WASHINGTON STATE AQUATIC HABITAT GUIDELINES PROGRAM

Stream Habitat Restoration Guidelines

2004

STREAM HABITAT RESTORATION GUIDELINES

FINAL DRAFT

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THE AQUATIC HABITAT GUIDELINES PROGRAM

The Stream Habitat Restoration Guidelines is one of a series of guidance documents being developed by the Aquatic Habitat Guidelines (AHG) Program. AHG is a joint effort among state and federal resource management agencies in Washington, including the Washington Departments of Fish and Wildlife, Ecology, Transportation, and Natural Resources; the U.S. Army Corps of Engineers; the U.S. Fish and Wildlife Service; and the Interagency Committee for Outdoor Recreation.

The AHG program was initiated in 1999 in support of salmon recovery efforts to ensure aquatic and floodplain restoration planning and design efforts were strategic, effective and the best use of limited resources. The scope of the program has since broadened to:

***The promotion, protection, and restoration of fully functioning marine, freshwater, and riparian ecosystems through comprehensive and effective management of activities affecting Washington's aquatic and riparian ecosystems*.**

Guidelines developed in the AHG program employ an integrated approach to marine, freshwater, and riparian habitat protection and restoration. That is, they seek to protect and restore the structure and function of whole ecosystems by striving to consider projects in their landscape and watershed contexts. Development of guidance documents and underlying scientific surveys has involved broad participation from academic, public, and private sector practitioners, planners, and regulators.

The following other AHG products are available for download at http://wdfw.wa.gov/hab/ahg/.

Guidance Documents:

- Integrated Streambank Protection Guidelines (2003)
- Design of Road Culverts for Fish Passage (2003)
- Fishway Guidelines for Washington State (draft)
- Fish Protection Screen Guidelines for Washington State (draft)

State-of-the-Knowledge White Papers (literature reviews):

- In- and Over-water Structures in Marine and Freshwater Environments
- Treated Wood Issues in Marine and Freshwater Environments
- Marine and Estuarine Shoreline Modification Issues
- Channel Design
- Ecological Issues in Floodplain and Riparian Corridors
- Dredging and Gravel Removal in Marine and Freshwater Environments
- Water Crossings (in progress)

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STREAM HABITAT RESTORATION GUIDELINES
CHAPTER 1

INTRODUCTION

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 Stream Habitat Restoration Guidelines within the 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, and Transportation, the United States Fish and Wildlife Service, and the United States Army Corps of Engineers. 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], and Fish Protection Screen Guidelines for Washington State[5]. All of these may be viewed as .pdf files 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, draft guidance documents, and news of upcoming training and other events.

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.

1.3 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[6], published in 1998.

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.

1.4 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 deed amendments or contracts 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.

1.5 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) limiting factors analysis, 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*.

1.6 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.

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STREAM HABITAT RESTORATION GUIDELINES
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, in the cases where stream processes were not understood, is a legacy of expensive failure. 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. There is growing recognition that true 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 considered at 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 the contributing 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 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 of soil depends 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 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** while promoting the development of deep soils. The vegetative canopy intercepts **precipitation**, allowing a portion to evaporate before reaching the ground, but subsequently inhibiting evaporation from the ground surface. Water use by vegetation (i.e., **evapotranspiration**) removes water from the soil. 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.

Water use by vegetation reduces total runoff from the associated land areas. However, the combined influences of vegetation and soil also greatly attenuates the movement of water through the watershed, dampening **peak flows**, sustaining streamflow during dry periods, and maintaining high water quality.

Water

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, arid watersheds, in addition to sparse vegetation, 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 winter rainfall, rain-on-snow events, or intense summer rainstorms, 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 summer. These produce a snowmelt runoff pattern that gradually increases until late spring or early summer and then gradually declines.

