, before the storm. Curve BC is the “rising limb” of the hydrograph showing direct runoff from the storm. At some point near or after the end of rainfall, ***peak flow*** is attained after which stream flow decreases (curve CD, the “falling limb”), returning to baseflow (curve DE). The area under the curve represents the volume of storm runoff.

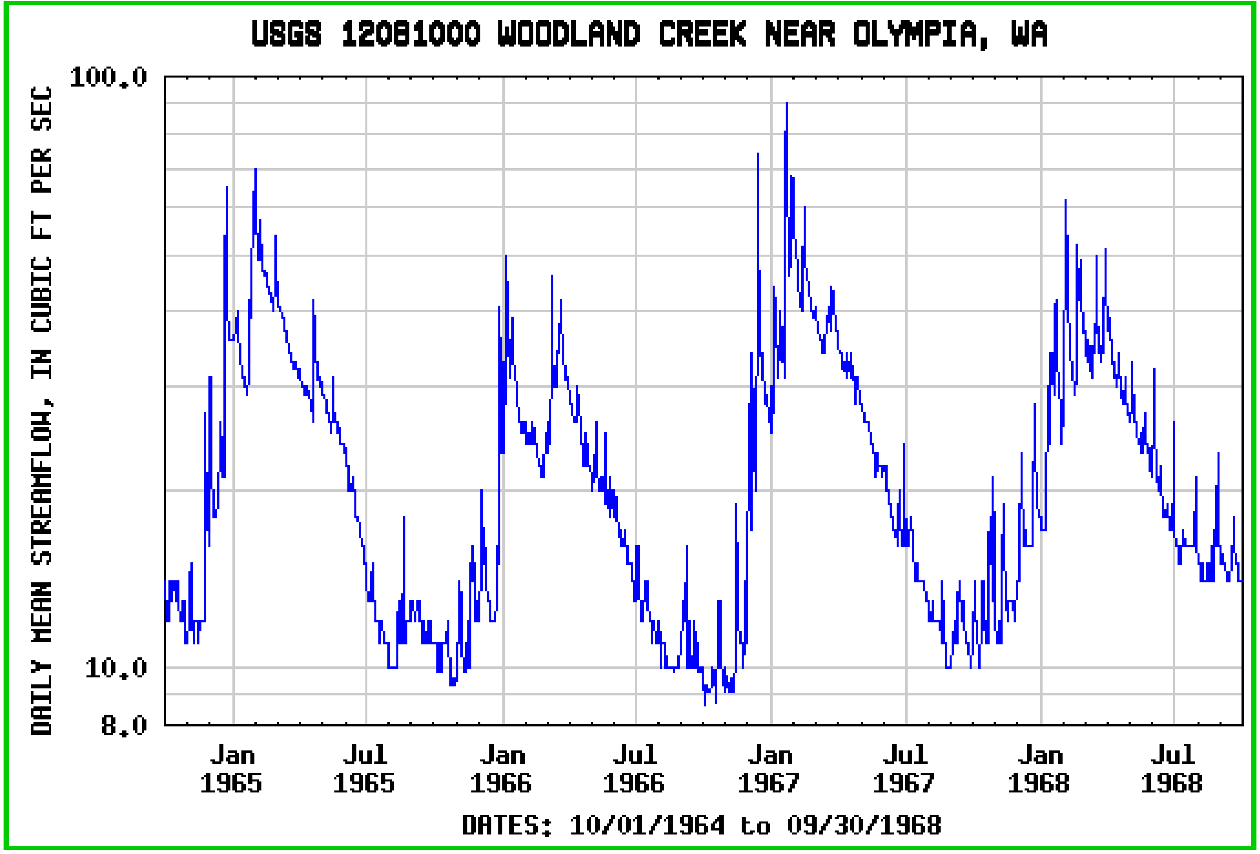
Figure 4. Specific components of a storm hydrograph. Adapted from Chow et al.[6]



The magnitude, duration, and timing of runoff, the distribution of runoff among different pathways, and amount of storage can determine a watershed's hydrologic response, or the streamflow resulting from runoff. Factors that alter runoff can change the hydrologic response; these may occur naturally (e.g., forest fire or beaver activity) or result from human activity. Changing land use, particularly urbanization or conversion to agricultural land, can alter runoff pathways and reduce watershed storage with potentially severe changes to a watershed's hydrologic response. Structural projects in rivers and streams, including dams, diversions for irrigation and municipal/industrial water supply, transportation works, and flood control projects can also significantly alter hydrologic response. Similarly, isolation of a stream channel from its floodplain by diking and channelization reduces natural flood storage capacity. Because of the direct connection between runoff, streamflow, and aquatic habitat, habitat restoration projects may be best accomplished by restoring natural storage capacity and runoff by removing impervious surfaces, restoring wetlands, replanting forested areas, removing levees, or adding structural complexity to stream channels and overbank areas.

Another example hydrograph, in this case, on an inter-annual time scale, is shown in Figure 5**.** Hydrographs are useful for establishing the variability and relative magnitude of stream flow over time. This example demonstrates how stream flow can vary within and among years.

Figure 5. Annual hydrograph for four years between 1965-1968, Woodland Creek. Adapted from USGS. Water Resources of Washington.[7]



Streamflow events, particularly floods, are typically characterized by their *return interval*. The return interval of a flow event is defined as the inverse of its probability of occurrence in any one year and provides a measure of its frequency.[3] For example, a 5-year flood has a 20% probability of occurring in any year, while the probability of a 100-year flood is 1% in any given year (see Table 1). However, a 5-year flood does not necessarily occur once every five years. If a 5-year event happens one year, the chance of it happening again in the following year is still 20%, and if 5-year events have happened in consecutive years, the chance of there being a 5-year flood in the third year is still 20%. Further, many flow statistics are derived from periods of record with fewer years than the recurrence interval of interest; 100-year flow values are usually not derived from 100 or more years of data, but are extrapolated from shorter periods of record. Because of climate periodicity (e.g. decadal climate cycles), several years of increased flood severity may be followed by periods of drought and can therefore skew return intervals estimated from periods of record that represent data collected only during a single decadal cycle.

Table 1. Return intervals and associated probability of occurrence. The inverse of a return interval is a probability of a given flow occurring in any given year. Specific return intervals are commonly applied in restoration and stabilization planning and design, but frequently without consideration of the associated probability of occurrence, which is often more informative.

Return Interval (years)	Probability of occurrence	Relevance
1	99%	Occurs, on average, every year
2	50%	Commonly used as surrogate for channel-forming flow or 'bankfull'
25	4%	Commonly applied for stability criteria for streambanks or instream structures
100	1%	Flood delineation for FEMA, commonly used for hydraulic design for flood-related criteria

1.2 Groundwater and the Hyporheic Zone

The importance of surface stream flow to creating and sustaining river forms, processes, habitats, ecosystems, and species is fully recognized. However, the importance of *subsurface* water is not as widely appreciated. In fact, the quantity, quality, and dynamics of water stored in the subsurface hydrological system can be crucial to the river environment and the life the stream supports.[8] Many subsurface hydrological systems are vulnerable to adverse impacts from poorly planned or executed works in the channel or on the floodplain.

Floodplains absorb and then release water from flood flows, attenuating downstream flood peaks and subsequently providing an important source of base flow that nourishes the stream between precipitation events and during prolonged dry seasons. Water stored in the saturated zone below the water table is referred to as groundwater, while storage in the partially saturated zone above the water table is termed soil moisture. That part of the subsurface system that is closely coupled to the stream is termed the *hyporheic zone*, defined as the area beneath the stream channel and adjacent floodplain where groundwater and surface water are exchanged freely.[9] Water in the hyporheic zone moves down and laterally across a valley by seeping through the interstitial spaces in floodplain soils and streambed sediments; this water is also intimately connected to stream and surface water bodies such as ponds and lakes. The area making up the hyporheic zone may be large: for example, on the Flathead River, Montana, the hyporheic zone extends as much as 2 kilometers (1.25 miles) away from the channel and is a greater source of nutrients to the stream than are the surface waters.[10] In contrast, sand-bed streams may exhibit less hyporheic storage and exchange and associated biogeochemical processing than steeper or coarser bed streams.[11]

Bolton and Shellberg (2001)[12] list the following habitat functions provided by the hyporheic zone:

- Water storage and retention
- Stream temperature regulation
- Physical habitat for hyporheic organisms including: invertebrates, spawning incubation, and fishes
- Refugia for hyporheic organisms
- Nutrient retention and transformation
- Controlling ecosystem metabolism

- Promoting aquatic and riparian habitat diversity

Connected floodplains are ecologically vital to stream geomorphology and river ecosystem health because between rainfall and flood events, and especially during long dry spells, subsurface water maintains a base flow in the stream. This base flow results from the movement of water stored in the floodplain into the channel via seepage through the bed and banks or spring-fed tributaries. In unmodified floodplains, the quality of this hyporheic water is typically high and its temperature is typically very stable; both of these attributes deliver important benefits to stream ecology in general, and for the rearing habitats of salmonids in particular. In temperate climates, in-flowing groundwater can substantially reduce the water temperature in pools during high summer ambient temperatures.[13, 14] Because of the importance of hyporheic flow to water quality and fish survival, interactions between a stream's surface and subsurface flows should be considered when planning, designing, and constructing stream works.

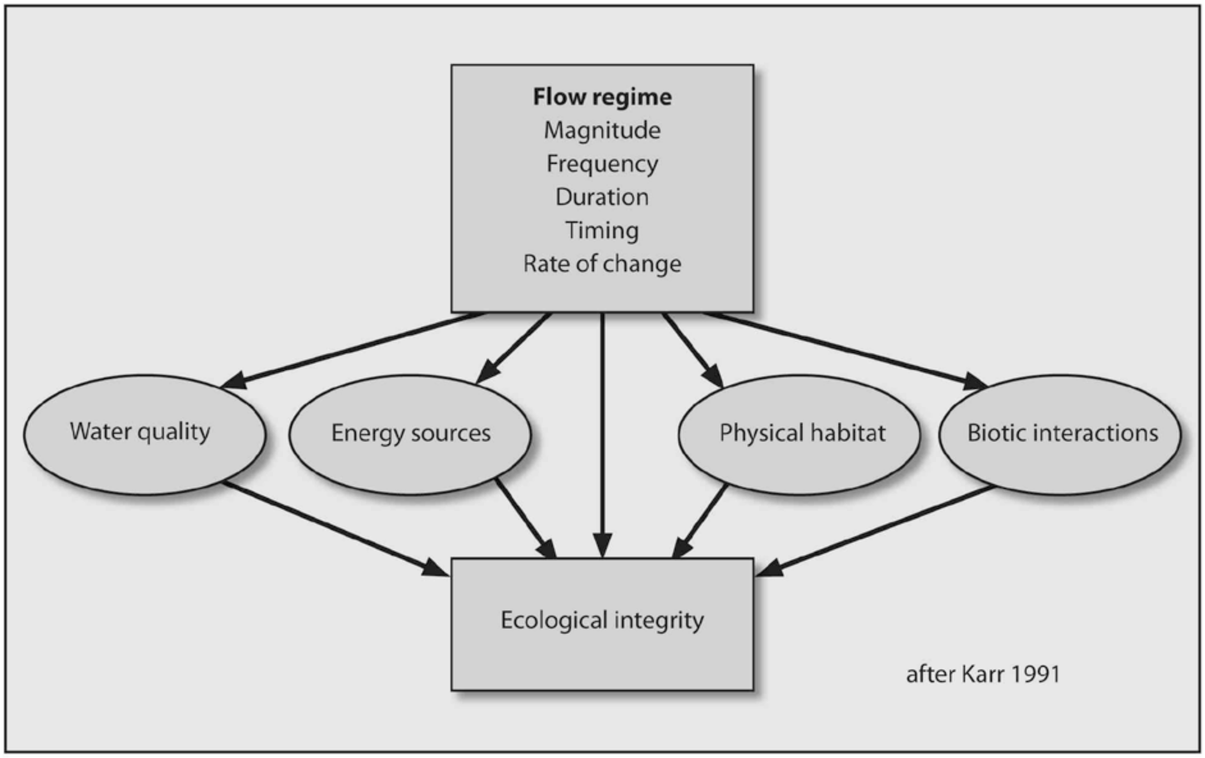
2 FLOW REGIME

Flow within a given stream typically exhibits a seasonal pattern, or flow regime, that reflects watershed characteristics and the general timing, intensity and form of precipitation. Within Washington, the character of flow regimes is influenced primarily by watershed elevation, basin geology, and climate. The magnitude, duration, frequency, and sequencing of variable flows can influence the physical and biological characteristics of a stream in several ways. High flows deliver energy and materials that create and maintain a channel's geometric form. Lower flows define the physical limits of aquatic and riparian habitats and are an important factor in a stream's ability to moderate heat and pollutant inputs. The hydrologic regime of a stream is a key element in planning, design, and evaluation of stream habitat restoration and stream bank protection projects.

2.1 Types of Flow Regimes

Flow regimes in Washington are characterized by a wide array of discharge conditions, ranging from base flows to extreme floods, and including spring freshets driven by snowmelt, short duration flash floods caused by thunderstorms, long duration floods of intermediate magnitude resulting from frontal rain, and prolonged periods of low or zero flow during summer droughts.[15] The flow regime is defined by the magnitude, frequency, duration, timing, and rate of change of these discharge conditions[16] and exerts a strong influence on stream habitat and associated biological communities.[17] It can be dramatically altered by changes in climate, land use, water use, and river regulation, which have a ripple effect on ecological integrity (Figure 6).

Figure 6. Flow regime influences ecological integrity (copied from RiverRAT). The flow regime is characterized by magnitude, frequency, duration, timing, and rate of change in flows, and influences numerous parameters that affect ecological integrity (after Karr[18]).

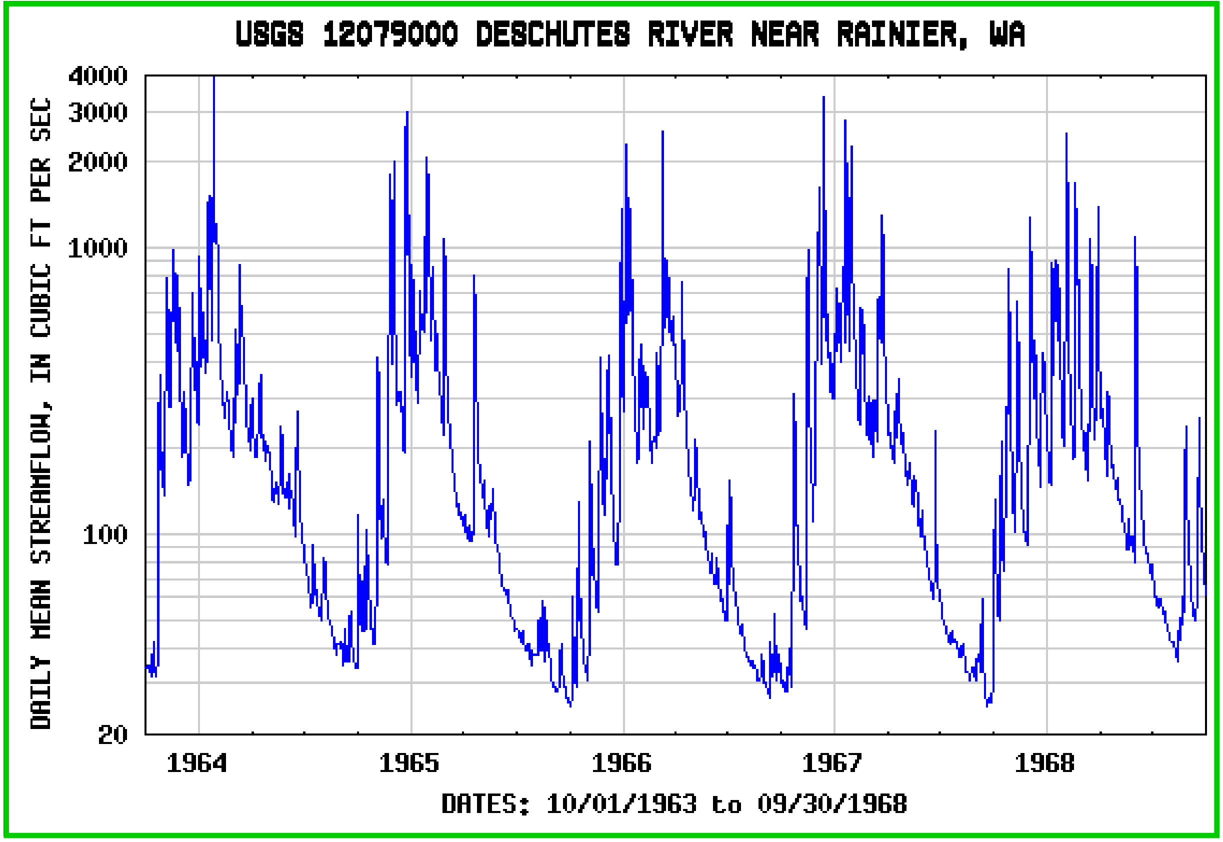


Natural flow regimes in Washington can be generally classified according to their differences in timing and volume of flow through the year. Figures 7 through 10 show typical hydrologic regimes of Washington, including rain-dominated (Figure 7), snowmelt-dominated (Figure 8), groundwater-controlled (Figure 9), and a bimodal rain-dominated with glacial snowmelt hydrograph (Figure 10). Figure 11 depicts a generalized distribution of these flow regime types.

<u>Rain-dominated flow regime</u>

Rain-dominated or rain-on-snow stream flow events appear on annual hydrographs as "spikes" extending over one-to-three days as shown below and are typical of western Washington rivers. Completely rain-dominated watersheds have average winter temperatures above 41° F (5° C).[19] Rain-on-snow events can result in significant runoff due primarily to the limited infiltration capacity of saturated or frozen soils under snow and the consequent runoff of most or all rainfall. Though rain does not significantly contribute to snowmelt, runoff from rain-on-snow can be exacerbated when rain occurs during periods of snowmelt. The rivers in these watersheds feature numerous, short duration high flows during the winter season due to winter rain or rain-on-snow events, which may result in extreme floods, particularly during periods of active snowmelt.

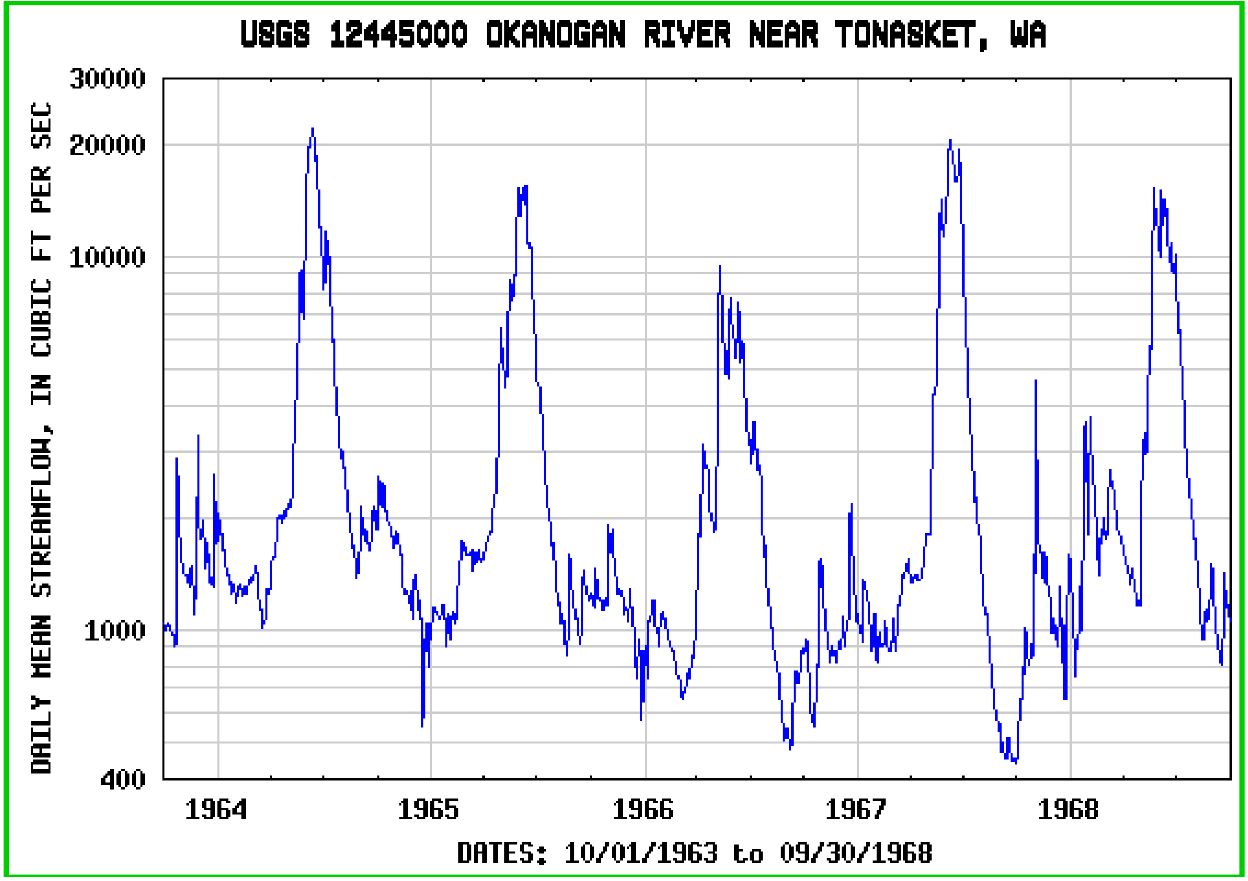
Figure 7. Rain-dominant hydrograph, 1963-1968, Deschutes River. Source: USGS. Water Resources of Washington[7]



Snowmelt flow regime

Streamflow from melting deep, high-elevation snowpack typically creates a broad and smooth hydrograph peak extending over weeks or months as shown below. Snowmelt dominant watersheds have average winter temperatures of less than 21º F (-6º C).[20] This type of event is common in streams draining the east slope of the Cascades and the west slope of the Rocky Mountains in eastern Washington. In high elevation coastal watersheds like the Cascade Mountains in Washington, 50% or more of stream flow is derived from snowmelt.

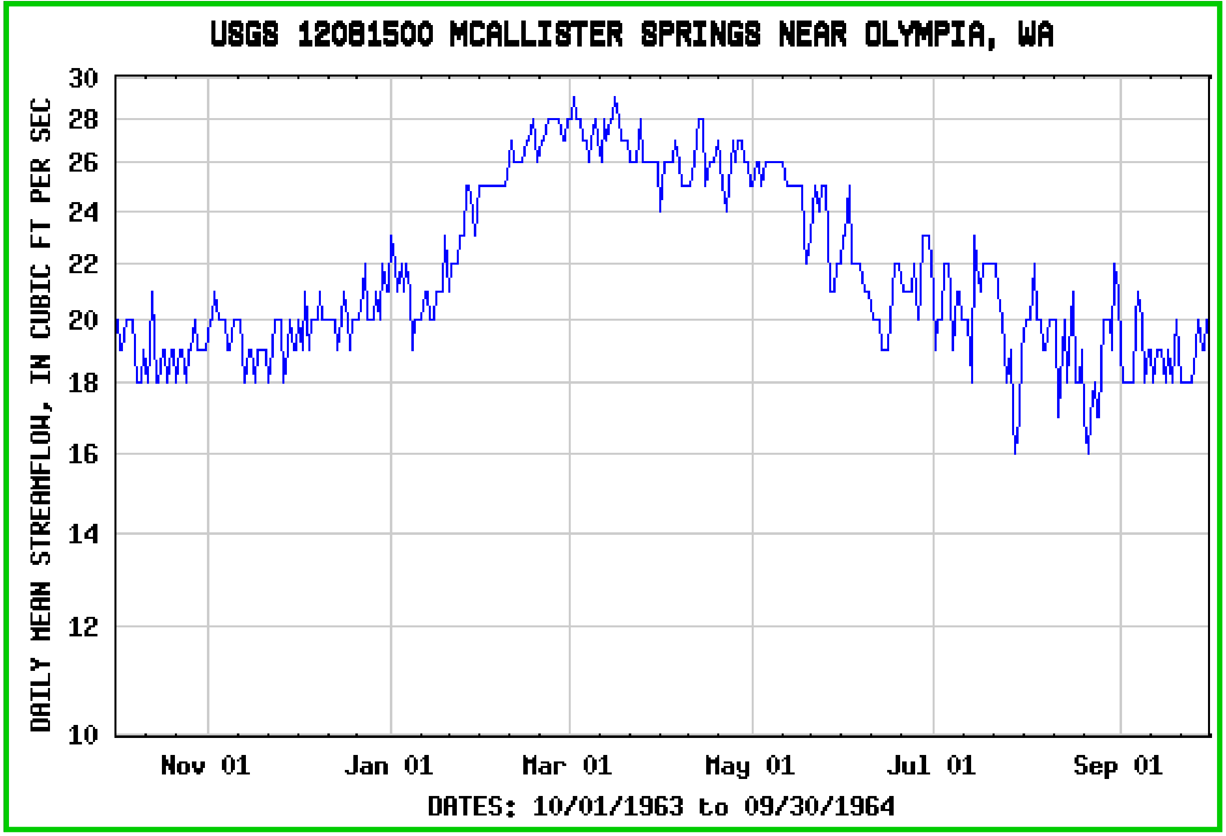
Figure 8. Snowmelt-dominant hydrograph, 1963-1968, Okanogan River. Source: USGS. Water Resources of Washington[7]



Groundwater flow regime

A stream that originates primarily from groundwater will have a moderated hydrograph indicative of sustained base flow. Due to their basalt-dominated geologies and vast, highly porous aquifers, rivers in the interior Columbia and Snake River basins experience high flows that are moderated by significant infiltration to groundwater aquifers; these groundwater inputs also maintain relatively high base flows during periods of low runoff. Groundwater discharge may rise and fall in response to seasonal precipitation patterns.

Figure 9. Groundwater-dominant hydrograph, 1963-1964, McAllister Springs. Source: USGS. Water Resources of Washington[7]



<u>Bimodal rain and snowmelt flow regime</u>

The annual hydrographs for coastal, mountainous regions and the interior Columbia and Snake River basins are often bimodal, reflecting a mixed regime of snowmelt and rainfall runoff. High summer streamflow influenced by glacial melt may still rise and fall daily during the summer months, as shown below.

Figure 10. Bimodal rainfall-dominant with glacial melt hydrograph, 1963-1968, Hoh River. Source: USGS. Water Resources of Washington[7]

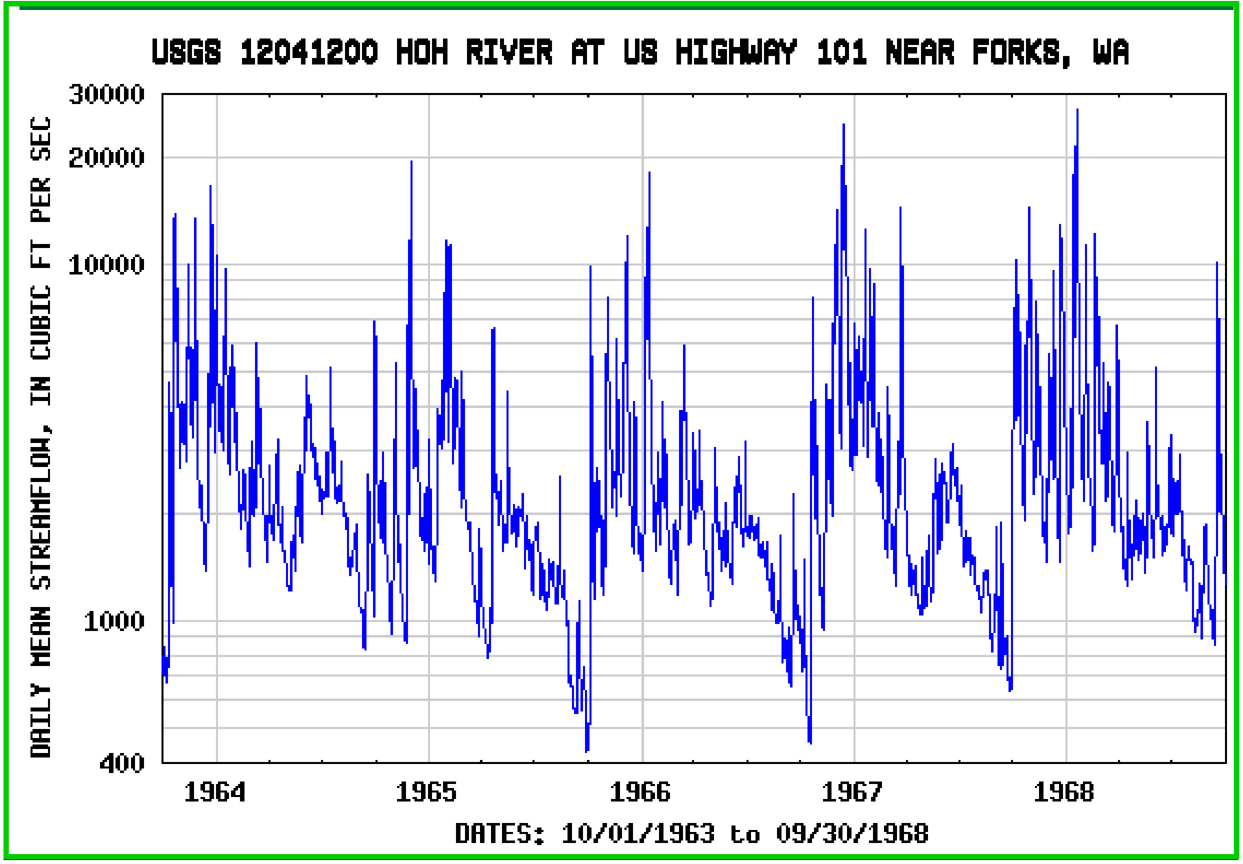
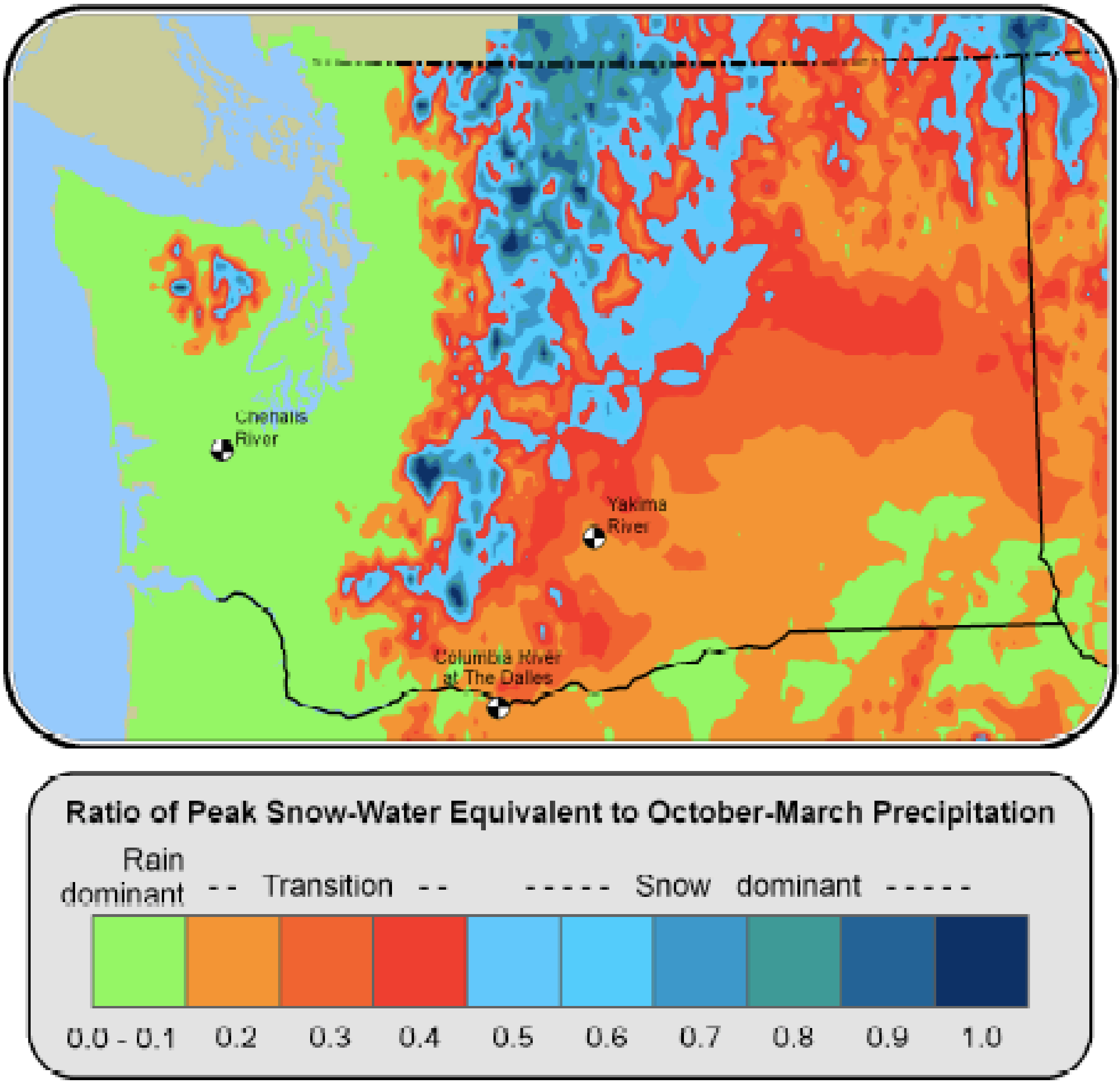


Figure 11. The average ratio of snow water equivalent (SWE) to October-March precipitation for the historical period 1916-2006 (Adapted from Elsner et al.[21], http://cses.washington.edu/db/pdf/wacciach3hydrology644.pdf)



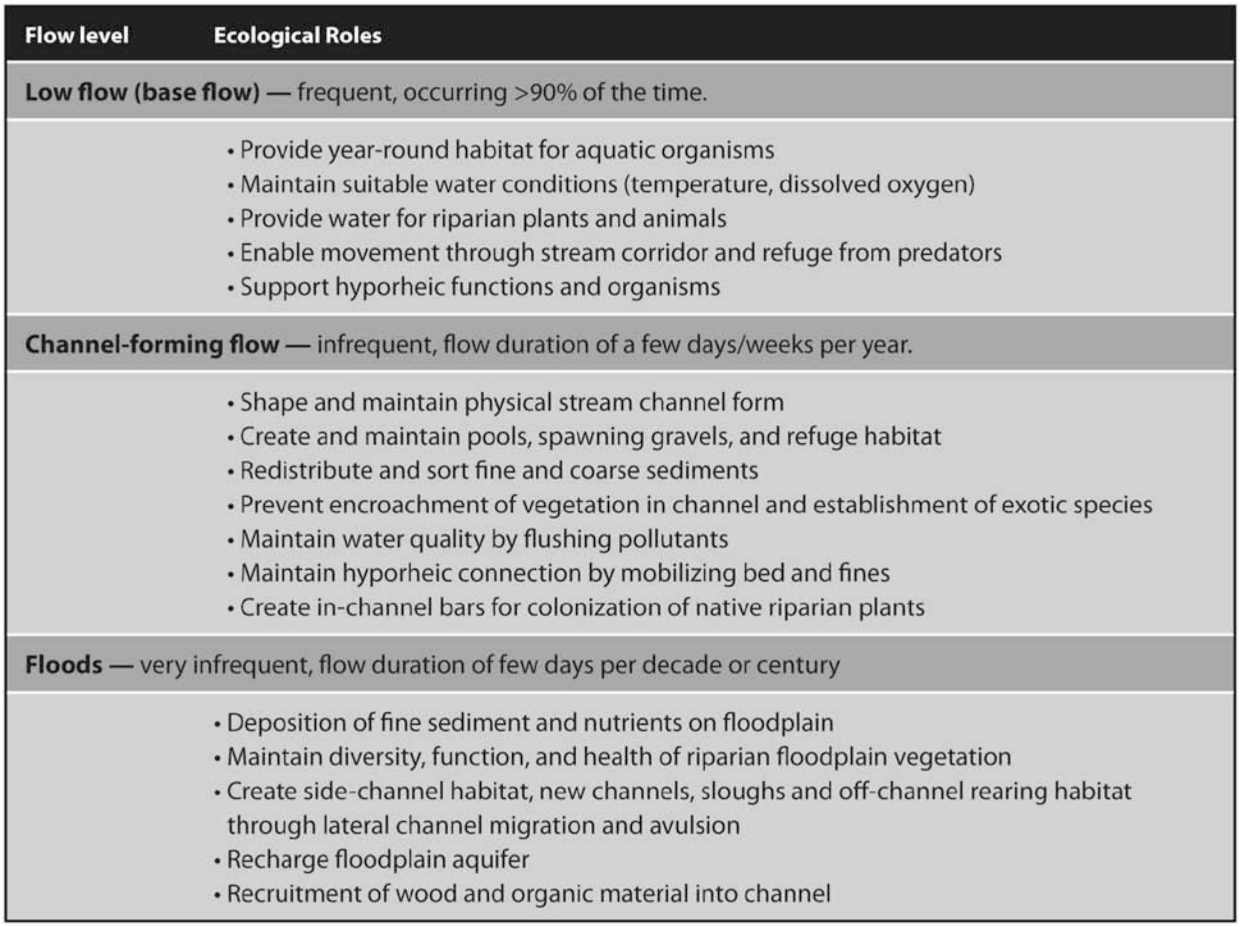
Ephemeral and Intermittent Streams

Flow in smaller rivers with little or no contribution from groundwater, or where groundwater fluctuates seasonally, may be ephemeral or intermittent. An ephemeral stream flows briefly in response to storms and has a bed that is at all times above the water table; an intermittent stream flows only at certain times of year and with the contribution of groundwater.[22] These streams are typically the most variable in terms of discharge, commonly featuring flashy hydrographs and extreme variation both within and between years. While short-term variations in discharge may be large in ephemeral streams, the seasonality of flow and response to rainfall is generally predictable.

2.2 Types of Flows for Sustaining Stream Ecosystems

The flow regime has been identified as a primary factor in sustaining the ecological integrity of river systems[16] and is a “master variable” in determining the abundance, distribution, and evolution of aquatic and riparian species.[23,24,25,26] Decades of ecological and geomorphic research shows that wide ranges of flows are essential to maintain stable and functioning habitat and ecological systems;[16] impacts to the character of these flows within a watershed can also be a dominant cause of habitat loss or degradation. The importance of the flow regime to channel form, habitat, and ecological function is summarized in Table 2. The spectrum of flows necessary to sustain functioning systems can be generally described using three discharge levels—low flow, channel-forming flow, and flood flow, as described below. For salmonids in particular, each population has evolved within the flow regime of their home river basin, typically adapting their life history to the distribution of high, intermediate, and low discharges making up the typical annual hydrograph. For example, the timing of their entrance to the river from the sea, upstream migration, spawning cues, incubation and emergence from spawning beds, and downstream migration to estuaries are all genetically programmed through centuries of adaptation to the hydrologic regime of their home basin.[27]

Table 2. Ecological significance of different river flows. (copied from RiverRAT). Seasonal flow variations correlate to varying ecological values and events. Flows can be generally categorized as low flow, channel-forming flow, or flood flows, each with specific ecological significance. (Adapted from Postel and Richter[28])



Flow level	Ecological Roles
Low flow (base flow) — frequent, occurring >90% of the time.	
	• Provide year-round habitat for aquatic organisms • Maintain suitable water conditions (temperature, dissolved oxygen) • Provide water for riparian plants and animals • Enable movement through stream corridor and refuge from predators • Support hyporheic functions and organisms
Channel-forming flow — infrequent, flow duration of a few days/weeks per year.	
	• Shape and maintain physical stream channel form • Create and maintain pools, spawning gravels, and refuge habitat • Redistribute and sort fine and coarse sediments • Prevent encroachment of vegetation in channel and establishment of exotic species • Maintain water quality by flushing pollutants • Maintain hyporheic connection by mobilizing bed and fines • Create in-channel bars for colonization of native riparian plants
Floods — very infrequent, flow duration of few days per decade or century	
	• Deposition of fine sediment and nutrients on floodplain • Maintain diversity, function, and health of riparian floodplain vegetation • Create side-channel habitat, new channels, sloughs and off-channel rearing habitat through lateral channel migration and avulsion • Recharge floodplain aquifer • Recruitment of wood and organic material into channel

Historically, fisheries management has tended to focus on a single flow or small range of flows to quantify habitat value and estimate restoration potential. Though capable of evaluating multiple flow scenarios, the prevalence of IFIM[A] (Instream Flow Incremental Methodology[29]) and PHABSIM[B] (Physical Habitat Simulation) in management approaches to evaluating and managing instream flows for fisheries habitat in the western United States has promulgated a "single-flow" perspective, emphasizing species-specific summer low flows as a primary concern.[28] This has erroneously implied that minimum flows are the single measure of acceptable habitat, where in fact, flow requirements for habitat are complex, particularly when considering multiple life stages of multiple species through the year. An important developing trend relates return interval flows to ecological criteria; for example, scientists are now

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[A] IFIM is a methodology developed to enable quantification of aquatic habitat as a function of stream flow, primarily in the context of altered or managed flow regimes.

[B] PHABSIM is a suite of software models developed to predict microhabitat conditions in rivers as a function of stream flow, and the relative suitability of those conditions to aquatic life, primarily in the context of altered or managed flows.

identifying the return interval flow that is significant during spawning periods, that is associated with the lower limit of woody vegetation, or that is significant for recruitment of woody debris. This characterization leads to better understanding of hydrologic statistics across disciplines, and reinforces the concept that various design discharges are relevant to a variety of project elements and project objectives. Doyle et al.[30] clearly described the relationship of discharge to ecological processes such as organic matter transport, nutrient transfer and retention, macroinvertebrate disturbance, and habitat availability.

Clearly, understanding components of the flow regime is fundamental to sound stream restoration project planning and design. This categorization of types of ecologically relevant flows is also a useful construct for evaluating hydrological components of watershed assessment, restoration planning and restoration design. Not only does the flow regime largely determine the character of physical habitat, but it also strongly influences the behavioral relationship between fish and their habitat – when and how they feed, spawn, seek refuge, and rear. Design criteria (see Chapter 5) for various project elements may be defined relative to specified flows extracted from the results of hydrologic analyses, such as channel-forming flow for channel dimensions, base flow for instream habitat, and flood flow for channel stabilization structures. Similarly, the probability of any particular flow occurring in any given year, expressed as the inverse of the return interval, is useful for evaluating the risk associated with failure of project elements related to that flow. For example, a design criterion for a recently constructed, bioengineered bank that mandates bank stability up to a 20-year flow for a period of 2-3 years implies a 5% chance of failure in each year (5% chance is the inverse of a 20-year return interval). The relevance of various flows to stream habitat restoration is summarized in the following discussions of low flow, channel-forming flow, and flood flow.

2.2.1 Low flow

Often referred to as base flow, low flow is the most frequent and persistent flow condition and consequently determines the amount of habitat available for much of the year.[28] Low flow periods provide the opportunity for aquatic organisms to conserve energy,[31] but are also typically the most sensitive to stresses associated with water withdrawals, water temperature, pollution, and predation.[16] The water level in a low-flow channel is important for revegetation or habitat projects. The survival and passage of fish and other aquatic species may depend on water availability, depth, and velocity during low flow periods. Survival of riparian plant communities and deep-rooted species is essential to habitat restoration and bank protection. Vegetation planted at the proper bank elevation can use soil moisture maintained during the growing season by base flows in the low-flow channel.

2.2.2 Channel-forming flow

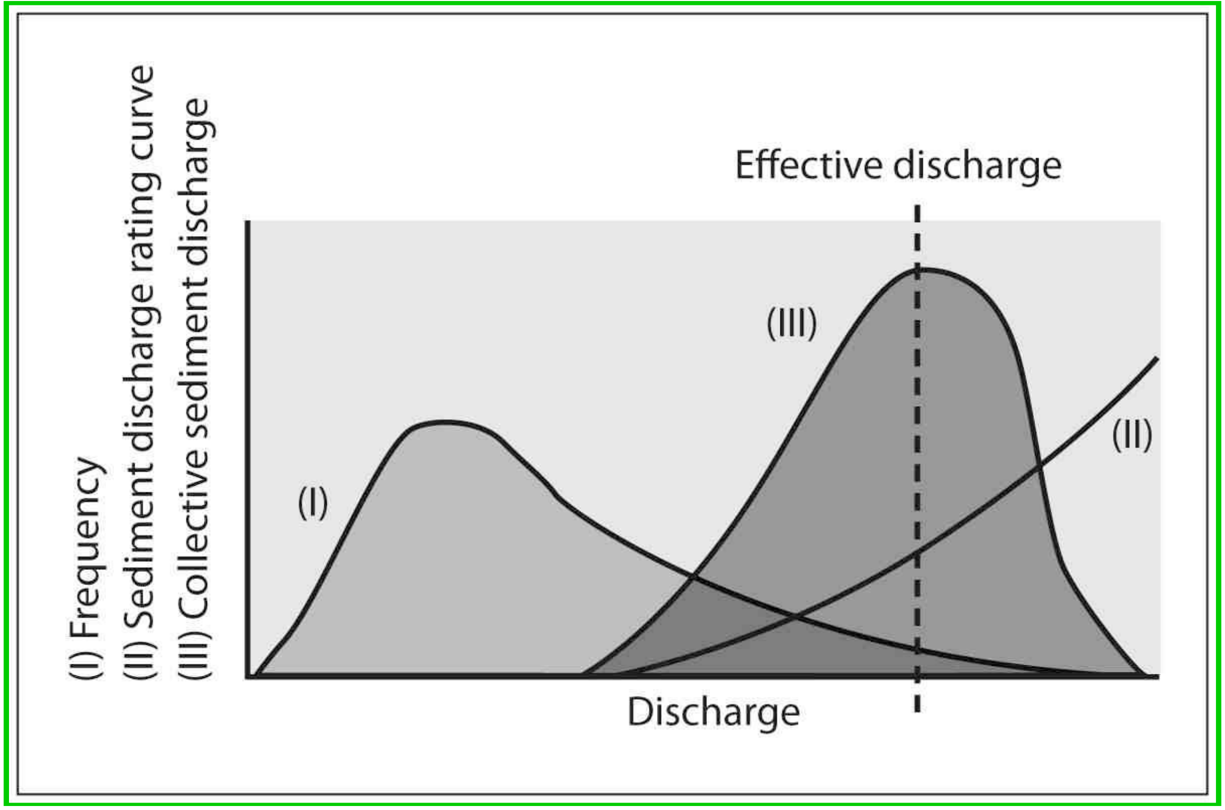
Channel-forming flow is a range of discharges that is dominant in driving the stream processes that shape the channel and its physical habitat (i.e., erosion, sediment transport, and deposition). The finding that intermediate flows with relatively short return periods, rather than rare, large floods, have the greatest influence on the physical form of the channel has long been one of the most influential paradigms in fluvial geomorphology.[26,32] Channel-forming flows redistribute sediment for spawning habitat, scour fine sediment from the streambed and spawning gravels, erode banks to supply coarse sediment and recruit large wood from the riparian zone, and play important roles in riparian plant propagation.[33,31] Hence, the occurrence of channel-forming flows is vital to ecosystems because without them habitat would neither be created nor renewed. As such, the channel-forming discharge is a keystone variable in evaluating stream systems and for stream restoration design.

The channel-forming discharge is commonly represented by one of three flow characterizations: (1) the effective discharge (Q_{eff}), (2) the bankfull discharge (Q_{bf}), or (3) a return-interval discharge, such as the 2-year flow (Q_2).[32,34,35,36,37] Effective discharge is commonly regarded as the preferred method for estimating channel-forming flow for stable channel design,[37,41] particularly where watershed hydrology is known or suspected to have changed due to land or water resource development. While application of a ‘bankfull discharge’ or ‘return-interval discharge’ is common in assessment and restoration design, it is important to understand that application of either of these surrogates for channel-forming flow may lead to significant misrepresentation of channel-forming flow. For example, where the channel is incised or aggraded, the bankfull discharge may no longer represent a channel-forming discharge because channel capacity has increased significantly with incision. Similarly, the use of a return period flow such as the 2-year flow, while convenient because it is easily derived from a flow record, is often inappropriate for a given site based on channel conditions. While numerous studies[32,38,39] have indicated a strong correlation between the 1- to 2-year flow and channel-forming discharge in natural alluvial streams, the data from which these correlations are derived represent primarily larger streams with perennial stream flow and may not apply to smaller streams, especially if they are ephemeral.[40] The range of flows and return periods that can be characterized as within the range of effective discharges varies among stream types and geographically. Among the many variables that influence the return interval estimate for effective discharge are stream type (refer to *Fluvial Geomorphology* Appendix or RiverRAT Section 6.2 for further discussion of stream types and classification), stream size, basin-specific geologic conditions including bedload character, hydrologic regime character, and vegetative characteristics of the bank and floodplain.

Effective discharge - Q_{eff}

The effective discharge is that flow which over a period of years transports the most sediment, and which consequently does the most work in forming the channel (Figure 12).[41,42] While researchers initially suggested that the effective discharge should be represented by a single flow, recent studies suggest an “effective range of discharges” that commonly consist of a range of flows of moderate frequency (typically between the 1- and 10-year events), which together transport the great majority (usually about 70%) of the sediment load.[43]

Figure 12. Hypothetical effective discharge curve (adapted from RiverRAT). The effective discharge curve illustrates that maximum volume of sediment transport over time, represented by the effectiveness curve, is a product of the flow frequency curve and sediment load rating curve (after Biedenharn et al.[44]).



<u>Bankfull discharge - Q_{bf}</u>

Bankfull discharge is the flow that just fills the channel to the top of the banks without spilling out on to the floodplain and is a commonly applied surrogate for channel-forming flow in contemporary restoration and management practices. Arguments for its merits as the channel-forming flow are actually linked to the effective discharge concept. As a channel fills with progressively greater discharge, its capacity to do work on the channel boundary by entraining bed and bank materials increases with increasing depth and velocity. At the point at which flow reaches the tops of banks, additional flow increases are largely distributed across a floodplain, and thus do not significantly add to the stream's in-channel capacity to entrain and transport sediment, or do work. Thus, bankfull discharge may approximate the effective discharge.[C] However, flows a little greater or less than the bankfull discharge may have nearly equal sediment transport capacities, and may have longer flow durations, making them more effective at transporting sediment than the bankfull flow over the long term. This observation supports the idea that there is an effective *range* of discharges, rather than a single flow, that determines the form of an alluvial channel.

[C] Bankfull discharge approximates the effective discharge ONLY *in stable streams that are in equilibrium*. Bankfull discharge measured in an incised or incising, modified or constructed, aggraded or aggrading, or widening channel will not approximate the effective discharge.

The precise definition of *bankfull* may vary as used by a particular practitioner or researcher. The work of Williams (1986)[45] is often quoted as indicating that a wide range of return periods may exist for bankfull discharge, but Williams' reference was to the "top of bank." The definition given by Dunne and Leopold (1978),[46] which bases bankfull flow on physical evidence such as scour lines, elevation of depositional bars, transition to perennial vegetation, and other field indicators, is more commonly used.[40] Therefore, the definitions of terms must be identified before comparing results from different researchers. Practitioners that measure or estimate bankfull discharge should clearly identify the methods used. In many situations, the term "channel-forming flow" may be a more appropriate descriptor and will help avoid confusion.

Return-interval discharge

Research in fluvial geomorphology and hydrology has shown a statistical correlation between bankfull discharge and flows with 1- to 2-year recurrence intervals in stable alluvial rivers where the dimensions of the channel are fully adjusted to the flow regime[32,39,40] Based on this, Q_2 is sometimes taken to represent Q_{bf} in stream project design, yet this is not always a safe assumption. It is, however, important to note that the relationships between bankfull, effective, and two-year discharges referred to herein were derived primarily from alluvial streams in humid regions and perennial streams in semi-arid environments.[41,47] More recent work focusing on the Pacific Northwest indicates that average bankfull discharges have recurrence interval ranges from 1.2 to 1.5 years (with standard deviation of 0.5) depending on ecoregion.[40] When data are stratified by ecoregion, humid areas of western Oregon and Washington have a mean value of 1.2 years, while dryer areas of Idaho and eastern Oregon and Washington have a mean value of 1.4 to 1.5 years. Recurrence interval discharges can be calculated using gauge data or regional regression analysis on non-gauged steams.[48,49] However, streams with ephemeral flow regimes, channels dominated by large wood, or those in valleys confined by bedrock will not necessarily exhibit the expected relationships between moderate-discharge, moderate-frequency flows, and channel form. Further, the return period for bankfull discharge may vary significantly from the 2-year flow in natural streams where the channel is either unstable or not fully adjusted to the current flow regime, or in channels that have been urbanized, channelized, altered for flood control, navigation, or land drainage.

2.2.3 Flood flow

Floods can be defined as flows that overtop the channel banks and inundate part or all of the floodplain.[50] It is often assumed that floods are the dominant force in shaping river systems, and to some extent this is true. During floods, the river interacts directly with its floodplain and valley, depositing sediment, nutrients, seeds, and plant propagules in lower energy areas, scouring the land surface where velocities are higher, recruiting large wood from floodplain forests, and recharging the shallow aquifer beneath the floodplain surface. Floods affect the channel, often dramatically. For example, a flood may excessively erode or deposit large amounts of silt in the channel where floodwater is prevented from spilling onto the floodplain by natural or artificial constraints such as high bluffs or flood embankments. Floods may trigger channel avulsion, where one course of the river is abandoned in favor of another. Channel avulsion is especially important in reinvigorating and renewing riparian and floodplain habitat and can contribute significantly to the formation of side-channel habitat.

Though floods may produce dramatic immediate effects along streams, these effects tend to be localized and may not be as geomorphically significant as the features produced by smaller, but more frequent events when considered at the reach scale. Flood flows in reaches that are hydraulically connected to their floodplain spill out of the channel, transferring stream energy (momentum) out of the channel where it is dissipated by the much higher relative roughness and shallow flow depth. Conversely, stream energy for channel-forming flows is dissipated within the channel, which is why the channel-forming flow often corresponds to about the bankfull discharge.

2.2.4 Low Duration

Flow duration is the length of time a given flow occurs, and is sometimes expressed as the length of time that a given flow is exceeded. Flow duration statistics are useful for projects that include habitat objectives for a specified life stage for target species, to insure sufficient flow and habitat to meet objectives. Flow duration may also be useful for quantifying sediment load, calculating floodplain inundation durations, or determining riparian plant suitability for a project site. Flow duration statistics require daily flow gage data or continuous flow runoff models for a specific season for which the design is relevant. Flow durations may not necessarily imply continuous flows at or above a given discharge – in their purest sense, durations represent only the percent of time through a season or a year. However, discharge data can also be used to determine continuous flow durations where it is relevant to habitat design or to evaluating habitat impacts.

2.2.5 Ordinary High Water

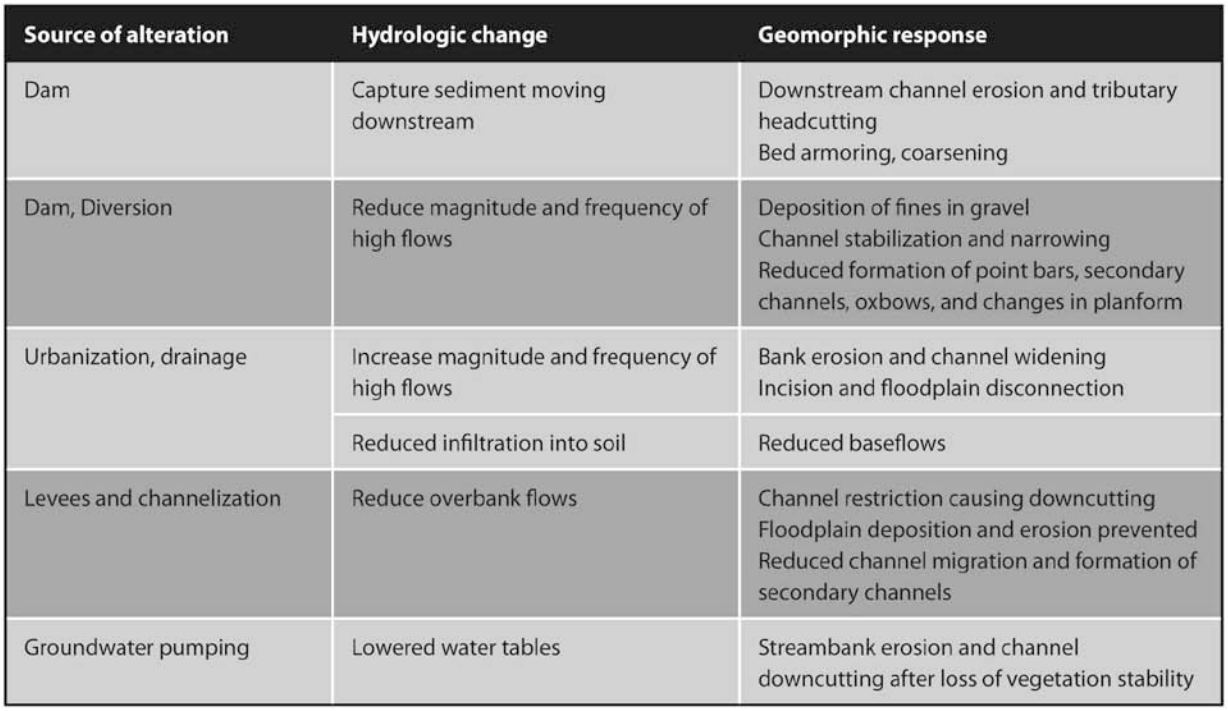
Ordinary High Water is a regulatory designation in Washington State used to regulate land use and development along shorelines. The “Ordinary high water mark” (OHWM) is defined in Washington as “the mark that will be found by examining the bed and banks and ascertaining where the presence and action of waters are so common and usual, and so long continued in all ordinary years, as to mark upon the soil a character distinct from that of the abutting upland…"[51] The OHWM is intended to define the transition between aquatic and terrestrial environments, and is an important component of delineating shoreline jurisdiction and applying the regulations under the Shoreline Management Act (SMA, Chapter 90.58 RCW). All uses and development within 200 feet landward (at a minimum) of the OHWM must be consistent with the SMA and with local comprehensive plans (i.e. Shoreline Master Programs). The OHWM may also affect other state and local rules and regulations, such as permitting requirements.

The Washington State Joint Aquatic Resource Permit Application (JARPA), which is necessary for permitting most stream habitat restoration projects, requires indicating work that will be conducted water ward of the OHWM. In some cases, identifying the OHWM may be necessary to determine the boundaries of State-owned aquatic lands, which will affect permit/approval requirements from WA DNR. See the *Typical Permits for Work In and Around Water* Appendix for additional information on these permit requirements. Apart from the regulatory significance and impact on permitting, the OHWM concept is of little practical value in restoration design, as its definition is ambiguous and does not serve design needs well. Please see the WA State Department of Ecology guideline manual *Determining the Ordinary High Water Mark on Streams in Washington State*[52] for additional information.

2.3 Anthropogenic impacts on flow regime

In the great majority of watersheds within the western United States, human settlement has affected both land and water resources, and has consequently altered river flow regimes (Table 3, from RiverRAT). Restoration or stabilization projects are often proposed to address the adverse impacts on channel morphology and habitat that result from anthropogenic changes to the flow regime. It is of particular importance in assessment and restoration design to evaluate the difference between pre-disturbance hydrologic regime and that resulting from anthropogenic impacts. Where hydrologic impacts are significant, these may be the primary cause of degradation, and therefore deserve consideration in restoration strategy development. Similarly, restoration planning should consider probable future impacts associated with anticipated land conversion or development, as well as the anticipated impacts of climate change (see Climate Change Impacts section below, and *Climate Change* Appendix). Restoration design must account for and accommodate past and future changes in hydrologic regime.

Table 3. Physical response to altered flow (copied from RiverRAT). Physical responses to flow alteration associated with various anthropogenic impacts (adapted from Poff et al. 1997).



Source of alteration	Hydrologic change	Geomorphic response
Dam	Capture sediment moving downstream	Downstream channel erosion and tributary headcutting Bed armoring, coarsening
Dam, Diversion	Reduce magnitude and frequency of high flows	Deposition of fines in gravel Channel stabilization and narrowing Reduced formation of point bars, secondary channels, oxbows, and changes in planform
Urbanization, drainage	Increase magnitude and frequency of high flows	Bank erosion and channel widening Incision and floodplain disconnection
	Reduced infiltration into soil	Reduced baseflows
Levees and channelization	Reduce overbank flows	Channel restriction causing downcutting Floodplain deposition and erosion prevented Reduced channel migration and formation of secondary channels
Groundwater pumping	Lowered water tables	Streambank erosion and channel downcutting after loss of vegetation stability

Anthropogenic impacts on flow regime can result from either direct impacts to the regime or indirectly, through land use. Direct and indirect impacts are summarized below.

2.3.1 Direct Impacts

Direct impacts to the flow regime include river regulation through impoundments, such as dams and reservoirs, or water diversions. Impoundments are constructed to store and release water, with the aim of regulating river flow for a variety of purposes, including moderating floods, generating hydropower, improving navigation, and providing water for dry-season irrigation or urban needs. Direct anthropogenic impacts on the flow regime from dams, impoundments, diversions, or hydropower operations include:

- reduction of the magnitude and frequency of high flows, including channel-forming and flood flows;
- increased duration of moderate flows;
- increased volume and duration of base flows, especially downstream of flood control reservoirs;
- increased rapid changes in discharge, especially downstream of hydropower dams; and
- changes in the seasonal timing and duration of high and low flows.

All of these impacts affect geomorphic processes and associated ecological functions. For example, accelerated rates of change in discharges due to releases from hydropower dams can affect riparian plant vitality and can also cause geotechnical instability in banks due to rapid drawdown that generates excess pore water pressures in poorly drained soils.[53] Widespread bank failures supply excessive amounts of fine sediment to rivers, with adverse impacts on both in-stream and benthic habitats. Similarly, water diversions take water primarily during dry periods when irrigation demand is greatest, thus adversely impacting habitat availability, stream temperature, cool water refuge, passage, hyporheic function, and riparian community health.[28] Impoundments also trap sediment, especially in the coarser size fractions, breaking continuity in the sediment transport system, which results in bed degradation and armoring.

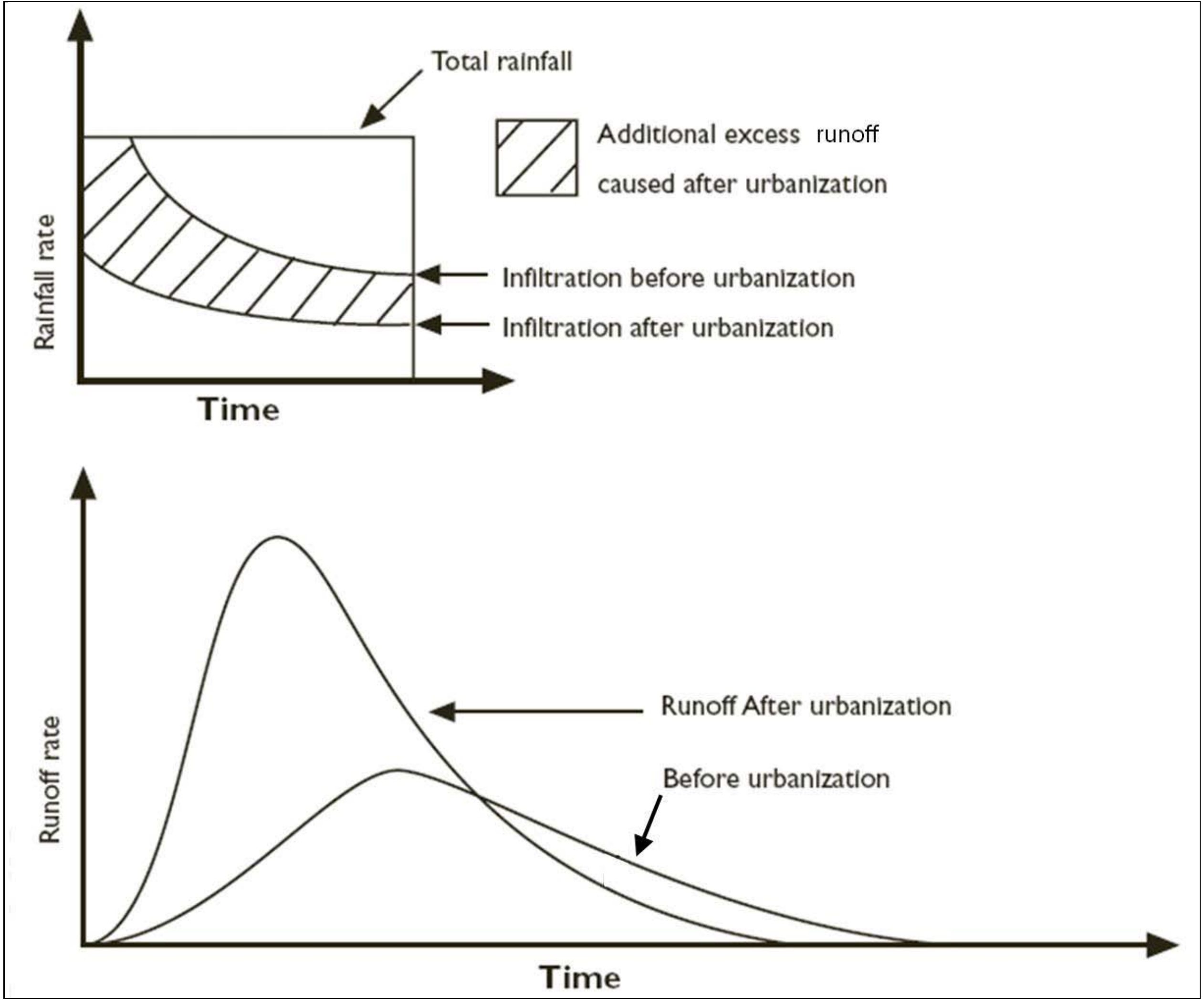
While most flow diversions in the western United States employ diversion structures in the channel, pumping of groundwater from alluvial aquifers can similarly affect low flows by drawing water from the stream into the aquifer, and fundamentally changing the dynamics of energy and nutrient exchange between stream channels and their hyporheic zone.[9]

2.3.2 Indirect Impacts

Indirect impacts on the flow regime resulting from land use are far more pervasive than the direct impacts of flow regulation. For example, conversion of a naturally vegetated watershed to agricultural, industrial, or urban land uses can have multiple impacts that dramatically affect the flow regime.[54,55] In this context, agricultural land use changes the watershed controls that determine rates of interception, infiltration, and evapotranspiration. When combined with associated changes in surface roughness, these alterations have multiple impacts on the rainfall-runoff relationship. Further, agriculture often involves irrigation withdrawals, which reduce low flows, as well as land drainage and flood defense works that alter the flow regime and stream processes. Additionally, irrigation return flows tend to increase in-stream water temperatures and decrease water quality, and may even artificially increase low flows with abnormally high water temperatures and nutrient loads.[54] Similarly, forestry operations can result in immediate and significant changes in the discharge, duration, and timing of flow events.[56] especially if a dense road network accompanies the operations. The multiple and cumulative effects of agriculture and forestry can radically reduce habitat availability and quality throughout a river system.

Urbanization converts significant areas of watershed land surfaces to an impermeable condition, reducing infiltration capacity and fundamentally changing the character of the runoff hydrograph. Also, urbanization involves the construction of gutters and drains that convey precipitation rapidly from its point of origin to the nearest watercourse. The outcomes of urbanization for the flow regime typically include dramatically reduced base flows and flashier storm flows, with shorter times to peak, higher peaks, and shorter recession curves (See Figure 13). The severity of these impacts varies regionally with development density and watershed size.[57]

Figure 13. Conceptual hydrograph changes due to urbanization. Adapted from Chow et al.[6]



The direct and indirect impacts of land use change affect all of the ecologically significant characteristics of the flow regime, including the magnitude, frequency, timing, duration, and rate of change of discharge conditions. These impacts have particular implications for aquatic and riparian organisms.[28] Ecological responses to these impacts are many and varied (Table 4).

Table 4. Ecological responses to alterations of varying flow components. (Adapted from Poff et al.[58]). (copied from RiverRAT).

Flow Component	Specific Alteration	Ecological response
Magnitude and frequency	Increased variation	Washout and/or stranding Loss of sensitive species Wash-out of organic matter Life cycle disruption Altered energy flow
	Flow stabilization	Invasion of establishment of exotic species leading to local extinction and altered communities Reduced water and nutrients to floodplain plants Encroachment of vegetation into channels
Timing	Loss of seasonal flow peaks	Disrupt cues for fish spawning, egg hatching, and migration Loss of fish access to off-channel habitats and refuge Modification of food web structures Reduction of riparian plant recruitment Reduced plant growth rates
Duration	Prolonged low flows	Concentration of aquatic organisms Reduction or elimination of plant cover Diminished plant species diversity Desertification of riparian community Physiological stress leading to reduced plant growth, morphological change, or mortality Reduced available habitat for aquatic species Passage barriers
	Altered inundation duration	Altered plant cover types
	Prolonged inundation	Change in vegetation functional type Tree mortality Loss of riffle habitat for aquatic species
Rate of change	Rapid changes in river stage	Wash-out and stranding of aquatic species Increased Streambank failure
	Accelerated flood recession	Failure of seedling establishment

2.3.3 Climate Change Impacts

Changes in climate triggered by human activity have far ranging effects on the flow regimes of even pristine and relatively undisturbed watersheds. Projected changes in climate change for near and long-term include a general increase in temperature and highly variable changes in precipitation. Modeling of projected change in precipitation patterns indicates high degree of variability influenced by geography and topography, and a significant degree of uncertainty in all model projections. Changes in temperature and precipitation will lead to change in hydrologic regimes that are dominant influence in the geomorphic processes that create and sustain habitat, in the timing of hydrologic events that affect habitat availability and quality, and in the fundamental hydrologic character of watersheds that influences freshwater ecosystem processes. Refer to the *Climate Change* Appendix for a thorough discussion of observed and predicted changes and implications to hydrologic processes and regimes. Because hydrologic impacts of climate change are expected to be significant, derivation of hydrologic values for use in restoration design must account for probable changes in hydrologic regime and consider the diminishing relevance of historic hydrologic data; specific strategies for accounting for climate change in design are provided in the *Climate Change* Appendix, and referenced in Chapter 4.

3 HYDROLOGIC ANALYSIS FOR RESTORATION PLANNING AND DESIGN

Estimation and characterization of stream discharge and flow statistics is necessary for understanding root causes of degradation, analysis of limiting factors, restoration planning and design. Hydrologic analyses characterize, usually through statistical analyses of historical records, the primary descriptors of the flow regime, including the magnitude, frequency, duration, timing, and rate of change of stream flow.[59] Hydrologic analyses characterize seasonal and inter-annual variation in the timing and volume of stream flow, and provide insights into how the regime has changed over time, as well as how it may change in future under alternative scenarios for climate and land use change. Understanding changes in the flow regime may be a crucial element in identifying the causes of existing problems, as well as identifying possible future stresses on river ecosystems. For example, evaluating historical flow records may reveal trends of change in the frequency or duration of channel-forming flows. Such trends may explain observed channel instability or indicate the susceptibility of the channel to future instability. Such trends may also indicate that derivation of flow statistics should be based on only a portion of the record, as data from earlier hydrologic conditions may no longer be valid for characterizing current conditions. Project designs are typically based on specific flow criteria such as low flows, effective discharge, or flood flows – for a discussion of relating specific flow criteria to project design, refer to Chapter 5 and to RiverRAT Appendix 2.

Flow statistics relevant to stream habitat, such as mean low flow (applied to evaluation of extent of low-flow habitat and habitat design), the 100-year flow (applied to flood inundation risk), maximum peak flows for any given month (applied to determine risk of construction inundation during construction months), or minimum flows for any given month (applied to passage design), can all be derived statistically from existing gage discharge data (see following sections), with careful consideration of impacts to the regime through the period of record and potential impacts of climate change. However, many streams are ungaged, or the period of record may be insufficient to derive significant statistics. In such cases, hydrologic investigations will also involve modeling stream flows to develop a synthetic flow record. The following sections provide descriptions of common hydrologic analysis methods and resources for further information.

3.1 Derivation of Discharge Data

Streamflow, or discharge, is an instantaneous value of the rate of flow in a stream. Discharge data needed for hydrologic analyses are typically derived from either gaged streams that measure streamflow periodically or continuously, or on ungaged streams from flow simulation models that predict streamflow. Common approaches and considerations for deriving discharge from gaged and ungaged streams are provided below

3.1.1 Data from gaged streams

Gaging stations, where they exist, can be important sources of flow data and information. Historical stream flow measurements at a gage can be used for hydrologic analysis if the period of record is long enough to be statistically significant. Historical records may be the only flow measurements available for a particular river where gaging stations are no longer in operation. The United States Geological Survey (USGS) maintains gages on many streams. Flow measurements for gaging stations are available from the USGS website (http://water.usgs.gov/osw/). Regional USGS offices may also help obtain more recent or historical data. In Washington State, many gages are also maintained by the Washington State Department of Ecology. Other state and local agencies, federal agencies (e.g., U.S. Forest Service, U.S. Fish and Wildlife Service, Bureau of Land Management, and Bureau of Reclamation), municipal water suppliers, and power companies are other sources of hydrologic data.

Gage data, particularly for gages operated by the USGS, are usually reported as mean daily flows. Instantaneous maximum and minimum daily flow values, which are useful for certain flow analyses, may be available for some gages. Because flow durations in highly impervious or smaller basins may have relatively short durations, peak flow statistics should be derived from instantaneous peak flow data sets rather than mean daily flow data sets if possible.

Regardless of the type of data reported by gages, careful consideration of changes to hydrologic conditions and the hydrologic regime must precede the use of these data for statistical derivation of flow statistics. For example, in watershed with a 50-year period of record that has undergone rapid development in the past 20 years, the full period of record will generate flow statistics that are not representative of current conditions. Rather, the period of record should be segmented, such that analysis is based on those data gathered *after* development has altered the flow regime. While this will shorten the applicable period of record and therefore reduce the certainty in derived statistical values, at least these values will not represent a hydrologic regime that no longer exists.

3.1.2 Data from ungaged streams

Discharge data from ungaged streams can be derived through direct measurement, hydraulic calculations, or runoff simulation models. Direct measurement of streamflow provides a single value of discharge at a point in time. Measurements taken at various stages can be used to develop a flow-rating curve that relates discharge to river stage. Stream gages typically measure stage and translate stage to discharge using a flow rating curve. Discharge is typically measured with either a mechanical current meter that measures flow velocity at sections across the stream and computes discharge (velocity × section area) as the sum of discharges for each section. In recent years, advances in technology have developed discharge measurement techniques using

Acoustic Doppler Current Profilers (ADCP) to measure stream velocity and stream depth. For more information on direct measurement refer to:

- http://ga.water.usgs.gov/edu/streamflow2.html
- http://www.ecy.wa.gov/programs/wq/plants/management/joysmanual/5meter.html

Streamflow can also be estimated using hydraulic relations. The most common hydraulic relation, and one that serves as the foundation for many hydraulic models, is Manning's equation. Manning's equation relates channel area, a roughness coefficient, and slope to estimate flow for a given cross section and depth. It is commonly used to calculate flow in a channel using channel geometry and other characteristics. The application of Manning's equation is detailed in the *Hydraulics* Appendix. Most hydraulic models are based on Manning's equation and require many of the same input values. Field measurements of discharge, based on channel dimensions and the Manning's equation, can be used to calibrate hydraulic models.

For projects in ungaged basins that require discharge values at multiple sites or where rapid or recent development renders historic discharge data inappropriate or insufficient, runoff and streamflow simulation models can provide discharge estimates. Runoff and streamflow simulation models predict streamflow based on simulated runoff from storm events and other inputs. They are most relevant in urbanized watersheds with hydrologic alteration due to impervious areas, flood control, and storm flow detention. The validity of hydrologic values derived from simulation models (as well as statistics derived from the synthetic data) is highly dependent on both the quality and extent of the data input to the models and the assumptions applied in operating the models, as most modeling requires the selection of specific parameters based on these assumptions. Simulation models may produce either single-event discharge values or simulated continuous flows:

Single-Event Runoff Models

Most stormwater and flood models are single-event runoff models. They model direct runoff by simulating rainfall events for certain conditions of precipitation intensity, infiltration rate, time of concentration, and time of travel, without antecedent soil-moisture conditions. These models are usually used for determining peak discharge on small, urbanized watersheds with assumed uniform basin characteristics.

Examples of single-event runoff models include:

- HEC-HMS: The HEC model simulates runoff from precipitation at any point in a watershed for a given storm. Menu-driven software, roughly equivalent to DOS version of HEC-1 model[60]. HEC-HMS develops a series of interconnected sub-basins with hydrologic and hydraulic components of surface runoff, a stream channel, or a reservoir. It calculates discharge but stage can be indirectly calculated from additional user input. The result of the model is a hydrograph at a specified location.

- TR-20: The US Natural Resources Soil Conservation Service, Project Formulation-Hydrology model Technical Release No. 20[61] provides analysis of flood events. TR-20 was formulated to develop runoff hydrographs; route hydrographs through both channel reaches and reservoirs, and combine or separate hydrographs at confluences. This model is applied to watersheds with peak flows from thunderstorms or high-intensity, short-duration rainfall.

- TR-55: The US Natural Resources Soil Conservation Service, Urban Hydrology for Small Watersheds Technical Release No.55 presents simplified procedures to calculate storm runoff volume, peak discharge, hydrographs, and storage volumes for floodwater reservoirs. These procedures are applicable in small urbanizing watersheds. The program provides peak runoff computations using a Graphical Peak Discharge Method, Tabular Peak Discharge Method, and Temporary Storage.

Continuous-Flow Simulation Models

Continuous-flow simulation models account for changes in stream flow resulting from changes in flow inputs. They are valuable for estimating discharges from a series of precipitation events, particularly in urban environments, and for determining frequency and probability of discharge resulting from various precipitation events.

1. GISWA: The Pacific Northwest National Laboratory has developed a GIS-based modeling system for watershed analysis that represents processes and feedbacks within the hydrology-vegetation system. GISWA is an enhanced version of the Distributed Hydrology Soil Vegetation Model[62] (DHSVM). GISWA allows modelers to compensate for road networks, impervious surfaces, and varying soil and vegetation conditions. The DHSVM includes a climate change application that can be linked with the PNNL Regional Climate Model to predict changes resulting from climate change. (http://hydrology.pnl.gov/projects/watershed.asp)

2. SWMM: The U. S. Environmental Protection Agency, Storm Water Management Model (SWMM)[63] can simulate precipitation and transport of water and pollutants through pipe and channel networks, storage treatment units, and receiving waters. It simulates both single event and continuous flows in storm sewers and natural drainage. It is used for prediction of flow, stage, and pollutant concentration.

3. HSPF: The Hydrological Simulation Program – FORTRAN (HSPF)[64] simulates runoff, streamflow, and water quality. HSPF uses the Stanford Watershed Model and input data such as precipitation, potential evapotranspiration, and snowmelt. The model considers four storage zones for precipitation (upper-zone storage, lower-zone storage, groundwater, and snowpack). It routes overland flow, infiltration, interflow, base flow, and flow-to-groundwater within the upper and lower zones to the watershed outlet. It simulates both single event and continuous flows. Typically three to six years of rainfall-runoff data are necessary to calibrate the various parameters, and adjustments are made until an acceptable level of agreement between simulated and recorded flows is established.

3.2 Derivation of Flow Statistics and Design Flows

Analysis of discharge data is used to evaluate historical changes in flow regime to explain observed channel changes, to predict future changes in hydrologic regimes to anticipate potential future impacts, or to derive specific flow values for design of stream habitat restoration projects.

Discharges necessary for stream habitat restoration planning and design typically include channel-forming flow (primarily for channel dimension and channel form design) and a variety of specific return interval discharges or duration discharges to meet specific design criteria (such as stability criteria for installed habitat features or channel banks).

3.2.1 Channel-forming flow

Channel-forming flows can be estimated by calculating the *effective discharge*, or by using a surrogate for effective discharge such as 'bankfull flow' or the 2-year flow.

Effective discharge is quantified with a channel sediment budget and flow duration analysis. A sediment budget can be complex, difficult, and expensive to develop and may be inappropriate for many projects. Flow duration refers to the time stream flows exceed a threshold value capable of moving various sediment sizes as determined through sediment transport analyses. Flow duration analysis requires gaged or simulated flow records of daily mean flows in non-urban channels or instantaneous discharges in urbanized channels. The following resources provide further guidance on how to calculate the effective discharge.

- Biedenharn et al. 2000[41] provides a detailed methodology for calculation of effective discharge.
- Barry et al. 2008 relates effective discharge calculation to prediction of bed load transport rate.

Bankfull discharge is often used as a surrogate for effective discharge. Bankfull discharge can be approximated in some cases by using Manning's equation and field measurements of channel cross-section as detailed in the *Hydraulics* Appendix. Measurement of channel width is discussed in detail in the *Design of Road Culverts for Fish Passage*[65] guideline. Guidelines for identifying bankfull indicators are provided in Dunne and Leopold (1978)[5]. A discussion of bankfull discharge and its relation to channel geometry in the Pacific Northwest is also provided in Castro and Jackson (2001)[40]. It is important to keep in mind that use of bankfull as a surrogate for channel-forming discharge is often inappropriate in streams that have been impacted by changes in sediment or hydrology. It is also hard to determine floodplain and channel boundaries for bankfull estimates in streams with numerous side channels and indistinct banks. Incised channels also do not have bank heights that relate to "bankfull" discharges[66] - bankfull flow may significantly exceed dominant discharge. Additionally, prolonged dry periods with low peak flows tend to narrow channels as vegetation progressively colonizes and stabilizes the bed and banks. Measuring channel geometry under these conditions would indicate a much smaller cross-section than would be found under a wetter regime. Catastrophic floods and debris flows change equilibrium channels and may also obscure historical geometry[67].

3.2.2 Return Interval Discharges

Restoration planning and design often requires the estimation of return-interval flows – discharges with a specific frequency or probability (the inverse of frequency). Return interval flows can be derived using either regional regression equations that relate flow to regional watershed and channel characteristics, or through statistical analysis of flow data (either gage or model-simulated flows).

Regional Regression

In order to estimate flood magnitudes for ungaged basins, the USGS has developed regional regression equations for Washington State.[68] These equations relate flood magnitudes calculated at gaging stations (using the Log Pearson III distribution) to watershed characteristics. The equations vary by region and can be applied to ungaged basins within the same region to estimate flood magnitudes at recurrence intervals ranging from the 2-year to the 100-year events. This method assumes similar meteorological and physiographic conditions for a region and flood-frequency curves of approximately the same slope. Regional regression equations are available from the USGS and common regression variables include basin area, mean basin elevation, and average annual rainfall. The regression equations, as well as published return interval flows for the many gaging stations used in the analysis, can be found in Sumioka et al, 1997[69] (http://wa.water.usgs.gov/pubs/wrir/flood_freq/). Guidance is also given for estimating flood flows for ungaged sites near gaged sites where a combination of regression equations and basin-area comparisons can be used. The USGS has also developed StreamStats, an automated web-based mapping method for applying the regional regression equations (http://water.usgs.gov/osw/streamstats/Washington.html).

Flow statistics

Frequency analysis is a method of interpreting records of hydrologic events to determine future probabilities of occurrence. It is often the basis for planning and designing aquatic habitat and streambank protection projects. One of the most common errors in hydrologic analysis is the derivation of hydrologic statistics from an entire period of record when mean values change over time. In watersheds impacted by climate or land use change, use of the entire period of record will distort the values derived for event return intervals and the associated values for the probability of occurrence. This is particularly relevant to higher frequency flows, such as the 2-year flow values that are commonly used as the basis for channel design. In watersheds subject to urbanization in particular, the frequency of a given discharge may increase dramatically, and what was once a 2-year channel forming flow in an alluvial channel may now occur many times a year. In such cases, it becomes imperative to segment the flow record to identify land-use change as a cause of channel instability and derive design values only from that portion of the record that represents existing hydrologic conditions.

An additional consideration in deriving statistics from flow records is the selection of peak flow data from the period of record. Two generalized forms of peak flow data include an *annual maximum series*, which includes the peak flow from each year of record (where number of peak flows equals the number of years of record), and a *partial duration series,* which includes all peak flow values above some threshold value. Commonly, the threshold discharge is selected such that there is more than one peak flow in most years included in the data series. A partial duration series is typically recommended as a preferred data series.[70] This distinction and application of a partial duration series is particularly important for deriving flow statistics that are more frequent than a 10-year flow. Derivation of flow statistics greater than the 10-year flow (i.e. 25-year or 100-year) are less sensitive to this distinction, and so either a partial duration or annual maximum series may be applied.[71]

Common resources for deriving hydrologic statistics from either gaged or simulated flow records include:

- PEAKFQ performs hydrologic statistics based on U.S. Geological Survey Bulletin 17B (U.S Water Resources Council 1982)[72] the federal standard protocol for flood frequency derivation. Associated with this Bulletin is a software package called PeakFQ that assists users in deriving statistics by performing flood frequency analyis using methods and assumptions from Bulletin 17B. Software is available from: http://water.usgs.gov/software/PeakFQ/
- HEC-FFA. The HEC Flood-flow Frequency Analysis program performs frequency computations of annual maximum flood peaks in accordance with USGS 1982[72.]

3.2.3 Indicators of Hydrologic Alteration (IHA)

Comparison of hydrologic conditions from different times, such as from past to present, or from present to future scenarios, can be accomplished using Indicators of Hydrologic Alteration. IHA is a comprehensive flow-data statistical software tool, developed by the Nature Conservancy, to evaluate deviation from normal hydrologic conditions and is an ideal tool to develop flow management scenarios for regulated flow systems. IHA is sufficiently sophisticated to be defensible, sufficiently user-friendly to be practical, and provides virtually all the statistical derivations needed to develop design discharge from stream gauge data. http://conserveonline.org/workspaces/iha

3.2.4 Uncertainty in derivation of Return Interval statistics

While flow probabilities can be useful for design and consideration of risk, it is equally important to consider the uncertainties inherent in hydrologic analyses. (Refer to RiverRAT *Appendix 3 – 3.5 Uncertainty and Risk* for further discussion of risk and uncertainty). Uncertainty in this context stems from unknown measurement inaccuracies, data limitations, inconsistent data quality, natural annual variability in stream flow, unknown future impacts of land use and climate change, and model uncertainty. Specifically with respect to the determination of return intervals, the length of discharge records must be considered. The period of record for discharge may range anywhere from a few recent or historic months, to a century or more. The uncertainty in calculating the return period for widely used design flows, such as the 2-year event, is high for short records but decreases markedly as records increase in length. A long record will also enable the consideration of extreme events such as droughts or wet periods, as well as provide the basis for evaluating land use impacts through a sensitivity analysis of selected statistics for different segments of the record. Conversely, calculating the 100-year flow is statistically uncertain even from 100 years of record. Experience shows that the magnitude of the theoretical 100-year flood has had to be reevaluated frequently in light of the many so-called 100-year floods observed recently in western states. Similarly, natural variability in channel form and dimensions at “bankfull” stage within a reach can lead to considerable uncertainty in estimates of bankfull discharge based on field measurements and hydrologic records.[73]

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APPENDIX D

SEDIMENT TRANSPORT APPENDIX

Sediment Transport Appendix

1 SEDIMENT TRANSPORT

The sediment cycle begins with the erosion of soil and rock in a watershed and transport of that material by surface runoff or by mass wasting. The transport of sediment through a river system consists of multiple erosional and depositional cycles, as well as progressive physical breakdown of the material. Many sediment particles are intermittently stored in alluvial deposits along the channel margin or floodplain, and ultimately re-entrained via bank and bed erosion. Total sediment loads consist of suspended load (the fine-grained fraction transported in the water column), bedload (the coarse-grained fraction transported along the channel bed) and dissolved load (materials in solution). The transport of sediment through the stream system depends on the sediment supply (size and quantity) and the ability of the stream to transport that sediment supply.

1.1 Sediment Transport Processes and Aquatic Habitat

The caliber (particle sizes), volume, and transport dynamics of sediment exert considerable control on channel form and geomorphic processes that create and sustain aquatic habitat in all river systems. Sediment caliber dictates what geomorphic features and associated habitat types (e.g., sand bed vs. gravel bed) will be characteristic of a given channel. Sediment volume can affect the stability of a channel, causing channel aggradation if the volume delivered is in excess of the transport energy available, and causing channel degradation if the volume delivered is less than the transport energy available. Sediment volume may also affect channel pattern and slope, with high volumes of coarse sediment resulting in relatively steep slopes, high width/depth ratios, and braided channel patterns.[1]

Some degree of sediment mobility is critical for the ecological health of a stream system. Booth and Jackson[2] note that anadromous salmonids "depend on particular combination of water and sediment fluxes to maintain favorable channel conditions." Most Pacific Northwest aquatic organisms have evolved within dynamic stream systems, in which pools, bars, and other habitat features are continually reworked and reformed. Physical habitat is created and sustained through processes such as the maintenance of pools and riffles, the formation of transient bars, side channels, and backwater areas, the deposition of spawning gravels, and the flushing of fines from bed substrate.

Sediment sorting through selective transport creates spawning habitat and quality habitat for benthic organisms, which in turn are food for aquatic species such as fish. The maintenance of pool-riffle sequence morphologies and the effective sorting of bed materials exemplifies balanced conditions of sediment caliber, hydraulic complexity, and transport energy that serve to generate and maintain quality aquatic habitat.

1.2 Sediment Transport and Stream Morphology

1.2.1 General

Sediment transport and storage count among the major interdependent variables that determine stream morphology. Many channel features, including depositional bars, riffles, steps, pools, and dunes are manifestations of sediment transport, erosion, deposition and in-channel storage.

Table 1 lists typical features and associated sediment transport characteristics for the seven basic channel types defined by Montgomery and Buffington[3]. Although a number of channel classification schemes exist, that of Montgomery and Buffington serves well for the purpose of examining the role of sediment transport in determining stream morphology.

Table 1. Channel characteristics, and corresponding sediment transport processes, based on the Montgomery and Buffington channel types (see *Geomorphology* Appendix).[3]

Channel Type	***Characteristic Features***	***Typical Sediment Source and Storage Characteristics***	***Corresponding Sediment Transport Processes***
Cascade	• "Disorganized" bed material typically consisting of cobbles and boulders, which are large relative to the channel depth and width • Small, irregularly spaced pools less than a channel width apart • Very steep gradient (8 to 20 percent)	• Predominantly colluvial channel boundaries • Alluvial sediment in small hydraulically-protected patches only • Generally low sediment load • Source reach	• Large, bed-forming materials typically become mobile only in large flood events (i.e., 50-100 yr events) or debris flows • Bi-modal transport: sand or gravel stored in low energy sites is transported by lesser floods on top of immobile streambed
Step Pool	• Discrete steps formed by large-diameter material separating pools containing finer materials • Pool lengths generally equal 1-4 channel widths • Steep gradients (4 to 8 percent)	• Predominantly colluvial channel boundaries, but steps are coarse alluvial bedforms • Finer alluvial sediment in small hydraulically-protected patches only • Generally low sediment load • Transport reach	• Like cascade channels, large, bed-forming materials typically become mobile only in large flood events • Bi-modal transport: sand or gravel stored in low energy sites is transported by lesser floods on top of immobile streambed
Plane Bed	• Characterized by long stretches of channel unbroken by steps, bars, or local slope changes. • Composed of sand to boulder sized materials (typically gravel to cobble) • Generally confined, but may have unconfined portions • Moderate gradient (2 to 4 percent)	• Transitional between colluvial and alluvial channel boundaries • Rudimentary or incipient floodplain deposition or bar development in some areas • Coarsened surface texture (armor) but often broken by large particles penetrating from subsurface • Generally low to moderate sediment load • Transport reach	• Portions of streambed fully alluvial, other portions mobile only in large flow events • May show bi-modal transport as above, but streambed becomes alluvial sediment source at moderate floods.
Pool Riffle	• Contain alternating topographic depressions (pools) and high points (bars and riffles) typically spaced 5-7 channel widths apart • Generally unconfined, with well-developed floodplains • Generally occur at moderate to low gradients (less than 2 percent) • Substrate varies from sand to cobble (typically gravel)	• Alluvial channel boundaries, except where abuts valley sides or obstructions • Well developed floodplain and bars • Coarsened surface texture (armor) is common adjustment to sediment load • Generally moderate sediment load • Response reach; adjustable channel boundaries and streambed structure	• Streambed becomes mobile during moderate floods, with active alluvial transport and deposition • Dynamic pavement exchanges sediment with bedload • Transport involves individual particles or subtle bedforms less that a few particles thick • Coarsened surface layer regulates sediment supply via the "hiding factor" • Range of bed sediment structures depending on sediment caliber and load
Dune Ripple	• Typically low gradient, sand bed channels containing relatively mobile dunes and ripples • Very low gradient (usually	• Alluvial channel boundaries, except where abuts valley sides or obstructions • Well developed floodplain and bars	• Streambed becomes mobile during low to moderate floods, with active alluvial transport and deposition • Transport involves bedforms including ripples, dunes, bedload sheets, etc. which

	less than 0.1 percent)	• No armor layer • Generally moderate to high sediment load • Response reach; adjustable channel boundaries	are much thicker than single particles
Bedrock	• Bedrock or clay bed • Moderate to high gradient for bedrock beds • Moderate to low gradient for clay beds, which can behave like soft “bedrock”	• Often, some alluvial material stored in scour holes and behind obstructions • Transport reach	• Generally reflect a high transport capacity relative to sediment supply or current lack of large roughness elements for sediment retention capacity • May be subject to dissolution of materials as dissolved load (e.g. limestone substrate)
Colluvial[A]	• Small headwater streams with minimal channel development • Often ephemeral or intermittent flow • High gradient (greater than 20 percent)	• Colluvial channel boundaries • Low fluvial sediment load • Source reach	• Weak or ephemeral fluvial transport • Long-term sediment flux from these channels appears to be dominated by debris-flows

The Pacific Northwest is a "sediment rich" region in comparison to other parts of the United States. A legacy of deep glacial deposits from the Pleistocene, and the presence of numerous active volcanoes, has created a landscape in which many rivers have moderate to high sediment loads, significantly, comprised of large amounts of coarse particles (gravel, cobble). This stands in contrast to less geologically active regions, where sediment deposits are mostly fine textured, and where the slow weathering of bedrock is the dominant source of coarse sediment. The implications of this observation are that sediment analysis takes a more preeminent role in the Pacific Northwest that it might elsewhere.

1.2.2 Effects of Vegetation on Sediment Transport

Vegetation profoundly effects sediment transport in three ways. First, vegetation regulates the supply of sediment delivered to the channel by surface erosion and mass wasting of upland soils. In addition to disrupting overland flow and promoting infiltration, vegetation binds the soil particles together with its roots and increases the cohesive forces on grains of soil by reducing the water content and shortening the amount of time that the soil is saturated.

Second, vegetation acts to create hydraulic roughness, disrupting the erosive force of water in the near-bank region and on floodplains. By affecting channel hydraulic capacity, vegetation increases channel-floodplain interactions, thereby limiting channel erosion at high flows in some locations, while encouraging scour or deposition in parts of the floodplain. Vegetative diversity creates channel complexity providing variability in local form roughness that locally reduces or increases the energy available for erosion and transport. These influences all lead to hydraulic complexity that can cause sediment sorting during deposition or sediment scour around resistant vegetation.

[A] The term “colluvial” usually refers to any stream with channel boundaries consisting of “colluvium,” that is, of material eroded from the local hillslope, as opposed to “alluvium,” which is material deposited by flowing water. In Montgomery and Buffington’s classification system, however, the “colluvial channel type” refers to small, steep, headwater streams in topographic depressions with little or no development of an eroded water course.

Finally, just as in upland areas, the root network increases the mechanical strength of streambank soils, and helps to dry out those soils, which increases the cohesion of soil particles. Vegetation increases bank strength, particularly in medium- to fine-textured soils. Vegetation makes possible the evolution of relatively deep, narrow channel cross-section and meandering planforms which transport sediment more efficiently than the wider, shallower channels that result when vegetation is reduced or absent.

1.2.2.1 Effects of Large Wood on Sediment Transport

Large wood in streams increases hydraulic complexity, influencing the local velocity fluctuations that determine the scour and deposition of sediment. The hydraulic resistance or "form roughness" of large wood is extremely important for energy dissipation, without which energy would be available to erode the streambed. Thus, the presence of wood tends to increase the sediment storage capacity of a reach. Other effects of large wood include sorting of sediment sizes, inducing bar formation, inducing local scour, and causing sediment deposition in channels and on floodplains that provide for riparian vegetation colonization and forest flood plain development.[4,5,6,7] Wood can actually "force" or induce the formation of pools, bars, and steps in channels that would otherwise not have these characteristics.[3] In extreme cases, logjams may force the presence of alluvial beds in otherwise colluvial or bedrock reaches.[3] Log jams play a major role in sediment transport dynamics, as water and sediment stored behind jams can be rapidly released, creating transport events ranging from small sediment pulses to high magnitude sediment and debris-laden dam outburst floods. Even small woody debris can form jams that give rise to outburst floods. This is a mechanism by which relatively small streams can transport large volumes of sediment, including larger than normal particle sizes.