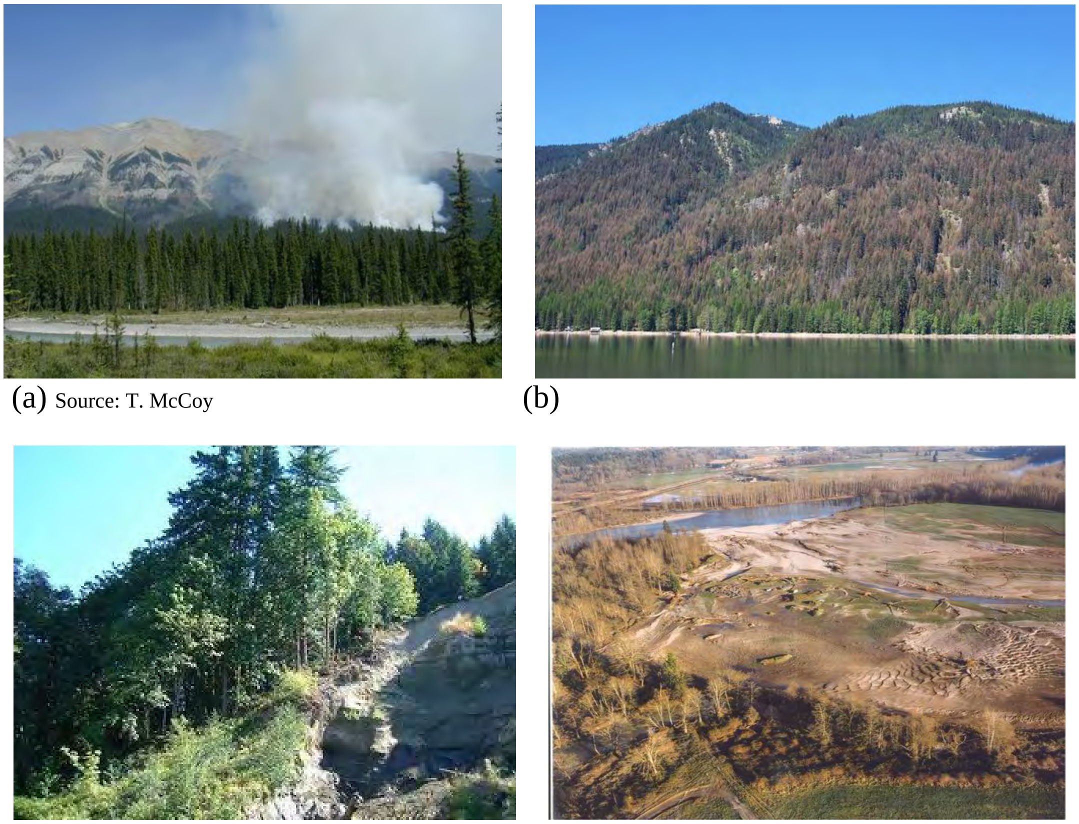
In watersheds where rainfall is the dominant form of precipitation, runoff occurs in response to storm events and the ability of the watershed to store precipitation. To a large degree, this ability is dictated by soil moisture conditions prior to the onset of the storm. Obviously, frozen and saturated 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 providing a definition for the term at this point:

> *"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, disease, landslides, and flooding – see **Figure 2.1**) 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.



(a) Source: T. McCoy (b)

(c) (d)

Figure 2.1. a) Fire. b) Insect outbreak leading to tree mortality. c) Deep-seated landslide. d) Aftermath of flooding.

Over a landscape scale, the disturbance-driven mosaic tends to remain in dynamic equilibrium during a given climatic period. It is the diversity inherent in this mosaic that provides diverse habitat[8][9][10]. 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 this habitat type 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 ponderosas, 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-succession, fire-intolerant species, such as western hemlock. In these ecosystems, however, fires occur with stand-replacing intensity that allows the establishment of early-succession plant species that require full sunlight and bare mineral soil, such as Douglas fir. 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 (i.e., soil formation), and the energy of flowing water. Erosion processes and rates are controlled by climate, topography, soils, and vegetation. Forested landscapes generally 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 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 with extreme rates occurring 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 2.2** illustrates the different types of erosion. All three types of erosion peak during storms or periods of rapid snow melt.

(a)

(b) Source: Paul Bakke

(c)

Figure 2.2. a) Surface erosion from a road. b) Mass-wasting. c) Bank erosion.