1.2.3 Effects of Floodplains on Sediment Transport

Floodplains play a critical role in sediment transport in alluvial stream systems. By functioning as a 'relief valve' for the stream during high flow periods, floodplains dramatically reduce the flow energy focused within the active channel. Alluvial stream/floodplain systems tend toward establishing an equilibrium that balances the inputs of sediment into a reach with the outputs leaving the reach. This equilibrium is reached by adjustments in the channel form such that just enough energy is present in the 'normal' high flow regime to maintain a balance between sediment deliveries and exports. A critical part of these energy relationships is the availability of the floodplain to accept flows that exceed the "bankfull" channel capacity. Typically, diking and other activities that restrict or eliminate floodplain connectivity disrupt this equilibrium, often leading to increased erosion within the diked reach, and excessive sediment deposition downstream.

Furthermore, during high flows, when a large majority of sediment transport occurs, vegetated floodplains tend to efficiently trap and store fine sediments. This stream/floodplain interaction is part of a positive feedback loop that develops the conditions for a vigorous riparian/floodplain plant community, builds banks, shapes channel geometry, and attenuates flows. All of these processes and system characteristics exert a strong influence on the transport of bed load.

1.2.4 Effects of Dams and Weirs on Sediment Transport

The trapping of sediment behind dams and weirs (e.g., in sediment detention basins) often results in the release of sediment-deficient water from the structure (at least until the feature no longer stores sediment). In effect, as long as a weir or dam acts as a sediment trap, it produces a "decoupling of the sediment transport conveyor belt.[8] As a result of the decreased sediment load, erosion and armoring (hardening of bed with immobile, large substrate) of the channel bed downstream of dam or weir often occurs, as smaller-sized materials are winnowed from the bed and are not replaced.[9] Below large dams, this bed coarsening and immobility is further accentuated by the controlled release of water, which mutes large peak flows, replacing short-duration, high-magnitude peaks with longer periods of elevated, but moderate, discharge.[8] Bed armoring can be preceded by incision if the size and gradation of the native bed material is small relative to hydraulic forces (i.e., if a great deal of fine material is winnowed out in the armoring process). Such incision is more likely in pool riffle, plane bed, and dune ripple reaches, where bed materials are more readily transported under average to moderately high discharges, than in steeper step pool and cascade reaches where the key bed elements are stable at relatively high discharges.

2 SEDIMENT TRANSPORT ANALYSIS

2.1 General

Sediment transport is one of the most important, but least evaluated components of stream habitat restoration design. As a design component, sediment transport analyses should focus on providing for sediment continuity, a factor that is repeatedly cited as a condition for true channel stability.[10] Channel stability in this context implies that there is no net aggradation or degradation of the channel bed, or more simply, that rates of sediment erosion and deposition are in approximate dynamic balance.[11]

Three basic types of sediment transport analysis exist, and it is important to know when each type is appropriate. The simplest type is the *channel competence* analysis, which seeks to determine what sizes of particles the channel can mobilize at a given discharge. The next higher level of complexity is analysis of *sediment transport capacity*, that is, the volume of sediment being transported over a given time. This can be done for a given discharge, or for the entire range of discharges encountered. It can be done as a total sediment volume, or be broken down by sediment size class. Finally, it is sometimes desirable to compute the *sediment budget* for the watershed, which quantifies not only total sediment in transport (usually as an annual mean), but also the volumes contributed by various sources, and the amount being exchanged with various storage components. A sediment budget can be complete or partial depending on objectives, and generally quantifies total average annual yield as opposed to sediment in movement at particular discharges. Sediment budgets will be discussed at the end of this appendix, and in more detail in the *Geomorphology* Appendix.

Channel competence is an appropriate level of analysis for streambeds that are being designed as "threshold channels", that is, a channel in which movement of the channel boundary material is purposely designed to be negligible. The term "threshold" is used because the applied forces from the flowing water are below the threshold for movement of the boundary material. Threshold channels generally do not accumulate alluvial sediment, but rather transport all of the sediment delivered to them from upstream. Channel competence analysis is sometimes also used, however, for analysis of fully alluvial channels that have mobile streambeds and banks, and are thus not threshold channels. Usually, an assumption is made that the sediment equilibrium can be achieved if a certain target sediment size is competent to move at a certain design discharge. For example, it is often assumed that if the D_{84} particle size is competent to move at geomorphic bankfull flow, then the channel will transport its entire sediment load. Though no theoretical basis exists for this assumption, it has been found empirically to work for alluvial channels with low to moderate sediment loads.[12] However, designing an alluvial channel with adjustable boundaries in the absence of sediment capacity analysis can be risky, particularly in channel reaches prone to receiving periodic pulses of sediment or in response reaches (see *Geomorphology* Appendix).

Channels that have high sediment loads, particularly channels located in depositional geomorphic settings (response reaches), call for analysis of sediment transport volume or capacity. Often, it is sufficient to compare the sediment transport capacity before and after a channel modification, or to compare transport capacity at one cross-section with that at another. In these cases, the computation need not be highly accurate, and the sediment capacity analysis may not be any more difficult than sediment competence analysis.

Accurate measurement and prediction of sediment mobility and transport volumes are notoriously difficult, for several reasons, which are summarized in Table 2.[13] Regression equations based on field sampling of sediment transport provide the most accurate rating curves[B] of sediment discharge to stream flow, provided there is enough data for statistical rigor, and that the data spans the range of flows needed to answer the desired questions. For example, if the objective is a design discharge to achieve sediment equilibrium, sampling should span the effective discharge, and if a flood plain is present, flows above bankfull are necessary. Sediment transport equations based on statistical regression alone cannot readily be extrapolated.

Whenever possible, sediment transport sampling data should be used to calibrate or aid in selection of transport equations. A physically-based model calibrated with field sediment transport data can reduce greatly the sources of error mentioned in Table 2, gaining accuracy with fewer samples and lower cost than a statistical rating curve.

Model results, especially if not calibrated with field sampling, tend to be more reliable as a comparative tool for “before” and “after” conditions rather than in determining absolute values. For this reason, analysis results should, in general, be used comparatively rather than absolutely. A number of practical sediment transport analysis approaches and techniques are presented below.

[B] A rating curve is an equation which relates a quantity of interest, in this case sediment transport rate, to water discharge. This is often done graphically or with statistical methods such as linear regression.

Table 2. Sources of difficulty in making accurate estimates of sediment transport capacity, based on discussion in Wilcock et al., 2009.[13] Refer to the *Hydraulics* Appendix for discussion of various hydraulic forces referenced in this table and document (e.g. shear stress).

Source of Error in Transport Computations	*Reason*
Sediment Transport Function	o Transport rates increase exponentially above threshold of motion, so small errors in estimated hydraulic shear stress can produce large errors in transport rate o Some commonly-used transport functions are inaccurate, particularly those which do not account for the coarsened bed surface layer or armor, and those calibrated for uniform sediment size (most rivers have mixed-size sediment)
Flow hydraulics and shear stress	o Difficulty estimating the partitioning of shear stress into the proportion available for sediment transport (skin friction versus total shear stress) o Spatial variability of shear stress is difficult to account for accurately o Unsteady and non-uniform flow, which includes accelerations that affect hydraulic shear stress, are usually ignored
Sediment size distribution	o Commonly used sampling techniques, such as Wolman pebble counts, have problems with bias, under-sampling of fine sediment fraction, and high observer variability o Spatial variability of streambed sediment can be high, and is difficult to account for without stratified (non-random) sampling or large numbers of samples
Shear stress threshold for incipient motion	o Threshold shear stress reported in literature varies by author, creating uncertainty over appropriate value unless calibration with sediment transport samples is performed o Threshold shear stress varies according to armor layer particle arrangement, roundness, embeddedness and sand content
Natural temporal and spatial variability of sediment transport	o Adjustment of stream channel boundaries and streambed texture may lag changes to sediment load, especially if sources are nearby or are quickly depleted o Some sediment sources (e.g. mass wasting, streambank erosion) are episodic, resulting in variable transport rate at the same water discharge o Bedforms, such as bedload sheets, locally influence transport rate when present

2.2 Estimating Streambed Sediment Size

Sediment transport evaluations generally begin with a determination of the size fractions of sediment present within a given reach of channel. The measurement of sediment caliber can be performed by several methods including pebble counts and sieve analyses of bulk (volumetric) streambed samples. Pebble counts are based on analysis of the relative area covered by given sizes, and essentially consist of measuring the intermediate axis of 100 (or, better, up to 400) individual sediment particles selected by fingertip, either at random, along a path, or within a grid.[14] This sample represents the surface layer, and the resulting particle size distribution will generally be coarser than the overall bed material distribution which includes the subsurface.

Though it is very common to characterize the particle size distribution of coarse riverbed material using the pebble count technique developed by Wolman,[15] this method, and its variants such as using a sampling frame, are problematic for use in sediment transport studies in streams that transport appreciable amounts of fine gravels or sand.[16] Pebble counts tend to be biased towards larger particle sizes.[19] As such, they are well suited to hydraulic roughness determination, but underestimate the presence of smaller size fractions, which can make up an appreciable portion of the bedload, even in gravel-bed streams. This is due to a “hiding factor” effect, whereby small particles lodge in crevices smaller than the fingertip, and due to a psychological tendency to choose a larger, more palpable particle during the sampling process.

The Wolman technique involves walking along a path, which could be a transect, zig-zag, or series of parallel lines, and at each step, selecting a particle beneath the toe of the boot with a fingertip. Frame sampling involves repeated placement of a sampling grid frame on the streambed, usually following a transect, and selecting particles under pre-determined grid points. This tends to result in less bias, lower operator variability, and more complete coverage than the Wolman method.[14] Evidence exists that a sample size of 100 particles is not enough to be able to statistically compare different sites, or for change over time, or even for D_{50} and D_{84} in poorly sorted streambeds with a full range of particle sizes.[17] Samples of about 400 particles represent the best compromise between increased accuracy and manageable sample size.

To avoid this bias, and to characterize the structure (layering) of the streambed, volumetric sampling with sieve analysis is necessary. The “barrel sampler” method, or the plywood shield method (see Figure 1), are standard volumetric sampling techniques.[17,18] The barrel sampler and plywood shield are means of isolating a patch of submerged streambed from the flow, so that a bulk sample of the bed material can be excavated without washing away the fine components or collapsing the hole. Sieve analysis is conducted on these bulk samples, which consists of sifting sediment through a series of standard sized sieves,[19] which have openings corresponding to a powers-of-two scale in millimeters (see Table 3). The amount of sediment remaining on each sieve is then weighed to determine the percent of the total weight of a given size fraction. The sample can be wet-sieved in the field, or can be removed to the lab, dried, and then sieved. Figure 2 shows a typical sediment size distribution. It is best to sample the armor or surface layer separately from the subsurface rather than mixing the two during volumetric sampling, as some transport models require one or the other, and the difference in size distribution between the surface armor and subsurface layer contains valuable information.[20] Sampling techniques which mix the surface and subsurface layers, such as shovel sampling or the McNeil sampler, are not recommended for gravel or cobble-bedded streams, since this would result in inaccurate characterization of particle motion thresholds and would violate the assumptions of most sediment transport models. Volumetric sampling will always be necessary in cases where the dominant bed material is sand or finer. When the material is very fine, suspended sediment analysis techniques, such as pipette analysis[21] are necessary to determine the size distribution.

Volumetric sampling requires judicious selection of representative alluvial deposits, since each sample covers only a small area. It is also important, for statistical accuracy, that the weight of largest particle present in the sample not be greater than some small percentage (say, 5 or 10 percent) of the total sample. For example, a surface layer where 64 mm particles are the largest size would require at least 7.5 kg to satisfy the 5 percent criterion. This could result in unreasonably large sample sizes in very coarse bedded streams, in which case it may be preferable to sample the armor layer with a pebble count and use a volumetric sample to characterize the subsurface for sediment transport.

Figure 1. Two types of shields for isolating a portion of the streambed from water flow in order to collect bulk sediment samples. Top: three-sided plywood shield (photo: Paul Bakke). Bottom: barrel sampler (photo: Kristin Bunte).

Table3. Wentworth scale for sediment particle size classification. Right column lists similarly-sized objects for reference.

Description		Sieve opening, mm	
	large	1024	
Boulder	medium	512	
	small	256	Basket ball
Cobble	large	128	
	small	64	Tennis ball
	very coarse	32	
Gravel	coarse	16	
	medium	8	
	fine	4	
	very fine	2	BB
	very coarse	1	
Sand	coarse	0.5	
	medium	0.25	
	fine	0.125	
	very fine	0.063	Grit
Silt		0.0039	Flour
Clay		0.00024	Goo

Figure 2. Surface (armor layer) particle size distribution, from a volumetric sample. Cumulative distribution shown as solid red line, with individual size classes as vertical bars. D50 = 42.3 mm, D84 = 81.2 mm.

2.3 Sediment Transport Sampling

Sediment transport sampling allows for measurement of quantities and size gradations in motion at given flows. This can be used to directly estimate sediment transport via statistical techniques, or to calibrate a sediment transport model. Generally, measurement of sediment transport is done when greater accuracy is required by the nature of the project or its geomorphic setting.

2.3.1 Bedload Sampling

Bedload, the coarse fraction of sediment transport, moves by bouncing, sliding and rolling along the streambed, is most commonly measured using the Helley-Smith sampler (see Figure 3),[22] which consists of a fine-mesh net mounted on a metal frame that can be lowered to the streambed. The frame is shaped to create mild Venturi suction that compensates for the hydraulic resistance of the net. Both cable mounted and handheld versions exist. The Helley-Smith sampler has the disadvantage of having a relatively small square opening (3 inches or 76 mm), making it inaccurate for particle sizes bigger than about half that size,[23] or roughly 38 mm. It is, however, relatively easy to use in the high discharges during which bedload is commonly measured. Sampling consists of placing the Helley-Smith on the streambed for a brief period (e.g. 1-2 minutes) of time at each of a series of stations spaced evenly along the cross-section, giving a measure of average transport over the total sampling time. This requires either wading the stream, or lowering the sampler from a bridge. Guidelines exist for building inexpensive temporary foot bridges for this purpose.[24]

More accurate but more difficult to deploy are various forms of bedload traps. These include nets with an upstream-facing rectangular opening anchored to the streambed,[25] and pitfall traps such as buckets countersunk into the streambed.[26] Net-type traps, like the Helley-Smith, measure bedload over short time intervals, generally in an hour or less. They require wading access during transport events. Pit traps are generally accessible only at lower flows. They are left in place throughout a bedload transporting event, giving an integrated sample over a range of flows, and are thus limited to streams having lower transport rates such that the traps do not fill before sample recovery can take place. These have the advantage of averaging out any pulses of bedload movement, but make it impossible to correlate a particular discharge with a particular transport rate.

Figure 3. Helley-Smith bedload samplers. Handheld model is on left. Model on right is for use with reel and cable equipment.

2.3.2 Suspended Sediment and Turbidity Sampling

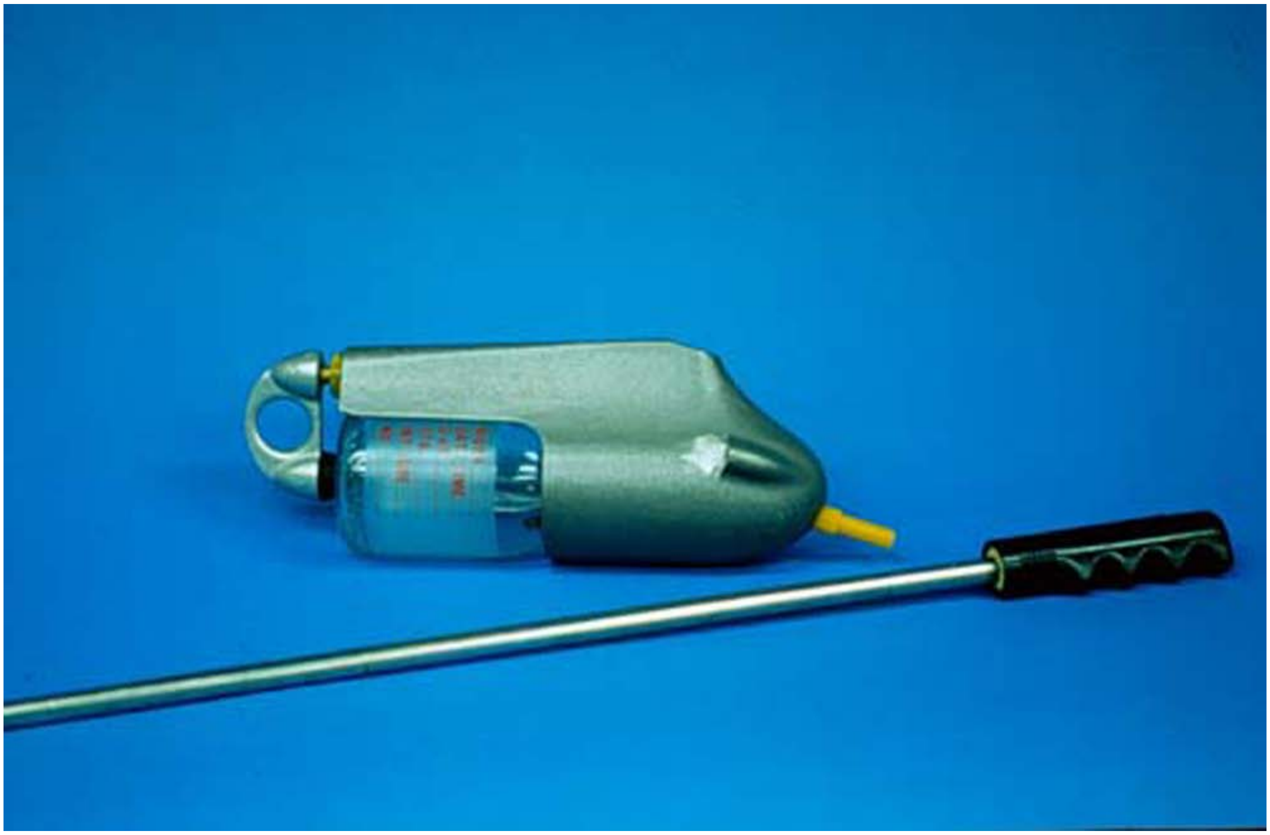
In alluvial streams, bedload provides the materials comprising the channel bed, but suspended load typically provides the materials making up the floodplain. Suspended sediment is often measured in habitat and water quality assessments, since it has direct impacts on health and behavior of fish and other organisms. It also can infiltrate the streambed, clogging interstitial spaces and producing an embedded streambed condition. Since suspended sediment can be a very significant portion of the total sediment load, it is of interest in projects and studies involving infilling of lakes or reservoirs. It is also of interest when restoration includes improved floodplain function, since this will usually include overbank deposition of suspended sediment.

Modeling of suspended sediment is difficult, because only a portion of it originates in the streambed and thus correlates well with hydraulic conditions. Much of the suspended sediment may be source-dependent, originating from episodic events such as streambank erosion, surface erosion outside of the channel, or erosion of mass wasting deposits. Thus, field measurement is often the only reliable way to quantify suspended sediment.

Direct measurement is done by obtaining a depth integrated sample of water during a sediment transporting event. The most scientifically rigorous way of doing this is with a depth integrating sampler, such as the DH-48 (Figure 4), which is designed to collect a water sample containing proportionately more water from parts of the water column that have higher velocity. Edwards and Glysson (1988) describe field protocols for this purpose.[22] Where less accuracy is required, it is possible to use ordinary 1-liter sample bottles, being careful to tip the bottle slowly as it is being filled, while moving it through the water column from bottom to top. Suspended sediment is usually analyzed by filtering the water sample then drying and weighing the extracted solids, giving a measure of total suspended solids in mg/l. Much less commonly, pipette analysis techniques are used to obtain a size distribution of the suspended sediment.

Turbidity is often used as a surrogate for suspended sediment in water quality and habitat assessment, since it is easy to measure in the field, and since relatively inexpensive electronic probes exist for long-term automated deployment. Turbidity is a measure of the light-scattering properties of the water, which correlates with suspended sediment concentration, but also is influenced by the physical characteristics of the particles themselves. Thus, to convert turbidity to suspended sediment, water samples must be taken concurrently with turbidity measurements, and then laboratory analyzed for total suspended solids, in order to create a rating curve (equation relating suspended sediment concentration to turbidity).

Figure 4. DH-48 depth integrated water sampler for collecting suspended sediment samples. Handle (partly shown at bottom) attaches to top of metal housing when in use.



2.4 *Bedload versus Bed Material Load*

Besides the bedload versus suspended load distinction, it is sometimes useful to classify the total sediment load in terms of its source rather than its mode of transport. *Bed material load* consists of that portion of the total sediment load which comes from the scour and mobilization of streambed deposits. This will include both bedload, and some portion of the suspended load. That portion of the total load which is not bed material load is then considered *wash load*, which consists of material so fine that it is essentially carried in the water column through the entire channel without settling out in the streambed in appreciable quantities. This bed material load/wash load distinction is particularly useful for sediment budget studies, and for comparing or contrasting different reaches, since only bed material load will appear in intermediate storage locations, such as on gravel bars and alluvial fans. The size threshold separating bed material load from wash load changes as one moves downstream.

Despite its advantages for geomorphic characterization, bed material load is much less straightforward to measure directly using commonly applied sampling techniques than bedload and suspended load. For that reason, determination of bed material load is rarely used in restoration design.

Some of the sediment transport equations to be discussed below actually predict “total load,” which in this sense means bed material load. This is commonly done with sand transport equations, since in sand-bedded streams, the distinction between bedload and suspended load is one of particle location rather than particle size. It is always important to know which terminology is being used when discussing sediment transport.

2.5 *Bedload Movement*

Bedload has two ways of moving, depending on dominant particle size, sediment transport rate, and hydraulic conditions, as summarized in Table 4. Where particles are coarse, sediment loads are low to moderate, and the hydraulic forces acting on the streambed only moderately exceed those required to mobilize a typical particle; individual particle movement best describes the bedload. Where particles are relatively fine, sediment loads are moderate to high, and the hydraulic forces acting on the streambed greatly exceed those required to mobilize a typical particle; groupings of particles called bedforms, such as ripples, dunes, and bedload sheets, dominate bedload transport.

In coarse-bedded streams, sediment transport is thought to directly involve the dynamic exchange with the coarsened surface layer (pavement, or armor layer), a layer roughly one particle diameter thick. Individual particles are sporadically dislodged from the bed, leaving a hole which can then “trap” another similar-sized particle or groups of smaller particles. In this way, the bed exchanges particles with the moving bedload while retaining its surface, the dynamic pavement, intact. The pavement or armor layer can persist at high flows, not needing to “break up” for transport to occur. If the streambed scours or fills over the course of a peak flow, the dynamic pavement rides up and down with it.

Generally, the coarser the sediment the more infrequent and concentrated in time the movement is, and the more rapidly transport rate increases with discharge. By contrast, in sand-bedded streams, streamers of sand bedload may be moving even at low discharge. Bedload transport in sand-bedded channels involves a layer of the streambed much thicker than single particle, usually aggregated into distinct bedforms such as ripples and dunes. Individual particles, which can be moving quite rapidly, become part of a bedform, and are swept downstream to become part of another bedform, as the bedforms themselves slowly progress downstream (in the case of ripples and dunes) or even upstream (in the case and anti-dunes). Bedload sheets are slow-moving, somewhat indistinct bedforms that occur in coarse bedded streams when sediment loads are high. These can be partly responsible for pulses of bedload that are often observed under moderate to high sediment loads.

Table 4. Characteristics of bedload transport.

Particle Size	***Sediment Load***	***Hydraulic Conditions***	***Mode of Bedload Movement***	***Features***
Coarse (gravel, cobble)	Low to moderate	Bed shear stress (see definition below) slightly greater than critical shear stress	Generally single particle, but bedload sheets can arise	Dynamic pavement (see text)
Coarse, but with high sand content	Moderate to high	Bed shear stress slightly greater than critical shear stress for coarse component	Generally single particle, but bedload sheets can arise	Dynamic pavement. Sand reduces the critical shear stress, resulting in higher transport rates
Fine (sand)	Low to moderate	Bed shear stress much greater than critical shear stress	Bedforms (ripples), or longitudinal streamers	Transport involves layer many particle diameters thick
	Moderate to high	Bed shear stress much greater than critical shear stress	Bedforms (dunes)	Much sand moves as suspended load as well
Very fine (silt, clay)	Any	Cohesiveness of particles makes bed resistant to entrainment; tends to be mobilized in clumps or flakes	Flakes or balls of “mud” may behave like bedload until worn down	Transport almost entirely suspended load; tends not to settle out again once mobilized

It is sometimes assumed in transport studies that bedload particles move from one riffle to the next riffle downstream in a given peak discharge. However, this is only a minimum distance, and the actual distance transported during a peak flow is better described as a distribution of distances that will depend on event duration, and will be larger for smaller particle sizes.

2.6 *Incipient Mobility of Sediment*

The assessment of streambed mobility within a channel requires measurement of the sediment size gradation present, as well as the transport energy available to mobilize that gradation. As mentioned previously, the evaluation of the hydraulic energy available to transport the size fraction present is sometimes sufficient for channel design.[27] This is referred to as "incipient mobility" or "channel competence," and addresses mobility purely in terms of sediment size mobilized, rather than sediment volume mobilized. Cases where incipient motion analysis may be sufficient for design include:

- Threshold channels (those with immobile streambeds)
- Channels with adjustable boundaries if sediment load is low
- Transport reaches (see *Geomorphology* Appendix)

Here, "low" sediment load means that the amount of sediment transported in a typical year would not be large enough to appreciably raise the streambed elevation if it were to accumulate in the reach.

The coarse fraction of a given sediment gradation is generally not in motion under low flow conditions. As flow increases, the energy imparted on sediment increases until at some point, the particle is mobilized. The point at which a sediment particle is just set into motion is referred to as incipient motion, and the hydraulic shear stress at incipient motion is called the critical shear stress.

Shear stress is a measure of the erosive force per unit area exerted by flow on the channel boundary. Though shear stress and its use in river hydraulics is covered in the *Hydraulics* Appendix, it is appropriate to describe it here as well, since it is key to understanding sediment transport computations. Total shear stress is partitioned into shear exerted on bed, banks, bed forms, wood, vegetation, etc.[28] Shear stress exerted on bed and banks is created by water flowing parallel to the boundaries of the channel, with the force acting parallel to the area. Total or average shear stress is calculated by the equation:[28]

$$\tau = \gamma R s$$

where τ is the shear stress, γ is the specific weight of water (specific weight of water is inversely related to water temperature and increases with suspended sediment content), R is the hydraulic radius (R = cross-sectional area of flow divided by the wetted perimeter), and s is the slope of the channel. For wide shallow channels with width/depth ratios of 12 or higher, channel depth can be substituted in place of hydraulic radius to simplify the equation shown above. In engineering practice in the U.S., shear stress is commonly expressed in units of pounds per square feet (psf), however, the SI unit, the Pascal (47.9 Pascals = 1 PSF), is used in most scientific literature. The water depth is a function of flow magnitude and channel geometry. Shear stress will therefore be greatest in steep streams, in deeper, narrower channels, and during high flows.

Bank shear stress, and maximum shear stress, can be estimated by multiplying the average shear stress value by a coefficient.[29] Maximum bed shear, based on a wide, trapezoidal channel, is approximately 1.37 times the mean shear stress, and acts at the channel midpoint. Maximum bank shear stress is about 1.08 times the mean, and acts at a distance $^1/_3$ up from the channel bed. Different channel shapes and bends will also affect the values for bank shear. Bank shear stress is much greater at outer bends in a meandering channel than in straight sections. Hydraulic models are often employed to compute shear stress. Refer to the *Hydraulics* Appendix for more information on the use of hydraulic models.

Critical shear is the shear stress required to mobilize sediment of a particular grain size. In order to calculate critical shear stress, τ_c, the Shields equation is used:[30]

$$\tau_c^* = \tau_c/(\gamma_s - \gamma)D$$

or, conversely,

$$\tau_c = \tau_c^*(\gamma_s - \gamma)D$$

where τ_c^* is the critical dimensionless Shields number for entrainment of a sediment particle of size D, and γ_s and γ are the specific weights of sediment and water, respectively, expressed in pounds per cubic foot (or Newtons per cubic meter in SI units). The Shields number represents, conceptually, a ratio of the shear stress (flow force per unit area) acting on the bed to the grain weight per unit area. Generally, the parameter D is taken to be D_{50}, the median grain size of the bed sediment, and, dimensionally, must be in units of feet (or meters in SI units). Early work on incipient mobility produced what has become known as the Shields diagram, a version of which appears in Figure 5. In this figure, the top curve represents the original diagram, which is based on flume studies the bed of which has a uniform particle size. Fully turbulent flow conditions typical of rivers during sediment transport are represented by values towards the right side of the diagram. The bottom curve is corrected to reflect the observation that in studies of rivers, 0.03 is a better approximation to the limiting value of τ_c^* under field conditions, when τ_c^* is computed using surface particle size. However, the critical Shields number actually depends on the structure (layering and packing of particles) present in the streambed. It can vary from 0.01 for finer, loosely-packed gravel to 0.24 for coarser surface particles that are imbricated and difficult to mobilize. Andrews[31] showed that τ_{ci}^*, which is the critical Shields number for a surface particle of size d_i, is given by:

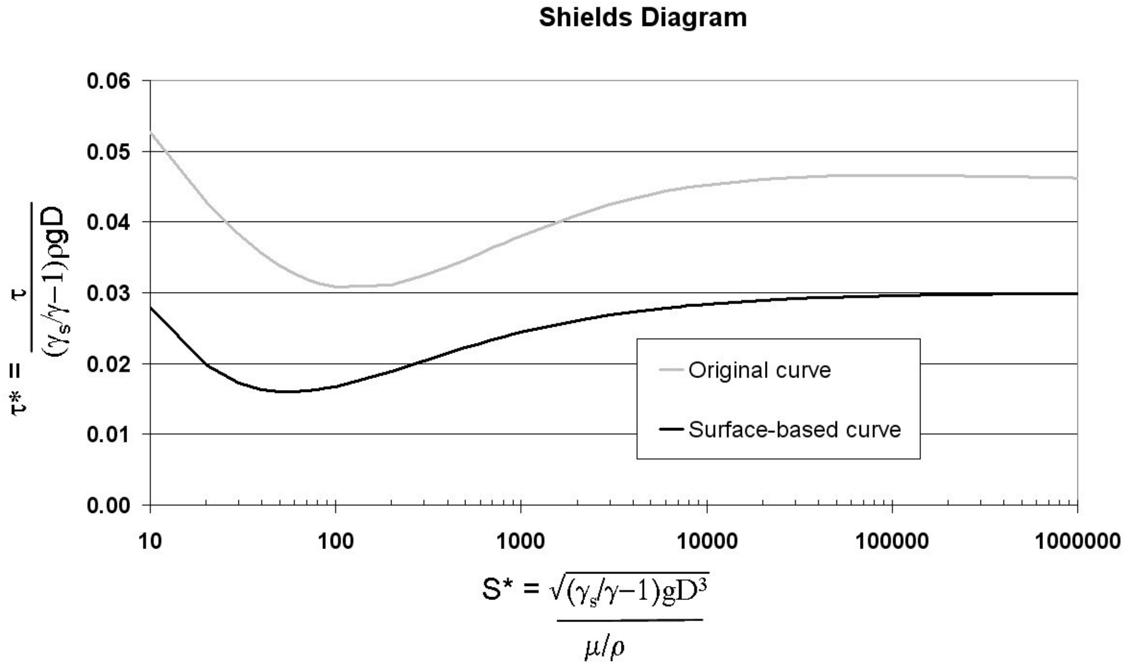
$$\tau_{ci}^* = 0.0834(d_i/d_{sub50})^{-0.872}$$

where d_{sub50} is the median particle size in the subsurface layer. Using a "typical" value of surface to subsurface D_{50} ratio[32] of 2.54, this equation suggests a typical τ_c^* of 0.037. Wilcock and Crowe[33] show that τ_c^* of gravel particles depends on sand content according to the relation:

$$\tau_{rm}^* = 0.021 + 0.015e^{-20F_s}$$

where τ_{rm}^* is the critical shields number for the average surface particle size, and F_s is the fraction of sand in the bed surface layer. This effect of sand, which reduces τ_{rm}^* from 0.036 (with no sand) to 0.021 (at 20 percent or more sand), occurs as the streambed transitions from being framework-supported (meaning that the large particles making up the bed contact and support each other) to matrix supported (meaning the gravel particles are "floating" in a matrix of sand, a situation resulting from high sediment loads). Incipient mobility of stream sediments has been actively researched for over 80 years, and a summary of this research can be found in Buffington and Montgomery, 1997.[34] Their work suggests that the lack of universal Shields parameter values warrants great care in selecting those values in mobility assessments.

Figure 5. Shields diagram for incipient motion, based on uniform-sized sediment. $\boldsymbol{\tau}^*$ is Shields number, a dimensionless ratio of bed shear stress to particle weight. $\boldsymbol{S}^*$ is a dimensionless particle diameter. The original Shields curve is shown in grey. This curve was later modified to fit the empirical observation that in gravel-bed rivers, critical $\boldsymbol{\tau}^*$ based on surface $\boldsymbol{D_{50}}$ approaches 0.03 (Parker[35]).



In incipient mobility assessments, the critical shear value is generally calculated using the $\boldsymbol{D_{50}}$ of the sediment gradation present.[36] The use of the $\boldsymbol{D_{50}}$ to characterize the bed material size in mobility analysis is based on the hypothesis of equal mobility,[37] and on the dynamic pavement concept of Parker et al. (1982)[38] for gravel bed streams. In this view, the coarsened surface layer (termed "pavement," rather than armor, to distinguish it from immobile surface layers) persists at all flows,[39] even though all available particle sizes are present in the bedload and capable of being mobilized. The surface coarsening "hides" smaller particles from the flow, thus rendering them less mobile, while coarser particles project into the flow. Thus, critical shear stress for smaller and larger particles tends to "equalize." The net result is equilibrium between the bed material and the bed load, which allows the stream to transport the coarse portions of its bedload supply at the same rate as its fine portions.[37] This "hiding factor" has been expressed mathematically, and can be used to predict critical shear stress of any particle size from that of the $\boldsymbol{D_{50}}$ size, and to estimate the $\boldsymbol{D_{50}}$ critical shear stress from the ratio of pavement to subsurface D_{50} as in the equation of Andrews (above).[40]

It bears repeating that shear stress acting on a particle is difficult to determine in steeper channels, and channels containing roughness elements like large wood, because a large proportion of the shear stress is manifested as form resistance (turbulence around large objects) rather than particle resistance (frictional drag on bed particles).[41] Heavy turbulence can make the difference between instantaneous shear stress at a point and calculated average cross section shear stress quite large. Large particles that project into the flow are better analyzed using drag force computations than shear stress. Nevertheless, many methods exist to "partition" the shear stress into particle resistance versus form resistance. A common technique in sediment modeling is to use one of the many equations available to predict resistance to flow (e.g. Manning's n) based on particle diameter and depth, converting this resistance into particle shear stress.[42] Commonly used particle resistance equations are those of Manning-Strickler,[43] Limerinos,[44] or Keulegan.[45]

Finally, it is sometimes preferable to use bedload sampling as a way to accurately calibrate the critical shear stress for a site of interest. Taking one, or better, a series of bedload samples in flows near the assumed threshold for sediment movement allows one to calibrate a sediment transport model.[46] The more state-of-the-art models use a "small but measureable" bedload transport rate as a surrogate for incipient particle motion. Once the model is calibrated, it can be used to predict threshold flow conditions for any particle size, while potential errors due to shear partitioning, and all but the last of the factors listed in Table 1, are eliminated.

2.7 Channel Competence-Based Methods in Sediment Analysis

As mentioned previously, many practitioners use channel competence methods not only to design threshold channels, but to assess stability of alluvial channels with adjustable boundaries. In this context, "stability" means that the channel neither aggrades nor degrades (incises). Some relationship between channel competence and channel stability must be assumed, and therefore, this practice is better suited to situations of low to moderate sediment load. Channels with high sediment load, response reaches, or reaches that are transitional between transport and deposition will usually require estimation of sediment transport capacity (volume) in addition to competence.

Sometimes, channel competence is described by a ratio of shear stress at a design discharge to critical shear stress for incipient motion. Johnson et al.[47], for example, defined channel stability by a bankfull shear stress ratio of 1. This implies that under conditions of sediment transport equilibrium, the median grain size is at incipient mobility at bankfull discharge. Furthermore, at a bankfull shear stress ratio of greater than one, the channel is likely to degrade; if the ratio is less than one, transport is near its maximum capacity and aggradation is likely. However, many practitioners consider incipient motion for the D_{84} at bankfull as a better "rule-of-thumb" design parameter.[48] Channel design allowing incipient motion for the D_{50} may result in channels that aggrade over time. Still others use incipient motion for the D_{100}, the largest alluvial particle, as a target design criterion.[49] This approach would almost certainly preclude development of alluvial deposits in the reach, and is thus appropriate for threshold channel situations where extra assurance of an immobile streambed is desired. Calculations done for a variety of grain diameters provides the designer with the greatest understanding of the sensitivity a particular channel configuration might have on sediment competency.

Typical shear stress ratios in gravel-bedded streams during commonly-occurring sediment transport events (e.g. near bankfull discharge) are between 1 and 2. As mentioned in Table 4, sand-bedded streams are characterized by shear stress ratios much higher than the critical value for individual particles, by a factor of 100 or so during bankfull discharge.[50] Bedforms, which are common in sand-bedded streams, significantly increase the shear stress necessary to initiate particle motion compared to critical values for a flat bed,[51] thus serving a similar role to the coarsened armor layer in establishing sediment equilibrium.

Incipient motion analyses can be used to design channel components, including habitat structures constructed with rock, or streambank protection, to be stable under a given discharge. Chen and Cotton[52] is a useful reference for design. Wilcock et al.[53] contains a good general discussion of channel competence and when it is an appropriate technique to use. For a more thorough discussion of channel competence methods in design, see Garcia.[54]

3 SEDIMENT TRANSPORT CAPACITY

Sediment size and incipient motion particle size are relatively easy to characterize from deposited bed sediments and hydraulic analysis. However, as previously mentioned, sediment volume, also called transport capacity, is much more difficult to quantify. Sediment volume is typically calculated using sediment transport equations, which are notoriously inaccurate[55] for the reasons mentioned in Table 2. Numerous sediment transport equations exist, each of which was developed for specific types of channels and sediment load conditions. As such, correct choice and proper application of an equation or model requires experience. An excellent primer and review of the topic can be found in Wilcock et al.[55]

Quantification of sediment volume likely will eventually become a routine part of stream restoration design once the limitations of sampling and reach characterization are reduced by new technology. Presently, however, the scope of many project design efforts does not include an analysis of sediment transport volume, and quantifying sediment transport remains one of the greatest challenges of, and limitations to, stream habitat restoration design. That said, unfamiliarity with sediment transport analysis techniques creates an impression that they are more costly and more difficult to interpret than is actually the case.

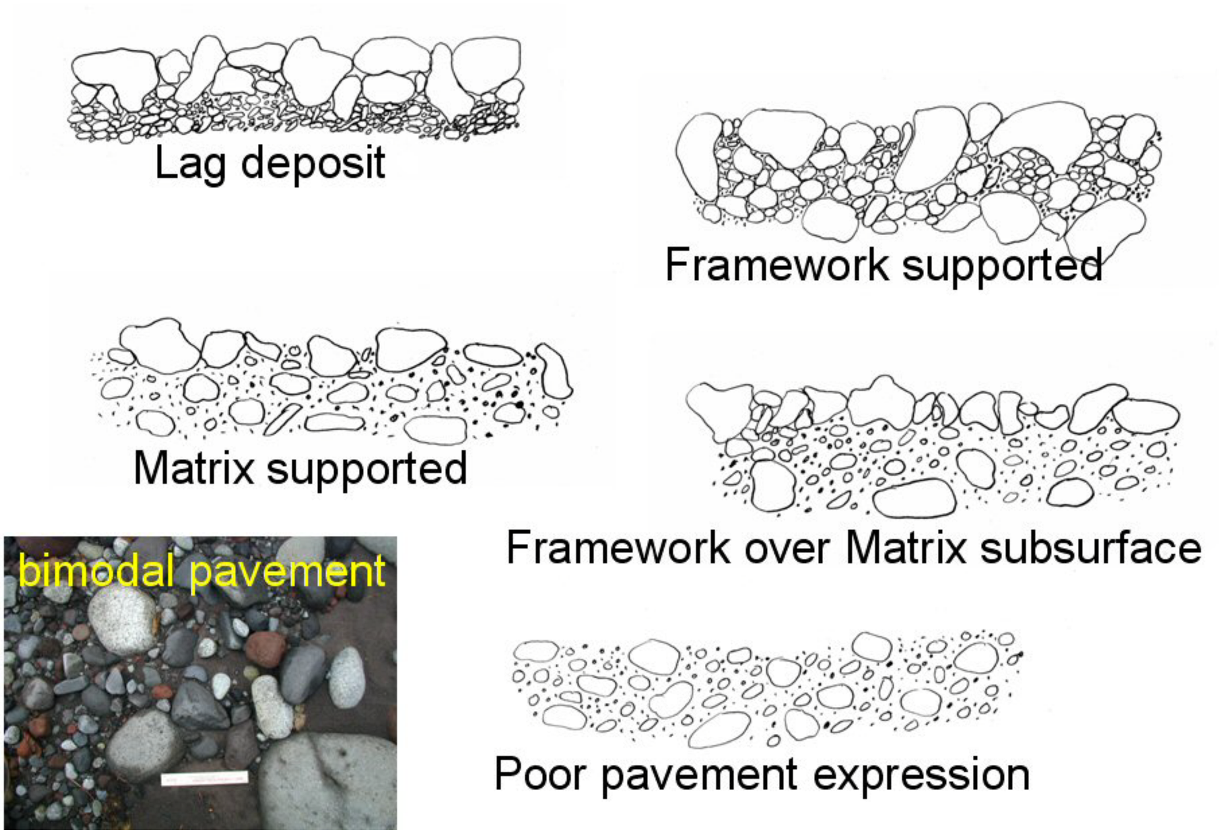
3.1 Predicting Bedload Transport Rates

Inferences can be made about sediment transport capacity and average sediment load (total volume transported annually) based on channel characteristics, and particularly, the structure of the streambed sediments. These inferences are useful to determine when sediment transport analysis needs to be done, and which type of equation or model is most appropriate.

Gravel-bedded streams display a variety of sediment structures, determined by flow hydraulics and sediment load. Some examples of this are shown in Figure 6. Lag deposits refer to an essentially immobile armor layer, which forms by winnowing of fine sediment from the bed surface when sediment loads are extremely low. This can form naturally in locations where local sediment sources contain material too coarse for transport, such as in certain mass wasting deposits. Management can create this condition as well by cutting off completely the upstream sediment sources, the classic case being dam construction.

If sediment loads are low to moderate, and essentially all sediment sizes are capable of being transported, a framework supported sediment structure will develop. This is characterized by a coarsened bed surface, and a finer subsurface in which the larger particles contact and support each other, as a framework. The coarsened surface layer is a dynamic pavement, which exchanges material with the bedload, as described above. Several of the state-of-the-art transport models in common usage (notably, those of Parker[56] and Parker and Klingeman[57]) are tailor-made for this channel condition.

Figure 6. Examples of streambed sediment structure. Except for the bimodal pavement, which is a photo of the streambed surface, all are partial cross sections, with the top representing the streambed surface.



Often, a gravel streambed will also have a substantial sand content. Sometimes the sand appears on the surface, filling spaces between gravel particles of an armor layer. This sand may move as streamers over the gravel during moderate or even low flow conditions, which is sometimes called "phase 1" transport.[58] The surface layer, when analyzed, will show a bimodal distribution, with peaks in both the sand and gravel range. This usually indicates that a local source of sediment, such as a tributary or some intense streambank erosion, is present, and that the sediment has not yet had time to develop a more typical “log-normal” distribution of sizes. Virtually none of the commonly used sediment transport models will adequately describe this situation. Design for stability of the gravel portion of the streambed will generally ensure transport of the sand component as well, at least to the next reach downstream. Reach assessment should be done to identify and characterize local sources, and identify whether the channel is in an aggrading state. Prediction of sediment transport rate may be difficult due to dependency of the sand component on the activity and persistence of its sources, and the fact that no good models exist for this situation.

When the entire streambed profile contains appreciable sand (more than about 10 percent), the subsurface may become matrix supported, meaning that the larger particles do not all contact each other, and are found "floating" in a matrix of fine particles. This generally indicates a moderate to high sediment load. Often, a matrix-supported subsurface is capped by a framework supported armor layer, which is a condition that can occur in equilibrium streams with moderate sediment loads having high sand content. If the matrix-supported condition exists in the surface layer as well, the sediment load is definitely high. Models designed especially for conditions of high sand content include Wilcok[59] and Wilcock and Crowe [60]. When high sediment load is indicated, other characteristics need to be examined to see whether evidence of recent aggradation exists, or whether the stream is naturally depositional.

Sometimes examination of the streambed structure uncovers features such as buried armor layers, which indicate an episode of aggradation. This is particularly common in depositional response reach settings. Although transport models can still be applied, care must be taken to interpret whether the sediment transport rates currently active are typical or transitory, and whether the rates indicated by a model reflect current conditions and future conditions.

A significant aspect of the equal mobility hypothesis mentioned previously states that in equilibrium streams, the "*bed-load* size distribution is approximated by that of the *substrate* for all flows capable of mobilizing most available gravel sizes"[61] (emphasis added). Note that "substrate" here refers to the subsurface[62], which is another case for determining D_{50} with volumetric sampling (see above). Although a number of authors have argued that bed-load size characteristics change in a phased or continuous manner in relation to discharge, the equal mobility hypothesis asserts that the long-term average bedload size composition, in equilibrium streams, is approximately the same as the streambed subsurface. This can be a useful piece of information when assumptions need to be made about the bedload composition or inferences made about bedload transport.

One use of this hypothesis is in the calculation of q^*, a dimensionless number related to sediment transport regime[63] in gravel-bed streams. One version of q^* is given by Barry et al.[64] as follows:

$$q^* = \left(\frac{\tau_{Q2} - \tau_{d50c}}{\tau_{Q2} - \tau_{d50cs}}\right)^{1.5}$$

Where τ_{Q2} is the bed shear stress at the two-year flood discharge, τ_{d50c} is the critical shear stress for mobilization of the d_{50} *surface* particle size, and τ_{d50cs} is the critical shear stress for mobilization of the d_{50} *subsurface* particle size, which is hypothesized to be the same as that of the annual bedload. Values of q^* between 0 and about 0.3 indicate a low sediment load, generally with coarse armoring and shear stresses never more than about 3 times the threshold for motion (as suggested by Whiting and Bradley[65]). Values between about 0.5 and 1.0 indicate high sediment loads, generally with much less armoring, and shear stresses that may often exceed the particle motion threshold by more than 3 times. Moderate to high q^* values suggest a higher response potential to changes in load or hydraulics, and the need for sediment volume calculations in channel design.

4 SEDIMENT TRANSPORT EQUATIONS AND MODELS

Numerous sediment transport equations exist, each of which was developed for specific types of conditions and purposes.

Table 5 lists a number of transport equations and the slope and sediment sizes for which they were developed. The applicability of most of the equations is related to the local bed particle size, sediment load, and channel type. Actual equations and detailed descriptions are available in standard sediment transport texts, (e.g., Chang[66]), or the highly readable discussions in Wilcock et al.[67], and Pitlick et al.[68]).

The most state-of-the-art models for gravel-bed streams are those that:

- Incorporate a hiding factor to account for the function of surface armoring, and
- Are calibrated with river data as opposed to flume data.

Unfortunately, some of the models (e.g. Meyer-Peter Muller[69]) still used in engineering practice do not fit these characteristics. Some model packages (e.g. SAM, HEC-RAS, CONCEPTS) either emphasize obsolete models, do not contain state-of-the-art models, or suggest untenable combinations of models, such as modeling the sand component of gravel-bed streams with a model developed on a large, sand-bed river where dune bedforms were the mode of transport.[70]

Whenever possible, the use of measured sediment loads for site-calibrating the sediment transport model[71],[72] is preferred. The BAGS model package (Bedload Assessment for Gravel-bed Streams) is a state-of-the-art system for doing this, and is readily available to the public.[73] In this approach, one of the above models, such as Parker et al.[62], or Wilcock[59] is calibrated to one or more bedload measurements (preferably, at least 4 or 5) from the site under study using a statistical optimization procedure. Errors due to differences between actual site characteristics or physical measurement techniques and those used in model development tend to calibrate out. The method not only yields a bedload transport function, but also can be used to obtain a site-calibrated critical flow for incipient motion, greatly reducing the uncertainty inherent in estimating critical shear stress from the literature. Standard procedures for bedload sampling, as described above, are available.[74] This approach yields greatly improved accuracy with little increase in modeling complexity. Although bedload sampling is somewhat time consuming, the sampling and calibration procedure is much less costly per unit of improved accuracy than the more-elaborate 2-D or 3-D modeling discussed below.

Although uncommon in practice, it is sometimes feasible to obtain enough measured sediment load samples to create a statistical regression model, a rating curve relating bedload transport rate to water discharge. Although accurate and easy to understand, a statistical rating curve is only applicable to the reach and range of flows where data was collected. Attempts have been made to create "generalized rating curves," such as using the ratio of sediment transport rate to bankfull transport rate, in order to allow these models to be extrapolated. However, the claim that these models can be exported to other stream networks is dubious since they are founded on statistical correlation rather than general physics or non-dimensional analysis. The model of

Barry et al. listed in Table 5 is a recent example of how the bedload rating curve approach can be regionalized. It is included here for the useful discussion it contains about the relationship between regression coefficients and channel/watershed characteristics. Use of this model, per se, for regions other than where it was developed is not recommended.

Table 5. Commonly used transport equations and the conditions for which they were developed.

Equation Name	***Year***	***Slope Range***	***Sediment Size***	***Data Source***	***Notes***
Meyer-Peter Muller[75,76]	1948	0.0004-0.02ft/ft	s.g = 1.25-4 Dm = 0.4mm - 30mm Distributions ranged from graded to sorted sediments	Flume tests: 15cm-2m wide 1cm-120cm deep no bed forms	Gravel bedload; Assumes unequal mobility, no hiding factor, thus not well suited to paved or armored beds
Toffaleti[77]	1969	n/a	River data: Ds = fine and medium sand (0.125-0.5mm) Flume data: Ds = 0.3-0.93mm	Based on data from seven rivers: 1ft-50ft deep; and, flume data from four investigators: 10.5in-8ft wide by 2in-2ft deep	Sand bedload in large rivers
Yang[78]	1972		0.137-7.01mm	Flume and field data, 0.037 to 49.9ft deep, but rarely exceed 3ft depth.	Total load; Sand bed
Parker et al. [79,80]	1982	0.00035-0.0108	Pavement 44-76 mm; Subsurface 18-28 mm	Five rivers: Width 5-198 m, Depth 0.31-6.4 m, Discharge 1.16-3500 m^3/s	Gravel bedload; Incorporates equal mobility, hiding factor
Ackers and White[81]	1973	N/a	Uniform sediments Ds > 0.04mm Ds < 28.1mm	Flume: depth < 0.4m Froude No. < 0.8	Total load
Engelund and Hansen[82]	1967		Dm = 0.19mm, 0.27mm, 0.45mm, 0.93mm. Geometric std dev – 1.3, 1.6 Application limits: Dm>0.15mm s.d. (Ds) < 2	Based on four flumes: 8-ft wide by 150-ft long) tests by Guy et al.[83]	Total load; Sand bed w/ dunes

Laursen[84]	1958	0.00043-0.00210	s.g. ~ 2.65 Dm = 0.011mm – 4.08mm Distributions ranged from well sorted to well graded	Based on various flume tests by others: Flumes ranged from: 10.5in wide x 40ft long to Laursen's 3ft wide x 90ft long Also compared results to three small streams: 0.12-1.3ft deep Dm = 0.277, 0.86, 0.287mm With good to fair results.	
Wilcock et al.[85,86, 87]	2002		Sand-gravel mixtures, with sand (<2 mm), in proportions from 6-59%. Flume studies: Surface 2.6 – 17 mm Subsurf. 5.3-12.2 mm Rivers: Surface 12 – 53 mm Subsurf. 1.2 – 20 mm	Flume studies and four gravel-bed rivers	Gravel bed rivers, using two-fraction (sand/gravel) bedload model
Barry et al.[88,89]	2004	0.0019 – 0.0509	Surface 38 – 204 mm Subsurf. 14 – 44 mm	24 gravel-bed streams in Idaho	Gravel bedload, using power function rating curves with coefficient determined by drainage area and exponent determined by streambed structure; should not be extrapolated to other regions

5 DESIGN APPROACH FOR SEDIMENT CAPACITY MODELING

Two general approaches exist to designing an adjustable alluvial stream channel. The first assumes that channel slope is fixed, and seeks to compute the channel depth and width at a given discharge for a given streambed sediment size. This approach can be applied when slope is fixed due to vertical constraints as well as lateral floodplain constraints. Analysis of adjustable streambeds with a known or constrained slope most often makes use of several hypotheses (sometimes called "extremal" hypotheses) which arise from application of general physical systems principles to rivers.[90]. These hypotheses include the minimization of total stream power, and the minimization of stream power per unit bed area, while simultaneously maximizing sediment transport and equalizing sediment transport throughout the reach. Chang[90] summarizes these system hypotheses and their application to river design.

A second approach is to compute the channel depth, width and slope from known sediment input rate at the design discharge. Upstream stable channel dimensions can be used to calculate an assumed sediment supply. Using this approach, design will ensure that the sediment entering the reach is transported out of the reach by manipulating channel dimensions. Channel designs will be iterated such that the channel dimensions are all capable of transporting the incoming sediment load. Because many combinations of channel dimensions will be able to do this, families of slope-width or slope-depth relations are the end result of this type of analysis. The designer then selects any combination of channel properties that are represented by a point on the curves. Selection may be based on minimum stream power, maximum possible slope, width constraint due to right-of-way, or maximum allowable depth.

5.1 Multi-dimensional Modeling

Besides the specific sediment transport equations, several sediment transport numerical model packages are available for use in river engineering and assessment applications. The simplest approach to sediment transport modeling is a one-dimensional approach. That is, using channel dimensions, flow conditions, and sediment characteristics, the model performs hydraulic calculations, and then using these hydraulic characteristics, calculates sediment loads for each of the channel reaches, at particular locations. The BAGS (Bedload Assessment for Gravel-bed Streams) package[91] is a model package of this type, which allows computation of sediment transport at individual cross sections using any of six state-of-the-art gravel transport models, including two options for site-calibrated models if bedload samples are available. Computations can be done at steady flow, a time series of steady flow increments that mimic a storm or annual hydrograph, or a flow duration curve that consists of a series of discharges and the fraction of time they occur. BAGS is very useful for producing sediment rating curves, for investigating the effect of changes in slope or cross section, and for doing effective discharge computations. It is the only model package currently available that is based entirely on newer, state-of-the-art transport models for gravel-bed or mixed gravel- and sand-bed rivers.

The next level of complexity is a one-dimensional model with adjustable cross sections. Based on the hydraulics, the bed sediment properties, and the sediment transport equation selected, a given cross section will have a computed transport rate. The difference between this transport rate and the input from the next cross section upstream determines whether the sediment will accumulate (aggrade) or be eroded (degrade) from the bed. The model thus allows the bed elevation or depth to change with each time step, approaching some steady state where there are no further channel adjustments. Alternatively, the model can be run with a rigid (non-adjustable) bed to compute sediment rating curves. A time series of steady discharge increments (mimicking a storm, a dam release schedule, or an annual hydrograph) drives the model, allowing determination of an equilibrium channel profile and cross section. This modeling approach is the basis for the Corps of Engineers HEC-RAS model[92] (which has supplanted HEC-6). Although widely used, the HEC-RAS/HEC-6 approach faces the primary limitations that it is a one-dimensional model and, more importantly, that out of the seven sediment transport equations it contains, only one (the Wilcock model) is a state-of-the-art gravel transport model,[93] in the sense mentioned previously, which can lead to use of obsolete or inappropriate equations. Being a one-dimensional model, it inherently assumes rigid side boundaries with no changes allowed in the channel width and no lateral migration. Unsteady flow can be approximated by increments of steady flow.

Slightly higher in level of modeling complexity is the quasi two-dimensional modeling approach. In this approach, both the channel depth and its width are considered adjustable. In FLUVIAL 12, which is a model of this type, the direction of width adjustment is based on the theoretically most probable distribution of stream power, and the rate of width adjustment determined by bank erodibility (soil properties) and sediment transport.[94] As discussed in the *Geomorphology* Appendix, a large-scale tendency exists for equalization of energy expenditure per unit area (stream power) along a channel, and a parallel tendency for minimization of total energy expenditure. In the GSTARS 2.0 model,[95] adjustable width is based on these principles, in addition to consideration of the bank slope angle. These models add a significant feature of width adjustment without adding significantly to data or analysis efforts needed. Of the six sediment transport equations found in FLUVIAL 12, one (Parker et al.[96]) is state-of-the-art for gravel bed streams. GSTARS contains 13 models in all, of which one (Parker[97]) is state-of-the-art for gravel. FLUVIAL 12 also simulates curvature-induced scour, increasing bed erodablility at cross sections where the user indicates presence of planform curvature. These are highly useful approaches for most river restoration designs, particularly those projects that will involve significant modification to channel alignment, slope, or sediment loads. Care must be taken in selection of sediment transport equation when these models are applied, since it is easy to use obsolete equations or inappropriate combinations of equations.

The CONCEPTS model[98] takes the quasi two-dimensional approach one step further by using a physically-based bank erosion model to adjust channel width. In this approach, bank stability is computed using a geotechnical model developed to predict mass wasting on steep soil slopes, coupled with a simple fluvial erosion model acting on the toe of the streambank. The streambank is allowed to erode back, widening the channel, until a stable bank angle is reached. This model has been found particularly useful in predicting evolution of incised, fine-textured streambeds, where a large portion of the sediment budget may consist of material eroded from streambanks rather than material originating upstream or from hillslope processes. Unfortunately, the CONCEPTS model does not incorporate state-of-the-art gravel transport equations, and uses untenable combinations of sand and gravel transport models, limiting its utility to fine-bedded streams.

The third level of modeling is the use of fully two-dimensional or three-dimensional modeling approaches. These models represent significant improvements in describing hydraulics and the spatial distribution of shear stress, but this comes at a significant increase in the level of effort needed both in terms of data and analysis expertise. A 2-D model requires complete topographic information for a site, such as obtained from a field topographic survey or from LIDAR coupled with bathymetry surveys. Nevertheless, utilization of 2-D modeling is beginning to become more widespread for large projects with high perceived risk to infrastructure or natural resources. 3-D modeling, which is even more rarely done, in particularly useful for describing the complex hydraulics of estuaries, where vertical variations in velocity and water density (driven by salinity and temperature gradients) cannot be ignored, and where tidal action creates multi-directional flow. Data input requirements for a 3-D model include, in addition to detailed bathymetry, vertical profiles of salinity and temperature. Input boundary conditions usually must come from other supporting models such as flow routing models and tidal forcing models.

6 SEDIMENT STORAGE

It is important for the channel designer to consider accommodating sediment storage within reaches. Designing a channel that transports all sediment inputs in a natural manner will, theoretically, prevent channel destabilization by excessive erosion or deposition. It does not, however, guarantee that the geomorphic and habitat benefits of sediment storage (e.g., as gravel bars) will be realized. On reaches where some degree of sediment storage is desired and appropriate, channel dimensions, planform, and roughness elements such as large wood should be varied to encourage and accommodate depositional features such as bars.

Determining the appropriate volume/extent of sediment storage is best done using an analog (reference) reach type of approach. Natural channels typically contain reaches characterized by deposition, transport, or relatively balanced sediment transport. Factors such as channel gradient, valley width, and wood presence/density in particular influence sediment storage on any given reach. Channel designers should take these factors into account and intentionally make provisions for sediment storage on reaches where such storage is appropriate.

7 SEDIMENT BUDGETS

Sediment budgets are normally an exercise done as part of a geomorphic analysis, to answer questions about watershed-scale sediment input, sources, routing, and storage. As such, they are introduced in greater detail in the *Geomorphology* Appendix. In contrast to the sediment characterization and modeling techniques discussed above, sediment budgets deal with larger spatial scales and longer time scales, such as annual averages, changes over many decades, and infrequent disturbances.

Sometimes, however, overlap exists between sediment analysis and questions related to geomorphic processes. For example, if we know that sediment input to the stream channel has increased, sediment modeling could be used to answer questions such as:

- Where will the introduced sediment be deposited?
- How long will it take for the channel to recover from a pulse of sediment from a landslide?
- How much deposition is likely to occur?

Likewise, if we know that sediment load has decreased, sediment modeling can help us answer questions such as:

- Where will channel incision likely to occur?
- How will the texture of the streambed change?

Each of these questions relevant to sediment budgets can be addressed, at least in part, with sediment transport and/or incipient mobility analysis.

Sediment transport modeling may also be used as a way to create a first-order screen for the effects of projects or management changes on the stream network. An example of one such modeling tool is the Sediment Impact Analysis Methods (SIAM) module,[99] available as part of the HEC-RAS system. SIAM is a hydraulic model, coupled with information on channel geometry, streambed sediment, and flow duration curve data to map out locations of sediment transport imbalance (excess input over output, or visa-versa) throughout the stream network. This can be useful for assessing locations of sensitive reaches, in assessing relative impacts of different management alternatives.

In contemplating the use of SIAM, one needs to keep in mind that it is not a sediment routing program, nor does it include adjustable channel boundaries. The gravel-bed sediment transport equations used in SIAM are, unfortunately, a selection that includes mostly those that are not state-of-the-art. Furthermore, the program allows users to create untenable combinations of models, such as using models developed for large sand bed streams where dune bedforms are the mechanism of sediment transport to estimate the sand component of bedload transport in gravel bed stream. However, as long as the user selects their transport function carefully, and interprets the results in a relative sense, SIAM can be a very useful tool for sediment analysis.

The sediment budget approach relies on tools which include maps, aerial photos and other remote sensing data (e.g. LIDAR), supplemented with geomorphic field techniques. Users interested in learning more about these techniques are referred to the following excellent reference:

- Reid, L. M. and T. Dunne, 1996. *Rapid Evaluation of Sediment Budgets*[100]

8 ADDITIONAL READING

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APPENDIX E
HYDRAULICS

HYDRAULICS APPENDIX

1 INTRODUCTION

The flow of water in streams and rivers falls within the realm of open channel hydraulics, which is the science of water flowing with a free surface and its interaction with the surrounding environment. Open channel hydraulics as applied to streams and rivers describes the expression of hydrology (the supply of water) on the landscape through the interaction with the bed, banks, and floodplain (morphology) of the system. For many stream restoration projects, hydraulics analysis is a critical component of the design phase and is necessary to understand existing conditions and the potential effects of proposed designs.

This document presents an overview of hydraulics analysis for the restoration practitioner. It begins with a brief description of fundamental hydraulic principles and variables. It then discusses types and appropriate uses of various hydraulic modeling techniques. It also includes a discussion of common design applications and hydraulic analysis tools that may be useful to the restoration practitioner. Though the material presented in this appendix is intended for engineers experienced with hydraulics, it may be useful to anyone involved with stream restoration.

While this document provides a broad overview of open channel hydraulics as relates to stream assessment and restoration design, the responsibility for selection of appropriate hydraulic analyses and procedures for any design rests with the practitioner. It is incumbent upon any practitioner in the field to gain an appropriate level of hydraulic expertise through academic and professional training. For more in-depth treatment of any of the principles and concepts described in this document, the reader is referred to the diverse open channel hydraulic texts that are available and utilized in academic instruction. A useful subset of these is:

- Chanson, H. 2004. The Hydraulics of Open Channel Flow: An Introduction. Elsevier, Oxford, U.K. and Burlington, MA. 651 p.
- Chaudhry, M.H. 1993. Open-channel flow. Prentice Hall, Inc., New Jersey. 483 p.
- Chow, V.T. 1959. Open-channel hydraulics. McGraw-Hill, Inc., New York. 680 p.
- Henderson, F.M. 1966. Open Channel Flow. MacMillan Publishing Oc., Inc., New York. 522 p.

In addition, many organizations have developed analogous open channel hydraulic manuals or summaries that may be useful supplemental reading. These include:

It can be downloaded at this link:

- Skidmore, P., C. Thorne, B. Cluer, G. R. Pess, J. Castro, T. J. Beechie, C. C. Shea. 2011. Science Base and Tools for Evaluating Stream Engineering, Management, and Restoration Proposals. U.S. Dept. of Commerce, NOAA Tech. Memo., NMFS-NWFSC-112, 255 pp. http://www.nwfsc.noaa.gov/assets/25/7946_01092012_143328_RiverRatTM112WebFinal.pdf
- NRCS 2007. Stream Hydraulics. Chapter 6 in Part 654 National Engineering Handbook, Stream Restoration Design
- USACE 1993. River Hydraulics. EM 1110-2-1416.
- USACE Ecosystem Management and Restoration Research Program has produced a number of focused summaries addressing particular aspects of hydraulic analysis for

stream restoration design. These can be found at:
http://el.erdc.usace.army.mil/products.cfm?Topic=technote

Selection of a hydraulic analysis approach depends on knowledge of the fundamentals of flow at each site and the objectives of the analysis. The assumptions associated with the analysis technique that is selected must realistically portray the essential flow characteristics. The selected approach must also generate information sufficient to answer the particular design questions at hand. The following sections provide information and guidance to the restoration practitioner that will be useful for making informed decisions regarding selection of appropriate hydraulic analysis methods.

2 FUNDAMENTAL HYDRAULIC PRINCIPLES AND VARIABLES

Thorough understanding of fundamental open channel hydraulic principles is critical for any practitioner engaged in restoration design. This section briefly summarizes these principles.

The fundamental equations of open channel hydraulics address conservation of mass and momentum.

2.1 *Conservation of Mass*

The law of conservation of mass as applied to an open channel requires that for a defined reach of stream that water enters and exits, the mass within the reach remains constant with time.[1] This leads to the *continuity* equation, defined below for the condition where the direction of flow is steady, along the stream-wise direction (i.e., one-dimensional steady flow):

$$Q = V_i A_i = V_1 A_1 = V_2 A_2 = \qquad \text{(Equation 1)}$$

Where: Q = discharge (L^3/T)
Where: L = length in feet, and T = time, typically expressed in seconds
V_i = average cross-sectional flow velocity at location *i* (L/T)
A_i = cross-sectional flow area at location *i* (L^2)

2.2 *Conservation of Momentum*

The law of conservation of momentum as applied to an open channel requires that for a defined reach of stream that water enters and exits, the rate of momentum entering the volume (momentum flux) plus the sum of all external forces acting on the volume be equal to the rate of accumulation of momentum.[1] Applied to one-dimensional steady flow, conservation of momentum can be defined as:

$$\Delta P + W_x - Ff = Q\rho\Delta V_x \qquad \text{(Equation 2)}$$

Where: ΔP = change in pressure force between two locations bounding the stream reach
W_x = force due to the weight of water in the x direction
Ff = force due to external friction losses between two locations bounding the stream reach
Q = discharge (L^3/T)
ρ = density of water
ΔV_x = change in velocity in the x direction between two locations bounding the stream reach

Applied to one-dimensional steady flow conditions, this leads to the *Bernoulli* equation, which is also referred to as the energy equation:

$$z_1 + y_1 + \alpha_1 \frac{V_1^2}{2g} = z_2 + y_2 + \alpha_2 \frac{V_1^2}{2g} + h_L \qquad \text{(Equation 3)}$$

Where: z_1, z_2 = elevations of the stream bed at cross sections 1 and 2
y_1, y_2 = depth of flow at cross sections 1 and 2
α_1, α_2 = velocity distribution coefficients at cross sections 1 and 2
V_1, V_2 = velocity of flow at cross sections 1 and 2
g = gravitational acceleration

2.3 Flow Energy State

The energy state of flow in an open channel can be summarized in terms of the balance between inertial and gravitational forces. This balance can be described in terms of the Froude number (Fr), defined below:

$$\text{Fr} = \frac{V}{\left(\frac{gd}{\alpha}\right)^{0.5}} \qquad \text{(Equation 4)}$$

Where: V = mean velocity
g = gravitational acceleration
d = hydraulic depth
α = velocity distribution coefficient

In an open channel, flow passes through *critical* flow conditions as it transitions between *subcritical* and *supercritical* flow states, defined below. *Critical flow* is an inherently unstable flow condition, where the influence of inertial and gravitational forces is exactly equal and the value of the Froude number is exactly 1.

Subcritical flow conditions occur when the flow is mainly influenced by gravitational forces and depth is greater than the critical depth. In subcritical flow, small water surface disturbances may travel both upstream and downstream, and flow at a cross section is controlled by the flow characteristics at downstream cross sections. For subcritical flow, the value of the Froude number is less than 1.

Supercritical flow conditions occur when the flow is mainly influenced by inertial forces and depth is less than the critical depth. In supercritical flow, small water surface disturbances only travel downstream, and flow at a cross section is controlled by the flow characteristics at upstream cross sections. For supercritical flow, the value of the Froude number is greater than 1.

2.4 Descriptions of Temporal Variability in Flow

The variability of open channel flow conditions with respect to time are generally described in through the concepts of *steady flow* and *unsteady flow*.

Steady flow refers to a state in which the conditions of flow do not vary with respect to time.

Unsteady flow refers to a state in which the conditions of flow are variable with respect to time.

2.5 Descriptions of Spatial Variability in Flow

The variability of open channel flow conditions with respect to space are generally described in the concepts of *uniform flow*, *gradually varied flow*, and *rapidly varied flow*.

Uniform flow refers to a state in which the velocity and pressure distributions are equal at all points along a given stream reach. Truly uniform flow is extremely rare in open channels. However, the assumption of uniform flow is a simplifying assumption that enables assessment of basic hydraulic problems with approximate methods.

Gradually varied flow refers to a state in which flow is characterized by relatively small changes in velocity and pressure distribution over short distances, with energy losses that occur due to changes in boundary roughness or channel shape. Gradually varied flow may occur in either subcritical or supercritical flow energy states, provided the flow does not transition from one to the other. Most numerical hydraulic modeling applications are based on the assumption of gradually varied flow.

Rapidly varied flow refers to a state in which flow is characterized by large changes in velocity and pressure distribution over short distances, often accompanied by successive transitions in energy state from subcritical to supercritical and vice versa in the form of a hydraulic jump. Rapidly varied flow may commonly occur in conjunction with hydraulic structures such as weirs and in steep, boulder bed streams where hydraulic jumps are prevalent. Many numerical hydraulic modeling applications include conventions to work around the occurrence of rapidly varied flow. However, precise depictions of rapidly varied flow require the use of scale physical hydraulic models.

2.6 Fundamental Hydraulic Variables

The physical attributes of flow at any point along a river or stream are described through fundamental hydraulic variables, which include water surface elevation, hydraulic geometry (area, wetted perimeter and hydraulic radius), energy gradient, flow velocity, and shear stress. After brief introduction below, basic approaches to estimate values for key variables for application to stream habitat restoration design are described in greater detail.

The *water surface elevation* is the vertical distance above a known datum for the free water surface in open channel flow at any given point along the stream. In natural channels, the water surface elevation varies horizontally and longitudinally along the stream.

The *area* (A) of flow is the summation of flow widths and depths within a channel cross section, which vary horizontally and vertically across the stream and longitudinally along the stream.

The *wetted perimeter* (P) is the length along the channel bed, banks and floodplain of the stream, measured normal to the flow path. These surfaces apply friction to the flow through hydraulic roughness. The free water surface is frictionless, and is thus not included in the wetted perimeter.

The hydraulic radius (R_{h}), is the cross-sectional area of the wetted channel (A) divided by the length of the wetted channel perimeter (P), at the flow being considered. This value is occasionally replaced by depth of flow, y. However, this should only be done when the width of the channel far exceeds the depth of the channel.

Energy gradient is the slope of the *energy grade line* (S_e), which combines the *hydraulic grade* *line* (the water surface slope) and the *kinetic energy head* (based on the flow velocity) at successive locations along the stream. This slope is equal to the hydraulic grade line and the average bed slope under uniform flow conditions, but diverges under all other flow conditions.

Water *velocity* (V) describes the speed at which a particle of water travels at any point along the stream. In natural channels, water velocity varies vertically, horizontally, and longitudinally along the stream.

Shear stress (τ) is the force that is applied per unit area by flowing water along the physical boundaries of the stream (bed, banks and floodplain) through friction. Shear stress causes water velocity to vary (typically increase) with distance from the stream boundary.

2.6.1 Estimation of Velocity

Manning's Equation is probably the most commonly used formula for basic hydraulic calculation in natural channels. The Manning's equation is used to estimate flow velocity (and hence discharge) at a single cross section based on cross section geometry, roughness and energy gradient. The major assumption associated with Manning's equation is that flow is steady and uniform.

In its most basic form, the equation relates flow velocity to hydraulic radius, hydraulic roughness and channel slope. Using the equation, one can determine:

- Average water velocity and discharge given wetted cross-sectional geometry, energy gradient, and roughness;
- Channel roughness given wetted cross-sectional geometry, slope, and discharge; and
- Channel slope given wetted cross-sectional geometry, discharge, and roughness.

Manning's Equation can be written in either velocity or discharge terms as follows (for English system of units):

$$V = (1.49/n)(R_h^{2/3} S_e^{1/2}) \qquad \text{(Equation 5)}$$

$$Q = (1.49/n)(\mathrm{A}R_h^{2/3} S_e^{1/2}) \qquad \text{(Equation 6)}$$

Where: V = average cross-sectional velocity (ft/sec)
n = Manning's roughness value
Q = discharge (ft^3/sec)
S_e = energy slope in (ft/ft)
R_h = hydraulic radius (ft) = A/P

Where: A = cross-sectional area of flow (ft^2)
P = wetted perimeter (ft)

For SI units, the coefficient value of 1.49 is replaced with a value of 1.

The Manning's roughness value *n* accounts for the resistance to flow presented by the channel. Higher *n* values correspond to *rougher* channels, such as those formed by large rock, wood, and rigid vegetation. Lower *n* values correspond to channels with smoother boundary materials and lower sinuosity. The Manning's roughness value also varies with stream stage, as boundary materials such as boulders have a higher relative roughness at low stream stage than at higher stages.

Appropriate values for *n* may be selected from tables based on qualitative description of the channel boundaries, or may be determined directly from a flow measurement. Guidance for estimating appropriate n values can be found in most hydraulic analysis/design references including Chow (1959) [1] and others.[2,3,4]

Because the energy gradient is often not known (because it is dependent on the velocity at successive locations along the stream), the energy gradient is often approximated from the water surface slope or channel slope. A standard and appropriate way to calculate channel slope from a surveyed profile is to base the elevation change on the elevations of the thalweg at "zero flow" points, or the edge of the water surface at corresponding locations, such as from one head of a riffle to the next. Zero flow points are the points in the bed that would control the pools upstream of major riffles if no water were flowing in the channel. In a braided channel, or channels without defined riffles, the mean bed elevation at successive locations should be used. The mean bed elevation should be determined from several closely spaced cross-sections over a long enough length of channel to not be influenced by local effects (such as a meander bend or hydraulic structure).

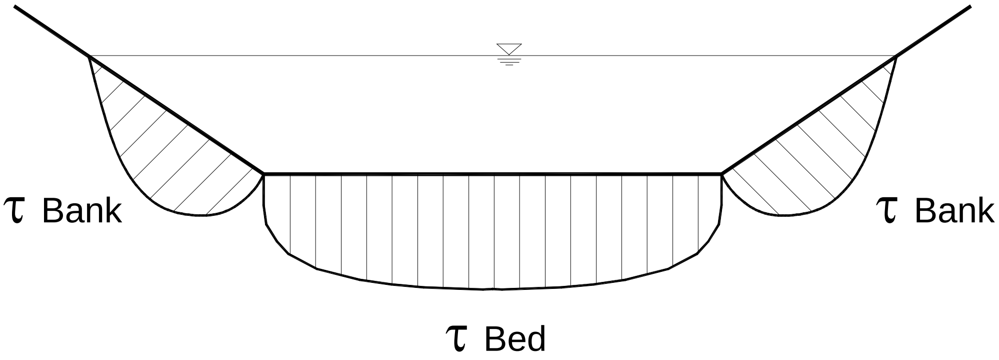
Backwater effects created by downstream flow controls are not accounted for in Manning's equation when applied at a single cross section. In reality, steady, uniform flow is practically nonexistent in natural settings. Nonetheless, Manning's equation is commonly used as a simple and convenient tool to estimate velocity (and hence discharge). It is generally understood and accepted that the results are approximate, and designers should keep this in mind when applying its results.

2.6.2 Estimation of Shear Stress

Shear stress is another important variable in habitat restoration design. Shear stress is a measure of the erosive potential of the flow at any given flow stage. Most frequently, materials placed along the boundaries of the stream (streambed, streambanks, and floodplains) are selected based on their ability to withstand shear stress of a certain magnitude that has been defined as critical for the design application. Shear stress is expressed in units of force per unit area (e.g., pounds per square foot).

Figure 1 shows the theoretical distribution of shear stress on the streambed and banks on a straight section of trapezoidal channel. In a design application, materials with greater shear resistance are required lower on the bank, while less robust treatments may be sufficient near the top of the bank. When designing habitat restoration features that include temporary surface protection such as biodegradable fabric, the designer must be sure that the shear resistance of both the temporary protection (e.g., coir fabric) and the long term surface treatment (e.g., vegetation) is adequate to withstand hydraulic forces at that location. In addition, when designing using vegetation as the primary erosion protection, factors such as species, site aspect, shade, soil type, moisture conditions, and local climate must all be considered.

Figure 1. Theoretical distribution of shear stress on bed and banks.



Typical shear stress distribution in a channel.

The equation for estimating shear stress in a straight reach is presented below. Modified methods to estimate bed and bank shear in straight stream reaches and bends, and as a function of height in the water column, are included in Section 4.2.

Bed Shear Stress is typically estimated through the following equation (shown for SI units):

$$\tau_{bed} = \gamma S_e R_h \qquad \text{(Equation 7)}$$

Where: γ = the specific weight of water (62.4 lbs/ft^3)
R_h = hydraulic radius (ft)
S_e = energy slope (ft/ft)

3 USE OF NUMERICAL HYDRAULIC MODELS

A model is a representation of an object, system or phenomena that allows for investigation of the properties of the system. Various different types of models with application to open channel hydraulics exist, including *conceptual models, analytical models, physical scale models, and numerical models*. These are defined below. However, this document focuses on numerical models due to their utility and frequency of use in stream restoration design.

A *conceptual model* is a qualitative representation developed to describe the essence of a system or object, and/or linkages between its essential components, for the purposes of communication, or for deliberation regarding its characteristics.

An *analytical model* is a mathematical representation developed to quantify the behavior of a system or phenomena. Analytical models range from simple to complex and may utilize empirically-derived equations and data. The Manning equation is an example of a simple analytical model common in open channel hydraulics.

A *physical model* is a physical replication of an object or system, often constructed at smaller scale. Physical models are commonly developed to simulate and explore complex hydraulic phenomena such as rapidly varied flow situations where the theory governing the phenomena may be poorly understood or difficult to depict numerically, or to determine coefficients that cannot be determined analytically.

A *numerical hydraulic model* employs numerical methods to solve systems of one to many equations directly or through iteration to simulate flow behavior and characteristics in a river or stream. Computers are used to execute numerical hydraulic models, which may simulate flow in one-, two- or three-dimensions, under varying assumptions regarding variability with respect to time and space. Numerical hydraulic modeling is the subject of the balance of this report section.

Due to its ability to portray conditions beyond the range of direct observation, numerical hydraulic modeling is an important tool used to apply open channel hydraulics in assessment and design. Modeling approaches vary from simple at-a-section methods to reach-scale one-dimensional step-backwater models such as HEC-RAS and two- and three-dimensional models capable of explicitly simulating complex flow patterns.

3.1 Spatial and Temporal Variability of Flow with Application to Numerical Hydraulic Modeling

As described previously, open channel flow in natural channels is variable across space (three dimensions) and time. However, for most hydraulic problems, it is possible to make assumptions with respect to flow variability in one or more spatial and temporal dimensions that enable simplifying analyses. This greatly facilitates the practical simulation of hydraulic characteristics to support the habitat assessment and restoration design process.

3.1.1 One-dimensional flow

In habitat restoration practice, one-dimensional numerical hydraulic models are by far the most commonly applied models. The primary dimension of analysis in a one-dimensional approach is the streamwise direction, with the simplifying assumption that vertical and lateral fluctuations in the velocity and pressure distributions may be ignored. One-dimensional models include simple tools that are primarily based on the assumption of uniform flow (at-a-station model) and simulation approaches based on the assumption of predominantly gradually varied flow (e.g., HEC RAS). One-dimensional models may also include conventions to work around the occurrence of rapidly varied flow (e.g., the ‘mixed flow’ simulation mode in HEC RAS), but do not explicitly simulate the flow through the rapidly varied flow zone.

3.1.1.1 At-a-station hydraulic analysis

At-a-station hydraulic analysis is performed using stream geometry data at a single cross-section. This approach may be appropriate for channels with very uniform geometry and where high confidence exists in locating hydraulic controls. The analysis should only be conducted at locations that serve as hydraulic controls and that are not affected by downstream channel conditions (e.g. backwater effects). It is typically conducted by applying the Manning equation, but other equations are also sometimes used (e.g. Chezy equation). Computer software programs are also available to perform at-a-station analysis. WinXSPro is a public domain program that performs at-a-station hydraulic calculations, based on the Manning equation. The latest version of WinXSPRO was developed by the USDA Forest Service Stream Systems Technology Center. The program and additional information are available at: http://www.stream.fs.fed.us/publications/winxspro.html

3.1.1.2 One-dimensional numerical models for simulating rivers and streams

With the exception of long uniform stream reaches, flow along a stream is controlled by downstream (during subcritical flow regime) or upstream (supercritical flow regime) channel characteristics. For subcritical conditions, a backwater profile is generated by a downstream hydraulic control such as a constriction, hydraulic structure, or higher bed elevation (e.g. riffle crest). In hydraulically long stream sections not impacted by structures or constrictions, boundary roughness will initiate a backwater profile through a condition referred to as 'channel control'. With the backwater profile, a higher water surface elevation occurs at an upstream section then would occur in a freely draining condition (i.e., not affected by constrictions, structures, or friction). The Manning's equation alone is not capable of modeling backwater profiles. A one-dimensional step-backwater model is the minimum tool capable of simulating this effect.

One-dimensional (1-D) numerical open channel flow models are based on conservation of mass (continuity) and momentum. They represent the river as a string of cross sections and assume cross-sectionally averaged flow, depth, roughness and energy grade slope in the calculations at each cross section. With respect to temporal variability, one-dimensional models may be executed for steady or unsteady flow assumptions. For the steady flow case, one-dimensional models typically solve the Bernoulli equation integrated with the Manning equation to balance the energy loss between successive cross sections along a stream. For the unsteady flow case, one-dimensional models typically solve the St.Venant equations that describe the conservation of mass and conservation of momentum with respect to time.

Examples of two popular 1-D flow models are presented below:

1. US Army Corps of Engineers (USACE), Hydrologic Engineering Center, River Analysis System Model, (HEC-RAS). HEC-RAS analyzes networks of natural and man-made channels and computes water surface profiles for subcritical or supercritical flow based on steady or unsteady one-dimensional flow hydraulics. The system can handle a full network of channels, a dendritic system, or a single river reach with an analysis of all types of hydraulic structures. Flow distributions between channels (such as around an island) can be modeled using the flow split optimization option. Additional capabilities sediment transport and water quality modeling. HEC GeoRAS uses GIS to pre-process input data and post-process results to create inundation mapps and other graphics.

2. Federal Highway Administration (FHWA), Water Surface Profile Model (WSPRO). WSPRO computes water surface profiles for subcritical, critical, or supercritical flow as long as the flow can be reasonably classified as one-dimensional, steady flow. It can be used to analyze open-channel flow, flow through bridges (single or multiple openings), embankment overflow, floodway analysis, and bridge scour.

3.1.2 Two-dimensional flow

Two-dimensional numerical models are less frequently applied in stream habitat restoration design, but their use is on the rise. They are used for projects where it is critical to explicitly simulate complex flow patterns where the simplifying assumptions regarding spatial variability required for a one-dimensional approach are not valid. Examples of such settings include wetlands, wide shallow rivers, sloughs, and floodplains, and inland and coastal bays and estuaries. Two-dimensional models may also be applied where secondary currents are predominant and it is necessary to simulate these for the design application, such as a critical river bends or hydraulic structures.

With the two-dimensional simulation approach, fluctuations in velocity pressure distribution are ignored in one dimension. Two-dimensional models may be either vertically-averaged or laterally-averaged. Vertically-averaged models are most commonly applied to habitat restoration assessment and design. Laterally-averaged models are more typically applied to long, linear reservoirs or lakes. Two-dimensional models may be applied for steady or unsteady flow assumptions, but are most typically applied for the steady flow case.

Two-dimensional models are more complex to develop with increased data needs. Consequently, their use is less frequent than one-dimensional, limited to cases where the two-dimensional approach is essential. They can require a comparatively large investment in time and resources and can be more numerically fragile than the one-dimensional models. Additionally, hydraulic scaling effects may limit the application relevancy on smaller streams with proportionally large boundary roughness characteristics. An experienced modeler should complete or oversee their use to ensure quality output is generated.

Model geometry is expressed through a computational mesh or grid, which is used to make continuous topographic and bathymetric data into discrete smaller sub-areas over which the 2-dimensional flow equations are calculated. The details of the computation grid vary by model, from rectilinear to curvilinear approaches. Within each cell, single average depth, water surface elevation, roughness, horizontal velocity, and flow direction is calculated. Output from 2-D flow models is readily available for applications such as external shear stress calculations. Some 2-D models have integrated shear stress and/or sediment transport algorithms.

Many 2-D modeling programs are available with flow and/or sediment transport capabilities. A few of the two-dimensional models in use include FESWMS/FST2DH (from FHWA), RMA-2/SED-2D (USACE), and MIKE-21 (DHI). The Surface Water Modeling System (SMS) by Aquaveo aids in the pre and post processing of data run by FESWMS and RMA-2. Section 3.3 below summarizes these and other models used in river projects.

3.1.3 Three-dimensional flow

Three-dimensional numerical models are applied in cases where the simplifying assumptions regarding spatial variability required for a two-dimensional approach are not valid, and explicit simulation of flow distribution in three dimensions is necessary. Three-dimensional models are increasingly more complex to develop with increased data and computational requirements, limiting their use to essential cases. The spatial domain of their application is typically small, such as near flow transitions associated with critical hydraulic structures.

Three-dimensional models are applied to flow dynamics in pools and river reaches; complex flow patterns around hydraulic structures; fish passage facility design; thermal mixing zone determination; reservoir/lake stratification analysis; effects of secondary currents on scour at bends and point bars; vortex/eddy generation due to hydraulic structures; water temperature transport; location and strength of eddies and vortices; water surface superelevation at bends, hydraulic structures, and other obstructions. A 3-D model can be used to provide fine-scale detail at potentially problematic locations identified by a 1- or 2-D model.

3.2 Good Modeling Practices

No universal set of requirements exists that govern the application of hydraulic analyses. The application of *Best Modeling Practices* (e.g., Stowa 1999[5]) to hydraulic analyses in general, and numerical modeling in particular, is ultimately the responsibility of the practitioner performing these analyses to support habitat assessment and restoration design. In addition, regulatory jurisdictions within which the analyses are performed may establish standards to be met for particular steps in the modeling process, such as calibration (e.g., FEMA 2010[6]). The following describes the general approach to the analysis and modeling process, which may be modified for particular applications with appropriate justification.

The analysis and modeling process consists of four steps following definition of a hydraulic problem and selection of an appropriate analytical tool:[57,8,9]

- *Initiation*
- *Calibration*
- *Validation*
- *Application*

Initiation involves the initial development of the model, which starts with the collection of field data to define the geometry of the system, establish boundary conditions, and enable calibration and validation as described below. The data are then assembled within the modeling framework and initial model runs are executed. The model results are evaluated for representativeness of the approach for the defined problem, obvious inconsistencies, inadequacies, or spurious results. Problems that have been identified are corrected through adjustment of the model input data or approach, or collection and introduction of additional data.

Calibration consists of model runs to simulate past observed events. Appropriate model parameters (e.g., those that cannot be measured, or for which uncertainty exists) are systematically adjusted until an acceptable degree of agreement between observed and simulated values is obtained. The acceptable degree of agreement is based on previously established criteria appropriate to the analysis, evaluated through the analysis of residual errors.

Validation consists of model runs to simulate past observed events that are independent of those used for model calibration as a check of the model calibration and the ability of the model to reproduce observed conditions. If the degree of agreement is not acceptable, additional model calibration effort may be needed (within a reasonable range of adjustment of model parameters).

Application consists of utilizing the calibrated and validated model in a predictive capacity to evaluate the hydraulic question or topic of analysis.

For design applications, a temptation may exist to assume that calibration and validation is not necessary because a model may not be calibrated to a future condition. While this is true, it is imperative that the extents of a model for a design application extend sufficiently beyond the limits of a design project to ensure that the simulation results are not affected by assumed model boundary conditions within the project limits. Calibration over the model reaches that bound the project will provide confidence that that model produces reasonable results at the margins of a project reach, so that the results of the design model can be used with confidence.

In some cases, models that are not calibrated and validated may be used in assessment applications to explore the behavior of a stream, in which the assessment is based on a relative comparison of the results of successive model runs, as opposed to the actual values estimated by the model. By focusing on the relative trends as opposed to the predicted values, uncertainties in model precision and accuracy may be thought to be canceled out. This approach can provide a valuable, effective preliminary assessment tool. Ultimately, however, it is incumbent upon the practitioner to be convinced that the uncalibrated and unvalidated models reasonably represent the function of the system in question.

3.3 Modeling Summary

The following table includes a few of the models that have most of the specific capabilities for evaluation and design of river and wetland restoration projects.

Table 1. Hydraulic models used for river and wetland restoration projects.

Model Name	Dimensional Assumption	For More Information
Hec-Ras[A] / GeoRAS	1	http://www.hec.usace.army.mil/software/hec-ras/
WSPRO[A]	1	http://water.usgs.gov/software/WSPRO/
MIKE 11	1	http://www.mikebydhi.com/Products/WaterResources/MIKE11.aspx
SRH-1D[A]	1	http://www.usbr.gov/pmts/sediment/model/srh1d/index.html
RMA2 [A]	1 , 2	http://chl.erdc.usace.army.mil/rma2
SED2D [A]	2	http://chl.erdc.usace.army.mil/sed2d
MD-SWMS/ FaSTMECH [A,B]	2	http://wwwbrr.cr.usgs.gov/projects/GEOMORPH_Lab/project-MDSWMS.html http://wwwbrr.cr.usgs.gov/projects/GEOMORPH_Lab/2D-Download.php
FESWMS/ FST2DH [A,B]	1 , 2	http://water.usgs.gov/software/FESWMS-2DH/
MIKE-21/21C	2	http://mikebydhi.com/Products/CoastAndSea/MIKE21.aspx http://www.mikebydhi.com/Products/WaterResources/MIKE21C.aspx
FLO-2D	2	http://www.flo-2d.com/
SRH-2D [A]	2	http://www.usbr.gov/pmts/sediment/model/srh2d/index.html
U^2RANS [A]	3	http://www.usbr.gov/pmts/sediment/model/u2rans/index.html
FVCOM[A]	3	http://fvcom.smast.umassd.edu/FVCOM/index.html
MIKE 3	3	http://mikebydhi.com/Products/CoastAndSea/MIKE3.aspx

[A] Public domain software.

[B] MD-SWMS and SMS (which is a component of FE-SWMS) are the graphical pre- and post-processors for the hydraulic models themselves, which are FaSTMECH and FST2DH, respectively.

Table **2** describes typical project settings and flow problems, and matches these with simplifying assumptions regarding temporal and spatial variability.

Table 2. Comparison of modeling approaches for various combinations of project setting and analysis scenario. 1, 2, and 3 refer to 1-dimensional, 2-dimensionsal and 3-dimensional approaches, respectively. Additionally, S refers to steady flow, while U refers to unsteady flow.

SCENARIO SETTING	Maximum flood water surface elevation	Flood wave routing	Maximum floodplain inundation	Detailed flow patterns in floodplain	Depict spatial variability of flow for a given discharge	Depict temporal variability of flow at a given location	Estimates of shear stress or velocity, averaged	Estimates of shear stress or velocity, explicit
Single thread stream, low w/d ratio, narrow floodplain	1 S	1 U	1 S	1 S	1 S	1 U	1 S	1 S
Single thread stream, low w/d ratio, broad, complex floodplain	1 S	2 U	2 S	2 S	2 S	2 U	1 S	2 S
Broad river channel, high w/d ratio, uniform bed substrate and roughness	1 S	1 U	1 S	2 S	2 S	1 U	1 S	2 S
Broad river channel, high w/d ratio, diverse bed substrate and roughness	1 S	2 U	1 S	2 S	2 S	2 U	1 S	2 S
Broad river channel, high w/d ratio, multiple flow paths separated by landforms	1 S	2 U	1 S	2 S	2 S	2 U	1 S	2 S
Tidal channel, simple floodplain	1 S	1 U	1 S	1 U	1 U	1 U	1 S	1 U
Tidal channel, complex floodplain	1 S	2 U	1 S	2 U	2 U	2 U	1 S	2 U
Estuary, simple longitudinal shape	1 S	1 U	1 S	1 U	1 U	1 U	1 S	1 U
Estuary, broad shape	2 S	2 U	2 S	2 U/ 3 U	2 U/ 3 U	2 U	2 S	2 U/ 3 U
Coastal Bay	2 S	2 U	2 S	2 U/ 3 U	2 U/ 3 U	2 U	2 S	2 U/ 3 U
Inland Bay	2 S	2 U	2 S	2 S/ 3 S	2 S/ 3 S	2 U	2 S	2 S/ 3 S
Stream or river entering lake	1 S	1 U	1 S	1 U	1 U	1 U	1 S	1 U

4 SELECTED APPLIED HYDRAULIC ANALYSES FOR RIVER RESTORATION

The following section provides additional application of the fundamental variables and concepts described in Section 2. Additionally, it should be noted that various methods for sizing riprap are listed in the Riprap technique of the Integrated Streambank Protection Guidelines (ISPG). Channel bed design is described in the Stream Simulation Culvert design of the Fish Passage at Road Crossing guidelines.

4.1 Permissible Shear Stresses for Selected Materials of Construction

Selected typical permissible shear stresses for various materials are shown in Table 3. Other summary resources also exist. It should be noted that the experimental conditions under which permissible shear stress values in tables such as these may vary greatly from the conditions in which a designer may wish to apply the referenced materials. Therefore, the values in Table 3 should be applied using professional judgment and considering site variables of the project location. Fischenich[10] provides additional information in Stability Thresholds for Stream Restoration Materials.

Table 3. Permissible shear stresses of various materials.

Material	**Permissible shear stress (psf)**
Straw with net	1.4
Coir mats and fabrics	Approx. 1-3 (varies by product)
Synthetic mats	Approx. 2-8 (varies by product)
Grassy Vegetation	0.4 to 3.7
1-inch gravel	0.3
2-inch gravel	0.7
6-inch rock riprap	2.0
12-inch rock riprap	4.0

Source: All but "coir mats and fabrics" and "synthetic mats" are from USDOT (1988).[11]

4.2 Extrapolation of Basic Shear Stress Estimation Techniques

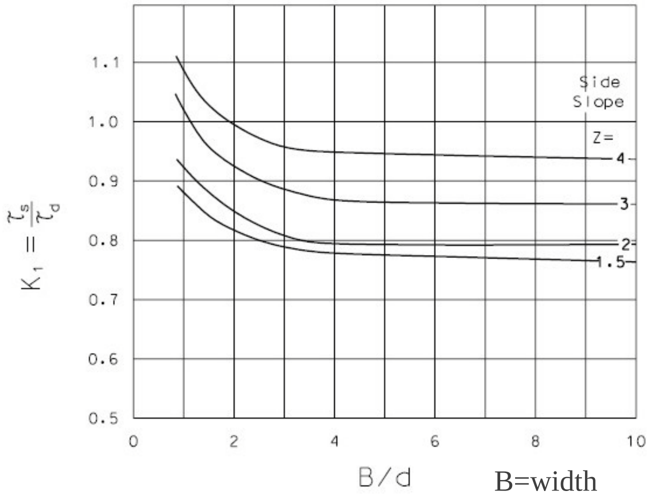
4.2.1 Bank Shear Stress in a Straight Reach

By approximating the channel cross-section as a trapezoid or rectangle, the maximum bed shear stress can be used to estimate the maximum bank shear stress. This stress acts approximately one-third of the distance up the bank (from the bed) and can be approximated by multiplying the maximum bed shear stress by a factor (see Figure 1). This factor, K_1, varies based on channel side slope and the ratio of bottom width to depth as shown in Figure 2. This approximation applies only to a relatively straight reach of stream.

Maximum bank shear stress in a straight reach.[11] $\tau_{bank} = K_1\tau_{bed}$ (Equation 8)

Where: τ_{bed} = maximum bed shear stress (lb/ft^2 [= psf])
K_1 = ratio from Figure 2

Figure 2. Side slopes, depth/width ratio.[11]



B=width
d=depth

Shear stress on the upper bank can be estimated using Figure 1. Based on this diagram, side shear vs. depth can be estimated using the following equation:

$$\tau_x = C\,\tau_{bed} \qquad \text{(Equation 9)}$$

Where: τ_x = bank shear at distance x from stream bottom (lb/ft^2 [= psf])
τ_{bed} = maximum bed shear stress (lb/ft^2 [= psf])
C = coefficient from Table 4

Table 4. Coefficient "C" vs. depth

Distance X (feet from stream bottom)	**C (From Lanes)**	**C (Recommend for design)**
y = stream depth (ft)	0.00	0.00
0.90 y	0.14	0.14
0.80 y	0.27	0.27
0.67 y	0.41	0.41
0.60 y	0.54	0.54
0.50 y	0.68	0.68
0.40 y	0.79	0.79
0.33 y	0.80	0.80
0.20 y	0.70	0.80
0.10 y	0.50	0.80
0.00 y	0.00	0.80

Note: Lane's shear diagram indicates zero shear at the base of the bank, but for design purposes it is recommended that the maximum bank shear, as calculated above, be assumed to be present for the entire lower 1/3 of the bank height.