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 downstream direction. Any land use altering one of the three basic watershed components - soil, vegetation, or water - will affect watershed functioning. Land use (e.g., logging, grazing, farming and urbanization) generally alters vegetation, often intercepting and diverting the movement of water. Land use may also directly affect the soil through compaction. Road building, in addition to removing vegetation, exposing soils, and creating impermeable surfaces, can drastically alter the routing of water through watersheds. 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 (speeding the drainage of 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 alters both soil depth and quality, causing 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 these processes, and by association, to 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 might 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, logging, 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 2.3**). Agriculture and urbanization represent major disruptions of native plant communities and ecosystems; additionally, irrigation and other water uses are inevitably associated with alterations to streamflow and groundwater.

Figure 2.3. 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 the 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. These have been described in a variety of typing systems (e.g., Leopold and Wolman 1957[11], Schumm (1977)[12], Mollard (1973)[13], Church (1992)[14], Kellerhars et al. (1976)[15], Rosgen (1994)[16], and Montgomery and Buffington (1998)[17]).

For the purposes of this discussion there is one overridingly important stream type concept. Alluvial (or unconstrained) stream channels are formed in sediments previously transported and stored by the stream. 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 2.4**). 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.

(a) Source: Paul Bakke **(b)** Source: E. Salminen

Figure 2.4.
a) An alluvial or unconstrained stream. b) A bedrock-controlled or constrained stream.

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 (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[18]. 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.

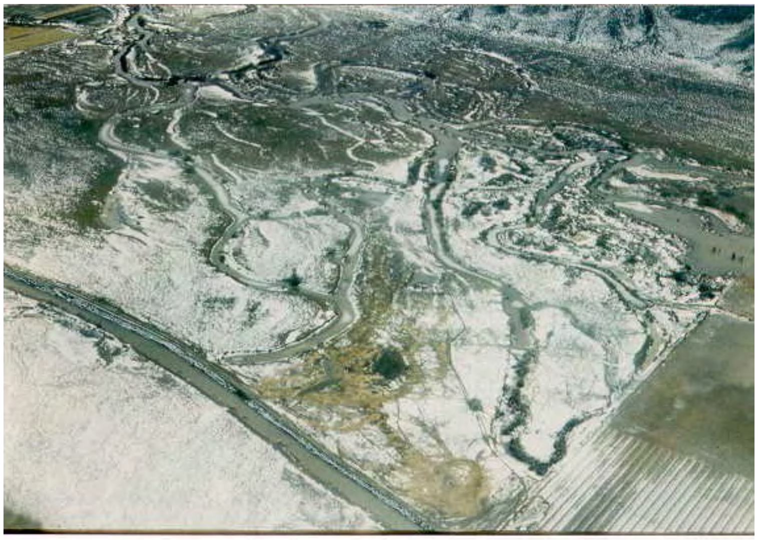
Alluvial channel reaches commonly adopt one of two basic forms, based largely on stream gradient and the character of the sediment. The first is the stream with a single, dominant channel. The **sinuosity** (i.e., the ratio between the length of the channel and the length of the corresponding valley floor) of these streams can vary widely. Although 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’[19] (see **Figure 2.5**).

(a) Source: © 2001 Robert Glenn Ketchum (b)

Figure 2.5.
a) A high sinuosity, low gradient, fine sediment stream reach. b) A low sinuosity, high gradient, coarse sediment stream reach.

The second basic form is the **braided** stream with multiple channels active at **base flow**. The exposed areas between channels can range from unvegetated bars that mobilize during every high flow to stable, vegetated islands (see **Figure 2.6**). 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 of log jams, usually accompanied by bedload deposition. Conditions that promote frequent channel change involve relatively steep gradient, large quantities of coarse bedload, and an abundant supply of wood.

(a) Source: T. McCoy (b) Source: U.S.G.S.



(c) Source: Yakima Indian Nation

Figure 2.6.