4.2.2 Shear Stress in Bends

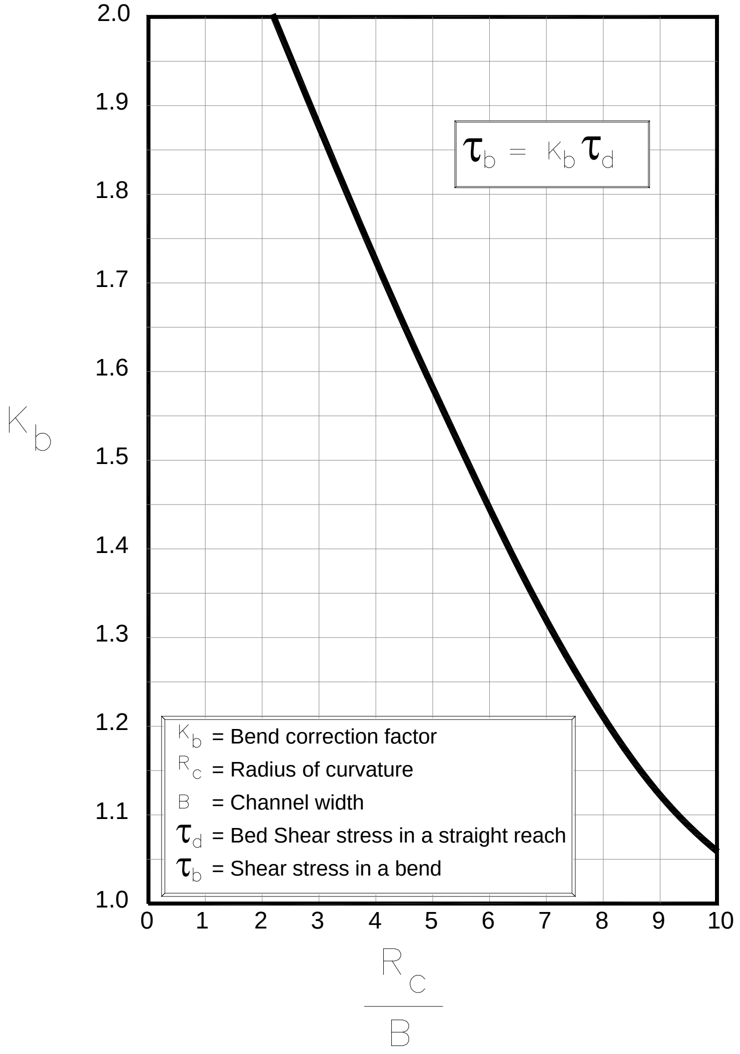
Flow around bends creates secondary currents that exert higher shear forces on the channel bed and banks than those found in straight sections. Several techniques are available for estimating shear stress in bends. A relatively simple and widely used method estimates maximum shear stress on channel banks and bed in bends (this equation does not differentiate between bank and bed shear stress).

The maximum bed/bank shear stress in a bend is:[11]

$$\tau_{bend} = K_b \tau_{bed} \qquad \text{(Equation 10)}$$

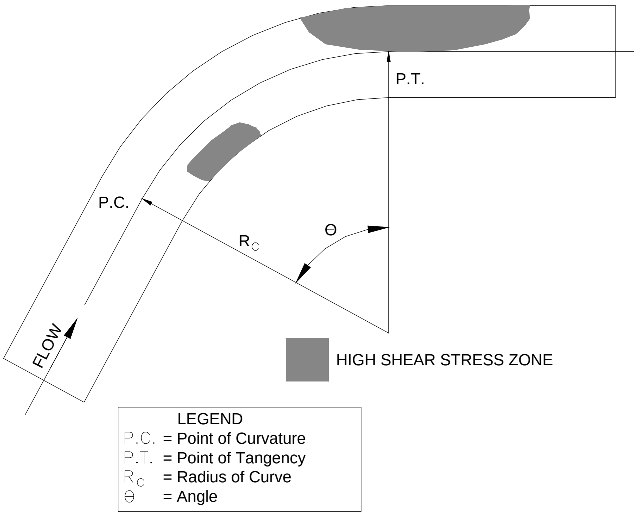
Where: τ_{bend} = maximum shear stress on bank and bed in a bend (lb/ft^2 [= psf])
τ_{bed} = maximum bed shear stress in adjacent straight reach (lb/ft^2 [= psf])
K_b = bend coefficient (dimensionless)
and: K_b = $2.4e^{-0.0852(R_c/b)}$
K_b can also be determined from Figure 3.
Where: R_c = radius of curvature of bend (ft)
b = bottom width of channel at bend (ft)

Figure 3. Bend scour correction factor chart.



The maximum bed/bank shear stress is primarily focused on the bank and bed on the outside portion of the bend (Figure 4).

Figure 4. Shear stress distribution in a channel bend.



Analysis of the vertical distribution of shear stress on banks in bends is not well defined. Secondary currents found in bends complicate shear analysis in these regions. Equation (8) can be used as a rough estimate of shear distribution on banks in bends, but it does not account for secondary currents. It is recommended that vertical shear distribution in bends be estimated by using Equation (8), judgment based on the severity of the bend and the degree of expected super-elevation of the water surface around the bend. Super-elevation of the water surface around a bend can be estimated as described in the following paragraph.

The water surface elevation increases around the outside of bends as the channel banks exert centrifugal forces on the flow. This super-elevation can be estimated using the following equation:

$$\Delta y = V^2 W/(gR_c) \qquad \text{(Equation 11)}$$

Where: Δy = super-elevation of water surface (ft)
V = average velocity of flow (ft/sec)
W = channel top width (ft)
g = acceleration due to gravity (32.2 ft/sec^2)
R_c = radius of curvature of bend (ft)

4.3 Estimation of Scour

Scour is an essential contributor to the creation of fish habitat and its maintenance. Many fish-enhancement projects promote scour. It is not the extent or magnitude of the scour that promotes the best habitat, but the frequency of the scour activity. Sites absent of scour tend to provide less habitat complexity than areas subject to moderately frequent scour events, given that intermediate-level disturbances promote aquatic diversity[12,13]. Sites that are subject to very frequent scour have less habitat value than areas subject to moderately frequent scour events.[14]

This appendix summarizes calculation methods to predict the depths of scour at embankments and instream structures. Accurate prediction of scour depth is invaluable when designing stream bank toes, cross-channel structures such as check dams, and anchoring systems. In addition, the calculation of scour depth allows the designer to predict the effectiveness of instream structures intended to induce scour.

Most of the scour equations presented here were developed to predict hydraulics phenomena associated with man-made structures, such as bridges, located within relatively large, often sand-bed, streams. In general, equations predicting scour in streambeds consisting of gravel and larger material are not considered as reliable as the more widely used equations based on homogeneous fine-grained sand substrate. Because of the lack of widely-used scour equations developed specifically for use on gravel-bed streams, the equations developed for sand-bed streams are presented in this appendix along with methods of modification and interpretation that allow their application to gravel-bed streams with larger bed material.

Paraphrasing passages from Pemberton and Lara[15] on channel scour:

> “The design of any structure located either along the riverbank and floodplain or across a channel requires a river study to determine the response of the riverbed and banks to large floods. Knowledge of fluvial morphology combined with field experience is important in both the collection of adequate field data and selection of appropriate studies for predicting the erosion potential.

> It should be recognized that many equations are empirically developed from experimental studies. Some are regime-type based on practical conditions and considerable experience and judgment. Because of the complexity of scouring action, it is difficult to prescribe a direct procedure. Bureau of Reclamation practice is to compute scour by several methods and utilize judgment in averaging the results or selection of the most applicable procedures."

4.3.1 Calculating Potential Depth of Scour

Anticipating the maximum scour depth at a site is critical to the design of a bank treatments and structures by defining the type and depth of foundation needed. Scour depth is also useful when designing anchoring systems or estimating the depths of scour pools adjacent to in-channel structures. Determining the maximum depth of scour is accomplished by:

1. Applying calculations based on information derived from a complete hydrologic and hydraulic evaluation of the stream.
2. Identifying the type(s) of scour expected. (See next section, Types of Scour).
3. Calculating the depth for each type of scour.
4. Accounting for the cumulative effects of each type of scour (If more than one type of scour is present, the effects of the scour types are additive.)
5. Reviewing the calculated scour depth for accuracy based on: experience from similar streams; conditions noted during the field visit; and an understanding of the calculations.

4.3.2 Types of Scour

Five types of scour are defined below:[16] Bend Scour, Local Scour, Constriction Scour, Drop/Weir Scour, and Jet Scour.

Local Scour – Local scour appears as discrete and tight scallops along the bank line, or as depressions in the streambed. It is generated by flow patterns that from around an obstruction in a stream and spill off to either side of the obstruction, forming a horseshoe-shaped scour pattern in the streambed. When flow in the stream encounters an obstruction, for example a bridge pier; the flow direction changes. Instead of moving downstream, it dives in front of the pier and creates a roller (a secondary flow pattern) that spills off to either side of the obstruction. The resulting flow acceleration and vortices around the base of the obstruction result in higher erosive forces around the pier, which move more bed sediment, thereby creating a scour hole.[17] The location around the pier is scoured because the bed is eroded deeper at the pier than the bed of the stream adjacent to it.

Bend Scour – When flow moves along a bend, the thalweg (the deepest part of the streambed) shifts towards the outer bank of the channel where bend scour occurs. Bend scour results from accelerating and spiraling flow patterns found in the meander bend of a stream. Sharper meander bends generate deeper scour than gentle bends. The maximum shear stress acting on a bend can be two or more times as high as the shear stress acting on the bed.[12]

Constriction Scour – Constriction scour occurs where the channel gradually or abruptly narrows generally due to a steepening channel slope or presence of an artificial hydraulic structure, such as a bridge opening, or a natural condition such as-a bedrock outcrop. The average velocity across the width of the channel increases, resulting in erosion across the entire bed of the channel at the constriction. If the bed material is erodible, the channel bed at the constricted section may be scoured deeper than the channel bed upstream or downstream. Large wood jams are another common feature that causes constriction scour. In addition, bank features such as rocky points or canyon walls, overly narrow, man-made channel widths (e.g., with groins), or well-established tree roots on a streambank in smaller channels can cause constriction scour.

Drop/weir Scour – Drop/weir scour is the result of plunging vertical flow as water pours over a raised ledge or a drop into a pool, creating a secondary flow pattern known as a roller. The roller scours out the bed below the drop. Energy-dissipation pools may result from drop scour. Pools below perched culverts, spillways, or natural drops (such as those found in high gradient mountain streams), are all causes of drop scour.

Jet Scour – Jet scour occurs when flow enters the stream in the same manner as flow ejecting from the nozzle of a hose. The entering flow could be submerged, or could impact the water surface from above. The impact force from the flow results in jet scour on the streambed and/or bank. Lateral bars, subchannels in a braided or side channel or tributary, or an abrupt channel bend can also create jet scour.

Because scour equations are type-specific, the first step in determining the potential depth of scour is to identify the types of scour that occur at the project site. For instance, an equation for calculating *Local Scour* will give an incorrect depth if applied to a site affected only by *Constriction Scour*. A combination of multiple scour mechanisms could be occurring and all must be identified and accounted for.

All of the scour equations presented are empirical. Empirical equations are based on repetitious experiments or measurements in the field, and therefore, can be biased towards a specific type of stream from which the measurements were made. In general, however, empirical equations are developed with the intention to error on the conservative side if applied correctly.

The scour equations may distinguish between *live-bed* and *clear-water conditions*. These categories refer to the sediment loading during the design event. *Live-bed conditions* exist when stream flow is transporting sediment at or near its capacity to do so. Under such conditions, erosion is somewhat offset by deposition, as stream flow needs to “drop” sediment in order to “pick up” new sediment. *Clear-water conditions* exist when stream flow is transporting sediment at a rate that is far below its capacity to do so. Such conditions often occur downstream of dams or sediment detention basins. Because clear-water stream flow is “sediment starved,” it has the capacity to entrain and transport sediment without significant net associated deposition. Accordingly, clear-water conditions usually produce deeper scour depths than live-bed conditions.

4.3.1.1 Local Scour

Research on scour has focused on local scour at bridge piers and abutments. If the geometry of an obstruction, such as a boulder or rootwad, can be equated to the geometry of a pier, then pier scour equations are applicable. If the location and shape of the obstruction more closely resembles a bridge abutment rather than a pier, then scour equations for bridge abutments should be used. Obstructions that resemble bridge abutments include large wood installations or similar structures that are attached directly to the streambank. Equations for estimating pier and abutment scour are presented below.

4.3.1.2 Estimating Pier Scour

Numerous equations are available for predicting scour depths near piers. In general, these equations have been developed for sand-bed rivers. However, when applied to streams with larger size bed material (i.e., gravel-bed streams), these equations will tend to give conservative results. The likelihood of the scour depths predicted by these equations being actualized is probabilistic. Predicted depth of scour may not be entirely achieved, may take quite a long time to occur, or may occur during the first large flood.

The pier scour equation (12) presented below includes an adjustment for bed materials that have a D_{50} of 6 cm or larger, and thus is applicable to gravel-bed streams. Judgment should be used to adjust the calculated value as appropriate based on observed stream conditions. In addition, the results of Equation (24) can be used to double-check the results of the pier scour analysis.

When using a pier scour equation to estimate scour near an obstruction, the obstruction must be represented as a pier. For instance, a boulder may be represented in the equation by a cylindrical pier of equal diameter. A log or rootwad may be represented as a round or square-nosed pier of the appropriate length. Note that the pier scour equations assume that the pier extends upwards beyond the water surface. When pier scour depth is calculated for obstructions that do not extend to the water surface (under the analyzed flow), the resulting scour depth should be reduced slightly, according to the judgment of the engineer.

One of the more commonly applied and referenced pier scour equations is the CSU (Colorado State University) equation presented below.[18] The CSU Equation does not differentiate between live-bed and clear-water scour, and is recommended for the analysis of both conditions. In addition, the CSU Equation includes a correction factor (K_4) to adjust for bed materials of D_{50} greater than or equal to 6 cm.

CSU Equation for piers

$$d/y_1 = 2.0\, K_1 K_2 K_3 K_4 (b/y_1)^{0.65}\, Fr^{0.43} \qquad \text{(Equation 12)}$$

Where: d = maximum depth of scour below local streambed elevation (m)
y_1 = flow depth directly upstream of the pier (m)
b = pier width (m) (Figure 5)
Fr = Froude number: $V/(g\,y)^{0.5}$ (dimensionless)
Where: V = velocity of flow approaching the abutment (m/s)
g = acceleration due to gravity (9.81 m/s^2)
y = flow depth at pier (m)

K_1 through K_4 are defined below:

Note that for the special case of round-nosed piers aligned with the flow:

$d \le 2.4$ times the pier width for $Fr \le 0.8$
$d \le 3.0$ times the pier width for $Fr > 0.8$

K_1 = Correction factor for pier nose shape:

For approach flow angle >5 degrees, $K_1 = 1.0$ (Figure 5)
For approach flow angle ≤5 degrees, choose the shape-specific correction:

square nose	$K_1 = 1.1$
round nose	$K_1 = 1.0$
circular cylinder	$K_1 = 1.0$
group of cylinders	$K_1 = 1.0$
sharp nose	$K_1 = 0.9$

K_2 = Correction factor for approach flow angle:

$$K_2 = (Cos\ \theta + L/b\ Sin\theta)^{0.65}$$

Where: K_2 = correction factor from Table 5
L = length of the pier that is being directly subjected to impinging flow at the approach angle (m) (Figure 5)
b = pier width (m) (Figure 5)
θ = flow angle of approach to pier (in degrees)
And maximum $L/b = 12$

Figure 5. Pier scour flow approach angle.

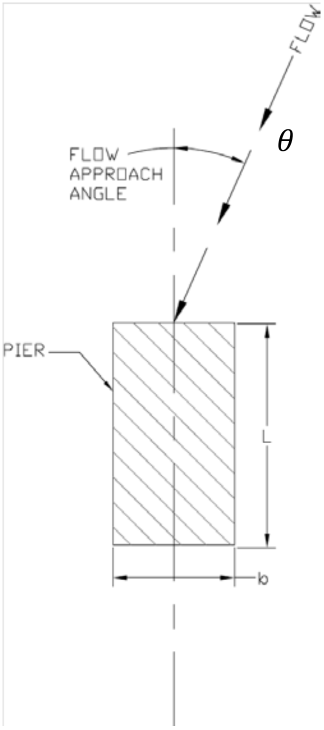


Table 5. K_2 for different flow angles of approach (θ) and pier length/width ratios (L/b).

θ	L/b = 4	L/b = 8	L/b = 12
0	1	1	1
15	1.5	2	2.5
30	2	2.8	3.5
45	2.3	3.3	4.3
90	2.5	3.9	5

K_3 = Correction factor for bed conditions, based on dune height, where dunes are repeating hills formed from moving sand across the channel bed. (Table 6)

Table 6. K_3 based on bed conditions as a function of dune development

Bed Conditions	Dune height (m)	K_3
clear water scour	N/A	1.1
plane bed & antidune flow	N/A	1.1
small dunes	0.6 to 3	1.1
medium dunes	3 to 9	1.1 to 1.2
large dunes	9≥	1.3

For gravel-bed rivers, the recommended value of K_3 is 1.1.

K_4 = Correction factor for armoring of bed material (scour decreases with armoring)

K_4 range = 0.7 to 1.0
$K_4 = 1.0$, for $D_{50} < 0.06$ m or for $V_r > 1.0$
$K_4 = [1 - 0.89\,(1 - V_r)^2]^{0.5}$, for $D_{50} \geq 0.06$ m,

Where: $V_r = (V - V_i)/(V_{c90} - V_i)$
$V_i = 0.645(D_{50}/b)^{0.053}\,V_{c50}$
$V_c = 6.19\,y_1^{1/6}D_c^{1/3}$

and: V = approach flow velocity (m/s)
V_r = velocity ratio
V_i = approach velocity when particles at a pier begin to move (m/s)
V_{c90} = critical velocity for D_{90} bed material size (m/s)
V_{c50} = critical velocity for D_{50} bed material size (m/s)
g = acceleration due to gravity (9.81 m/s^2)
D_c = critical particle size for the critical velocity, V_c (m)
y_1 = flow depth directly upstream of the pier (m)

4.2.1.3 Top Width of Scour Hole at Pier

USDOT[18] recommends using 2 times the scour depth as a reasonable estimate of scour hole top width in cohesionless materials such as sands and gravels. Scour hole top width is measured from the edge of the pier to the outside edge of the adjacent scour hole.

4.2.1.4 Estimating Scour at Abutments

Like pier scour equations, abutment scour equations have generally been developed for sand-bed rivers. When applied to streams with larger size bed material (i.e., gravel-bed streams), these equations will tend to give conservative results. The scour depths predicted by these equations may not occur, or may take quite a long time to occur, on gravel-bed streams. As USDOT[19] reports: "reliable knowledge of how to predict the decrease in scour hole depth when there are large particles in the bed material is lacking." Nonetheless, the equations that are available work for sand-bed rivers, and their results, yield a conservative estimate for scour depth on gravel-bed streams. As always, judgment should be used to adjust the calculated value as needed based on observed stream conditions. On coarse-grained streams, this will usually mean reducing the calculated value somewhat. The results of Equation (24) can be used to double-check the results of the abutment scour analysis.

The Froehlich Equation[18] presented on the following page can be used to estimate scour at an abutment or abutment-like structure. Several variables are included in the equation to describe parameters such as the abutment shape, angle with respect to flow, and abutment length normal to the flow direction. When using this equation to calculate scour for a structure such as a logjam, these parameters should be used, along with good judgment, to describe the structure as best as possible. Note that the abutment scour equation assumes that the abutment extends upwards beyond the water surface. When abutment scour depth is calculated for obstructions that do not extend to the water surface (under the analyzed flow), the resulting scour depth should be reduced slightly, according to the judgment of the engineer.

Froehlich Equation for Live Bed Scour at Abutments

$$d/y = 2.27\ K_1 K_2 (L'/y)^{0.43} Fr^{0.61} + 1.0 \qquad \text{(Equation 13)}$$

Where:

d = maximum depth of scour below local streambed elevation (m)

y = flow depth at abutment (m)

K_1 = Correction factor for abutment shape
- vertical abutment = 1.0
- vertical abutment with wing walls = 0.82
- spill through abutment = 0.55

K_2 = Correction factor for angle of embankment to flow = $(\theta/90)^{0.13}$

Where: θ = angle between the downstream channel bank line and the abutment alignment
- θ >90 degrees if embankment points upstream
- θ <90 degrees if embankment points downstream

L' = length of abutment projected normal to flow (m) or A/y

Where: A = flow area of approach cross section obstructed by the embankment (m^2)

Fr = Froude number of flow upstream of abutment or $V/(g\ y)^{0.5}$

Where: V = velocity of flow approaching the abutment (m/s)

g = acceleration due to gravity (9.81 m/s^2)

1.0 is added as a safety factor.

4.2.1.5 Clear-Water Scour at an Abutment

USDOT[18] recommends using the live-bed equation presented above to calculate clear-water scour.

4.3.3 Bend Scour

Scour occurs on the outside of channel bends due to spiraling flow as described previously. Bend scour removes materials from the bank toe, potentially precipitating general bank erosion or mass failure.

4.3.3.1 Quick Methods

Bend scour can be quickly estimated using the following two methods. Field observation/measurement of scour at established bends can yield a quick indication of the magnitude of scour to be expected if correlated to the flows that produced the scour. A first estimate can also be obtained by assuming the scour in any given bend to be about equal to the flow depth found immediately upstream and downstream of the bend.[20] This estimate will be somewhat conservative for mild bends.

4.3.3.2 Calculation Methods

Research on scour in bends has produced several empirical equations. Below are three such methods by Thorne, Maynord and Wattanabe. When used with professional engineering judgment, these equations should produce reasonable estimates of bend scour. Please pay particular attention to the notes related to each method and select a method for design based on the appropriateness for the given conditions.

Thorne Equation

Hoffmans and Verheij[20] presented the following equation developed by Thorne based on flume and large river experiments. The mean bed particle size varied from 0.3 to 63 mm. This equation is applicable to gravel-bed streams. Metric or English units may be used.

$$d/y_1 = 1.07 - log(R_c/W - 2) \text{ for } 2 < R_c/W < 22 \qquad \text{(Equation 14)}$$

Where: d = maximum depth of scour below local streambed elevation (m or ft)
y_1 = average flow depth directly upstream of the bend (m or ft)
W = width of flow (m or ft)
R_c = channel radius of curvature at channel centerline (m or ft)

The width of flow (W) in Equation (14) corresponds to the width of active flow. This width is subject to engineering judgment, however, this width often corresponds to the bankfull top width for streams that are flowing near or above bankfull stage.

Maynord Equation

Maynord[21] reviewed bend scour estimates for natural, sand-bed channels and presented one bend scour equation by Wattanabe and a second method by S. Maynord. The Maynord and Wattanabe equations are listed below. These equations are useful for predicting scour depths on sand-bed streams and for determining conservative scour depths (for comparison to other methods) on streams with coarser bed materials.

$$D_{mb}/D_u = 1.8 - 0.051(R_c/W) + 0.0084(W/D_u) \qquad \text{(Equation 15)}$$

Where: D_{mb} = maximum water depth in bend
D_u = mean channel depth at upstream crossing $(area/W)$
Where: area=cross-sectional area of flow
R_c = centerline radius of bend
W = width of active flow at upstream end of bend

Notes:

- Equation 15 was developed from measured data on 215 sand-bed channels.
- The data were biased for flow events of 1-5 yr return intervals.
- Equation will not apply when higher return intervals occur causing overbank flow exceeding 20% of channel depth.
- No safety factor is incorporated into this equation- this is the mean scour depth based on the sites measured.
- Maynord recommends a safety factor of 1.08.
- The equation is limited to: 1.5 < R_c/W < 10 (use R_c/W = 1.5 when < 1.5), and limited to: 20 < W/D_u <125 (use W/D_u = 20 when < 20).
- English or metric units may be used.
- The width of flow in Equation 15 corresponds to the width of active flow. This width is subject to engineering judgment. However, this width often corresponds to the bankfull top width for streams that are flowing near or above bankfull stage.

Wattanabe Equation

$$d_s/D = \alpha + \beta(W/R_c) \qquad \text{(Equation 16)}$$

Where: α = $0.361\,X^2 - 0.0224\,X - 0.03940$
X = $\log_{10}(WS^{0.2}/D)$
S = bed slope
d_s = scour depth below maximum depth in unprotected bank
W = channel top width (water surface width)
D = mean channel depth (area/W)
Where: area=cross-sectional area of flow
β = $2/\left(\pi 1.226\left(\left(1/\sqrt{f}\right) - 1.584\right)\phi\right)$
$\succ$ = Darcy friction factor= 64/Re
Where: Re = Reynolds number
ϕ = $1/\left[1.5f\left\{\left(1.11/\sqrt{f}\right) - 1.42\right\} sin\,\sigma + cos\,\sigma\right]$
σ = $tan^{-1}\left[1.5f\left(\left(1.11/\sqrt{f}\right) - 1.42\right)\right]$

Notes:

- Results correlate well with Mississippi River data and underpredicted Thorne and Abt data (1993) by about 25%.
- Limits of application are unknown.
- A safety factor of 1.2 is recommended with this method.
- English or metric units may be used.

4.3.4 Constriction Scour

Constriction Scour equations were primarily developed from flume tests with the constriction resulting from bridge abutments. However, these equations apply equally well to natural constrictions or constrictions caused by installation of instream structures such as groins.

4.3.4.1 Live-bed constriction scour

The following equation for live-bed constriction scour was developed primarily for sand-bed streams. Its application to gravel-bed streams is useful in two ways:

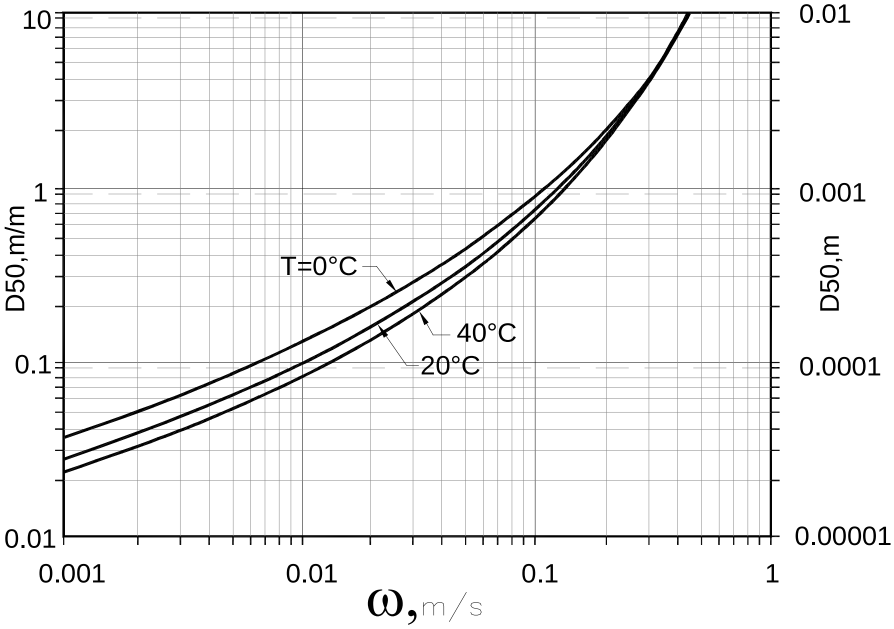
1. It provides a conservative estimate of scour depth, and
2. It can, by extrapolation of the data in Figure 6, provide scour depth estimates for streams with gravel-sized bed materials.

Coarse sediments in the bed may limit live-bed scour due to a phenomenon called armoring. The channel bed of a stream may contain layers of non-cohesive sediments alternating from finer grained to coarser, to finer, to fine mixed with coarse with a hard layer of cohesive sediment or bedrock at the bottom. Armoring is defined where the coarser material end up on top of finer material and protects the finer from resuspension.

Grab samplers frequently cannot reach the deeper substrate layer, so grab samples often may not be indicative of what lies beneath the superficial substrate. What is beneath may be armored or not. That depends a lot on the sequence of larger and smaller highwater events. To determine what is below the surface substrate could require core sampling and/or or jetting a 1-inch steel pipe down to hard bottom.

When coarse sediments are present, scour depths under live-bed and clear-water conditions (see next section) can be calculated. As always, judgment should be used to adjust the calculated value as appropriate based on experience and observed stream conditions. On coarse-grained streams, this will usually mean reducing the calculated value somewhat.

Figure 6. Fall velocity (ω) of sand sized particles.



Laursen Equation for Live-Bed Conditions[18]

$$y_2/y_1 = (Q_2/Q_1)^{0.86}(W_1/W_2)^A,\ d = y_2 - y_0 \qquad \text{(Equation 17)}$$

Where: d = average depth of constriction scour (m)

y_0 = average depth of flow in constricted reach without scour (m)

y_1 = average depth of flow in upstream main channel (m)

y_2 = average depth of flow in constricted reach after scour (m)

Q_2 = flow in constricted channel section (m^3/sec)

Q_1 = flow (m^3/sec) in upstream main channel (disregard floodplain flow)

W_1 = channel bottom width at upstream cross section (m)

W_2 = channel bottom width in constricted reach (m)

A = exponent from Table 7

Table 7. Exponent “A” based on U^*/ω

U^*/ω	A	Mode of Bed Material Transport
< 0.5	0.59	Mostly bed load
0.5 to 2.0	0.64	Mostly suspended load
> 2.0	0.69	Mostly suspended load

Components of U^*/ω are:

U^* = shear velocity = $(gy_1S_e)^{0.5}$(m/s)

Where: g = acceleration due to gravity (9.81 m/sec^2)

S_e = slope of energy grade line in main channel

ω = fall velocity (m/sec) of bed material based on D_{50} (see Figure 6)

Notes:

- As presented here, this equation assumes that all stream flow passes through the constricted reach.
- In review, coarse sediments in the bed may limit live-bed scour. When coarse sediments are present, it is recommended that scour depths under live-bed and clear-water conditions (see following equation) both be calculated and that the smaller of the two calculated scour depths be used.

4.3.5 Clear-water conditions

The following equation calculates constriction scour under clear-water conditions. Unlike the live-bed equation presented above, this equation makes allowance for coarse bed materials.

Laursen Equation for Clear-Water Conditions[18]

$$y_2 = \{0.025\ Q_2^2[D_m^{0.67}W_2^2]\}^{0.43},\ d = y_2 - y_0 \qquad \text{(Equation 18)}$$

Where: d = average depth of constriction scour (m)

y_0 = average depth of flow in constricted reach without scour (m)

y_2 = average depth of flow in constricted reach after scour (m)

Q_2 = flow in constricted channel section (m^3/s)

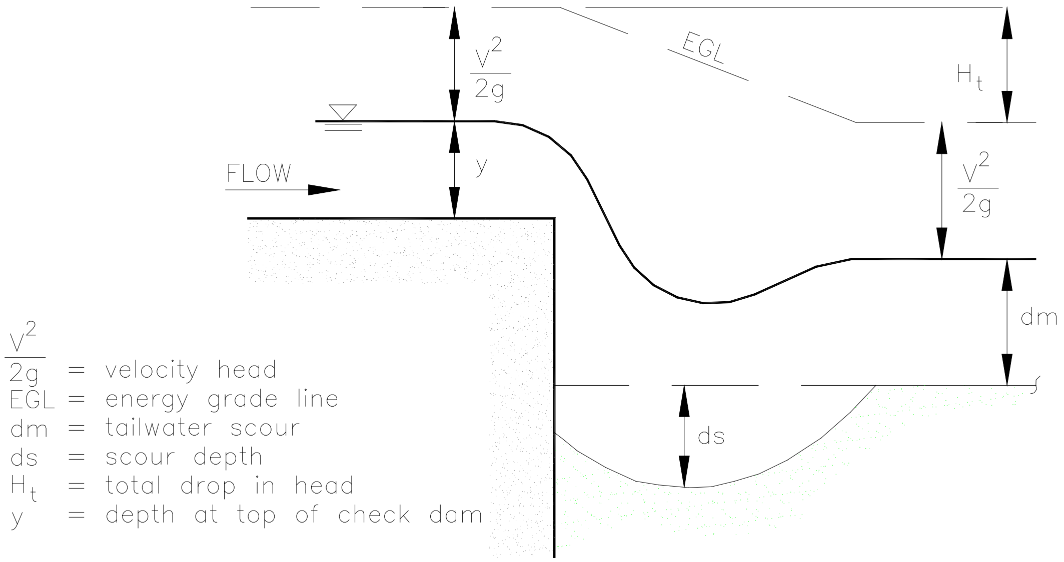
D_m = 1.25 D_{50} = assumed diameter of smallest non-transportable particle in the bed material in the constricted reach (m)

W_2 = channel bottom width in constricted reach (m)

4.3.6 Drop/Weir Scour

Two equations are presented here for estimating scour depths for flow pouring over a weir, step pool, grade control structure, or drop structure. Figure 7 shows the typical configuration of such structures. The equations were developed to estimate scour immediately downstream of vertical drop structures and sloping sills.

Figure 7. Schematic of a vertical drop caused by a drop structure.



True vertical drop structures typically include weirs and check dams constructed of materials able to maintain sharp, well-defined crests over which streamflow spills. Check dams and weirs constructed of logs and tightly constructed rock can create hydraulic conditions associated with vertical drop structures. Structures constructed of loose rock usually form a sloping sill.

Equation (19) is recommended for predicting scour depth immediately downstream of a vertical drop structure and for determining a conservative estimate of scour depth for sloping sills. Equation (20) specifically addressed sloping sills constructed of rock. When designing check dams, weirs, grade controls, and similar structures, it is recommended that the designer utilize these equations as applicable (using professional judgment) to estimate expected scour depth immediately downstream of the structure. Estimates of length of scour pool can be used to guide spacing of successive drop structures to allow sufficient energy dissipation at each structure. Spacing of successive drop structures should exceed the length of scour hole to enable stream substrates to accumulate at the face of the downstream drop structure reducing risk of erosion flanking the structures. Additional discussion of drop structures is presented in WDFW's Design of Road Culverts for Fish Passage (2003).[22]

U.S. Bureau of Reclamation Equation – Vertical Drop Structure[15]

$$d_s = KH_t^{0.225}q^{0.54} - d_m \qquad \text{(Equation 19)}$$

Where: d_s = local scour depth (below unscoured bed level) immediately downstream of vertical drop (m)
q = discharge per unit width ($m^3/s/m$)
H_t = total drop in head, measured from the upstream to downstream energy grade line (m)
d_m = tailwater depth immediately downstream of scour hole (m)
K = 1.9

The depth of scour calculated in Equation (19) is independent of bed material grain size. If the bed contains large or resistant materials, it may take years or decades for scour to reach the depth calculated in Equation (19). Alternatively, less durable bed materials and/or large flow events may lead to very rapid scour.

Laursen and Flick Equation – Sloping Sill[23]

$$d_s = \{[4(y_c/D_{50})^{0.2} - 3(R_{50}/y_c)^{0.1}]\} - d_m \qquad \text{(Equation 20)}$$

Where: d_s = local scour depth (below unscoured bed level) immediately downstream of vertical drop (m or ft)
y_c = critical depth of flow (m or ft)
D_{50}= median grain size of material being scoured (m or ft)
R_{50}= median grain size of stone that makes up the grade control, weir, or check dam (m or ft)
d_m = tailwater depth immediately downstream of scour hole (m or ft)

Equation (20) predicts scour depth at the base of a sloping sill with slope of 1V:4H. This equation can be used to estimate scour at the base of a short riffle, or similar ramp-like structure.

4.3.7 Jet Scour

Though jet scour is a phenomenon associated with streams, it is not typically a component of streambank or instream structure design. In special cases where jet scour may be desirable or unavoidable, analysis is necessary, so the designer should consult a hydraulic design manual such as Simons & Senturck[24] for guidance. Please refer to the Recommended Reading section of this appendix.

4.3.8 Check Method - Bureau of Reclamation Method

A method developed by the Bureau of Reclamation provides a multi-purpose approach for estimating depths of scour due to bends, piers, grade control structures, and vertical rock banks or walls. The method is usually not as conservative and possibly not as accurate as the individual methods presented above.

4.3.8.1 Regime Equations Supported by Field Measurements Method

The Bureau of Reclamation method computes an “average” scour depth by applying a systematic adjustment (STEP 2) to the results of three regime equations: the Neil Equation, a modified Lacey equation, and the Blench equation (STEP 1).

STEP 1

Neil Equation

Obtain field measurements on an incised reach (one which does not flow overbank except at very high discharge) of the river from which bankfull discharge and hydraulics can be calculated. Units are metric or English.

$$y_s = y_{bi}(q_{di}/q_{bi})^m \qquad \text{(Equation 21)}$$

Where: y_s = scoured depth below design flow level in incised reach, which is adjusted in STEP 2 to yield predicted scour depths (ft or m)
y_{bi} = average bankfull flow depth in incised reach (ft or m)
q_{di} = design flow discharge per unit width in incised reach (cfs/ft or m^3/s/m)
q_{bi} = bankfull flow discharge per unit width in incised reach(cfs/ft or m^3/s/m)
m = exponent varying from 0.67 for sand to 0.85 for coarse gravel

Modified Lacey Equation

The Lacey equation was modified with the Blench method of zero bed-sediment transport. An incised reach is not required for this application. Units are metric or English.

$$y_L = 0.47\ (Q/f)^{0.33} \qquad \text{(Equation 22)}$$

Where: y_L = mean depth at design discharge (ft or m)
Q = design discharge (cfs or m^3/s)
f = Lacey's silt factor = 1.76 $D_{50}^{0.5}$
Where D_{50} must be in millimeters.
D_{50} = mean grain size of bed material.

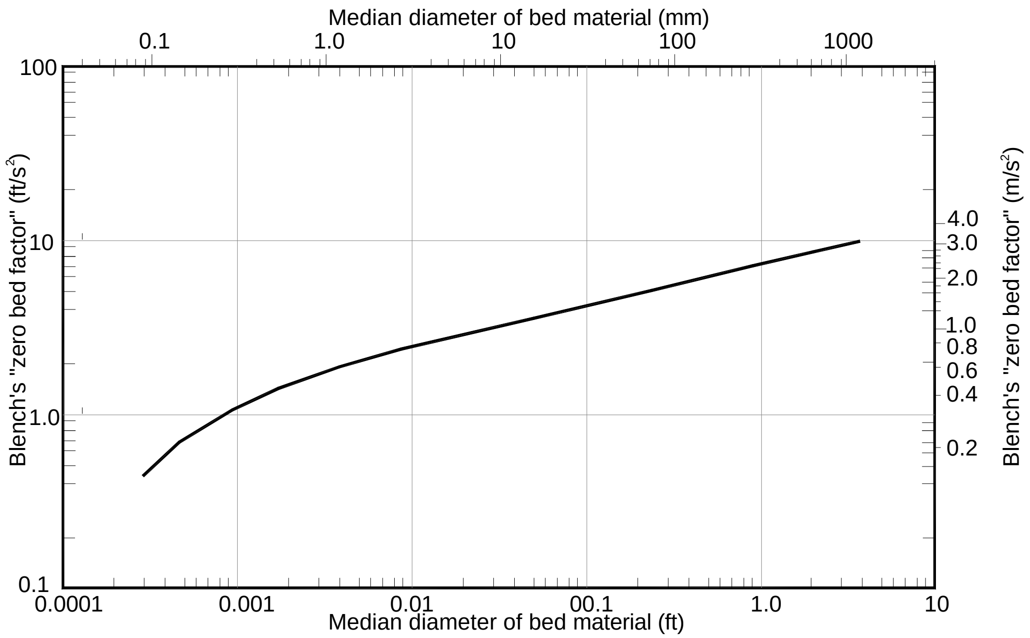
Blench Equation

For zero bed factor (clear water scour) and units are metric or English.

$$y_B = q_d^{0.67}/F_{b0}^{0.33} \qquad \text{(Equation 23)}$$

Where: y_B = depth for zero bed sediment transport (ft or m)
q_d = design flow discharge per unit width (cfs or m^3/m)
F_{b0} = Blench's zero bed factor, from Figure 8 (ft/s^2 or m/s^2)

Figure 8. Chart for estimating F_{bo}.



STEP 2

Adjustments to Neil, Modified Lacey, and Blench Results (subscripts N, L, and B identify each)

$$d_N = K_N\, y_N \qquad d_L = K_L\, y_L \qquad d_B = K_B\, y_B \qquad \text{(Equation 24)}$$

Where: d_N, d_L, d_B = depth of scour from Neil, Modified Lacey, and Blench equations
K_N, K_L, K_B = adjustment coefficients for each equation as per Table 8

Table 8. Adjustment coefficients based on channel conditions

Condition	**Neil - K_N**	**Lacey - K_L**	**Blench - K_B**
Bend Scour			
Straight reach (wandering thalweg)	0.5	0.25	0.6
Moderate bend	0.6	0.5	0.6
Severe bend	0.7	0.75	0.6
Right angle bend		1.0	
Vertical rock bank or wall		1.25	
Nose of piers	1.0		0.5 to 1.0
Small dam or grade control across river	0.4 to 0.7	1.5	0.75 to 1.25

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APPENDIX F

PUBLIC SAFETY

Public Safety Appendix

1 INTRODUCTION

The following appendix provides general guidelines for addressing public safety concerns associated with stream habitat restoration projects. These guidelines can serve as an outline of a process of inquiry that can provide the due diligence required by a project lead to incorporate public safety into the design process discussed in greater detail in Chapter 5, *Designing and Implementing Stream Habitat Restoration Techniques.*

1.1 Overview of public safety concerns

Public safety associated with stream habitat improvements has many facets. Most notably perhaps are recent concerns highlighting conflicts between public recreation and large wood habitat structures. However, public safety concerns also include the interaction that habitat measures may have with flooding of riparian lands, increased erosion of stream banks and beds, and integrity of public and private infrastructure and property such as structures, roads, dams, buildings, and utilities. These concerns are shared across a broad audience of stakeholders that include local sheriff departments, river user groups, and regional authorities that have operational or maintenance responsibilities, as well as public and private landowners.

The interaction of public river users and in-stream obstructions, in most cases, carries the highest risk to public safety. While the guidelines in this appendix address the range of concerns associated with public safety and stream habitat restoration projects, an emphasis is placed on risk to recreational users and others that frequently interact with rivers.

1.2 Balancing public safety concerns and habitat restoration goals

Rivers and streams carry inherent risks to public safety. Stream habitat restoration projects can increase or decrease these risks at different locations along a stream reach. An example of how a restoration project may increase risk is by placing large wood habitat structures along a streambank or in the middle of a stream that could pose a hazard to river users. An example of how a restoration project may decrease risk is by lowering channel gradient or reducing streambank heights thereby reducing channel velocities and providing better escape routes. The level of risk associated with a given restoration project should be evaluated at all project stages, including identification of goals and objectives, various investigations, alternatives analysis, design, construction, and post-construction. Throughout all phases of a restoration project, it is critically important to engage stakeholders and ensure they have the opportunity to provide comment at a time when their suggestions can successfully be incorporated into the project.

Of primary importance is the need for project designers to adequately document the decisions, actions, and the process used for addressing public safety and the reasons for these decisions and actions throughout each phase of a project. This is particularly true given the absence of defined standards of practice for addressing public safety for restoration projects.

As discussed in Chapter 5, risk evaluation is often a subjective, qualitative, and uncertain process and will vary from project to project. This is largely due to the complexity of dealing with the natural environment (natural rivers that have inherent dangers; variability in river conditions and risk in different locations and at different flows), variations in public use (locations of use, times of use, type of use, and level of user expertise) and even the procedures used to determine risk. As such, risks for any given project are situational specific and should be evaluated relative to the user groups associated with the project, stream type, project context, and project components as discussed later in this appendix. In this process, it is important to also consider the responsibility of public users to be safe when using rivers. The primary focus of this appendix is on how restoration designers can reduce risk to public safety although recreational users and other affected groups should be knowledgeable of their shared responsibility in reducing risk. Public outreach efforts should reiterate the responsibility of river users to wear proper safety equipment, gain knowledge of safe river travel, and abstain from using intoxicating substances while using rivers.

Some organizations and agencies such as the River Safety Council in Washington State,[1] Washington Department of Transportation (WSDOT), King County,[2,3,4,5,6] , Natural Resource Conservation Service[7] and American Whitewater[8] have or are beginning to develop design guidance and specific design standards for addressing public safety for restoration projects. The guidance developed by these different organizations and agencies often have different approaches for addressing public safety. Consequently, uniformly accepted state-wide or local guidance is not currently available and, in most cases, methods for addressing public safety are up to the discretion of the project proponents, designers, and stakeholders.

2 APPROACH FOR ENSURING PUBLIC SAFETY

Public safety considerations surrounding habitat projects are too often identified as an issue when final designs are reviewed by the stakeholders or agencies. Designers often identify public/private infrastructural risk or flooding issues during their goals and objectives development phase but often overlook or dismiss recreational use as data on recreation is usually assumed to be unavailable. This occurs despite the pledge taken by registered professionals (e.g., engineers, fisheries biologists, geologists, surveyors) to safeguard life, health and property and promote public welfare. The Revised Code of Washington (RCW) 18.235.130[9] states “The following conduct, acts, or conditions constitute unprofessional conduct for *any license holder* or applicant under the jurisdiction of this chapter: (4) Incompetence, negligence, or malpractice that results in harm or damage to another or that creates an unreasonable risk of harm or damage to another”.

Funding sources too, emphasize and much too often directly support minimal design efforts to maximize the dollars spent on implementation/construction. Despite these challenges, it is essential that design teams thoroughly explore project goals and objectives and forward public safety considerations through each project phase to ensure compliance with Washington State’s professional licensing provisions.

As standard practice, each project should:

1. consider public safety early and throughout habitat restoration project planning, design, construction, and post-construction.
2. engage and make reasonable efforts early and throughout project development to understand and define public safety concerns that the public and stakeholders may have throughout the life span of a project.

3. document the due diligence process for addressing public safety (document the public safety decisions/actions that were made/implemented and why).

These three tasks should be tailored to project size and relative impacts discovered as the project develops. Some projects will require minimal efforts, while others warrant significant efforts. Regardless of project size, every project should follow a prescribed pattern of investigation.

3 INTEGRATING PUBLIC SAFETY INTO THE DESIGN PROCESS

A thorough stream habitat restoration design process or standard of practice is described collectively in Chapters 4 and 5. Public safety considerations need to be integrated early and throughout the project design process. Changes to designs late in the process can be expensive and can cause unnecessary tensions among designers and stakeholders. For consistency, we address public safety in tandem with the components of the project design process as described in Chapter 5.

3.1 Goals and objectives

Project design should begin by defining the purpose and specific desired outcomes for restoration. Specific and measurable goals and objectives should then be developed based on this effort. An important part of the design process should be to identify and minimize risks to public safety. The amount of detail associated with public safety will depend on many factors including: (1) the number and types of individuals potentially at risk such as recreational users, adjacent landowners, and workers that frequently interact with streams and rivers, (2) size of the project, (3) location of the project, and (4) type of project. Components of the design process that account for public safety can be addressed through design criteria that identify specific, measurable attributes of each design component (see Chapter 5). Examples of items to be considered that may have adverse effects on public safety and that may be incorporated into a project's design criteria often include:

- Identification of issues of concern to the public and stakeholders (landowners, river users, environmental groups, tribes, public agencies, emergency responders, etc.).
- Identification of potential issues associated with infrastructure (roads, pipelines, bridges, dikes and levees, irrigation structures, various floodway designations etc.).
- Identification of potential issues associated with project features (habitat features, construction access/staging, material stockpiles, dewatering, river side trails, fishing/boating access, etc.).
- A relative ranking of risk associated with each project objective and associated project element. These can be broken into categories such as 'acceptable', 'tolerable', or 'unacceptable' and can be helpful in identifying project components where a low, medium, or high level of consideration is required for addressing public safety risk.

The development of specific objectives must go beyond the typical client/landowner design team discussion and include gathering information and thoughts from user groups and public safety organizations. This is particularly true for reaches of stream with regular recreation, infrastructure risk and/or other potential safety hazards (e.g., in-stream obstacles).

3.2 Survey and analysis

This investigative phase of project design serves as the design's technical foundation. It involves gathering necessary site and historical data, conducting technical analyses for characterizing and analyzing existing conditions, deriving input values for subsequent design analyses, and predicting restoration outcomes relative to project objectives for different alternatives. This phase of a project should include data gathering for issues identified in the goals and objectives phase.

Table 1 provides an example of the type of existing conditions data helpful in evaluating public safety risk. Some of the information in the table may not be available for a given project. Depending on the project size and potential risk to public safety, it may be necessary to conduct more in-depth studies to evaluate risk. Public user group characteristics listed in Table 1 may have already been compiled by public agencies or organizations for different reaches within a jurisdiction or watershed. Consult local governments, sheriff's departments, landowners, river recreation groups and businesses, and natural resource and transportation agencies to gather relevant information. A particularly useful resource for river conditions and public use information is the American Whitewater river info website which provides data such as river difficulty, flow range, access points, and hazards for over 350 rivers in Washington.[10] Much of the existing reach characteristics listed in Table 1 should be collected as part of the stream habitat survey and analysis for a given project as described in Chapter 5, Section 5.1.1.

Table 1. Example of existing conditions data for evaluating risk to public safety.

Category	Risk Evaluation Items	Considerations for Each Item
Public User Group Characteristics	Groups of the public at risk?	Recreational users such as swimmers, boaters, fisherman, and tubers; workers that frequently interact with streams and rivers such as surveyors, construction and maintenance workers, and river scientists; the travelling public who use bridges, roads, trails, and other infrastructure that come close to or intersect streams and rivers; and adjacent and downstream property owners.
	Locations of use for different groups and method of travel?	In stream, along banks, on roads/bridges; in kayaks, canoes, tubes, on foot.
	Frequency and timing of interaction of different user groups with the project?	High, medium, or low frequency. Seasonality of use. Public event dates. Range of flows when recreation is common.
	Skill level of identified user groups?	Beginner, intermediate, advanced.
	Ease of access?	High, medium, low. Are there frequent and easy places to access the river?
	Accident reports for the project reach?	Number of incidents, types of incidents.
Existing Reach Characteristics	Project location?	Remote, rural, urban.
	Valley type?	Wide, moderate, confined. Are there easy escape routes along the reach?
Existing Reach Characteristics	Channel type, planform?	Pool-riffle, step-pool, plane-bed, cascade. Is there significant site distance upstream of obstacles to allow users to direct themselves away in adequate time?
	Channel gradient?	High, medium, low. Does the river have a high velocity that would make it difficult to avoid obstacles?
	Dominant hydrologic regime and stream flow rate?	Range of stream flows and typical flows when different public users are accessing the stream.
	Existing obstructions?	Large woody debris jams, boulders, natural grade drops, hydraulics or holes, constrictions, eddies, etc.
	Public and private infrastructure?	Roads, bridges, culverts, levees, weirs, dams, etc.

This phase of the project can also involve identifying and notifying stakeholders affected by the project and ensuring that they are part of the process for evaluating public safety risk and defining project design alternatives. These groups might include some or all of the following: adjacent and downstream landowners, river users (e.g., paddling, fishing, and hunting clubs), river guides, fishing and hunting outfitters, environmental groups, tribes, public agencies, law enforcement, and emergency responders. Identified stakeholders should be notified of the project via various forms of communication such as letters, e-mail, phone calls, in-person contact, brochures, signage, websites, and media outlets.

3.3 *Conceptual alternatives evaluation*

For any given habitat restoration project, a myriad of alternatives, or suites of project techniques and associated project elements may exist to remedy the problem and achieve desired project outcomes. The procedure for developing concept alternatives, weighing the different alternatives, and selecting a preferred alternative is described in detail in Chapter 5, Section 5.1.2.

For each alternative, the risk to public safety should be considered. Table 2 provides a summary of items to consider when evaluating the risk to public safety associated with different concept alternatives. The table is not an exhaustive list but provides common elements for consideration. Items in Table 2 should be considered in tandem with the public user group and existing conditions information collected in the survey and analysis phase of the project (summarized in Table 1).

Table 2. Proposed conditions data for evaluating risk to public safety.

Category	Risk Evaluation Items	Considerations for Each Item
Proposed Project Elements	Overall project elements	• Are project components increasing risks to public safety (e.g., placement of large woody debris may increase risk of capsizing boats and of entrapping swimmers, removal of a dam or levee may decrease risk)?
	Location of in-stream features/improvements	• On the outside of a meander bend? • In a constricted reach? • In a location with inadequate sight distance to allow boaters or swimmer time to safety exit the water or inability to circumnavigate the structure? • Is there an opportunity to portage around structure? • In a location that creates dangerous channel hydraulics? • Located upstream or in proximity of bridges or other infrastructure that could be compromised if the habitat structure fails? • Placed in close proximity to recreation access points or in locations where significant public interaction is expected?
	Position of in-stream structures	• Are in-stream structures positioned or angled in such a way that increases potential for pinning or entrapping a boat or swimmer? • How do different flow levels affect hydraulics or positioning of eddie lines?
	Design characteristics of in-stream structures	• How are the in-stream structures anchored in place? • Has adequate ballasting been provided to ensure stability? • Is the structure causing straining (phenomenon by which swift water flowing through a structure tends to draw floating objects toward

Category	Risk Evaluation Items	Considerations for Each Item
		and into it)? • Are the anchoring mechanisms (i.e., cable, bolts) creating a hazard? • Are sharp objects protruding from the structure creating a hazard? • Have any elements been considered to reduce the potential for straining or pinning such as placement of deflector logs or turning rocks?
	Design life of in-stream structures	• What is the design life of an in-stream structure and the potential for failure? • What are the implications for public safety and infrastructure if the in-stream structure fails?
	Changes in flooding or bank/bed erosion potential	• Will the project increase flooding potential? • Will the project increase bank or bed erosion? • Will the project increase risk of an avulsion? • Will increased flooding potential increase risk to public safety?
	Changes in flooding or bank/bed erosion potential	

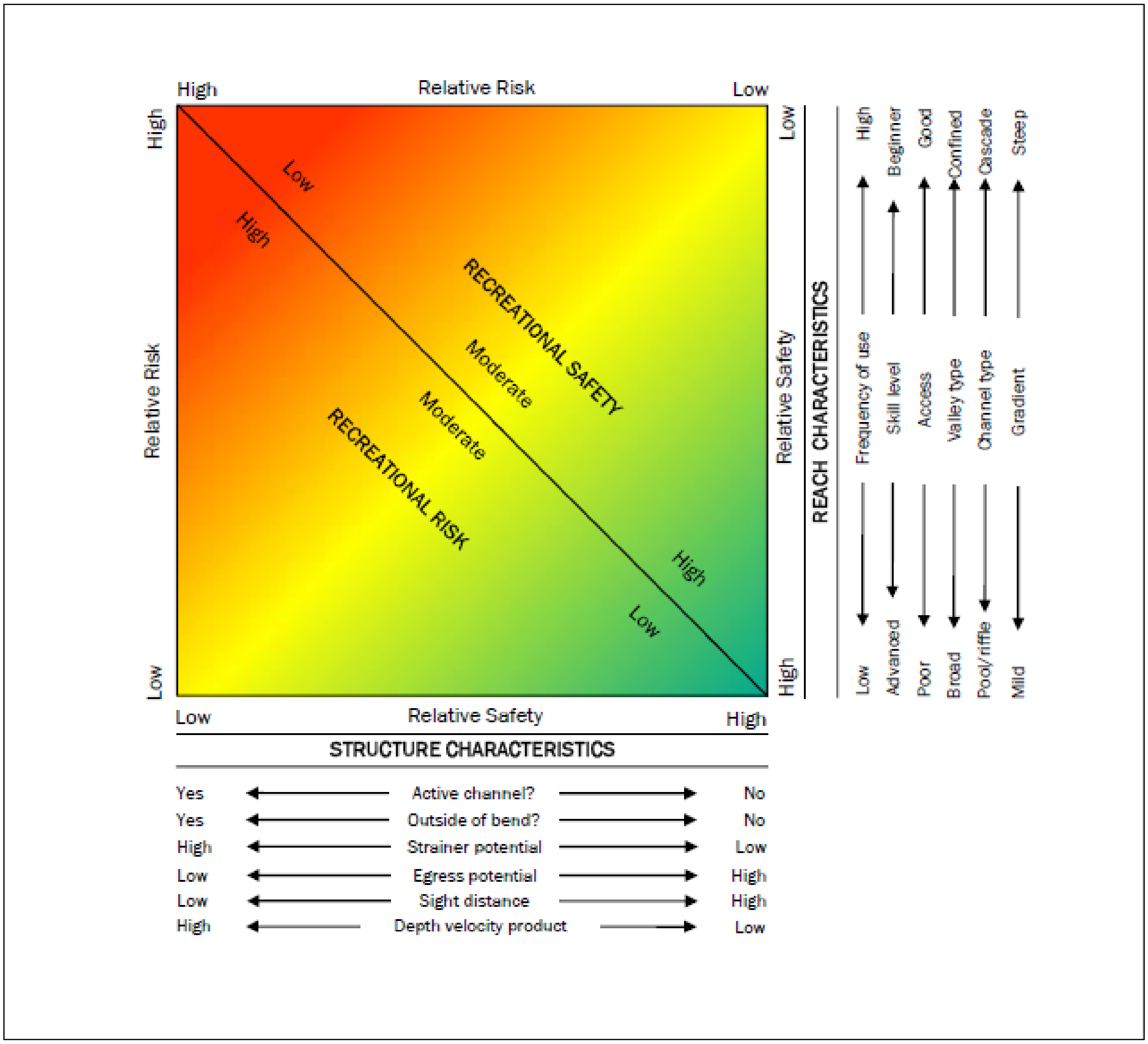
The information collected in Tables 1 and 2 can be organized and evaluated using a matrix such as the one developed by GeoEngineers[11] and presented in Figure 1. This type of matrix can be a useful tool for determining a relative ranking of public safety risk (e.g., acceptable, tolerable, unacceptable) for each alternative. It should be noted that the matrix in Figure 1 is specifically focused on the relative risk to recreational users when placing in-stream structures such as large woody debris and is based on the characteristics of the structure(s) and the characteristics of the reach. A project may include other design components and affect other members of the public such as the traveling public or adjacent or downstream landowners for which this matrix may not be applicable. Any matrix or set of matrices used for evaluating public safety risk should not be used as a standalone tool; rather, they should be used in context with other gathered data for understanding risk to public safety and long-term liability, and should be evaluated alongside other project goals and objectives for gaining an overall understanding of a project's potential impacts and benefits.

Identified stakeholders should be included in the evaluation of concept alternatives and should be provided the opportunity to interact with the design team and comment on the different alternatives. This interaction can take place via public meetings, one-on-one communication, and/or public comment periods. Public involvement and outreach is critical for all projects although the level of involvement analysis and outreach typically increases or decreases commensurate with the project size and potential impact to public safety.

In most cases, the selected final alternative can achieve the desired habitat enhancement outcomes while also adequately minimizing risks to public safety and future liability. If a project is located in an area with considerable risk to public safety and the chosen alternative is not able to reduce this risk sufficiently, the project team and stakeholders must decide the best way to address the discrepancy. Possible methods for addressing the discrepancy may include: providing public safety signage, moving public access points, implementing additional or alternative habitat measures, or reconsidering the project scope or location. This evaluation should take place on a case-by-case basis and be mutually decided upon by the project team and affected stakeholders. Once these issues are resolved, the alternative and all its unique goals and objectives are then furthered on to the design phase.

GEOENGINEERS

Figure 1. In-stream structure safety assessment matrix (GeoEngineers[12]).



3.4 Design criteria

Design criteria are developed directly for each project element defined for the selected alternative. Development of design criteria is discussed in detail in Chapter 5, Section 5.1.3. Design criteria for public safety should be derived directly from the investigations into issues discussed in 3.1 above. These criteria will directly affect how the design team crafts various project elements. Typical criteria establish guidelines or boundaries for the design and often include the following:

- Criteria associated with the public and stakeholders (access conditions, fencing, sight distances, season of use considerations, signage etc.).
- Criteria associated with affected infrastructure (criteria for habitat feature scour, rates of deformability, hydraulic stability, influences on flood heights etc.).
- Criteria associated with project components and phases (criteria for in-water structures, habitat components, construction access/staging, material stockpiles, dewatering, etc.).

Some general suggestions on public safety design criteria are offered in the reference materials provided in Section 6 below.

3.5 Design

Project design typically occurs in a number of stages, generally categorized as concept-level design, draft or intermediate design, and final design. The design process is described in detail in Chapter 5, Sections 5.1.3 and 5.1.4. Stakeholder involvement should continue throughout the design phase to ensure that stakeholders agree on the chosen design alternative and understand the potential habitat benefits and potential risks to public safety. Substantial changes occurring during the final design stages may require additional input from the project team and stakeholders depending on the project size and potential impact to public safety.

In the early stages of design, particular attention needs to be paid to these primary design elements:

- Hydrology and how it varies with seasons or levels of public use.
- Hydraulics and any changes in flooding (amount, extent, and location) as a result of channel/floodplain modification, addition/removal/modification/ affected bridges, roads, dams, buildings, utilities, levees, and/or in-stream habitat structures and how these change with varying flow levels.
- Physical hazards that may be created/removed as a result of channel/floodplain modification, addition/removal/modification/damage/ bridges, roads, dams, buildings, utilities, levees, and in-stream habitat structures.

The design team will need to determine how the project can be designed to account for identified public safety risks (e.g., location, orientation, elevation, and size of structures/obstructions; anchoring methods; degree of interaction between flowing water and placed structures at different flows). If specific safety mechanisms are to be incorporated, such as safety signage and maps along the project reach, the language and location of these signs should be included as part of the design plans and specifications. Regardless of the measures considered and incorporated into the design, it is very important that the design team documents how public safety concerns were addressed during the design phase. This can be facilitated by relating what measures were taken to meet public safety design criteria established for each project element.

Documenting safety considerations and measures taken to reduce risk is part of a due diligence process that every project design team should undertake. Documentation should also include discussions with stakeholders throughout the design process. This action will help ensure that the intent of the design team lives beyond project implementation. It also provides a basis for future stakeholders to better understand the circumstances surrounding the chosen design alternative and understand the desired habitat benefits as well as public safety risks/benefits. Another consideration design teams should address is an appropriate monitoring schedule for project components and post-construction communication/outreach to the public and affected stakeholders. This action should identify key personnel or user groups that will implement the habitat monitoring, maintenance, repairs, communication/outreach, and adaptive management measures called for during the life of the project. Developing a schedule for evaluating project components can ensure that the risks to public safety do not increase over time as well as provide the design team with a mechanism to ensure that their project continues to perform as intended over the project's design life.

4 CONSTRUCTION

Most construction contracts require the operators to submit a traffic, site and public safety plan. These plans are commonly updated weekly during regular meetings of the construction team, client and various stakeholders. Prior to construction, stakeholders should be notified of the construction schedule and provided information on the construction plans, potential safety hazards specific to the construction phase, and alternate access points during construction.

As the project proceeds, the construction project team should ensure that public safety signage, maps, and contact information for project personnel are maintained during the construction phase. Any necessary updates to public safety concerns also need to be regularly disseminated to those affected. Also, it may be warranted to update project documentation following implementation if as-built conditions vary significantly from final designs.

5 POST-CONSTRUCTION

After construction is complete, stakeholder communication and education should continue via the monitoring entities identified during the design phase. Communication with the public and stakeholders may need to continue via multiple methods including updates to location maps, replacement of educational and warning signage, personal communication with identified outreach personnel, and website information including a comment section for reporting concerns and problems. The communication/outreach personnel may also choose to partner with local river guiding and rescue organizations to encourage or offer river safety and rescue training to river users.

Monitoring of project design components should continue on the schedule identified in the design phase. Monitoring will help determine when project components are degrading and in need of repair or removal. As described in the previous paragraph, avenues of communication and reporting should be in place to allow for public comment and reporting when a structure has degraded to the point of posing a significant risk to public safety. The monitoring team should establish actions to be taken in the event that modification of project components leads to increased public safety concerns or liability.

Adaptive management is a critical component of most habitat restoration projects. Over time, projects should be periodically evaluated to determine the need for modifications, repairs, and/or enhancements based on items such as new information, policies, public safety risks, and changing river conditions. Stakeholder meetings may continue as part of the adaptive management process.

6 PUBLIC SAFETY POLICIES AND REFERENCES

As discussed above, definitive guidance or standards of practice for minimizing public safety risk associated with stream habitat restoration projects are generally unavailable. Some organizations and agencies such as the River Safety Council of Washington, Washington Department of Transportation (WSDOT), and King County are starting to develop design guidance and specific design standards for addressing public safety for restoration projects. Development of this type of guidance is on-going and, thus far, mostly jurisdiction specific. In addition, these guidelines were developed by various organizations and are not necessarily representative of the broad range of interests held by the various stakeholders concerned about habitat restoration and risks to public safety. In the absence of generally accepted definitive guidelines, these resources can provide a starting point for evaluating and addressing public safety risks.

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[1] River Safety Council. 2007. Proposed Safety Guidelines for the Construction and Placement of Large Woody Debris (LWD) Affecting Streams used for Recreation in Washington State. www.riversafetycouncil.org.

[2] King County. 2010. Procedures for Considering Public Safety When Placing Large Wood in King County Rivers. King County Department of Natural Resources and Parks. Seattle, WA. [March] http://www.kingcounty.gov/environment/watersheds/general-information/large-wood.aspx

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[4] King County.2009. Large Wood Stakeholder Committee Final Report and Recommendations. King County Department of Natural Resources and Parks. Seattle, WA. [October] http://www.kingcounty.gov/environment/watersheds/general-information/large-wood.aspx

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[6] King County. Large Wood References. 2009. King County Department of Natural Resources and Parks. Seattle, WA. [December] http://www.kingcounty.gov/environment/watersheds/general-information/large-wood.aspx

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This document lists approximately 400 references from scientific literature emphasizing peer reviewed articles and also includes a handful of technical reports, reviews, and books on large wood in rivers.

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[8] Colburn, K. 2012. Integrating Recreational Boating Considerations into Stream Channel Modification Design Projects. American Whitewater. Cullowhee, NC. 15 pp. http://www.americanwhitewater.org/content/Article/view/articleid/31325/

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[10] American Whitewater. River Info – National Whitewater Inventory. Washington River List. www.americanwhitewater.org/content/River/view.

[11] GeoEngineers. 2011. Public Safety Assessment of Habitat Enhancement – Fobes and Skookum Reach Restoration South Fork Nooksack River, Whatcom County, Washington *for* Lummi Nation Natural Resources. Bellingham, Washington.

[12] GeoEngineers. 2011. Public Safety Assessment of Habitat Enhancement – Fobes and Skookum Reach Restoration South Fork Nooksack River, Whatcom County, Washington *for* Lummi Nation Natural Resources. Bellingham, Washington.

APPENDIX G

ANCHORING AND PLACEMENT OF LARGE WOOD

Anchoring and Placement of Large Wood Appendix

1 INTRODUCTION

This appendix describes methods and design considerations for anchoring wood in waterways for the purposes of stream habitat restoration. Single or multiple pieces of large wood are commonly used in streams and rivers as habitat features, fish-passage structures, and bed- and channel-stabilization features. Use of large wood can play a crucial role in habitat formation when used alone or in combination with other techniques to create natural channels and enhance bank protection projects. Properly sited, placed, and anchored large wood can assist in providing reliable bank protection as well as enhance the structural and hydraulic complexity of the channel. In contrast, poorly sited, placed, inadequately sized, or improperly anchored large wood has a high probability of becoming dislodged during high flows, possibly resulting in failure of project objectives and potential impacts to downstream infrastructure and habitat.

As discussed elsewhere in this document, natural processes, including disturbance, play a pivotal role in channel evolution and habitat productivity. These processes result in the recruitment of large wood to stream channels and govern the retention, movement, and transport of wood into and out of the system. Where possible, restoration projects should accommodate and encourage disturbance.[1] This includes restoring, to the extent possible, the natural large wood dynamics that will create the habitat conditions to which stream biota have become adapted. In many cases, this will involve allowing for some adjustment or deformation of placed large wood over time; in other cases, greater levels of stability may be required. The required level of stability will also need to reflect the level of risk to infrastructure and public safety (see Chapter 5 and the *Public Safety* Appendix). To accommodate a range of potential stability objectives, this appendix discusses a range of placement and anchoring techniques. A discussion of natural stability is included, as well as a description of artificial anchoring techniques including passive anchors, flexible anchors, and rigid anchors. Additional placement considerations are provided for a variety of installation types and functions.

The selection of correctly sized large wood is fundamental to the success of a project because it minimizes the need for anchoring; however, proper placement is needed to optimize stability and function. Naturally stable wood is discussed in the *Large Wood and Log Jam* technique of these guidelines. Complex placements that emulate unaltered conditions are best because they have the greatest flexibility in adapting to changing channel and flow conditions while providing long term stability.[2] Though non-intrusive (no added stability) techniques should be the first option to be considered, these are frequently inadequate to meet stability objectives. In these cases, passive anchoring techniques, such as using gravel ballast of similar size to what occurs naturally in the stream bed, should be considered as an alternative. The use of flexible anchors and then rigid anchors should be considered next. As risks associated with large wood increase, more highly engineered solutions may be required.

2 FORCES ON WOOD IN STREAMS

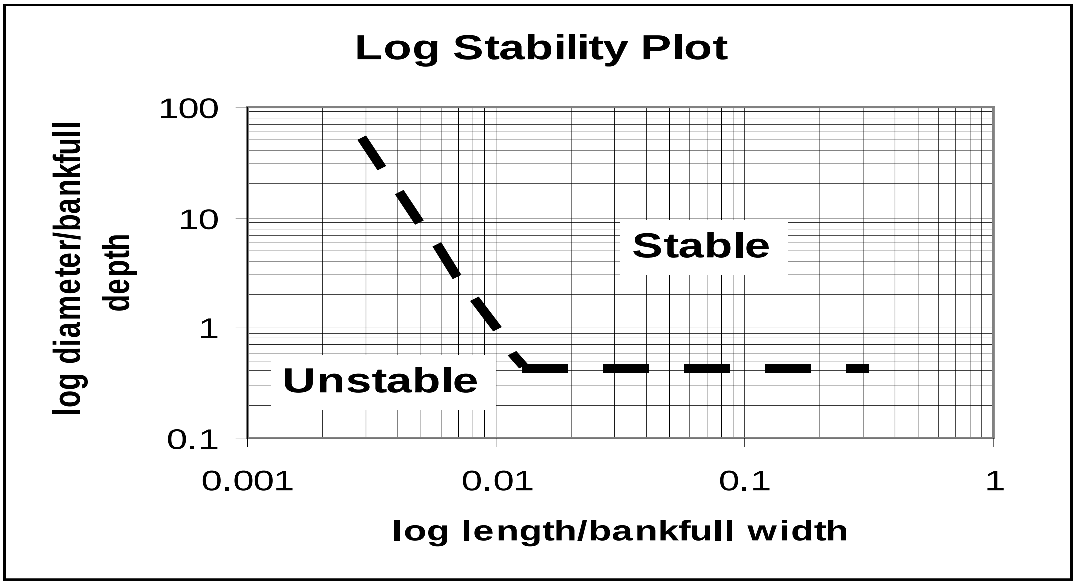
This section provides background information on forces of wood in streams and how to calculate them. Depending on the experience of the designer and the type and scale of the project, additional reference materials will need to be consulted. References are provided throughout this section and a full list of references is provided at the end of the document. The designer is encouraged to consult these as needed in order to develop a comprehensive design.

The design of anchoring systems should consider the balance of forces between (1) structure buoyancy and weight, and (2) drag forces and frictional resisting forces. Structure buoyancy and weight calculations are relatively straight forward, while drag and friction calculations are prone to error due to varying shape and orientation of the members; variable direction, velocity, and depth of flow; and the unpredictable potential for a structure to collect additional debris. Logs extending into the current may be prone to substantial oscillation and vibration, which are complex and difficult to evaluate. These uncertainties in predicting forces on structures in a river lead to the necessity for a substantial factor of safety in anchoring design. A minimum factor of safety of 1.5 is recommended for most low-energy locations, and minimum 2.0 in high-energy systems or where hazard to public safety or infrastructure may exist. Factors of safety less than 1 may be appropriate for enhancement projects in remote areas. Professional judgment is necessary. The practitioner should take into account public safety concerns, including swimmers and boaters, proximity to culverts or bridges, docks, irrigation withdrawals, and the response of channel bed and banks in the vicinity of the installation.

The analysis of wood stability is in part dependent upon the type of project, ballasting or anchoring style, and the size and character of a stream. The type of project will influence the selection of a factor of safety and the level of analysis (high for urban streams with risk to infrastructure and low for enhancement projects in rural areas). The stability of natural wood is dependent on stream order.[3] First- and second-order tributaries are generally less competent at displacing and transporting large wood, whereas higher-order streams are able to move wood readily and frequently. This is important to recognize in the design of large wood projects, especially in large rivers. In addition, an engineered approach to designing large wood projects implies a level of accuracy and predictive powers not commensurate with the materials and situation; we are working in an intrinsically chaotic system that the simplified engineering discussed here addresses incompletely.

For projects on major rivers, or those that involve the placement of a large number of pieces, an empirical approach used by Abbe et al.[4] may be employed. Abbe et al. surveyed and cataloged existing wood pieces at study sites, measuring size and channel geometry and determining stability. Figure 1 is a dimensionless plot of log length/bankfull width vs. log diameter/bankfull depth; stable and unstable zones are indicated.

Figure 1. A simplified log stability plot, adapted from Abbe et al.[4]

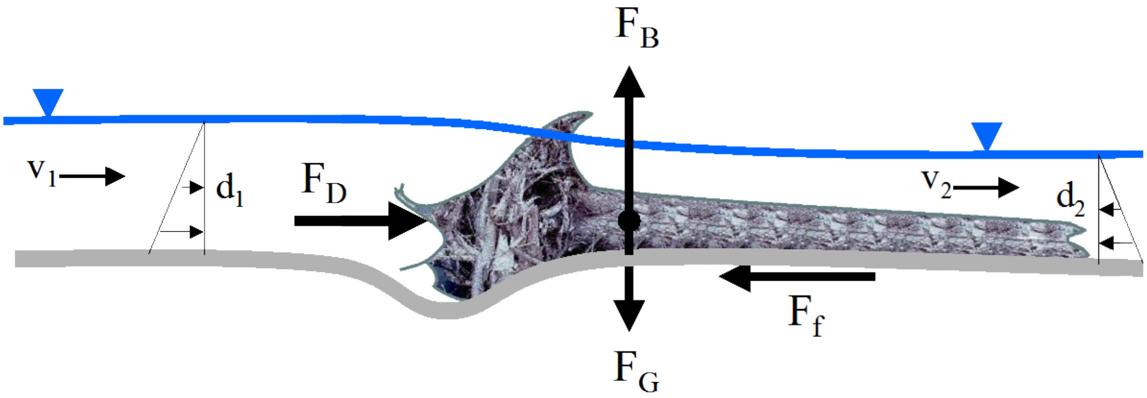


Bankfull width and depth should be determined for the reach where natural, stable wood is measured. This simple relationship is not a substitute for thorough stability analysis but can serve as a planning tool and may help to verify results.

Designing and building instream structures with large wood is a rapidly evolving science, so the practitioner should remain aware of novel advances in modeling that improve understanding of the complex processes surrounding this kind of restoration. The current standard approach to analyzing the stability of wood in streams is to view logs or log jams as flow obstructions.[2] The various treatments of this approach have all dealt with single pieces, log and boulder combinations and simple jams.[5, 6] Large log jams have been treated as a combination of individually stable logs.

A typical complete analysis of forces on wood in streams is best accomplished with: hydrologic analysis to predict the frequency and magnitude of flooding; and hydraulic analysis to determine the local conditions (stage, velocity) associated with those floods acting on the log(s); and buoyancy and momentum analyses to determine the stability of a structure subjected to a given design flood. The practitioner is advised to apply an appropriate factor of safety to provide additional stability to offset the many unknown destabilizing factors that are difficult to predict. These factors may include dam/reservoir operations, vandalism, decay rates, breakage, debris recruitment, reach-scale changes, scour, anchor ice, high-density fluid (debris flows), and ice flows.

Figure 2. Forces acting on a submerged log.



where, F_B = buoyant force, F_G = the weight of the log, F_D = the dynamic fluid force, and F_f = the friction force. The buoyant force and weight of the log oppose each other in the vertical dimension. The buoyant force is equal to the weight of water that is displaced by the log. Wood floats when the buoyant force exceeds the weight of the log. The vertical forces are calculated as follows:

$$F_G = Vol_{wood} \times \gamma_{wood} \qquad \text{(Equation 1)}$$

$$F_B = Vol_{woodSubmerged} \times \gamma_{water} \qquad \text{(Equation 2)}$$

Where:

γ_{water} is the Specific Weight of water, 62.4 pounds/cubic-foot (lbs/ft^3 or pcf)

γ_{wood} is the Specific Weight of the particular wood. In some references, the Specific Weight is listed as the Density of wood, also with units of pcf. If it is listed as the unitless Specific Gravity, then Specific Weight can be calculated as SG x 62.4 pcf.

Vol_{wood} is the total volume of wood and $Vol_{woodSubmerged}$ is the volume of the portion of submerged wood.

Assuming a log of constant diameter, its volume is roughly:

$V_{log} = \pi / 4 \times diam^2 \times length$

If roots are attached, add the root mass volume, estimated as:

$V_{roots} = \pi / 4 \times diam^2 \times thickness \times 0.6$

The 0.6 factor accounts for void space in the roots. Adjust as needed.

The Specific Weight (density) of wood depends upon the species and moisture content. The range for northwest conifers in the dry condition is from 22 to 34 pounds per cubic foot. Several websites exist that provide typical wood densities. Information about the typical wood densities for a variety of tree species can be found at The Engineering Toolbox's website at http://www.engineeringtoolbox.com/wood-density-d_40.html.

The volume of the submerged log must be determined from predicted flood elevations. Many designers assume the fully submerged condition for ballasted log jams ($Vol_{woodSubmerged} = Vol_{wood}$). Castro and Sampson[5] recommend that if the weight of the log does not exceed the weight of displaced water by at least 50 percent, then some sort of ballast should be designed to hold the log in place, such as gravel ballast, boulders, cabled boulders, or anchors. D'Aoust and Millar[6] describe ballast boulder design in detail. Drury[7] outlines a gravel ballast design method (not discussed in detail here) that consists of determining the depth of gravel backfill required to reduce buoyant forces and increase friction to counteract dynamic fluid forces on an individual log.

In the horizontal direction, frictional force is a stabilizing force that works in the opposite direction of the dynamic fluid forces acting on the log or root wad. Friction force, F_f is developed between the log and channel substrate, the net weight of the log acting as the normal force, F_N and the tangent of the internal angle of friction of the sediment as the coefficient of friction, $\mu = \tan\phi$:

$$F_f = \mu F_N \qquad \text{(Equation 3)}$$

The coefficient of friction is the tangent of the angle of repose for the material[5]. The coefficients of friction range from 0.4 for fine sand to 0.9 for gravel and boulders. No empirical data exist to justify the application of this model to real situations, though all of the references cited here use this approach.

The references mentioned in this section only address the frictional contact with the bed, whether from the log itself or the ballast rock. Other anchoring mechanisms may assume part or all of this resisting function, such as cabling, pinning or pilings.

The dynamic fluid forces F_D, or drag, are generally destabilizing forces calculated by the empirical relationship,

$$F_D = \left(\frac{v^2}{2g}\right) A_{SW} C'_D \, \rho_w \qquad \text{(Equation 4)}$$

where v is the mean incidental flow velocity, ρ_w, the density of water, and g the acceleration due to gravity (adapted here for English units)[2]. A_{SW} is the area of the submerged wood normal to the incident flow. Coefficient of drag, C'_D, is a function of an object's shape, orientation to flow, grouping and boundary conditions. Values range from 0.4 for a single log angled 15 degrees downstream off the longitudinal axis to 1.2 for a blunt root wad disk oriented upstream.[5 6 8] Groupings of closely spaced large wood elements, less than 2 or 4 diameters, are hydraulically efficient and may, in the case of two cylinders spaced 2 diameters apart, have a combined drag of less than a single isolated cylinder[8].

The drag coefficient is strongly influenced by boundary conditions, particularly when the blocking ratio, B, is greater than about 5 or 10 percent[8]. The blockage ratio is:

$$B = \frac{Ld}{A} \qquad \text{(Equation 5)}$$

Where A is the cross sectional area in flow, d the diameter or width of the debris in flow and L the projected length of the debris in flow.

In flume experiments, Gippel [8] developed a regression creating a resistance coefficient with up to 30% blockage. Since this empirical coefficient now takes into account other forces besides drag, notably hydrostatic forces, it should be considered a composite "resistance" coefficient, so that conceptually it is not confused with a coefficient that accounts only for drag. The resistance coefficient is a function of B and the coefficient of drag in infinite flow C'_D. [8]

$$C_D = 0.997C'_D\,(1-B)^{-2.06} \qquad \text{(Equation 6)}$$

As mentioned above, this relation holds true for up to 30 percent blockage, but as B increases above that, upstream velocity decreases and drag force decreases at which point hydrostatic forces begin to dominate. In this scenario, a debris structure transforms from an obstruction into a dam. Young[9] modeled wood in a flume at higher blockage ratios, though it may be difficult to apply his findings to force analysis since he looked primarily at backwater effects. In order to cause pool formation and gravel sorting, Washington Department of Fish and Wildlife (WDFW) engineers found that in streams less than ~5 m (16 ft) wide, large wood had to occupy 40 or 50 percent of the bankfull channel, a situation that looks increasingly like a dam. In order to analyze a case like this, the designer may need to apply momentum analysis in order to account for the role of other forces on an instream structure. The momentum equation for one-dimensional analysis is:[10]

$$\sum F = \rho Q(v_2 - v_1) \qquad \text{(Equation 7)}$$

The sum of the forces, $\sum F$, acting on a control volume include all the relevant forces, notably drag, shear and hydrostatic head, which must equal the change in velocity, v, times the water mass transferred, ΔQ. Hydrostatic head may be calculated, as it would be for a dam, as the difference in the pressure force, F_P, between the up and downstream sides for any given unit width of the cross-section:

$$F_P = \frac{1}{2}\gamma d^2 \qquad \text{(Equation 8)}$$

Where γ is the unit weight of water and d the depth.

Shear may be neglected where it is negligibly small,[10] although longer, rough structures may cause a velocity gradient with associated shear. Drag is computed as above, unmodified for constriction. Several factors complicate this approach, such as non-uniform velocity distribution,[11] so that results from a simplified one-dimensional model may include substantial errors. It is prudent to check all computations with discharge estimates using roughness as a surrogate for the obstruction[10] or modeling the large wood placement as a flow contraction modeled with empirical data (*e.g.* bridge rating curves).[12]

Shields[13] noted that drag forces are likely to be greatest during the first few major flow events and will diminish as the channel boundaries are shaped by turbulence and constriction. An increase in the specific gravity of wood (waterlogging) and the increase in ballast with sedimentation will also increase stability over time. Design charts for specific structures are shown in Slaney.[14]

3 TYPES OF STABILITY

Four common alternatives exist for securing or stabilizing placements of large wood in/near water. In order of preference for habitat formation, they are:

1. **No added stability** -- where wood is supplied to the stream and allowed to be stable without manipulation or, as conditions develop, moved by the flow.
2. **Passive stability** -- where the weight and shape of the structure is the anchor, and movement at some flow level is acceptable (includes ballast).
3. **Flexible stability** -- such as tethering the structure so some degree of movement is allowed with varying flows.
4. **Rigid stability** -- holding the logs permanently in place with no movement allowed.

3.1.1 *No Added Stability*

In the sphere of restoration activities, wood placement without anchoring is preferred when the restoration of ecosystem functions is a specific goal. Disturbance that mobilizes wood and the disturbance that mobile wood causes are part of a productive ecosystem[15] when one looks at landscape-level restoration.[16] Wood has a certain level of inherent passive stability due to its weight and dimensions. The no added stability approach simply means that one must understand that the wood is free to mobilize and adjust. The risks should be carefully evaluated, and the owner should be aware of liability associated with mobile wood. This approach works well in remote areas or for projects with a large land area and a single landowner (e.g. industrial timber, state land, or federal land).

3.1.2 *Passive Stability*

Passive stability uses the weight and shape of a structure itself to provide resistance to movement. It does not include the use of exterior anchors. Log jams can be passively stabilized by the weight of large wood pieces, rootwads, and frictional resistance with the bed (see Section 2, *Forces on Wood in Streams*).

Bracing a log against trees or bedrock is also a form of passive stabilization (Figure 3). This is an often-observed pattern with large stream wood that should be used whenever possible. In some cases, logs can be oriented so that increasing hydraulic forces increase the bracing effect and the resulting stability. If opportunities exist to apply this approach, it should be preferentially used.

Ballasting a structure with gravel and/or boulders placed within a matrix of logs can provide additional weight (see Figures 4 & 5). Cabling wood pieces to other wood or boulders within the matrix can improve passive stability.

The passively stabilized structure may adjust to scour or become mobile at high flows, but the size and shape of the structure keeps it from moving a great distance. This may be a preferred approach for some habitat mitigation structures.

Figure 3. Log braced against existing live tree (Bear Creek, Pacific County, WA


17 6'98

Figure 4. Log jam using gravel ballast (North Fork Stilliguamish River, Snohomish Co., WA.

Figure 5. Log jam using gravel ballast (North Fork Stilliguamish River, Snohomish Co., WA).

3.1.3 *Flexible Stability (tethered large wood)*

Flexible stability can be provided by tethers that allow the large wood structure to easily shift with changing flow stage or direction (see Figure 6). Tethers are appropriate where the structure is providing roughness or cover and where exact positioning of the feature is not critical. Such an approach may be used to provide a base for other debris to collect and stabilize at a specific location. The anchoring system must account for this added load. Tethered structures move with the current, scouring or "mining" erodible surfaces within their scope. Under certain circumstances, this may be considered a desirable outcome, though in some situations local scour is not acceptable and the tether must be designed to prevent the structure from moving too near the bank. Secure tethering requires that anchors be attached at more than one point on the structure to prevent twisting of the tether. If a tethered structure floats, it can allow flood flows to pass under them, presumably reducing stress on the structure,[17] until the depth of water exceeds the length of the tether. Increased stress on flexible anchoring can be caused by static forces such as leveraging, twisting, or prying actions, and dynamic forces such as vibration, oscillating drift, and surging. Flexible stability is most appropriate for backwater and other low-velocity areas and should be used with caution in high-energy stream channels.

Figure 6. Large wood tethered on long cables to large drilled boulders (Sauk River side channel near SR 530, Skagit Co., WA).

3.1.4 *Rigid Stability*

A rigid anchoring system is one in which wood is not allowed to move, float, or rotate. Rigid anchoring is usually desired where long-term grade control or direct bank protection is the objective, or where infrastructure or public safety could be put at risk. Some structures that are embedded in the bank can lead to continued bank failure if they shift or move downstream, or cause excessive scour. Due to the required permanence of this approach, it is essential that the structure being anchored is properly designed and positioned. All forms of stabilization can be used. Common anchoring methods include cabling to a buried anchor (deadman), pinning to bedrock, cabling to boulders or standing trees. Rigid anchoring can also be accomplished by direct burial of part of the structure in the bank or a boulder pile. Large wood anchored tightly to bedrock or logs embedded in a barb, groin, or rock toe are examples of rigid anchoring (see Figures 7 & 8).

Figure 7. Habitat logs anchored in bank with additional boulder ballast (E. F. Issaquah Ck, I-90 Sunset Interchange, King Co., WA).

Figure 8. Large wood anchored in groin (Cedar River, Darre Dam project, King Co., WA).

4 METHODS OF STABILIZING

Common methods of anchoring large wood include:

1. **Ballast and Burial** -- the addition of weight to the structure.
2. **Pilings** -- vertical wood poles driven or buried into the bed or banks used to brace logs.
3. **Cabling or Chaining** -- secures large wood members to other members or to existing trees or other bank features. Biodegradeable materials such as manila rope may also be used.
4. **Pinning --** fastening logs together using rebar pins or long bolts (i.e. threaded rods).
5. **Deadman Anchors** -- buried objects that are cabled to a structure. The weight of the material over the deadman anchor provides the ballasting force.
6. **Anchoring to Bedrock and Boulders** -- large wood is held down to bedrock with chain or cable glued into holes drilled in the bedrock.
7. A **combination** of the above methods.

4.1 *Ballast and Burial*

Any object that adds to the weight and frictional resistance of a structure is considered ballast. Since rock generally has much greater density than wood, a rock ballast ranging from gravel to boulders is commonly used to counteract buoyancy[18]. Ballasting log jams with gravel has become standard practice (see Figures 4 & 5). When ballasting by burial with gravel, risk exists that gravel could be washed away or scoured, causing a log to float out. This can create a risk to downstream property, a reduction in mitigation value and a loss to the restoration project at that location. Careful design can minimize risk. For instance, the potential for erosion of the ballasting gravel can be reduced if the top of the structure is designed to match the floodplain elevation. By mimicking floodplain dynamics, conditions can be provided to support vegetation establishment. The plants can increase long-term stability by forming persistent features in the same fashion as vegetated bars or islands.[2]

Within the stream, unballasted logs can be vulnerable to movement or adjustment. Individual logs imbedded in gravel are much more stable than unburied logs. They can provide habitat in the form of local bed scour while resisting incision and general bed scour. As a general rule of thumb, a log is ballasted with factor of safety (FS) = 2 when burial depth over the top of the log is equal to the log diameter.

A log structure can also be ballasted using boulders. Examples include logs embedded in a boulder cluster or in a groin (see Figure 8), burying the log in the bank with added boulders for ballast (see Figure 7), or adding boulders into the matrix of a log jam (Figures 9 & 10). Buoyancy as well as horizontal hydraulic forces must be accounted for in design. When calculating ballast requirements, use the submerged weight of the ballasting material. Rocks do not float but they still have buoyancy force acting on them. The submerged weight of a boulder depends on the density of the rock, but a typical submerged boulder weighs 60 percent of its weight in air.

Figure 9. Bank protection using large wood anchored by a combination of techniques; rock ballast, cabling, and pilings (Klickitat River, WA, Inter-Fluve, Inc.).

Figure 10. Large wood anchored using a combination of techniques; rock ballast, cabling, and pilings (Samish River, Skagit Co., WA).

When ballasting, the designer must be wary of large diameter logs because of the enormous buoyancy force they have when fully submerged. Buoyancy increases geometrically with diameter. When comparing two submerged logs of equal length, one with twice the diameter of the smaller log, the larger log has four times the buoyancy force. Looking at it another way, a 1.3-m (4-ft) diameter log has 16 times the buoyancy force of a 0.3-m (1-ft) diameter log of the same length. The designer may find that for large diameter logs, no feasible amount of boulders will provide FS=2, and that some amount of burial will be required.

Another approach to ballasting is to stack additional logs on top of a structure. Since large diameter logs have the greatest buoyancy, these should be reserved for use as the top ballasting logs where they are unlikely to become lifted and subsequently entrained. Logs that remain above the design-flood elevation provide dry weight to the structure. The logs may either be attached or unattached to the structure. However, this is not appropriate for confined channels where flood flows may achieve great depths. Since this type of structure may be higher than adjacent banks and can block a significant flow area of the channel, it may not be appropriate to use next to erodible banks or high-risk areas without additional bank protection.

Boulders can be attached to large wood using cables or chains. This increases the submerged weight of a log and its friction with the stream bed. Concrete blocks can also be used; anecdotal information on concrete blocks in streams indicates that they are less stable than boulders. Hydraulic considerations indicate that flat surfaces increase lift and drag as compared to rounded shapes.[11] In addition, concrete is prohibited in many bank protection or mitigation projects. See *Cabling and Chaining* below for risks.

Logs can also be anchored through partial or full burial. Burial is typically achieved by excavating a trench or large area in a streambank, where logs are placed and then backfilling with sediment. Depth of excavation depends on channel hydraulics, substrate characteristics, bank material, channel dimensions, existing vegetation, and the size of the log(s). Because the soil replaced in the trench will be loose and subject to scour, it should be compacted and protected (see *ISPG* for protection techniques). The potential for scour around a log jam against non-cohesive banks, especially in areas that have been excavated and re-filled, may require additional local bank protection.

For log jams, hydraulic conditions around a jam often result in sediment deposition on the downstream side. The key foundation log(s) of the jam can be oriented so that this deposition buries much of the bole of the log(s), thereby increasing the effective weight and, hence, the stability of the log jam. This process can be accelerated by using excavated sediments during construction to partially bury the log(s).

4.2 *Pilings*

Where equipment access allows and soils are appropriate, structures can be anchored with piles (see Figures 11 & 12). A professional engineer will be needed to determine the structural requirements for using pilings as anchors.

Figure 11. Piling used to increase stability of log jam (Salmon Cr, Jefferson Co., WA).

Figure 12. Log pinned to installed piles (Grays River, WA, Lower Columbia Fish Enhancement Group).

Pilings are appropriate in streams with moderate to fine-sized bed material. Cemented hardpan and bedrock will refuse pilings. Piles can be installed by pile driver or by installing the pile in an excavated hole and backfilling. In soft clays, moist silts, or sands, plies can be installed by excavator by excavating a shallow hole, pushing the pile down into it, and driving by pushing or pounding with the excavator bucket. Sharpening one end of the log may help. A thumb attachment on the excavator is recommended. Some soils are suitable for installing the pile in a deep excavated hole and backfilling. Clayey and silty soils can be excavated to great depths without caving in. Also, sandy soils will stand up for a short duration if the moisture content is just right, but cave-ins can happen suddenly so safety is an important consideration when excavating in sandy soils. It is important to compact the backfill to minimize erosion potential of the disturbed soils.

Gravels and cobbles are sometimes unsuitable for pile installation by excavation because they rapidly cave in and flow to the center creating a very wide hole. To install piles into gravels and cobbles, a pile driver is recommended (see Figures 13 & 14). In some cases, pointed steel caps have aided in driving log pilings into a gravel/cobble bed. A vibratory pile driver is highly recommended for driving into most materials because it is quick, relatively quiet, and causes virtually zero disturbance. It is even possible to install piles in flowing water with very little turbidity using a vibratory pile driver. In areas where great scour depths are anticipated, large debris loadings are expected, or pile longevity is a concern, deep and strong piles can be in the form of steel H-pile, square pile, or round pile. Pilings can be pushed horizontally into banks as long as soil composition is able to provide appropriate stability.

Figure 13. Logs with tapered tips installed with impact pile driver (Cowlitz River, WA, Inter-Fluve, Inc.).

Figure 14. Logs installed with vibratory pile driver (Lewis River, WA, Inter-Fluve, Inc.).

The matrix of pilings, logs, sediment and vegetation may be all that is required to hold a structure together. If necessary, pins or cables can be used to attach logs to pilings. Logs can be wedged between pilings and ballasted by boulders if needed, or held in place by cable strung between a number of pilings.

For stabilization against horizontal forces, typical piling designs require one-half to two-thirds of the piling length to be buried below the streambed surface. This is critical for structures where the pilings are located near or in the scour zone of the structure. Piling depth must be determined with consideration for the potential scour depths resulting from the design flood acting on the pile, the associated log jam, and any potential accumulated debris. When pilings are used to provide stability to log jams, locating at least some of the pilings away from the scour zone of the jam may be required. Using horizontal bracing logs to distribute the force against multiple pilings will improve jam stability.

For resisting buoyancy (vertical forces), stability is primarily provided by skin friction along the buried portion of the pile. A larger diameter log pile has more surface area to provide greater pullout resistance due to friction, but the larger pile is also more buoyant. As the log diameter increases, the volume of wood will increase at a greater rate than surface area. Therefore, in areas where deep pile depths are not feasible, smaller diameter log piles are preferred because they are less buoyant. Smaller log piles are easier to drive as well.

Although smaller logs are preferred for pullout resistance and installation ease, the strength and longevity of the wood become limiting factors. Piles lose strength due to degradation caused by impacts, abrasion, and decay. Piles may be susceptible to breakage due to debris loading or impacts. Large diameter piles are stronger and last longer than small diameter piles.

Pile pullout resistance due to skin friction is a function of pile diameter and length, density of wood, submerged length, buried depth, and the internal friction angle, unit weight, and relative density (loose or dense) of the soil the pile is buried in. A thorough explanation of the design equations, variables, and limitations can be found in Section 4-3 "Pile Capacity", of USACOE EM 1110-2-2906, Design of Pile Foundations.[19]

4.3 *Cabling or Chaining*

This method includes anchoring large wood with various materials including cable, wire rope, chain, rope and straps. Where a permanent, rigid anchor is desired, cable (wire rope) and chain are appropriate choices. If temporary anchoring is the goal, the use of hemp or other biodegradable, natural-fiber rope or strap may be the solution. Synthetic rope or straps are photodegradable and have a life expectancy somewhere between cable and biodegradable ropes.

Cabling or chaining implies a level of control and permanence that seeks to reduce risk of failure. Cabling is often employed in high stress or high-risk situations. Yet, cable can deteriorate rapidly with constant flexing and abrasion. Cable fragments and frayed ends are a hazard to humans and animals. Cables, which snap under high tension, may have powerful recoil. Chain reduces some of these risks, but the more important underlying issue might be that if the structure itself is under too great a stress, placement should be reevaluated. The designer should determine whether other approaches, like ballasting, might be effectively applied to the situation before resorting to cabling.