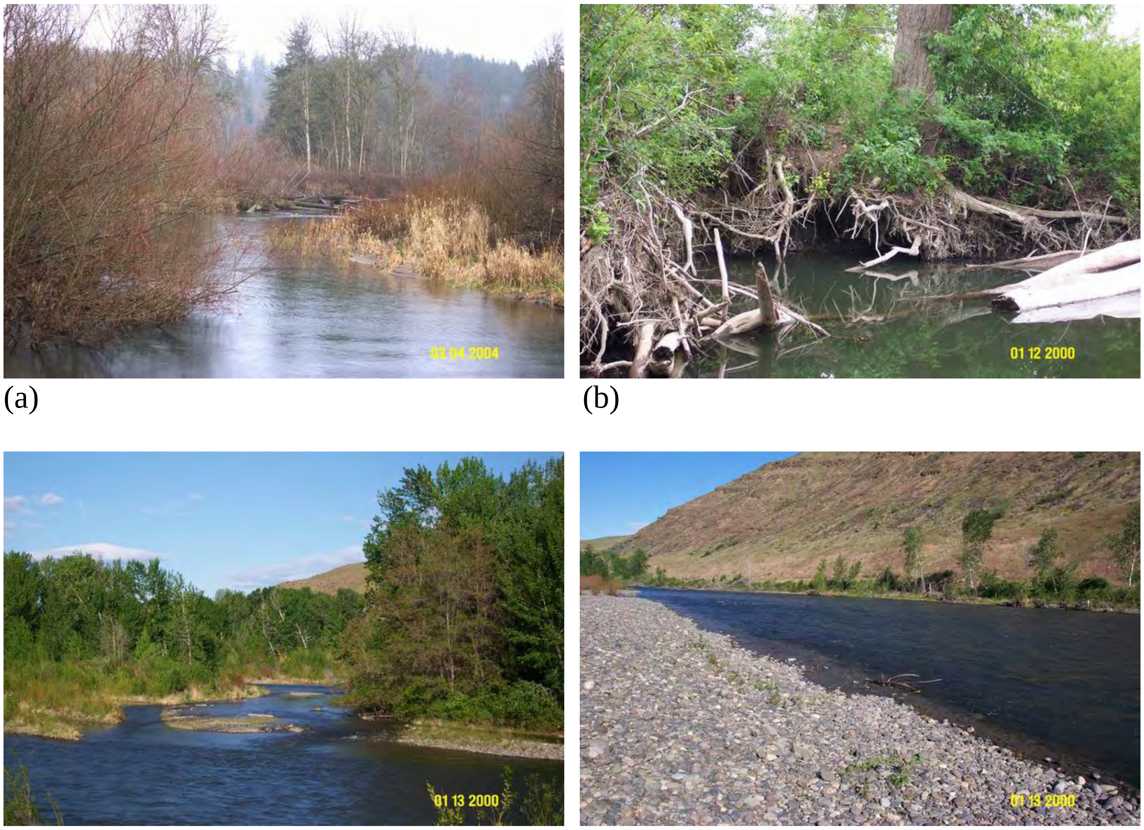
a) A braided stream with extensive unvegetated bars, indicating frequent channel change.
b) A braided stream with partially vegetated bars, indicating an intermediate level of channel stability.
c) A braided stream with vegetated islands and multiple stable channels.

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, the system is self-regulating, balancing imports and exports of water, sediment, and energy through adjustments to channel geometry. Because alluvial channels are, by definition, sculpted out of previously transported sediment, flows capable of mobilizing sediment are an essential component of channel development.

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 2.7**). 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.



(a) (b)