Cable (wire rope) made of galvanized or stainless steel should be used for corrosion resistance. Cable can be cut in the field using guillotine-type cutters, which tend to leave a frayed end that can be difficult to insert into holes, or by using a skill saw with a metal cutting blade, which makes a cleaner cut. The best way to cut cable in the field is with a hydraulic shear, which can be carried in a backpack and weighs approximately 15 pounds. When using epoxy to secure the cable to a boulder, the cable needs to be cleaned with acetone prior to applying epoxy.

Cables are typically connected to each other and to anchors and woody debris using cable clamps. Cable clamps are a weak point in cable anchors. Using a factor of safety of two to three times the estimated loading is prudent in the dynamic environment of streams. Improperly placed clamps can reduce the efficiency of the connection up to 40 percent of the cable strength. Thus, it is important to pay careful attention to clamp design and construction. Clamp efficiency is affected by orientation, tightening, spacing and the number of clamps used. The minimum number of *galvanized malleable* wire rope clips (clamps) ranges from three for 3/8-inch-diameter cable to four for 1/2-inch diameter cable. Using *drop forged* and *stainless steel* wire rope clips: two clips for 3/8-inch-diameter cable and three clips for 1/2-inch diameter cable. Standard wire rope clamps on a thimble eye obtain up to 80 percent of the strength of the rope when properly made. Specialty hardware can form eye loops with up to 100 percent of the cable strength. Flemish loops (a hand-formed loop) only develop up to 70 percent of the strength of the wire rope.[20]

When attaching cable to logs, always remove the bark from the area enclosed by the cable, otherwise the cable will loosen as the bark degrades. To prevent the cable from slipping along the log, the cable should be wrapped around the log two or three times and clamped (see Figure 15). If additional security is needed, a shallow notch around a portion of the log circumference will improve the bind. Drilling holes through logs is not recommended because it can encourage decay, decrease strength, and cause extreme stress in the cable if the log rotates about the joint. If rigid anchoring is required, a winch or choker is necessary to tension the cable properly before tightening the attachment hardware. Following the installation of cable, any wood movement should not create slack in the cable. Staples can be used in addition to cable clamps to secure cables to large wood. When installing staples, avoid excessive crimping of the cable. When cabling to a live tree, it is recommended to prepare a loose loop to avoid girdling the tree as it grows.

Figure 15 Logs cabled to boulder ballast (Klickitat River, WA, Inter-Fluve, Inc.).

Cable leading to buried anchors through a riprap blanket may become damaged by point loads or abrasion caused by angular stones. Numerous instances exist where the cables have been severed at the rip rap surface resulting in the loss of large wood. Chains, while still subject to abrasion, are likely to fair better than cable.

4.4 *Pinning*

The word “pinning” has entered the restoration idiom with two different meanings. One is a steel rebar or all-thread pin used to connect individual pieces of large wood, to attach large wood to other anchors, or to serve as direct anchors (by being driven into the substrate). The other is a manner of anchoring a log against or between live trees or other immobile objects; this is termed “bracing” for the purposes of this document and is discussed under the Passive Stability Section (see Section 3.1.2).

The need for steel pins in some situations shows that either the large wood is not large enough to remain in place by itself or it is in an inappropriate situation. The main concern with steel pins is that they do not allow the structure to shift and settle, therefore fully active soil and log contact pressures are not developed. This leaves uneven stress distribution, so that one part of a large jam, or a single pinned joint carries a disproportionate amount of the load potentially causing the pin to bend or break. Cabling is preferred because it does not require a drilled hole, and it is more flexible to accommodate minor shifts or rotations of the structure. However, the use of pins leaves behind less non-native and potentially hazardous materials in the channel after the wood breaks apart, and may be more aesthetically pleasing because it is less noticeable than cable wraps (see Figure 12).

Other concerns associated with pinning include adequate strength, durability of materials and security of attachment. Determining forces on large wood in rivers is challenging, so using conservative factors of safety in design is recommended. Durability of steel pins depends upon the corrosive or electrolytic nature of the soils and water, which may greatly reduce longevity at some locations.

Pin-attachment effectiveness depends upon the materials used. Threaded rods and rebar are the most common materials used. Rebar pinning relies on shaft friction to maintain attachment. Using a cable clamp at one or both ends or bending the protruding rebar end reduces the chance of pullout. When using threaded rods or bolts as connectors, large washers should always be used. Pilot holes are necessary for driving pins through large logs, and special, extended-shaft auger bits must be made for drilling through stacked logs.

Angle iron plates with four holes on each end for lag bolts or spikes have been used successfully in high-energy environments. These should be used to supplement cable in debris jams within higher-energy environments. Half-inch lag bolts or spikes at least six to eight inches long should be used.

Pieces of debris have also been anchored using various lengths of rebar driven into the streambed or bank. The rebar is driven through a pilot hole in the debris and into the streambed using a fence-post driver, sledgehammer or vibrator hammer with a special adapter for the rebar. These applications have had poor success due to difficulty in driving the rebar to adequate depth and the varying ability of subsoil to secure the rebar. For this reason, this method is not recommended as the sole method of anchoring treatments requiring long-term, rigid anchors.

4.5 *Deadman Anchors*

A deadman is a common form of anchor using a wide array of potential materials. The concept of a deadman is to bury an anchor in the bed or bank. The anchor is held down by the wedge of soil that is above it (or between the anchor and loading point). An advantage of a deadman anchor is that it can be placed in the bank away from the potential erosion zone and keeps heavy equipment out of the stream. A structure usually requires at least two deadman anchors or a combination of a deadman and other anchors, however, a single deadman might be used as a tether anchor.

Commercial deadman anchors are available that can be driven or screwed into the soil. The driven style is inserted to design depth and then “set” or activated by providing tension on the anchor, which causes the deployment of legs or plates that provide the anchorage. These anchors depend on the shear strength of the soil and are best used in cohesive soils. They are not suitable for friction soils, especially unconsolidated gravel beds. Much anecdotal information surrounds the use of these anchors. The main complaint deals with the connecting cables “working” in the soil as the log shifts or vibrates in the stream flow, creating a hole deep enough to release the anchor or otherwise leading to increased erosion.

Buried boulders, logs, concrete blocks or steel shapes are also used as deadman anchors. They have the advantage of their weight adding ballast, and they have more bearing area than commercial anchors. A drawback of this method is that by disturbing the native soil, erosion can take place that could reduce the weight of the anchoring soils or even destabilize the anchor. In the application of concrete blocks as deadman anchors, the anchor tie should be cable- or chain-wrapped around the block, not through the lifting eye on the block since the fitting may be made of metal that degrades rapidly and it is designed to accommodate force in a direction that may not be the same direction that will be applied when the anchor is installed (e.g. axial vs. lateral stress).

Designing deadman anchors requires information on soil characteristics, such as the weight and internal friction angle, which will determine the style, depth, and number of anchors required. Design guidelines are explained in detail in "*An Earth Anchor System: Installation and Design Guide*"[21].

The manufacturer’s specifications should always be followed for commercial anchor systems. During implementation, it is recommended to conduct a pullout test using a cable tension meter to determine the actual strength of the soils that the anchor is installed in, and then make adjustments to anchor quantities as needed for overall pullout resistance. Be careful to not install anchors close together because the pinning soil wedge developed from one anchor may cross onto the soil wedge of another anchor, decreasing stability.

The movement of anchored debris can cause the anchoring cable or chain to slice through and loosen the soil lying between the anchor and the debris. When this occurs, the soil becomes more susceptible to erosion. For this reason, deadman anchoring systems should be designed so they minimize the range of movement of a piece of anchored debris. Multiple, strategically located anchors will typically restrict woody debris movement more effectively than a single anchor. If movement of the woody debris is desired, an alternative anchoring system, such as ballast or pilings, should be considered. Anchors can be placed at an angle between the streambed and bank material or directly in the streambed if the bank material is weak, which will also result in less erosion if the anchor fails catastrophically. An analysis of maximum scour depth should be completed if anchoring into the streambed.

4.6 *Anchoring to Bedrock and Boulders*

When structures are to be placed on or near bedrock or anchored to boulders, the rock can be drilled and anchors set. See Figures 9, 10, & 15 for examples of boulders used to anchor large wood. The bedrock or boulders must be suitable and durable. The rock should be free from segregation, seams, cracks and other defects tending to reduce its resistance to weathering. Attachment to bedrock or boulders can be accomplished by inserting cable, rebar, threaded rod or rock bolt anchors into a hole filled with the appropriate grout or adhesive as required by the manufacturer. Oiled cable must be carefully cleaned with acetone or muriatic acid to allow proper bonding with the adhesive. The drilled hole must reach into unfractured rock to develop full anchor strength, and it must be of a depth and diameter as specified by the manufacturer. Many types of anchor adhesives exist on the market. The type selected should take into account wet conditions, possible oversized holes, and other typical complications.

The following are steps recommended by typical product literature for attaching threaded rod or rebar to bedrock or boulders using an epoxy adhesive (similar techniques can be used for rock bolt anchors):

1. Drill the anchor hole typically 1/16 inch larger in diameter than the rod or 1/8 inch larger in diameter than the rebar. Cable has also been used as an insert, but some failures have been observed, probably due to the non-uniform surface relative to the drilled-hole alignment. If using cable, a better method would be to attach the cable to a rod or rebar;
2. Clean the hole with a wire brush. Use air to blow out the hole to remove all dust and debris;
3. If the cable or steel rod is lubricated, clean the cable using acetone or muriatic acid;
4. Inject the adhesive into the hole per the manufacturer's specifications;
5. Insert the rod or rebar, and turn it slowly until the end contacts the bottom of the hole (air pockets at the bottom of the hole reduce bonding strength);
6. Make adjustments to the fastener before specified gel times, and
7. Allow curing to occur (curing time is a function of temperature and varies from one to three hours).

Some adhesives may require dry surfaces for proper bonding. Prior to using an adhesive, it is important to verify the conditions under which the adhesive functions most effectively and to make sure the product has not reached or exceeded its expiration date. Using adhesives that require dry surfaces should not be used on structures to be cabled instream.

If applied properly, some adhesives can hold to the point of cable failure.[22] While some systems provide adhesion under water, in practice they are difficult to apply in a flowing stream with consistent success. It is important to consider how wood will be cabled during the construction and placement. Failure to consider cabling specifications during construction will reduce cabling effectiveness and structural integrity.

Another common anchoring method is to use threaded expansion anchors or rock bolts. There are a variety of commercial expansion anchors available. Advantages of rock bolts over glued-in cable or steel rod include faster installation time and achievement of full strength upon installation (no drying time necessary). A disadvantage of mechanical anchors is that they are more susceptible to vibration effects than glued anchors. Another type of rock bolt anchor is the groutable rebar type. This anchor is set and then pressure grouted to seal and fill all voids and cracks in the rocks. This type can be used in weaker rock.

Cable can be threaded through a hole drilled in the rock. Any large diameter hole is acceptable, although the standard rock quarry drill, which is approximately 3 inches in diameter, are economically drilled right at the pit. A length of hydraulic hose can be threaded over the cable to reduce fraying and crimping.

4.7 *Combinations of Anchoring Methods*

Anchoring methods are often used in combinations suited to the particular task at hand. For instance, a bank protection project may consist of logs cabled to each other, pinned between pilings and ballasted with boulders (see Figures 9 & 10) or a log jam may be piled up to an elevation above the floodplain and buried in gravel ballast (see Figures 4 & 5). It is up to the designer to mix and match the anchoring techniques presented here (and any other feasible techniques) to produce an effective anchoring system for a specific project. Creative use of large, standing trees, bedrock, boulders and sharp bends to passively anchor or establish large-wood accumulations are techniques used to create stable wood habitat that emulates unmanipulated habitat. The ability to visualize stream response to various flood stages during construction at low flow is necessary. Understanding the geomorphology, hydrology and hydraulics of the site during design enables one to better visualize flood stage and use what already exists on-site to help construct a solid wood habitat project.

5 PLACEMENT CONSIDERATIONS IN STREAMBANK PROTECTION PROJECTS

The information below pertains to placement of large wood in conjunction with streambank protection projects. Placement considerations for stream habitat restoration projects are discussed in the Stream Habitat Restoration Guidelines (SHRG), *Logs and Log Jams* technique.

Large wood can enhance the effectiveness of bank-protection treatments while mitigating the treatments' negative effects on fish habitat. The use of rock and other bank-hardening materials in streambank-protection projects often results in the loss of fish habitat. Rock revetments create relatively smooth banks, resulting in high near-bank velocities, loss of cover and a reduction in structural and hydraulic complexity. Structural and hydraulic complexities created by large wood are important components of fish habitat enhancement. Juvenile fish use increases when large wood is included in rock revetment projects.[23, 24] Placement of large wood is therefore considered a preferred form of mitigation. As an added benefit, some sites have shown that wood added for habitat restoration performs a bank-protection function as well. Downstream velocities are decreased and energy is dissipated in the form of turbulence around the large wood, encouraging deposition and reducing near-bank scour, while enhancing complex rearing and holding habitat for salmonids at low[25] and high flows. Whenever possible, large wood should be placed in locations and configurations where it would be expected to occur naturally, which increases its reliability in providing fish and wildlife habitat.

The design of large wood projects must be carefully considered to ensure their success in meeting project goals. Unfortunately, the failures of some bank-protection projects involving large wood for habitat mitigation have been wrongly attributed to the wood rather than to the designer for not creating an integrated project. As designers become more adept at incorporating large wood into streambank-protection projects, its effectiveness and frequency of use will increase.

A variety of strategies are available for placing wood in mitigation and restoration projects with a full range of anchoring options. The options range from simple delivery of wood to the channel[26] to fully restrained wood with cable or chain. Refer to the Stream Habitat Restoration Guidelines (SHRG), *Logs and Log Jams* technique for more information on methods and design considerations for adding wood to streams.

Large wood should not be placed during emergency conditions or for the purpose of alleviating emergency bank erosion problems. Large wood can only be anchored or placed effectively in relatively calm and/or dewatered environments. It also requires careful planning and design, which is not feasible during a true emergency.

5.1 *Large Wood for Catching Debris*

It is generally accepted that the greater the wood density found in a given reach, the greater the densities of juvenile salmonids[27] and a greater diversity of channel features with associated aquatic communities.[28] Large wood, used as mitigation, should be installed as dense clusters or have the capability of recruiting other debris from the stream. Single logs provide little habitat by themselves; and, as time passes, isolated rootwads become featureless stumps providing little cover.

Wood recruitment is the stream's habitat-revitalizing force, adding complexity and renewing cover over time. Streambank-protection techniques made of rock are not effective at recruiting wood on their own, so large wood should be incorporated since it tends to collect other debris and encourages the recruitment of even more wood. For maximum wood recruitment potential, logs with rootwads should be positioned so that a portion of the rootwad is above the flood-flow water surface. Floods recruit large wood as the banks erodes, drawing large and small trees into the active channel. Small trees and wood material added to the channel float downstream and are often captured by existing downstream log jams. If logs with rootwads are installed alone and low on rock revetments, they will not collect this liberated debris as it floats by. The ideal solution is to have wood at various elevations on the bank to ensure recruitment at all flows.

In systems with high banks and infrequent out-of-bank flows, the wood stays along the thalweg in the deeper, faster moving water and does not tend to accumulate along the banks. In order to recruit debris, large wood in rock-treated banks must stick out into the flow and be high enough to capture floating debris. Wood tends to accumulate at the downstream ends of meander bends[29]; this is a good place to expect wood recruitment on placed large wood.

5.2 *Large Wood in Rock Toes or Revetments*

Rock for bank-protection projects is frequently sized according to a minimum stable dimension or gradation. These stability equations and tables are for smooth banks with flow running on an alignment parallel to the bank. When wood is added to the revetment design, failure may result from turbulence or redirected flow unanticipated in the original rock-sizing criteria. The designer must account for these hydraulic forces in sizing stone and the determination of stone layer thickness. Experience suggests that it is best to use the largest rock available for rock revetments, toes, groins and barbs that incorporate large wood. Refer to the discussion about Riprap in Integrated Streambank Protection Guidelines (ISPG), Chapter 6, *Techniques for Rock Sizing Information*. While it may save money to use the minimum stable rock size for a particular project, the increase in risk may be unacceptable when also using wood. During floods, wood buoyancy and upstream wood collection cause shifts in hydraulic forces; and, together with impacts from large, floating logs, can quickly make conventionally-sized rock inadequate to hold wood in place. A good understanding of the worst-case flood forces that could occur at the project site enables a design that will be long-lived and emulate the size of material that would naturally occur at each site.

The use of such large rocks and logs necessitates a filter between the native material and structure, such as layered bedding, especially in fine-sediment banks and streambeds. Successful projects use progressively finer granular layers between the rock and the native bank material. Fine-grained soils may require small-diameter crushed rock or screened sand and gravel, followed by quarry spalls and light, loose riprap. Refer to the discussion about subsurface drainage in Chapter 6 for more information regarding selection of filter materials between riprap and native materials. Another approach is to use a well-graded pit run rock to provide the filter layer behind the riprap.

In low energy streams, large logs can be embedded in a boulder toe with rootwads extending into the channel. Placing the logs near the streambed will encourage local scour, which provides cover and refuge opportunities. In confined streams with deep flood flow, additional logs can be placed at higher levels to collect debris and provide additional velocity refuge opportunities.

5.3 *Large Wood in Groins and Barbs*

Large wood is used in groins about the same way it is used in rock toes and revetments (see Figure 8). However, a few added complications exist. Large logs with intact, finely branched rootwads are preferred for use in groins. They should be placed at bed level for cover purposes and also at higher stages to encourage recruitment. Logs need to be well embedded in the structure, placing one-half to two-thirds of the lower part of the tree trunk in the rock. The rock size should be increased to act as ballast; unless, as has been recommended, the largest rock available is already specified.

The positioning of large wood in the structure is the subject of some debate. It depends, in part, upon whether the structure is a barb or a groin. Barbs are positioned low and produce less scour and turbulence. As a result, sediment tends to accumulate around them and a new bankline develops. If large wood is placed near the bank upstream or down-stream of a barb, it is likely to be in a deposition zone, and its value as cover is reduced or eliminated. To enhance fish habitat, it is useful to place large wood near the tip of barbs; however, designers have expressed concerns that this is the area of highest stress, and large wood may destabilize the structure and reduce its effectiveness as bank protection. This concern applies primarily to high-energy environments. Using wood on the end of a barb could cause problems if it collects additional wood and allows hydraulic scour to be focused on the bank the barb is designed to protect. Large wood, if placed near the tip, should be positioned low in the water column to provide cover, while reducing its ability to collect debris.

In contrast to barbs, groins are high structures that trigger more pronounced turbulence and scour which results in the area near the bank being scoured. however, placing large wood in the area can provide good cover and complexity. wood can also be placed near the tip on the upstream face of groins. usually more rock exist in groins than in barbs, so wood can be held more securely.

6 REFERENCES

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APPENDIX H

TYPICAL PERMITS REQUIRED FOR WORK IN AND AROUND WATER

Typical Permits Required for Work in and Around Water Appendix

Local, state, and federal permits may be required for any activity that takes place in or around waters of the state, including habitat restoration projects. The type of impacts a project generates and the project location determine which permits are required. The Governor's Office of Regulatory Assistance (ORA) can help determine which local, state and federal permits are needed for your project. The ORA may be reached by phone at 360-407-7037 or (800) 917-0043, or online at http://www.ora.wa.gov/default.asp. The website offers and online project questionnaire that can assist you in determining permits required for your project. T he ORA also publishes *The Permit Handbook: Commonly Required Environmental Permits for Washington State*[1], available on line at http://www.ora.wa.gov/resources/handbook.asp. Contact the city or county where your project is located for information on local permits that may be required.

Contact permitting agencies early in the project planning process to ensure that all necessary permits are obtained before work is scheduled to begin. In addition, if the project is located on either state-owned forest or aquatic lands, the Department of Natural Resources (DNR) should be contacted for an authorization to lease state land. Delaying agency coordination increases the likelihood of costly design modifications or project rejection. Early contact not only prevents construction delays, it can result in an effective and/or less expensive project.

All permits require a review process that takes time to complete. Some reviews are relatively fast (less than a month) while others may take several months. The time needed to complete the required permit process should be carefully considered when developing project planning, design, and construction schedules, especially given the relatively short allowable work period for many types of in-stream construction projects. Project proponents must plan ahead, especially when time-sensitive grant funding is utilized. Besides time, many permits require fees and rent is charged for the use of state lands. Fees may be either a flat rate or a percentage of the project's total cost, whereas rents are based on surrounding land values.

The discussion below is intended to familiarize the reader with the permitting process. The information provided and the specific permits required are subject to change. Contact the appropriate permitting agencies for the most accurate current information.

1 HOW THE ENDANGERED SPECIES ACT AFFECTS PROJECT PERMITTING

The purpose of the ESA is to ensure the long-term survival of native fish, wildlife and plants; and the habitat upon which they depend. Listings of several fish species, marine mammals, birds and plants in Washington State under the Endangered Species Act (ESA) have added complexity to obtaining permits for work in or around water. The ESA applies to everybody subject to the jurisdiction of the United States, including state and federal agencies, cities, counties, tribes, and individuals. One component of ESA compliance requires obtaining a permit for any action that has the potential for "take" of a listed fish or wildlife species. "Take" is defined as to "harass (create the likelihood of injury to listed species to such an extent as to significantly disrupt normal behavior patterns which include, but are not limited to, breeding, feeding, or sheltering), harm (including significant habitat modification or degradation that results in death or injury to listed species by significantly impairing behavioral patterns such as breeding, feeding, or sheltering), pursue, hunt, shoot, wound, kill, trap, capture, or collect, or attempt to engage in any such conduct" (ESA Section 3[19]). NOAA's National Marine Fisheries Service (NOAA Fisheries Service) and U.S. Fish & Wildlife Service (USFWS) have the responsibility of ensuring that proposed activities will not jeopardize the continued existence of a listed species, or destroy or adversely modify their critical habitat.[2] NOAA Fisheries Service has jurisdiction over all fish and wildlife species whose life cycles reside mainly in the marine environment, including salmon. USFWS has jurisdiction over inland and terrestrial species of fish, wildlife and plants whose life cycles reside mainly outside the marine environment.

All proposed activities that may affect any listed fish, wildlife, or plant species, positively or negatively, require review by NOAA Fisheries Service and/or USFWS. The goal of this review is to assess the potential impacts of the proposed activity on listed species, and avoid and minimize adverse effects. These reviews can provide legal coverage for incidental "take" that may occur as a result of otherwise legal project activities. Under the ESA, coverage of a proposed activity may be achieved in one of three ways.

1.1 Section 7 Consultation

A Section 7 consultation is required whenever a federal nexus exists for a project. Federal nexus is defined as; all activities carried out, funded, or permitted by a federal agency. A Section 7 consultation applies to species listed as either threatened or endangered. In an ESA Section 7 consultation, the federal agency responsible for constructing, funding, or permitting the project will be responsible for consulting with NOAA Fisheries Service and/or USFWS, as appropriate.[3] That federal agency is referred to as the "action" agency. The U.S. Army Corps of Engineers (Corps) typically acts as the action agency for most projects in Washington that involve in-water work.

A Section 7 consultation proceeds in the following manner. A Biological Assessment (BA) or similar analysis of project effects on listed species must be prepared; either by the action agency or by the applicant and provided to the action agency for edit and review. Limiting the action agency's involvement to a review may significantly speed up the BA process. Three possible determinations may be made by the action agency:[2]

a. "No effect" indicates no probability of any effect on listed species by the proposed activity exists. A "no effect" determination does not require NOAA Fisheries Service or USFWS review.

b. "May affect, not likely to adversely affect" indicates the proposed activity does not have the potential to hinder the attainment of relevant properly functioning indicators and/or effects are expected to be discountable, insignificant, or completely beneficial (i.e. has a negligible probability of taking proposed or listed species, or destroying or adversely modifying their habitat). This determination requires informal consultation with NOAA Fisheries Service and/or USFWS, resulting in a written concurrence with the action agency's determination.

c. "May affect, likely to adversely affect" indicates that the proposed activity has the potential to hinder attainment of relevant properly functioning indicators, has more than discountable, insignificant, or beneficial effects on the species or its habitat, or has a more than negligible probability of taking proposed or listed species or destroying or adversely modifying their habitat. This determination requires formal consultation with USFWS and/or NOAA Fisheries Service. NOAA Fisheries Service and/or USFWS will conduct a jeopardy analysis and issue a Biological Opinion (BO, or BiOp) regarding whether or not an activity is likely to jeopardize the continued existence of listed species or destroy, or adversely modify designated critical habitat for listed species. Following this analysis, NOAA Fisheries Service and/or USFWS will either authorize the proposed activity outlining reasonable and prudent measures to minimize the impact of any "take", or else suggest reasonable and prudent alternatives to the proposed activity if they exist.

NOAA Fisheries and the USFWS have developed a suite of resources to assist in ESA Section 7 permitting. The River Restoration Analysis Tool, or *RiverRAT* (http://www.restorationreview.com/), was developed to facilitate consistent and thorough evaluation of the potential impacts of proposed projects on river habitat, specifically in an ESA Section 7 context. The tool is supported by a source document that provides a comprehensive synthesis of the watershed and river sciences relevant to restoration planning and design, a project risk evaluation matrix, and a separate comprehensive checklist of information necessary to include in BAs and permitting documents. The project information checklist and project screening matrix will assist the project sponsor with identifying project impacts and the information necessary for the preparation of a BA to address ESA consultation requirements. The *RiverRAT* tool will walk you through a series of 16 questions that parallel the phases of restoration project development. Each question is designed to help you evaluate whether a project has addressed fundamental considerations at each step of the project development process. You will be able to record your responses and thoughts for each question, and print a final report to document your review. Using *RiverRAT* resources to guide the ESA Section 7 permitting requirements will greatly improve the permitting process for both permittees and agency reviewers.

1.2 Section 10 Consultation

If no federal nexus exists, the property owner can get federal assurances regarding their liability for listed and candidate species through a Section 10 Incidental Take Permit. This permit requires the development of a Habitat Conservation Plan (HCP). Under Section 10, the project sponsor will be responsible for development of the HCP and directly applying to NOAA Fisheries Service and/or USFWS, as appropriate. As such, coverage under section 10 may be more costly and require more of the project sponsor's time than a Section 7 consultation.

Section 10 of the ESA allows NOAA Fisheries Service and USFWS to permit the "take" of listed species by non-federal entities provided that it is done for scientific research or enhancement purposes or it is incidental to, and not the purpose of, carrying out an otherwise lawful activity. Applicants for an Incidental Take Permit must submit a HCP to NOAA Fisheries Service and/or USFWS for review as appropriate. The HCP must identify at a minimum: 1) the impact of any "take" associated with the proposed activity, 2) steps that will be taken to minimize and mitigate for impacts, 3) available funding, and 4) what alternative actions were considered and why they were not utilized. Following a public comment period regarding the HCP and permit application, NOAA Fisheries Service and/or USFWS can issue an Incidental Take Permit if they find that: the taking will be incidental, the applicant will minimize and mitigate the impacts of the “take”, the applicant will ensure adequate funding for the proposed plan, and the taking will not appreciably reduce the likelihood of the survival and recovery of the species in the wild.[4]

1.3 Section 4(d) Rule

Section 4(d) of the ESA allows NOAA Fisheries Service and USFWS to issue regulations deemed necessary and advisable to provide for the conservation of threatened species. These regulations may exempt certain activities from “take” prohibition. Different 4(d) exemptions may apply to different species or runs of fish. Project proponents should contact NOAA Fisheries Service and/or USFWS to find out if their proposed activity is exempt under Section 4(d) “take” limits. Note that the 4(d) exemptions only apply to specific species or runs of fish listed as threatened. They do not apply to species listed as endangered.

Always check with NOAA Fisheries Service and USFWS, even if you are not working directly in a waterbody. Activities in the watershed may significantly impact a waterbody. Projects in or near waterbodies may also impact non-aquatic listed species, such as birds nesting in nearby trees, plants growing in the floodplain, or mammals that use the project area as a travel corridor or foraging area. Unauthorized “take” of endangered or threatened species can result in both civil and criminal penalties!

1.4 Expedited Federal ESA Consultations

Specific to Salmon Recovery Funding Board (SRFB) funded projects, grant recipients may be eligible to use expedited federal permitting processes for habitat restoration and protection projects affecting ESA-listed fish under the jurisdiction of NOAA Fisheries Service through the Habitat Restoration Program (Limit 8 of the Section 4(d) rule of the ESA).

The Habitat Restoration Program may be used only with projects that:

a. Receive some funding from the SRFB.
b. Only affect species listed as threatened (not endangered) under the ESA.
c. Involve species, such as steelhead and salmon, under the jurisdiction of NOAA Fisheries Service. It does not cover species, such as bull trout, under the jurisdiction of USFWS.

Additional eligibility and application information is available in the SRFB Manual 18; http://www.rco.wa.gov/documents/manuals&forms/Manual_18.pdf and http://www.rco.wa.gov/documents/fact_sheets/Permit_Streamlining_fact_sheet.pdf.

The Fish Passage and Habitat Restoration Programmatic expedited permit applies to any restoration project that meets ALL of the following criteria:

a. Must have the potential to affect fish listed as threatened or endangered under the ESA.
b. Must require a U.S. Army Corps of Engineers’ regulatory permit.
c. Must be a restoration action included in at least one of the nine categories of restoration listed in the Programmatic Biological Opinion.
d. Must be on private or public lands other than those managed by the U.S. Forest Service or Bureau of Land Management. If your project is on national forest lands, a separate process is in place and you should work with your local U.S. Forest Service office.

A major advantage of projects permitted through the Fish Passage and Habitat Restoration

Programmatic is that a Biological Assessment is not required. Potential effects to ESA-listed fish are assessed using the Specific Project Information Form (SPIF). To apply, fill out the SPIF and send it to the U.S. Army Corps of Engineers' Regulatory Office. http://www.nws.usace.army.mil/PublicMenu/Menu.cfm?sitename=REG&pagename=2008FishRestoration

The Corps reviews the form for completeness and sends it to the NOAA Fisheries Service and USFWS for review and approval. Electronic approval from the Services will occur within 30 days. Information on eligibility or process requirements is available at: http://www.nws.usace.army.mil/PublicMenu/Menu.cfm?sitename=REG&pagename=2008FishRestoration.

2 MAGNUSON-STEVENS FISHERY CONSERVATION AND MANAGEMENT ACT (MSA) - ESSENTIAL FISH HABITAT

The MSA requires all Federal agencies to consult with the NOAA Fisheries Service on all actions, or proposed actions, permitted, funded, or undertaken by the [federal] agency, that may adversely affect designated Essential Fish Habitat (EFH). For the state of Washington, EFH has been designated for 3 species of Pacific salmon, 83 species of groundfish, and 5 coastal pelagic species. Note: the Fish Passage and Habitat Restoration Programmatic expedited permit discussed above provides coverage for EFH.

For more information and guidance on EFH, including assessments, templates, and a list of designated EFH for your area, please see the NOAA Fisheries Service's EFH website at http://www.nmfs.noaa.gov/sfa/index.htm#achieve

3 COMMONLY REQUIRED PROJECT PLANNING PERMITS AND AUTHORIZATIONS

The following text describes the most commonly required project planning checklists, permits and authorizations when conducting activities in and around waters of the state, including habitat restoration projects. The information provided here is a summary of that provided in The Permit Handbook: Commonly Required Environmental Permits for Washington State,[1] where more detailed information is available, http://www.ora.wa.gov/resources/handbook.asp.

3.1 State Environmental Policy Act (SEPA)

SEPA is a review process to ensure that state and local government officials consider environmental values when making decisions about plans and projects. It is required for all state and local agency actions (including providing funding or issuing permits for project proposals, and the adoption of plans, regulations, or ordinances for non-projects) unless those actions are specifically exempted by the SEPA Rules (WAC 197-11-800 to 880) or RCW 43.21C.035, .037, and .0384. The Lead Agency will ask the applicant to fill out an environmental checklist that describes how a proposal will affect the environment. The Lead Agency will vary. If the project proponent is a non-federal government agency within the State of Washington, that agency shall be the Lead Agency (WAC 197-11-926). In the case of private project proposals, if a local permit is required, the local city or county will be the Lead Agency. If no local permits are required but one or more state permits is required, one of the state agencies requiring a permit will be the Lead Agency, according to the order of priority given in WAC 197-11-936. Refer to WAC 197-11-922 through 950 for a complete description of Lead Agency rules and the method and criteria for Lead Agency selection.

Once the environmental checklist is submitted, the Lead Agency will either:

a. Issue a Determination of Non-Significance (DNS) or a Determination of Mitigated Non-Significance (MDNS) indicating that, in their opinion, the project will not have a significant adverse environmental impact or that mitigation has been identified to reduce the impacts sufficiently. Mitigation measures are changes or conditions added to your proposal that will avoid, minimize, or compensate for adverse impacts. Other agencies issuing a permit, and interested parties (i.e. the public) will be provided a comment period. Significant impacts raised during the comment period must be addressed by the project. After which, the permit processing of a DNS or MDNS can proceed if no further significant concerns are raised.

b. Determine that an environmental impact statement (EIS) is required. This indicates that the project will have a "probable significant adverse environmental impact". An EIS is a document that identifies potentially harmful environmental effects of various project alternatives, as well as ways to minimize and mitigate for the negative effects to the greatest extent possible (but not achieving a non-significant threshold). The Lead Agency will begin the process by issuing a determination of significance/scoping notice for agencies and the public to review and provide comment. "Scoping" is done to identify key issues related to the project that will be evaluated in the EIS.

Agencies will use the information in the EIS, DNS, or MDNS when they are making permit decisions. Permit conditions may be added to reduce the adverse impacts of a proposal. Under very rare circumstances, if an EIS shows likely adverse environmental impacts exist that cannot be reduced to an acceptable level, licenses or other approvals for the proposal may be denied. It is also possible for permits to be denied under applicable permit regulations. Additional information on SEPA, including the SEPA handbook, is available online at http://www.ecy.wa.gov/programs/sea/sepa/e-review.html.

3.2 National Environmental Policy Act (NEPA)

NEPA is a similar process to SEPA that applies to federal agencies making decisions regarding permits, licenses, or approvals. It is triggered whenever a project receives federal funding or if any federal permits, licenses, or approval are required. Under NEPA, the Lead Agency is required to use an environmental assessment (EA) to determine the extent of environmental impacts associated with a project. Response of the Lead Agency may be:

a. Issuance of a categorical exclusion (CatEx), indicating that the project is exempt from NEPA documentation requirements;

b. Issuance of a finding of no significant impact (FONSI), indicating that a project will not significantly impact the environment, or

c. Determination that an EIS is required, if the project will significantly impact the environment.

Participation in either the NEPA or SEPA process does not exempt a project proponent from participation in the other process. However, the state or local agency has several options to reduce redundancy between the two processes. It may confer with federal agencies to develop a joint NEPA/SEPA EIS; develop a supplemental EIS to cover SEPA requirements that are inadequately addressed under NEPA, or, if the NEPA document is adequate, adopt it under SEPA (Note that issuance of a CatEx under NEPA does not exempt the project from SEPA review).

3.3 Joint Aquatic Resource Permits Application (JARPA) and Associated Permits or Approvals

The JARPA is a consolidated application that can be used for all types of water-related projects. Each agency reviewing the JARPA application has its own review period and fee schedule for permit issuance. Contact the local city or county planning office before submitting a JARPA application to them, as not all local government agencies use JARPA. Online permitting resources are available at:
http://www.epermitting.wa.gov/site/alias__resourcecenter/jarpa_jarpa_form/9984/jarpa_form.aspx

The JARPA may be used to apply for the following permits:

- *Hydraulic Project Approval (HPA)*
  Required for any work that uses, diverts, obstructs, or changes the natural flow or bed of marine and fresh state waters. This approval is issued by the Washington Department of Fish and Wildlife (WDFW).
- *Shoreline Management Act Permit (including Substantial Development, Conditional Use, Variance Permit, or Exemption)*
  Required for any development or activity valued at $5,000 or more that is located on the water or shoreline area. It is also required for any use or activity that interferes with normal public use of water/shorelines of the state regardless of cost, and uses that constitute a conditional use or variance under the local master program. Shorelines are lakes, including reservoirs, of 20 acres or greater; streams with a mean annual flow of 20 cubic feet per second or greater; marine waters; plus an area landward for 200 feet measured on a horizontal plane from the ordinary high water mark; and all associated marshes, bogs, swamps, and river deltas. Floodplains and floodways incorporated into local shoreline master programs are also included. The local city or county government issues this permit.
- *Floodplain Management Permits and/or Critical Areas Ordinances*
  Required for work (including development and filling or grading activities) in frequently flooded areas, geologically unstable areas, wildlife habitats, aquifer recharge areas, and wetlands. The local city or county government issues this permit.
- *Section 401 of the Clean Water Act Water Quality Certification*
  Required of any applicant for a federal license or permit to conduct any activity that may result in any discharge into surface waters. This includes the discharge of dredge and fill material into water or wetlands. A 401 Certification is required whenever a US Army Corps of Engineers' 404 permit is required. This certification, stating that the discharge complies with federal and state law requirements, is issued by the Washington Department of Ecology (Ecology).

- *Section 404 of the Clean Water Act Permit: Discharge of Dredge and Fill Material*
  Required when placing a structure, excavating (including land clearing), or discharging dredged or fill material into waters of the United States, including wetlands. The U.S. Army Corps of Engineers issues Section 404 permits.
- *Section 10 of the Rivers and Harbors Act Permit: Work in Navigable Waters*
  Required for any work in or affecting navigable waters of the United States, including wetlands. The U.S. Army Corps of Engineers issues Section 10 permits.
- *Section 106 of the National Historic Preservation Act:* All projects requiring Federal approval are reviewed for consistency with Section 106 of the National Historic Preservation Act to ensure that the proposed activities will not disturb archeological significant sites. The U.S. Army Corps of Engineers typically ensures compliance with Section 106 during the 404 review process.
- *Section 9 of the Rivers and Harbors Act Permit*
  Required for construction of a new bridge or modification to an existing bridge over a navigable waterway. The Coast Guard issues the Section 9 permit.

Two alternative JARPAs are currently available that simplify the process for securing permits for some types of fish habitat enhancement and watershed restoration projects. All others use the regular JARPA. The alternative JARPA processes are:

1. Streamlined Process for Fish Habitat Enhancement Projects

Projects qualifying under RCW 77.55.181 are entitled to a streamlined HPA process, and will be exempt from SEPA as well as from all local government permits and fees. However, qualifying projects are still subject to state and federal permits and their review schedules and fees. The WDFW has 45 days to make a determination. Within that period, the local government has 15 days to submit their comments to WDFW. If the project qualifies, WDFW must approve or deny the HPA within 45 days. Large scale projects that impact other governmental interests (e.g. police, fire, wetland protections) may not be eligible for this process.
To apply for the streamlined process, the applicant must submit a complete JARPA and the JARPA attachment: Fish Enhancement JARPA Form which can be accessed at the following link:
http://www.epermitting.wa.gov/Portals/_JarpaResourceCenter/images/default/JARPA_supplement_fish_enhancement9_22_10%20REVISED.doc

To qualify for the fish habitat enhancement expedited permit application process, projects must accomplish one or more of the following:

- Elimination of human-made fish passage barriers, including culvert repair and replacement; or
- Restoration of an eroded or unstable streambank employing the principle of bioengineering, including limited use of rock as a stabilization only at the toe of the bank, and with primary emphasis on using native vegetation to control the erosive forces of flowing water; or
- Placement of woody debris or other in-stream structures that benefit natural reproducing fish stocks.

And must be approved in one or more of the following ways:

- By WDFW, through the Salmon Enhancement, or Volunteer Cooperative Fish and Wildlife Enhancement Programs,
- By the sponsor of a watershed restoration plan as provided in chapter 89.08RCW,
- By WDFW, as a department-sponsored fish enhancement or restoration project,
- Through the review and approval process for Washington Conservation District sponsored projects, where the project complies with design standards established by the Conservation Commission through interagency agreement with the USFWS and the Natural Resource Conservation Service, or
- Through a formal grant program established by the legislature or the WDFW for fish habitat enhancement or restoration.

Approval to qualify for the process is not the same as permit approval. The HPA is still required prior to conducting work.

2. Expedited Permit Application for Watershed Restoration Projects

Qualifying projects under RCW 89.08.450 through 89.08.510 are also entitled to a streamlined permitting process and are exempt from the requirements of SEPA and permit fees. The expedited permit application has two parts: the expedited permit application and the JARPA. he expedited permit application is a worksheet to help applicants determine whether or not the project qualifies for this process. Qualifying projects are exempt from needing a Substantial Development Permit, but they may still need a Conditional Use Permit or Shoreline Variance under the local shoreline master program.

The expedited process may only be used for projects designed to enhance fish and wildlife habitat. To qualify for the watershed restoration project expedited permit application process, a project must:

- Be part of a watershed restoration plan that has undergone public review pursuant to SEPA requirements,
- Be principally designed to enhance fish and wildlife habitat, and
- Meet one of the following criteria:
  - A project that affects less than 10 miles of stream reach, in which less than 25 cubic yards of sand, gravel or soil is imported, removed, or disturbed, and in which no existing vegetation is removed except as necessary to facilitate additional plantings;
  - A project for the restoration of an eroded or unstable streambank that employs the principles of bioengineering and has a primary emphasis on using native vegetation;
  - A project primarily designed to improve fish and wildlife habitat by removing or reducing impediments to migration of fish or enhancing the fishery resource available for use by all citizens of the state, provided that any structure, other than a bridge or culvert or instream habitat enhancement structure associated with the project, is less than 200 square feet in floor area and is located above the ordinary high water mark of the stream.

Contact your local conservation district, the Washington Conservation Commission, or the ORA for more information regarding the expedited permit process.

3.4 Aquatic Use Authorization

Anybody wishing to use state-owned aquatic lands, which includes: tidelands, shorelands, and beds of navigable lakes and rivers, (including owners of adjacent lands) must get authorization from the DNR. Besides responsibilities for long-term ecosystem protection, the DNR is charged with ensuring the value of the land for current and future citizens of Washington. Information required on the application includes location; proposed use; existing structures; project description; local, state, and federal regulatory requirements; and a property survey. Application processing time generally ranges from six months to one year. An aquatic land use rental fee may also apply. For additional information contact your regional DNR office (http://www.dnr.wa.gov/AboutDNR/Regions/Pages/Default.aspx). The application can be downloaded at: http://www.dnr.wa.gov/BusinessPermits/HowTo/LeasingLandTransactions/Pages/aqr_how_to_lease_aquatic_lands.aspx.

4 OTHER PERMITS THAT MAY APPLY

The following is not an all-inclusive list, but covers most other permits that may apply. Again, contact the ORA for further information.

4.1 Forest Practices Approval

A Forest Practices Approval (FPA) Permit is required before beginning any forest practice (harvesting, reforestation, road construction/abandonment, fertilization, prevention, and suppression of diseases and insects, tree salvage, brush control, and/or chemical application). This approval is issued by the DNR. In planning counties, the local government entity (LGE) is the review/approval authority for timber harvest associated with conversion of the property from forestry to another land use. However, not all LGEs in planning counties have assumed this jurisdiction from DNR. Where LGEs have not assumed jurisdiction, and in non-planning counties, timber harvest associated with conversions is reviewed/approved by DNR.

4.2 Coastal Zone Management Certification (CZM)

Required for U.S. Army Corps of Engineers authorized projects, and/or when applying for certain federal permits or funding. The project proponent prepares the certification. Ecology reviews the certification and the proposed project for compliance with state environmental requirements.

4.3 Noxious Aquatic and Emergent Weed Transport Permit

A Noxious Aquatic and Emergent Weed Transport Permit is required for transporting whole or parts of various plants that have been designated as noxious weeds by the Washington State Noxious Weed Control Board. The Director of Agriculture issues the permit.

4.4 Short-term Water Quality Modification

A Short-term Water Quality Modification is required for the use of aquatic herbicides or pesticides, including those used to control noxious and non-noxious aquatic plants. Ecology issues this permit.

4.5 Stormwater Discharges from Construction Sites

Construction site operators are required to be covered by a Construction Stormwater General Permit if they are engaged in clearing, grading, and excavating activities that disturb one or more acres and discharge stormwater to surface waters of the state. Ecology issues this permit. An Erosion and Sedimentation Control Plan may be required. Additional information can be found online at http://www.ecy.wa.gov/programs/wq/stormwater/construction/.

4.6 Hazardous Waste Release Notification

Ecology must receive prompt notification of any spills or releases of hazardous substance that occur that have the potential to impact human health or the environment. This includes spills resulting from breaks in the hydraulic lines and fuel hoses of construction equipment.

4.7 Cultural and Historical Resource Review

Current Washington state law requires a permit from the Washington Department of Archaeology and Historic Preservation (http://www.dahp.wa.gov/) to remove or excavate any Native American human remains, burials, or to excavate any Native American archaeological site. A permit is also required to remove or excavate historic archaeological resources that are eligible or listed in the National Register of Historic Places or to recover any submerged historic aircraft or historic shipwrecks, or remove any archaeological object from such sites.

Governor's Executive Order 05-05, Archaeological and Cultural Resources (www.governor.wa.gov/execorders), directs state agencies to review all capital construction projects using state funding for potential impacts to cultural resources. "Cultural resources" means archeological and historical sites and artifacts, traditional areas, and items of religious, ceremonial, and social uses for tribes. You may be asked to complete a cultural resource/archaeological survey. Archaeological surveys are undertaken by archaeologists employed by a wide variety of agencies and the private sector. Survey costs need to be included within project planning. The consultation must be completed before construction begins.

If federal permits, licenses, approvals, funding, or agencies are involved in or regulating the project, your project must comply with Section 106 of the National Historic Preservation Act. You, or your consulting archaeologist, will need to contact the lead federal agency regarding site evaluation.

4.8 Pesticide Permits

Anyone planning to use pesticides, herbicides, insecticides, miticides, or other such products should contact the Washington State Department of Agriculture (WSDA) Pesticide Management Division at (877) 301-4555 to determine if, and what type of, a license or permit may be required.

Many people involved in the pesticide industry are required to obtain at least one of nine different pesticide licenses issued by the WSDA. A licensee may only perform the technical activities (agricultural weed control, aquatic weed control, structural pest control, etc.) for which they have been certified. In addition to a license, permits may be required for applying certain pesticides. These permits generally cover certain geographical areas and times of the year.

Before pesticides are used in or near water, a Short-term Water Quality Modification Permit from the Washington Department of Ecology will likely be required. Some cities and counties also have special requirements related to pesticide use, so it is important to check with them especially when considering pesticide use in sensitive areas, such as wetlands, surface waters, and groundwater recharge areas and other environmentally sensitive areas.

4.9 Other local permits

These may include, but are not limited to, Clearing and Grading Permits, and permits required for compliance with Critical Areas Standards. Critical areas are locally designated wetlands, geological hazard areas, aquifer recharge areas, fish and wildlife habitat conservation areas, and frequently flooded areas.

4.10 FEMA

Permitting for projects involving large wood placements (refer to the Large Wood Technique) may require additional analysis and documentation. In some cases, LW projects may require a "no-rise" analysis to demonstrate that LW placements will not result in a rise in the Base Flood Elevation (i.e. 100-year flood). This is a Federal Emergency Management Agency (FEMA) requirement as part of the National Flood Insurance Program (NFIP). A no-rise analysis may be required by the local jurisdiction responsible for managing the NFIP program. A no-rise analysis must be conducted by a licensed engineer or hydrologist, and can be an expensive process. However, FEMA Region 10 has issued a policy statement that may reduce the analysis burden for fish enhancement structures. This policy statement is included in the Region 10 NFIP Guidebook.[5]

4.11 Wetlands

If work will occur in or near wetlands, Federal, State, and Local governments may all have specific permit requirements. At the Federal level, the Army Corps of Engineers regulates wetlands under the Clean Water Act and Coastal Zone Management Act. Washington State agencies regulate wetlands under the Hydraulic Code, State Water Pollution Control Act, Shoreline Management Act, and the Forest Practices Act. Local governments such as the County or City, regulate wetlands under the Growth Management Act and the Shoreline Management Act.

5 REFERENCES

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[1] Washington Department of Ecology. 2011. *Permit Handbook: Commonly Required Environmental Permits for Washington State*. Publication Number 90-29. 222 pp. http://www.ora.wa.gov/resources/handbook.asp

[2] National Marine Fisheries Service (NMFS). 1999. *The Habitat Approach: Implementation of Section 7 of the Endangered Species Act for Actions Affecting the Habitat of Pacific Anadromous Salmonids*. National Marine Fisheries Service, Northwest Region, Habitat Conservation and Protected Resources Division. 12 pp.

[3] U.S. Fish and Wildlife Service and National Marine Fisheries Service. 1998. *Endangered Species Consultation Handbook – Procedures for Consultation and Conference Activities*

Under Section 7 of the Endangered Species Act. Washington, D.C.