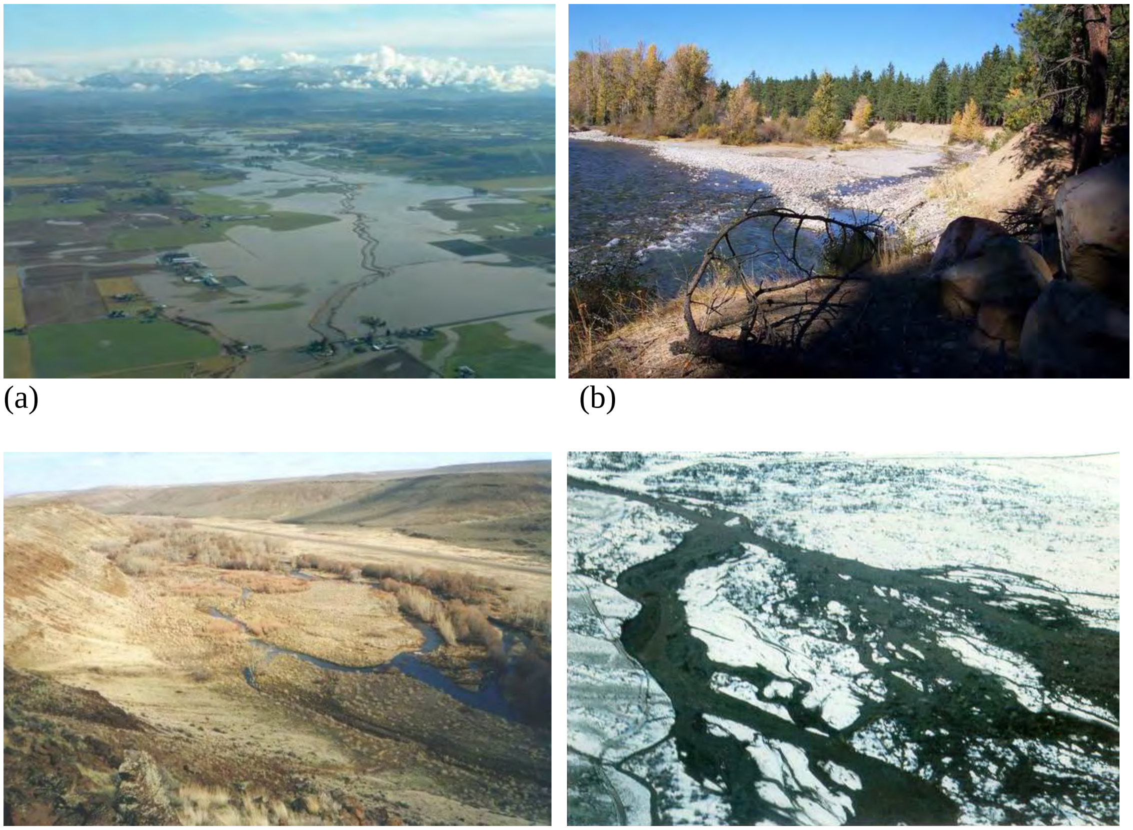
(c) (d)

Figure 2.7. 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 downstream of c). 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 1 1/2 to 2 years. In a study of 76 streams in the Pacific Northwest, Castro and Jackson (2001)[20] 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 2.8**). 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 2.8. A stream reaching bankfull flow. Source: Yakima Indian Nation

The tendency to flood during relatively minor 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 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 2.9**). 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.



(a) (b)

(c) Source: Yakima Indian Nation

(d) Source: Yakima Indian Nation

Figure 2.9. 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. d) Distributary channels convey flood flows on an alluvial fan.

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. 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** (See **Figure 2.10**). When meandering streams are in equilibrium, point bar crests approach the elevation of the floodplain. Conversely, point bar development that does not crest near the level of the floodplain is symptomatic of an incising and degrading channel. Under equilibrium conditions, lateral accretion does not add to, or subtract from, the area or height of the floodplain.

Figure 2.10. A formerly straightened channel reestablishes a meander pattern.
Source: Yakima Indian Nation

Vertical accretion is caused by floodwaters carrying sediment out of the channel and depositing it on the floodplain (see **Figure 2.11**). Thus, 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.

(a) Source: Yakima Indian Nation (b)

Figure 2.11 a) Lateral accretion: sand and silt deposited on the point bar of the meander shown in **Figure 2.10**. 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 a natural part of channel evolution that can also be accelerated by human activities. Chute-cutoff, the most regular and predictable form of avulsion, is a result of channel lengthening through 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 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 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 2.12**).

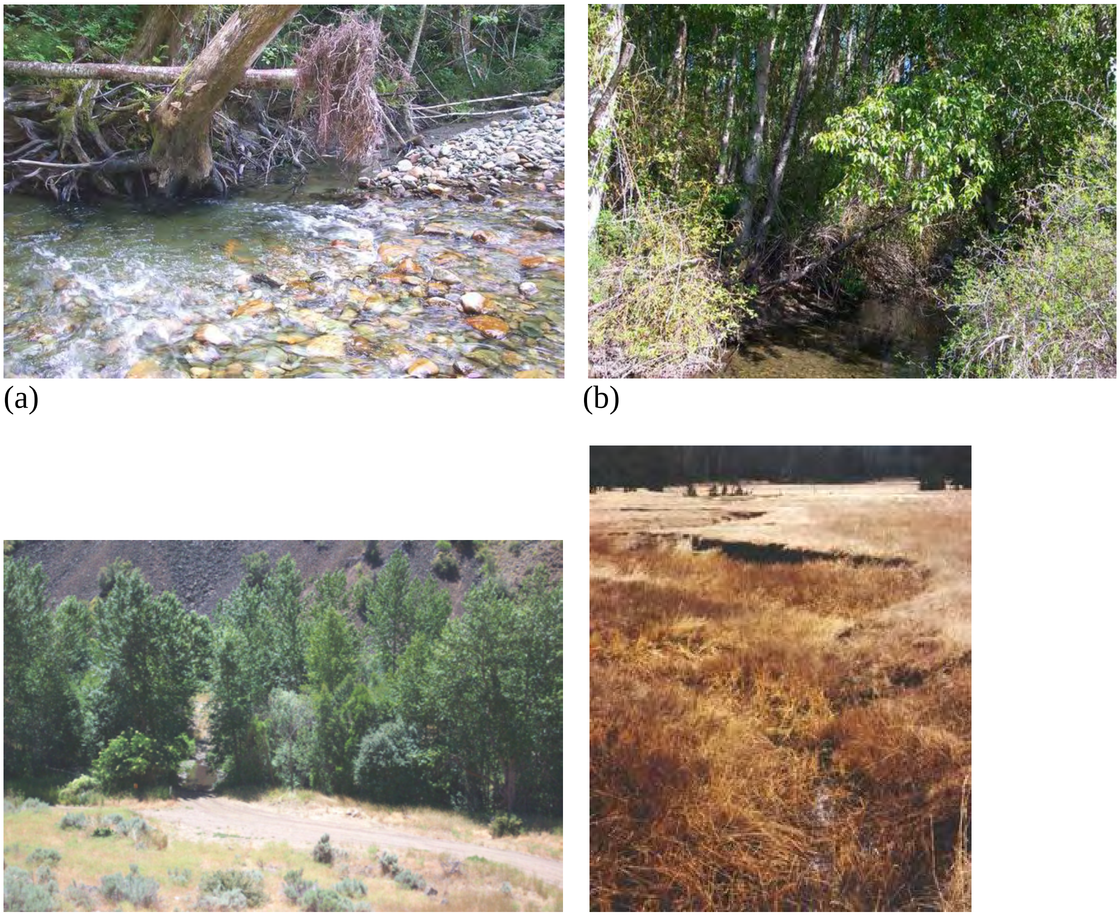
Figure 2.12. Oxbow lakes resulting from meander cutoff.
Source: U.S.G.S.

Less predictable, and normally associated with major floods, is a major re-routing of the channel 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, progressing in the upstream direction, of the streambed. 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 there is a vertical, or near-vertical discontinuity 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 2.13**). If the flood duration is sufficient to allow the headcut to work 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.

(a) (b) Source: Yakima Indian Nation

Figure 2.13. 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).

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 2.14**).



(a) (b)

(c) (d) Source: Yakima Indian Nation

Figure 2.14. 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.

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 (further damping 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 in near-stream sediments that can freely mix with surface flow) occurs effectively only 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 product 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, can impair hyporheic functioning.

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. Flow paths can be long and relatively deep, and are often concentrated in buried former channel courses known as **paleochannels** [21].

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 far below 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 there is virtually no lateral seepage from the stream and a hole dug 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[22].

The distribution and extent of hyporheic zones depend upon the volume and texture of sediment underlying the channel and floodplain. 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[23]. For a more thorough discussion of hyporheic flow, refer to the *Hydrology* appendix and Edwards (1998).