[4] U.S. Fish and Wildlife Service and National Marine Fisheries Service. 1996. *Habitat Conservation Planning Handbook*. Washington, D.C.

[5] FEMA. 2009. *NFIP Floodplain Management Guidebook – 5th Edition*. Produced by FEMA – Region 10, Bothell, WA.

APPENDIX I

CONSTRUCTION

Construction Appendi

1 INTRODUCTION

This appendix is intended to provide a broad overview of construction considerations. Because site-specific conditions and project-specific criteria significantly influence construction approaches, a comprehensive discussion of construction techniques is beyond the scope of this section. However, careful consideration of the topics listed here should assist stream restoration and rehabilitation practitioners to develop a comprehensive work plan for accomplishing project goals with respect to construction issues.

Construction issues can significantly influence both the feasibility and design of a stream rehabilitation project. The constructability of stream rehabilitation or restoration proposals is a primary design criterion during project scoping. *Constructability* refers to the technical and financial feasibility of an overall stream rehabilitation proposal and its constituent treatments or techniques. The selection of construction methods will therefore be determined by affordability, availability of equipment, access to work sites and regulatory constraints.

2 CONSTRUCTION PREPAREDNESS

During the construction phase, when the design is finally implemented, the success of a project is determined by several factors, including constructability, contractor experience, and construction oversight.

Construction preparedness factors determine the relative ease or difficulty of addressing common issues on a stream restoration project, such as: site access, construction timing, use of best management practices, protection of fish life, stream diversion, isolation of the work area, fish exclusion and site restoration.

2.1 Constructability

Several factors influence the constructability of a project, including: difficulty of the project, suitability of the site, land ownership, utility locations, and available access. One way to improve constructability is to seek input from construction experts during design that can help identify both potential difficulties and more efficient ways to complete the project.

Constructability should be considered well before work begins. However, additional constructability issues, although hopefully not major ones, often arise after construction begins, forcing the project team to respond rapidly to efficiently manage the schedule and the budget impacts of the problem. Table 1 provides a summary of constructability considerations.

Table 1. Summary of constructability considerations

Constructability Considerations
Evaluate all access options (various routes, equipment types, etc.)
Develop a construction sequencing plan
Obtain necessary written agreements early
Work from stream banks, platforms or gravel bars when possible
Consider how and where equipment will be used
Design access road to suit the use and setting
Employ specialized equipment to minimize impacts when practical
Avoid sensitive soils and vegetation when possible
Working in deep and/or turbid water tends to reduce quality control of the construction
Use existing access points
Construct temporary access points with minimal impacts
Identify stockpile locations
Identify constraints due to utilities
Consider seasonal weather and ground conditions

2.1.1 Site Access

Site access is often one of the most involved issues during construction. Crews need access to the work site, staging areas, stockpile areas, as well as to refueling, maintenance and parking areas. Site limitations such as terrain, location of utilities, land ownership, existing infrastructure, sensitive landscapes, and critical habitats are constructability issues that may influence how access is provided. For this reason, site limitations should be considered during all phases of design and construction, and addressed by preparing a construction sequencing plan, an outline of the major tasks and their sequential order of construction. Developing a conceptual construction sequencing plan early in the design process will help identify and resolve many aspects of constructability that are dictated by site limitations. In developing the plan, the designer should consider the benefits and drawbacks to all possible access options to determine the most cost effective, practical and least impacting option. The preferred access alternative may involve using adjoining properties, when impacts can be reduced, the length of travel can be shortened or cost savings can be had.

Some landowners may be willing to allow construction access on a temporary basis, and others may decline. To minimize misunderstandings, written landowner access agreements need to be established during the planning phase of the project, prior to final design and permitting, and well before construction begins. It can be helpful when making such a request to provide the landowner with a drawing or sketch on an aerial photo to show specifically what is needed. It is also wise to spell out in an access agreement what will be done to restore the land owners' property, such as removing temporary rock, regrading, revegetation, etc.

Construction of most stream restoration projects will require some degree of heavy-equipment mobility along and near the bank (Figures 1 and 2). Construction can be conducted from the bank, from a temporary platform, or from the channel. Highest consideration should be given to working outside the channel, from the banks. When it is not feasible to complete the work from the banks, construction of a temporary platform should then be considered. A typical temporary platform is constructed of large rocks as the base with smaller rock on the working surface, or an array of temporary pilings. An alternative is to operate equipment positioned on a barge within the channel. Unique site characteristics usually determine where construction is conducted.

Figure 1. Heavy equipment access for log cribwall construction on Beaver Creek. Source: Inter-Fluve, Inc.

Figure 2. Spider Excavator placing rocks and logs in Whatcom Creek. Source: Inter-Fluve, Inc.

While some stream projects can be constructed solely with hand labor, most will require heavy equipment. Consider the types of equipment necessary to build the project, where the equipment will operate, refueling locations, parking and stockpile site locations. Temporary access roads may need to be constructed to transport materials and equipment to the site.

2.1.2 Access Roads

Access roads must be designed and built according to the needs of the equipment, taking into account road grade, equipment size and weight distribution, and also vegetation, habitat impacts and stormwater runoff. In particular, the need for equipment to maintain traction will drive important design decisions if ground conditions at the site are slippery, steep or soft. Street-legal dump trucks in particular are limited in their ability to travel on unpaved roads. Many types of equipment are able to travel on softer roads, causing less damage to soils because their weight is better distributed. Excavators, tracked dump trucks and other vehicles can be outfitted with extra wide tracks to reduce weight impacts and soil compaction. Specialized equipment, such as spider excavators and helicopters should be considered to improve efficiency of building the project. Horses can also be used for transporting materials and as a substitute for heavy equipment in many remote or access-limited areas.

In relatively non-sensitive areas (e.g., meadows, pastures, woody riparian areas), access roads can be constructed by placing road gravel on geotextile materials laid directly on the ground surface. Some of the plastic products on the market (PVC, PVE, etc.) can be used to reinforce low-load-bearing soils. This approach is appropriate when access roads will be used frequently for hauling materials or equipment or for refueling operations. Access can also be achieved using temporary mats (e.g., linked tires, cabled ties, landing mats) to “walk” equipment across sensitive areas on a limited interval basis. This assumes little or no materials will be transported in or out of the site for the duration of the project, and whatever equipment is needed can be housed and maintained at the site.

Access through a riparian area should be carefully marked to minimize impacts and to aid in the subsequent restoration efforts. Use existing access points when available and construct new access points in a manner that minimizes riparian impacts. When habitat impacts from construction activity exist, mitigation may be required to compensate for lost functions.

2.1.3 Construction Platform

Construction of most bank-protection projects will require some degree of heavy-equipment mobility along and near the bank (Figure 3). Construction of bank protection can be conducted from the channel, from the bank or from a temporary platform. Site limitations may determine where construction is conducted.

Near-bank construction platform. Traditionally, most operations are conducted in the bank and in near-bank areas. This requires either a sizeable bank-reconstruction area (which may facilitate conducting construction activities entirely within the bank-treatment footprint), or it results in considerable impact to near-bank environments. In the latter case, remediation of near-bank environments is required.

Figure 3. Construction platform for major streambank restoration, Little Miami River, Ohio**.** Source: Inter-Fluve, Inc.

Between-bank construction platform. When site restrictions require that construction must occur within the channel banks, a number of options exist. Of particular note, the channel can be partially or completely dewatered. Dewatering a channel will require protocols for cleaning equipment, refueling equipment and handling fluid spills. Advantages of this type of operating platform include minimizing impacts to near bank areas during construction and enabling detailed manipulation of the channel bed and bank toe for habitat enhancement without the interference of flowing water during construction.

Temporary construction platform. An alternative to dewatering for between-bank construction is a temporary fill platform within the channel, constructed from large rock (with a small rock work surface). Temporary platforms can also be constructed within the channel on temporary pilings. A third alternative is to operate equipment positioned on a barge within the channel. This is particularly appropriate for dredging and excavation activities.

2.1.4 Utilities

Existing utilities are commonly found within a project site or along access routes to the site. Careful review of the site will reveal most utilities present, including power lines, railroad tracks, pipelines, buried cables, sewers and other common utilities. All utilities owners must be contacted to evaluate hidden utilities and to identify or establish protocols for working near or within utilities' rights-of-way. Urban project locations with many site limitations may require the temporary or permanent relocation of utilities to accomplish project objectives.

Impacts due to adverse weather conditions need to be factored into the access plan. For example, it may be necessary to construct a longer access route to avoid seasonally wet areas. Scheduling construction for times when the ground is either dry or frozen can also reduce impacts associated with access roads. Snow-covered, frozen soils can often be traveled with wide-track equipment with reduced impact to underlying vegetation or soils. Special care should be taken to avoid construction during potential snowmelt conditions. Similarly, dry conditions reduce many impacts associated with soil compaction and soft soils.

2.1.5 Stockpile and Disposal

Any significant movement of materials on-site, off-site or within the site will require a stockpile area for temporary storage of construction or waste materials. Stockpiling of construction materials (e.g., gravel, rock, soil, fabric, wood materials) and disposal of waste materials (e.g., excavated bank materials, vegetation, trash) should be considered during the construction sequencing. Careful consideration of stockpile size and location will facilitate construction, reduce cost and limit damage to sensitive areas. The location of stockpiles can significantly increase or decrease cost relative to cycle time for construction operations. Figure 4 shows an example of logs stockpiled near the construction site.

Figure 4. Stockpiling logs and soils on Beaver Creek. Source: Inter-Fluve, Inc.

2.1.6 Construction Window

The timing of construction will often be determined by regulatory mandates intended to reduce water-quality impacts to critical components of fish life cycles such as migration and spawning. The timing for construction projects that affect state waters varies throughout the state, depending upon the species present in the watercourse. Contact the Washington Department of Fish and Wildlife Area Habitat Biologist for information on allowable construction work windows. Habitat biologist for your geographical coverage area may be found for the project area at the following website: http://wdfw.wa.gov/conservation/habitat/ahb/. Once the allowable construction window has been identified for your project, additional factors such as hydrologic, precipitation and revegetation considerations will assist in determining the most appropriate time to operate within the established work window.

2.1.7 Hydrology and Precipitation

Hydrologic analyses that can be helpful in determining an appropriate time for construction include analyses of seasonal variations in average and peak flows. From the standpoint of feasibility and cost-effectiveness, construction should occur when average seasonal flows are low and the likelihood of high-flow events is at its lowest. This will vary geographically, depending upon the dominant hydrologic character of a watershed. Further information on methods for determining hydrologic character and approaches to hydrologic analyses are available in *Hydrology* Appendix.

2.2 Contractor Experience

Construction projects in and around streams require unique experience, which not all general contractors possess. The level of relevant experience the construction team has affects the amount of oversight the project manager must provide to interpret the design, and it can greatly influence the project, schedule and budget. Project proponents should take great care to select a highly qualified contractor with relevant work experience related to the project at hand. Typically, public works projects must select the lowest responsive, responsible bidder and that selection of the contractor on the basis of qualifications is restricted to minimum qualifications. Overall, the greater the potential for having to use an inexperienced contractor, the greater detail is needed in contract drawings and specifications.

2.3 Construction Oversight

Having an experienced inspector provides a great advantage to a project proponent. A good inspector becomes very familiar with the site and studies the design to anticipate constructability issues. A good inspector communicates effectively with the contractor to convey the project proponent's wishes. Perhaps most importantly, a good inspector ensures the project construction satisfies the project objectives and protects the financial interest of the project proponent. Project objectives should be defined in the contract and construction documents so that the contractor and inspector understand why the project is being built the way it is. Unfortunately, stream projects are often subtle and complex and it should be assumed that without specialized training, inspectors will not understand the project objectives and may not be qualified to ensure that criteria are met. It is essential to have a well qualified (properly trained) inspector on-site to ensure the project objectives are met and key criteria are satisfied.

It is recommended that the project proponent, design engineer, construction inspector, and construction foreman meet before construction begins. Key topics to discuss may include:

- **Project scope and intent**: The project proponent, the design engineer, and the construction inspector should meet with the construction team to discuss the intent of the project and key elements of the project.
- **Project schedule:** Planning is the major responsibility of the foreman to ensure that work occurs in an orderly manner, and necessary materials, equipment and personnel are available when needed.
- **Permits:** Conditions in the permit application materials and permits describe what can and cannot be done to build a project. Typically, permits are obtained by the project proponent or design team before the construction team has been assembled, so the

construction team must be informed about permit provisions and how they may impact the work.

- **Materials:** The importance of utilizing the correct materials should be discussed with the construction team before materials are purchased or delivered to the site. For example, the proper size and distribution of streambed sediments is critical for a successful project. Even when the plans carefully specify these materials, without proper understanding of the intricacies of those specifications by the purchaser or supplier, the wrong materials may be purchased and delivered to the site. The inspector is responsible for reviewing material specifications and ensuring that the materials used adequately match the specifications.

3 CONTRACT DOCUMENTS

Most traditional bid-build contracts include not only a basic agreement, but also other attachments, such as the design drawings and project specifications. In other words, the drawings and specifications are part of the agreement made between the owner and the builder, so they must be complete and accurate to ensure the intended outcome and to avoid costly disagreements.

3.1 Construction Drawings

The primary form of communication between the designer and the builder are the construction drawings. Misunderstandings often arise when construction drawings lack detail or contain inaccurate information, and misunderstandings almost always result in delays and cost overruns.

A drawing set should include both existing and proposed features of a site so the builder knows what is to be built and in what setting. Complete plans help the builder plan the work efficiently to minimize construction time and cost. Components of a complete set of construction drawings include site plans, design details, profile (elevations) drawings, cross sections and notes.

A good site plan shows all of the existing topographic features, roads, parking areas, buildings, other structures, and of course water bodies. It should also include all of the proposed features, including temporary items such as access roads and staging areas. Ideally, the entire project site can be shown on one page and then portions of the site can be shown at a reduced scale on subsequent pages. Profile and section drawings show the channel slope and shape, materials to be used, bank slopes, depth of bed materials, and excavation and fill lines. Longitudinal sections or profile views are a useful method of showing the gradient of the channel and features such as pools, riffles, weirs, and other types of grade controls. Cross section drawings are useful for showing the shape of the channel, bank slopes, the depth of excavation, the depth of fill materials, as well as the elevations for proposed weirs, bank protection elements and large wood features.

Detail drawings flesh out the specifics of how and where certain features are to be constructed. Details should show the types of materials to be used and should explain in a stepwise manner how each individual feature will be built. Some contracts lack separate written specifications. In those cases, the plans need to include very specific notes and call outs to explain how things are to be done.

Channel profiles need to show both the existing and proposed ground elevations to demonstrate how the proposed features fit the site. Undersized culverts often accumulate sediment upstream of the pipe and develop a scoured channel downstream of the pipe. The profile needs to extend far enough upstream and downstream to clearly identify the impacts of the existing crossing and all work proposed in the project reach.

3.2 Principle Drawing Elements

What follows is a comprehensive list of the principle elements that should be included in restoration project design drawings. Not all of these elements are necessary for every project. A culvert removal on a low-volume forest road may not need to show as many of these details. But a bridge in an urban environment will need all the following elements, and possibly more, to satisfy all of the expected construction requirements. These elements are part of a complete design, but they are not necessarily part of construction drawings and some may occur in specifications rather than drawings when the contract is written. What the contractor needs to know and what the designer and permit writer need to know are often different. An example of a site plan is shown in Figure 5.

1. **Site plans** and elevation view drawings provide an overview of where features are located and the geographic orientation of those features, including:
    a. Property lines and easements
    b. Project limits
    c. Clearing limits and areas not to be disturbed
    d. Significant vegetation
    e. Existing and proposed elevations (contour lines)
    f. Existing and proposed roads, parking areas, buildings, etc.
    g. Existing utilities
    h. Road drainage details, such as cross drains, sedimentation ponds and outfalls into the channel
    i. Existing and proposed stream channel alignment (thalweg and channel width)
    j. Existing and proposed stream channel features, such as large wood and bank protection
    k. Important geomorphic features such as slope failures, bedrock outcrops, log jams, and floodplain elements
    l. Alignment of stream, culvert and road
    m. Features of new channel alignments, such as pools, riffles, steps, woody debris placement, etc.
    n. Floodplain restoration elements, grading, vegetation, and invasive species control areas
2. **Channel profiles** of the stream thalweg showing the reach-level behavior of the stream. For clarity, existing and proposed changes should be shown on the same drawing.
    a. A minimum of 20 channel widths upstream and 20 channel widths downstream of crossings, or 150 ft, whichever is larger. Longer profiles may necessary if the existing channel is heavily disturbed.
    b. Thalweg, water surface (at the time of survey) and top of bank on profile.
    c. Relevant channel features such as riffles, steps, pools, rocky outcrops, nearby culverts, etc. Water surface profile should be taken at one flow.

d. Proposed changes in channel elevation. Proposed regrading of the channel anticipated including: regrade upstream, grade control structures or other profile adjustments. Attach elevations to all of these features.
e. Features of new channel alignments, such as pools, riffles, steps, woody debris placement, etc.
f. Proposed crossings (if applicable), including key features
g. Elevation and spacing of channel features adjacent to any crossings
h. Bank protection

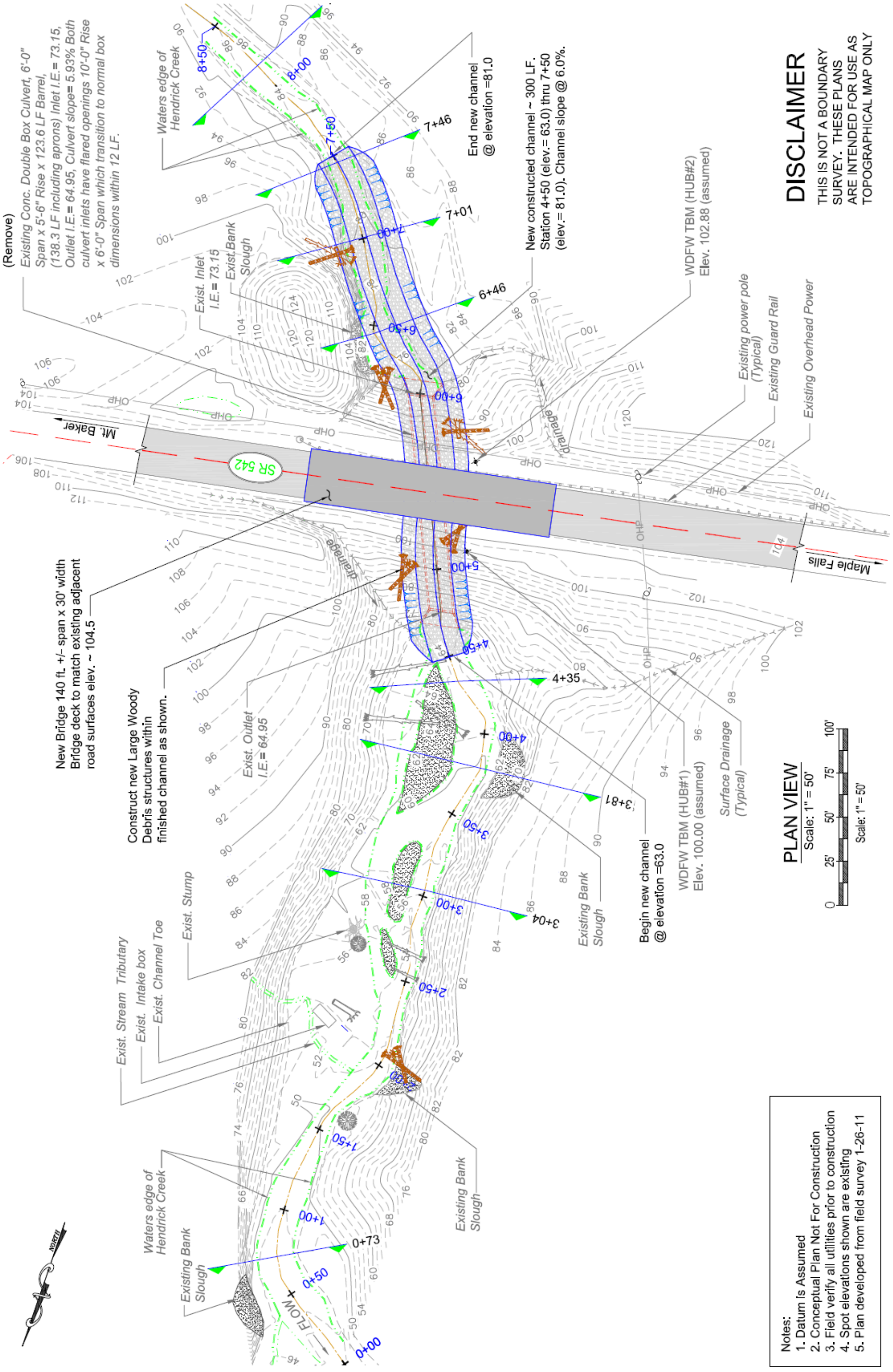
3. **Cross sections** showing location of the stream channel in the floodplain. Indicate channel width and bed composition.

   a. Channel width
   b. Existing and proposed side slopes
   c. Location and composition of bed materials
   d. Location of habitat and channel morphology features
   e. Bank protection
   f. Crossings (culverts and bridges, if any) to show the relationship between the crossing structure, the constructed channel beneath and the adjacent natural channel

4. **Design details** should include specific information explaining how the proposed work is will look when completed, how existing and proposed features tie together, what materials are to be used, and in some cases the process to be used to complete the work.

   a. Construction materials (large wood, streambed gravels, vegetation, etc.)
   b. Large wood dimensions, orientation, burial depth and anchorage
   c. Boulder dimensions and burial depth
   d. Planting specifications
   e. Slope stabilization and restoration details
   f. Erosion and sedimentation control plans during construction
   g. Permanent erosion control measures
   h. Dewatering plans
   i. Fish exclusion plans

Figure 5: A site plan showing principle channel and infrastructure features (WDFW project files).



3.3 *Specifications*

Specifications are technical descriptions of materials to be used on a project, as well as the methods to be employed to complete the work. Specifications also often include timing restrictions, permit conditions, material requirements and various other construction details. Along with the design drawings, specifications supplement the written contract between the owner and the contractor. As far as the stream channel is concerned, relatively few specific specifications exist, although these are vitally important; the materials that make up the bed, banks, and habitat features must be carefully specified in order to ensure the success of the project.

4 EROSION AND SEDIMENT CONTROL

Erosion control includes all measures to check the migration of soil materials from a construction area into areas where moving water can carry them away. Sediment control includes all measures to reduce turbidity associated with construction activities. The success of erosion and sediment-control methods greatly depends upon weather patterns during the season of construction, dewatering methods applied and the character of the hydrograph at the project site. The period of construction will determine the method of erosion and sediment control required. Careful consideration should be given to inundation levels and flow durations derived from hydrologic statistics (see *Hydrology* Appendix).

Erosion control includes both the prevention of soil loss through soil cover and the trapping of soils eroded by surface flow. Erosion-control mechanisms must be effective during precipitation events and/or during inundation by stream flow. In areas that are above anticipated inundation levels, the potential for soil loss through erosion can be reduced by applying mulch (e.g., straw, wood chips and other organic materials), hydroseeding, or adding biodegradable, chemical or synthetic soil stabilizers. Areas that may become inundated by flowing water during high-flow events should be protected by geotextile fabric. The Washington State Department of Ecology has guidance on erosion-control techniques in the *Stormwater Management Manual for Western Washington*.[1]

Besides preventing soil loss, eroded soils must be trapped before reaching the stream. This is best accomplished using standard silt-barrier approaches, such as straw bales or a silt fence. The design and specification of silt barriers must include inspection and maintenance schedules, as well as a schedule for removal. Silt barriers require cleaning when they reach 50 percent of capacity.

Sediment control is intended to minimize the input of sediment associated with constructing bank treatments. However, it is unrealistic in most circumstances to expect complete control of sediment inputs, because the installation process for most sediment-control systems itself generates some turbidity. While there are a variety of sediment filters available that are advertised as having moving-water applications, these are impractical and ineffective for controlling sediment except on very small streams. Dewatering the site or isolating the construction area from moving water can largely control sediment input. In many cases construction of a stream project can be done in a dewatered area which can aide in collection and removal of sediment from construction practices. Dirty construction water collected from sumps needs to be handled appropriately by infiltrating in a well vegetated swale or treating it in an approved manner to remove contaminants prior to discharge to the stream.

5 STREAM BYPASS

A stream bypass (also referred to as dewatering) in a construction area may be essential to enable construction and to provide a required degree of sediment control for water-quality protection. Protection of fish life must include both isolation of fish from harmful conditions at the construction site and prevention of offsite impacts due to degraded water quality. Provisions must be made to ensure fish are not harmed due to the project while attempting to migrate upstream or downstream. Upstream fish passage through temporary stream bypasses is often not required for short duration projects conducted within approved annual in-stream work windows. Isolating fish from the work area can be accomplished by using either a total bypass to reroute the entire stream through a temporary channel or pipe, or partial bypass to exclude fish from a certain area, such as along one stream bank.

Flows can be diverted with pumps or passive systems such as side channels, canals or tubes. Flow diversion requires careful consideration of the backwater effects on diversions: pump capacities, diversion-channel capacities and outfall protection. Gravity bypass systems require less monitoring than gas or diesel pumps, which require someone on site or other special consideration if left running overnight. Diversion outfalls require temporary erosion-protection measures to prevent scour at the point of return flow from the diversion channel or pipe. Additionally, pumps require screens designed to Washington State & National Marine Fisheries Service specifications to prevent harm to fish (see *Draft Fish Protection Screens for Washington State*[2], WDFW 2000, http://wdfw.wa.gov/publications/pub.php?id=00050).

All types of stream bypasses must include a recovery plan to ensure safe capture and relocation of fish trapped in the work zone when the stream flow has been diverted. Fish can be recovered manually from remnant pools and transferred by bucket to downstream reaches.

The design and implementation of dewatering systems is often underemphasized. Hydrologic analyses should be conducted to determine the appropriate design criteria for a stream bypass. At a minimum, dewatering systems must be able to divert two-year peak flow during the period of construction. A two-year peak flow is the flow that has a 50-percent chance of occurring each year during the construction period. This magnitude of return flow will need some qualification based on the period of construction. For instance, during the summer period, the two-year flow may be appropriate; but, during the winter, preparation for a greater-magnitude flow event will be necessary.

The probability of a dewatering system being overwhelmed by storm flows can be determined using standard hydrologic analyses. In scenarios where it is impractical or impossible to design a dewatering system that can handle storm flows, it is important to determine the extent to which the dewatering systems will be inundated during such flow events and for how long. Before proceeding with construction of a stream project, the potential consequences of inundation due to high seasonal flows should be estimated and the risk of such occurrences calculated.

When available, the analyses should be based on data sets derived from peak flows covering the construction window for the period of record. The risk of inundation, based on a probability of occurrence for a particular flow level, can then be used to gauge the relative costs associated with inundation. The cost of inundation may include lost work, lost time, damage to equipment and sediment influx in the stream.

5.1 Complete Bypasses

An alternative to diverting a channel is to use a cofferdam, which isolates the project site from the water in the channel (see Figure 6). A cofferdam is an impermeable structure installed parallel to a streambank that allows water on the landward side of the structure to be pumped out, leaving the area contained by the structure free of water. Cofferdams can be created using jersey barriers, hay bales and impermeable curtains or water-filled tubes. The use of a cofferdam may confine the channel, raising water-surface elevations. Application of cofferdams will, therefore, require careful modeling of the impact on water-surface elevations during all anticipated flows.

Figure 6. Dewatering an urban stormwater channel in preparation for stream restoration. The Menomenee River is diverted through a pipe, with coffers at each end defining the work area. Note track hoe on temporary in-channel pad. Source: Inter-Fluve, Inc.

Commercially available cofferdam systems can be applied on larger river systems. These systems can often withstand overtopping during large events. Design of coffer-dam dewatering systems should consider the infiltration rate of seepage flow from the riverbed and from banks and will require additional and constant pumping systems to address the infiltration flow. In-flow will likely be extremely turbid due to construction activities. Therefore, a sediment detention and settling basin will be required for water pumped from within the dewatered construction area.

Cofferdams vary in size from just a few sand bags to sheet piling. The materials used to construct them can be just about any clean and durable items. Some of the most common items used to build small cofferdams are sandbags, plastic sheeting, rocks, and concrete blocks. For projects in large rivers, rows of concrete blocks weighing several thousand pounds each and high capacity sand-filled bulk bags (25 cubic feet or more) may be used in place of ordinary sand bags. Commercially available cofferdam systems can be applied on larger river systems. These systems can often withstand overtopping during large events.

In lakes or tidally influenced areas, sheet piling may be necessary to construct a barrier capable of withstanding the forces exposed to it. Water filled inflatable dams, up to 12 feet or so in height, are a relatively new technology. Inflatable dams are tubes of geotextile and polypropylene, which come in rolls up to 100 feet in length. Longer dam lengths can easily be achieved by overlapping multiple tubes. Inflatable dams are most effective on relatively smooth substrate such as sand or small gravels. As a note of caution, unlike concrete blocks, rock, etc., these dams are neutrally buoyant and are thus easier to dislodge in deep swift water unless anchored properly.

Installing and removing cofferdams requires planning to ensure water quality is maintained, particularly in water bodies with a substantially fine-grained substrate. Sometimes the impact of installing a cofferdam exceeds the impacts of working without one, in which case a project may be built in the water, if allowed by the permitting agencies.

The use of a cofferdam may confine the channel, raising water-surface elevations. Application of cofferdams will, therefore, require careful modeling of the impact on water-surface elevations during all anticipated flows. With discretion and the approval of the Habitat Biologist, short term cofferdams on low flow streams may not need to be modeled.

Design of coffer-dam dewatering systems should consider the infiltration rate of seepage flow from the riverbed and from banks and will require additional and constant pumping systems to address the infiltration flow. In-flow will likely be extremely turbid due to construction activities. Water collected from sumps needs to be handled appropriately by infiltrating in a well vegetated area or treating it in an approved manner to remove contaminants prior to discharge to the stream.

Assembling the bypass needs to be done in a thoughtful manner to ensure fish are not harmed in the process. The process typically begins with placing block nets up and downstream of the project area and biologists capture and safely relocate fish trapped in the work zone. Then a plastic bypass pipe or plastic lined channel is installed. Next a small cofferdam is slowly built upstream of the work area, and the stream is diverted through the pipe. Then a cofferdam is built at the downstream end to isolate the work area completely. Biologist make a final pass through the work area to remove any remaining fish. Finally, when the work area is free of both flowing water and fish, construction may begin.

Upon completion of the construction activity in the channel, stream flow is gradually reintroduced to the work area, which will likely produce sediment upon initial rewatering. Prior to introducing stream flow, a system should be implemented to capture sediment and turbid water, and to handle it appropriately by infiltrating in a well vegetated area or treating it in an approved manner to remove contaminants prior to discharge to the stream.

5.2 Partial Isolation - Working in Wet

Working in the water without a bypass is sometimes feasible and practical when: installing a containment system would cause greater impacts than it would prevent, working in deep or swiftly flowing water, turbidity is not a concern, fish can be excluded by nets or screens, or fish are not present.

As discussed in the cofferdam section, installing and removing certain types of cofferdams in certain settings may generate significant impacts to water quality. For example, installing a sheet pile cofferdam in an estuary with predominantly fine sediment would be expected to generate significant turbidity. Employing a floating boom and/or silt curtain to partially isolate turbidity caused by the construction activity may be much more suitable.

Partial isolation minimizes the continued release of sediments that would occur with flowing water. For this reason, work can occur in standing (versus flowing) water behind a barrier. Sediment will be released, but in smaller quantities. When the barrier is removed, sediment will be released. However, it will be distributed as a single pulse rather than a continuous stream and will result in substantially less sediment input than would otherwise occur under flowing water conditions. Water quality impacts will need to be carefully considered before applying this approach; they may even prevent the use of this approach.

6 TEMPORARY CROSSINGS

Often equipment must cross a stream during construction. Temporary crossings will be covered in Chapter 5 of *Water Crossings Design Guidelines* (previous editions titled Design of Road Culverts for Fish Passage), WDFW 2012. This guideline is under development. Publication is planned for mid-2012 and will be located on the Aquatic Habitat Guidelines website at http://wdfw.wa.gov/conservation/habitat/planning/ahg/. The reader is encouraged to check this site periodically to obtain the latest publication.

7 FISH EXCLUSION

Excluding fish from a work area is the key to protecting fish life from harm related to stream construction projects. Stream projects in fish-bearing waters with any type of stream bypass must have an exclusion and recovery plan to ensure safe capture and relocation of fish trapped in the work zone when stream flow has been diverted. Fish exclusion is generally accomplished by installing screens or nets to isolate an area, and then fish trapped in the work zone can be captured and relocated. Capturing fish is usually accomplished with large seine nets, dip nets and sometimes using electro-fishing equipment.

Metal screen panels or mesh nets are typically used to form physical barriers to exclude fish. Care must be taken to install the barriers in a manner that prevents undue risk of harm to fish. Screen panels placed perpendicular to swift flowing water pose an impingement risk to fish. The ideal exclusion barrier is located in a low velocity area, so that fish may approach the net or screen and swim away from it at will. Debris must be removed from barriers regularly to prevent water from going over or around the barrier and allowing fish into the work zone.

8 CONSTRUCTION RESTORATION

Construction restoration includes re-establishing areas disturbed by a project to conditions equal to, or better than, those which existed prior to the project. A typical construction restoration plan involves eradicating invasive plant species, revegetating by planting native trees and shrubs, and stabilizing slopes against erosion by seeding with an acceptable grass species or applying mulch. Refer to the *Riparian Restoration and Management* technique for guidance on riparian planting.

Successful revegetation is largely determined by the timing of planting efforts. Ideally, revegetation components of riparian areas will be conducted to maximize the potential for survival of the plant materials installed and to enhance their ability to grow quickly. Further, the success of many bioengineered techniques will require that vegetative cover be maximized in the least amount of time possible following construction. This requires minimizing the period of dormancy of installed materials between installation and the following growing season and ensuring ideal moisture conditions, which are often specific to species and plant forms installed, following construction. Detrimental moisture conditions may include either drought or inundation.

Some plant materials must be installed during construction, while others may be installed months after construction to enhance survival and success. For instance, seed must be placed under geotextile fabrics during construction. Similarly, some techniques that incorporate cuttings or other dormant materials may be integral to the structure of the protection measure (Figure 7). However, many plant materials, such as cuttings, tubelings and rooted stock can be planted following construction, during ideal soil-moisture conditions to improve survival rates.

Figure 7. Installing rooted willow cuttings during fabric encased soil lift construction. Source: Inter-Fluve, Inc.

9 HEAVY EQUIPMENT

A wealth of heavy-equipment types is available for construction projects. The equipment used can play a big role in progress rates and efficiency and, consequently, cost. A rule of thumb is to use the largest, most appropriate equipment available, given site limitations, to maximize efficiency in moving and installing materials. However, this general rule must take into account site-specific limitations (e.g., turning radii and material size) and the need to perform detail work. Most standard types of equipment, including excavators, loaders, dozers and trucks are available in a range of sizes from miniature (Bobcat or smaller) to extremely large (e.g., mine-operations equipment).

Figure 8. A track hoe excavator manipulating a large root wad and bole. Source: Inter-Fluve, Inc.

Landscape sensitivity may also be a consideration for equipment selection. While large equipment weighs more, many models essential for bank-protection work, including excavators, dozers, loaders and even dump trucks can be equipped with tracks rather than wheels. Tracks are able to distribute a vehicle's weight more evenly across a larger area than wheels can. Consequently, for the same piece of equipment, the weight per square inch of track is less in comparison to rubber tires.

Some projects will require specialized equipment that most contractors do not own or have at their ready disposal. When specialized equipment is required, progress rates are often slowed, resulting in an increase in per-hour operational costs. Consequently, construction costs may be increased by both hourly rates and slowed progress. For example, a street-legal dump truck can typically haul eight to 12 cubic yards of material. In ideal conditions, which include dry, flat ground, a tracked truck has a capacity of six cubic yards of dry fill. However, in most conditions where a tracked truck is necessary, a typical load is less than four cubic yards of relatively dry material and considerably less if the material is wet.

Specialized equipment for bank-protection applications includes:

Spider Excavator: A spider excavator is an articulated-arm excavator that operates on four independent legs rather than two tracks. It can *crawl* and perch on relatively steep slopes, and it can "walk" across channels with minimal impact. It can often access areas that traditional, tracked equipment cannot (see Figure 2).

Bobcats: Bobcat is a brand of small earth-moving equipment that can run on four rubber tires or on tracks and has the ability to use a number of different tools for a variety of applications. Bobcats can be outfitted with loaders, dozer blades, hoes, drills and numerous other tools. They are ideal for moving and installing materials within small areas.

Helicopters: Helicopters can be used to import materials to remote areas (Figure 9). They can be practical and cost-effective for any imported earth materials, including wood, large boulders, fabric or artificial materials.

Figure 9: A Chinook helicopter is used to transport and locate large woody debris in a sensitive stream site not easily reached by conventional heavy equipment. Source: Inter-Fluve, Inc

10 REFERENCES

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MONITORING APPENDIX

****This appendix is the 2004 edition and has not been updated. The Aquatic Habitat Guideline Program will be working to update it in the future****

This appendix is intended to provide general guidelines for developing monitoring plans for streambank protection and stream restoration projects. Monitoring is defined as the collection and assessment of repeated observations or measurements over time to evaluate the effectiveness of restoration or management actions. It is never too early to consider a monitoring plan for a restoration or management action. Deciding if monitoring is important, what to monitor and why will help clarify the uncertainty associated with the activity, allow you to measure success, and will help build a better understanding of cause and effects.

1 REASONS TO MONITOR

Monitoring allows stakeholders to measure the effectiveness of projects through time and under a range of changing environmental conditions such as flooding or drought, channel shifts and erosion, beaver activity, or the effects of animal grazing. In addition, monitoring helps identify maintenance and project repair needs, and can provide information on ways to improve and refine management/restoration techniques. Monitoring can also be used to evaluate watershed restoration strategy—not limited to a single project, to learn from mistakes and adapt future restoration projects to the lessons learned.

Monitoring is designed and conducted to provide data useful to understand why techniques and practices work, and, equally important, why some fail. Thus modifications to a restoration project, and future projects in the same watershed, are informed by data analysis, rather than trial and error. Monitoring is an essential component of project design and evaluation, and is required not only to determine success of the restoration project, but critical to restoration program accountability and improvement. Monitoring is also a critical component of adaptive management. Because of uncertainties about the physical and ecological behavior of complex river systems, restoration needs to remain flexible enough to allow project modification in response to system responses identified through monitoring.[1]

This appendix will introduce the key components of monitoring streambank protection and stream restoration projects. Additional information on monitoring streambank protection and stream restoration projects (hereafter referred to as projects) can be found in the *Techniques* chapters of the Integrated Streambank Protection Guidelines (ISPG)[2] and Stream Habitat Restoration Guidelines (SHRG).

2 TYPES OF MONITORING

The following types of monitoring are not mutually exclusive and often the distinction between them is determined more by the purpose of monitoring than by the type and intensity of measurements.[3]

1. Baseline monitoring: characterizes existing conditions. The intent of baseline monitoring is to capture temporal variability of resource indicators before the

project begins. Baseline monitoring establishes the benchmark against which success of the project can be measured.

2. Implementation monitoring: assesses whether project activities were carried out as planned. This is also sometime called compliance monitoring. For example, was large wood (of the appropriate size) placed in the stream according to the restoration plan?

3. Effectiveness monitoring: Effectiveness monitoring is used to evaluate whether the project had the desired effect on resource indicators (e.g., habitat conditions or stream processes). For example, a post project survey documents changes in pool depth or volume after placement of in-channel large woody debris when compared to baseline.

4. Validation monitoring: is used to establish a cause-and-effect relationship between the project and the biological indicator (e.g., fish or macro invertebrates) the project was intended to benefit.[4] For example did large woody debris placed in the stream result in fish density changes in the stream reach.

3 MONITORING PLAN

Monitoring begins during project planning as existing conditions are assessed and project alternatives developed. Monitoring plans should be written during the planning phase when the goals and performance criteria are developed for the project. During the planning phase, project objectives, restoration measures, criteria for achieving and measuring success, contingency measures, and evaluation techniques should be fully explored. Clearly defining project objectives is central to post-project evaluation.

All monitoring should be based on a plan which includes 1) background on the projects (i.e., what is known about effects on this type of project etc., 2) the questions to be answered via monitoring, 3) methods for collecting and analyzing data, and 4) expected results, and 5) budgets. The reason for monitoring should be clearly stated prior to the collection of data. Monitoring can be a powerful tool to evaluate project success and impacts, watershed restoration strategy success, to compare the effectiveness of various techniques, and to determine the need for maintenance activities and repairs. However, monitoring without a definable goal is a waste of time.

4 MONITORING PLAN DEVELOPMENT

The following list can serve as a checklist of topics and details that should be included in any monitoring plan. See chapter 6b of Stream Corridor Restoration by the Federal Interagency Stream Restoration Working Group[5] (http://www.usda.gov/stream_restoration/newgra.html) for details on how to develop a monitoring plan based on a similar outline.

Planning

Step 1: Define the question the monitoring is supposed to answer.

Determine what decisions will be based on the results of monitoring and how results will guide decision-making.

Step 2: Develop a strategy to answer those questions

- Avoid mission creep
- Develop a broad strategy based on:
- Before/after study design
- Treatment/control study design

Step 3: Choose performance criteria. Monitoring plan design should utilize knowledge of the system being studied.

- Link performance to goals
- Develop criteria
- Identify reference sites

Step 4: Choose monitoring variables and methods

- Use statistical expertise in design so that method chosen can detect a meaningful change
- Resource indicators selected should be sensitive to change
- Establish methods for sampling design, sampling protocol, and sample handling/processing
- Determine the level of effort and duration of monitoring consistent with questions and everything else

Step 5: Estimate cost

- Cost for developing the monitoring plan itself
- **Quality assurance**
- Data management
- Field sampling program
- ***Laboratory sample analysis***
- **Data analysis and interpretation**
- Report preparation
- Presentation of results
- Get budget commitments

B. Implementing and Managing

- Clearly define roles and responsibilities
- The designer of the monitoring plan should participate in all phases of project
- Enact quality assurance procedures
- Analyze the data and interpret the results as soon as possible
- Manage the data
- Provide for contracts

C. Responding to the Monitoring Results

- Maintenance
- Adding, abandoning, or decommissioning plan elements
- Modification of project goals
- Adaptive management
- Documentation and reporting
- Dissemination of results
- The technical analysis in a monitoring report should discuss options to address project deficiencies and result in regular monitoring reports.[6]

5 BASELINE DATA

We focus on baseline data below because it is an integral part of monitoring that is often left out of monitoring plans. Prior to commencing maintenance or restoration actions, baseline data should be collected. This data can be used to document starting conditions against which success can be measured. It is important to consider the timing of monitoring. Baseline-data collection and subsequent monitoring should be conducted at the same time of the year relative to fish life cycles, plant phrenology, bird migration and hydrologic conditions, [6] unless restoration objectives dictate otherwise. Baseline data collection may include, but should not be limited to:

- Establish permanent benchmarks (located away from areas of potential bank erosion);
- An as-built survey to document the project's configuration relative to permanent benchmarks;
- A summary of site hydrology (including location of the nearest gauging station if one exists and is relevant) and values for critical flows that will be used to initiate monitoring events;
- Document aerial photography, summary of erosion history and any other geomorphic data pertinent to project design;
- Document pre-project site and reach data pertaining to fish and wildlife use, the riparian corridor, floodplain function and overall habitat condition; and
- Document any other conditions related to project objectives.

Additionally, baseline data should be collected using the methods established in the monitoring protocol. It is crucial that qualitative and quantitative baseline-data collection be thorough and appropriate to provide a sound foundation for subsequent data collection and monitoring[6]. Keep in mind that all monitoring plans need to be tailored to the project and questions being posed.

6 GEOGRAPHIC ESTENT OF MONITORING

It is important to identify the geographic extent of monitoring if a project includes risks or benefits to the upstream or downstream channel or habitat processes. The longitudinal extent of impacts is related to the scope of the project, the geomorphic setting and the specific technique applied. As a general rule, a study reach that is 20 to 50 channel widths in length should be sufficient for monitoring impacts to channel form[7]. It is important to remember, however, that the longitudinal extent of monitoring is site-specific and should be based on specific project objectives.

7 MONITORING DURATION AND FREQUENCY

Both the duration and frequency of monitoring are important components of a monitoring plan. A monitoring duration of three years should be considered a minimum for most bank protection and stream restoration projects. A three-year monitoring period allows a project to be exposed to a range of flows and gives vegetation time to pass form the critical establishment period to a more mature phase. However, changes in channel form may require a high flow or a series of high flows that have a low probability of occurrence during a three-year period. In other words, the geomorphic success of a project may not be properly evaluated until such flows occur. In addition, riparian vegetation may take many years of growth before its success in bank stabilization or providing stream shade and temperature reductions can be evaluated with any confidence. Any upstream and downstream project effects will likely require a series of high flows before they become apparent. It may be appropriate to extend monitoring activities following certain flow events, for example within one month of any 10-year or greater flow. The primary determinants of a monitoring period should be project scope and risk. Projects with numerous structural components that are subjected to considerable scrutiny or exposed to substantive risk should probably be monitored for five years. Monitoring these projects for a shorter period of time may fail to detect important indicators of project performance.

Monitoring frequency refers to how often monitoring activities will occur during any monitoring year and what time of year they should occur. In many cases, a single, annual monitoring effort is sufficient. The monitoring frequency many need to be based on the occurrence of specific flood events, especially when project risk is a factor, such as when a project is protecting a valuable resource, or project failure could endanger a valuable resource. Alternatively, the monitoring frequency may be systematic during certain times of year. For example, it may be appropriate to conduct all habitat monitoring on one frequency interval that is tied to spawning schedules; while whole bank protection and in-stream structures are monitored on another frequency that is tied to hydrologic sequences. An economical solution to limited monitoring budgets is to adjust the schedule of the monitoring plan so that more intensive, quantitative data is collected during the critical first three years. After this initial period, the scope of monitoring can be reduced. For example, vegetative success may be sampled intensively for statistical analysis during the first three years. But after that, a qualitative descriptor of revegetation patterns may be sufficient to evaluate project success. After a few years, the objectives, scope, and monitoring duration may change to reflect maintenance needs, rather than to achieve success criteria.

8 EXAMPLES OF RESTORATION OBJECTIVES

Table 1 provides some examples of restoration objectives linked to monitoring variables (adapted from Kondolf and Micheli 1995).

General Objectives	Monitoring Variables
Improve channel dimensions, pattern, profile and stability	Channel cross sections
	Flood stage surveys
	Width-to-depth ratio
	Rates of bank or bed erosion
	Longitudinal profile
	Aerial photography interpretation
8.1.1.1 <u>Protect Streambank</u>	Channel cross sections
	Streambank profile
	Bank pins to measure rate of bank erosion
8.1.1.2 <u>Improve aquatic habitat</u>	Water depths
	Water velocities
	Percent overhang, cover, shading
	Pool/riffle composition
	Stream temperature
	Bed material composition

	Population assessments for fish, invertebrates, macrophytes
	Fish passage barrier assessment
	Large woody debris survey
8.1.1.3 Improve riparian habitat	Percent vegetative cover
	Plant species density
	Plant size distribution
	Plant age class distribution
	Plantings survival
	Plant reproductive vigor
	Bird and wildlife use
	Aerial photography
Improve water quality	Temperature
	Ph
	Dissolved oxygen
	Conductivity
	Nitrogen
	Phosphorous
	Herbicides/pesticides
	Turbidity/opacity
	Suspended/floating matter
	Trash loading
	Odor
Recreation and community involvement	Visual resource improvement based on landscape control point surveys
	Recreational use surveys
	Community participation in management

9 TABLE REFERENCES

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- This document provides methods for measuring riparian vegetation % cover, species density, size/age distribution and reproductive vigor. Johnson, D. H., N. Pittman, E.

Wilder, J. A. Silver, R. W. Plotnikoff, B. C. Mason, K. K. Jones, P. Roger, T. A. O'Neil, and C. Barrett. 2001. Inventory and Monitoring of Salmon Habitat in the Pacific Northwest - Directory and Synthesis of Protocols for Management/Research and Volunteers in Washington, Oregon, Idaho, Montana, and British Columbia. Washington Department of Fish and Wildlife. Olympia, Washington. 212 pp.

- This document reflects an effort to establish a consistent format for the collection of salmonid habitat data across the Pacific Northwest. Its objectives are to: 1) provide a synthesis of the salmon habitat protocols applicable to the Pacific Northwest, 2) recommend a subset of these protocols for use by volunteers and management/research personnel across the region, 3) link these protocols with specified types of habitat projects, 4) establish a Quality Assurance/Quality Control framework for the data derived from the use of these protocols, and 5) to the degree possible, identify the format and destination where the data is routinely sent.

10 ADDITIONAL READING

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