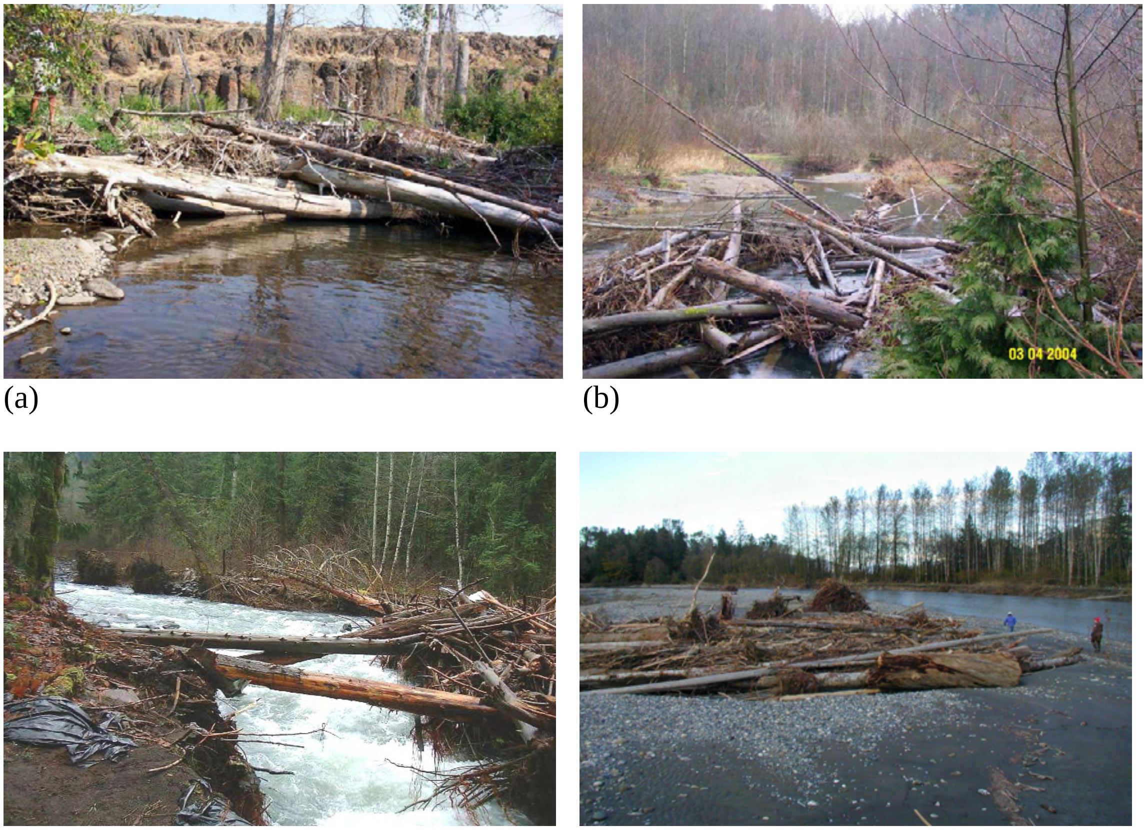
2.2.4 Influence of Large Wood on Stream Morphology

Forested alluvial streams are often heavily dependent on physical interactions with large wood for channel development and stability. In addition to live trees stabilizing stream banks, large wood frequently exerts a major influence on stream channels[24]. 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 2.15**). 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 [25].

Figure 2.15. Natural large wood drop structure. Source: Yakima Indian 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 wood, leading, in time, to structurally distinctive log jams[26] (see **Figure 2.16**) 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**[17 26].



(a) (b)

(d) (e) Source: Paul Bakke

Figure 2.16. a) Channel-spanning log jam. b) Log jam accumulated along the bank. The key piece in this jam is a large tree that toppled into the stream while remaining rooted in the bank. c) 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.

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.

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 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 lasting influence on the stream.

Another factor involves the typical characteristics of large wood pieces that are delivered to the channel. Some tree species 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 log jams and accumulations. These typically develop around key pieces in the channel, at the heads of high flow channels, along the outside of meander bends, on point 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[27]. 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 tend to break, 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. As with the other stream system components, the characteristics of the natural 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 2.17**). 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.

(a) (b)

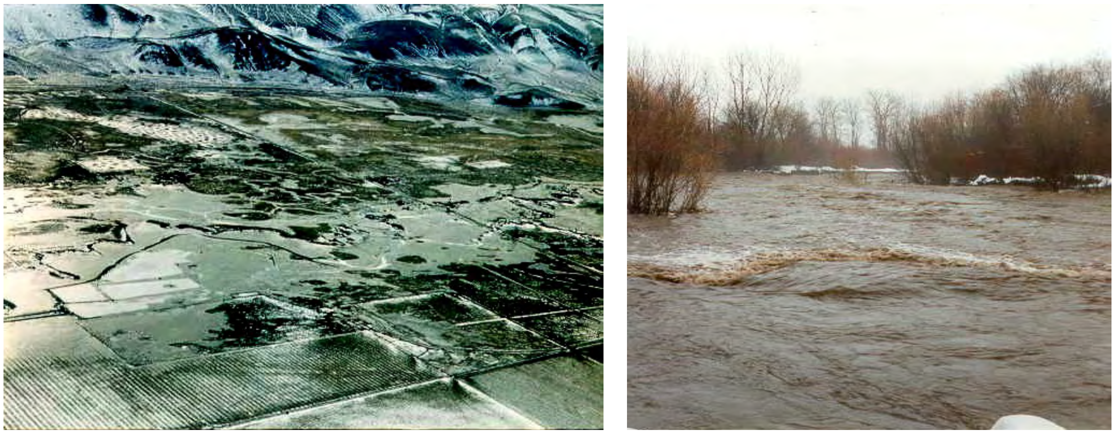
Figure 2.17. a) West-side beaver pond. b) East-side beaver pond.

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. 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 2.18**). 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.



(a) Source: Yakima Indian Nation (b) Source: Yakima Indian Nation

(c)

Figure 2.18. a) Extensive flooding in a low-gradient system. b) High flows generated by a rain-on-snow event. 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 reestablishes. For example, channels that straighten and widen in the course of a large flood, through the processes of revegetation and sediment capture, will gradually narrow and regain sinuosity. Equilibrium, once reestablished, then 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 baseflow- 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. Conversely, streams in the humid, temperate maritime regions are generally more resilient and quicker to recover. **Figure 2.19** provides examples of base flows in different systems.

(a) Source: Paul Bakke

(b)

Figure 2.19. a) Typical small, humid-system stream at base flow. 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 loss of soil moisture storage, 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 2.20** for examples of direct and indirect channel disturbance.

(a) (b)

Figure 2.20. 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 some degree 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 does so indirectly through its dominant role in the disturbance regime. Climate change is both natural and inevitable. Its effect on ecosystems is a product of the magnitude and rate of change. The least determinate but most profound disruption to watershed and stream functioning caused by human activities are the potential effects of significant, rapid, human-caused climate change.

Climate change inevitably leads to ecosystem change. Stream systems will be directly affected through changes in the amount and timing of streamflow and sediment yield, and indirectly through changes to the plant communities. 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).

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 will translate into higher, earlier annual peak flows and longer, lower base flows, i.e., more severe flooding and drought.

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 precludes 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 channel is adjusting the balance among the different mechanisms of energy dissipation, and the adjustment period corresponds to the early stages of the 'actively degrading' trend mentioned above (see **Figure 2.21**).

Figure 2.21. 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 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. 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.

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 2.22**). 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 2.22. 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 colonizing bars are often the first sign that recovery processes are underway, although in order to 'count', vegetation must have survived through at least one high flow period. If persistent through high flow conditions, these pioneers create zones of reduced flow velocity, promoting deposition of finer sediment. Such sediment capture is key to initiating 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 has 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 2.23** contrasts vigorous and decadent cottonwood communities.

(a) (b)

Figure 2.23. 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

Stream ecosystems extend well beyond the channel, taking in the entire stream corridor. The stream corridor is comprised of the stream channel, its shoreline, the **hyporheic zone**, and the surrounding floodplain and **riparian area,** encompassing and connecting both aquatic and terrestrial habitat. As previously noted, stream corridors are frequently disturbed. Aquatic ecosystems and their constituent organisms have evolved accordingly – with high system resilience (i.e., ability to recover from **disturbance**) and a variety of adaptations that enable organisms to survive the tremendous range of conditions occurring annually and episodically. These adaptations generally capitalize on key attributes of stream ecosystems, such as habitat complexity, and connectivity. Note that, because ecosystems are dynamic in space and time, suitable habitat will not be available to all species in all streams at all times.

2.3.1 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[28] [29] [30]. 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[31].

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 2.24**). 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 2.24. High quality aquatic habitat is the result of structural and hydraulic complexity.

2.3.2 Habitat Connectivity

Although connectivity within the stream corridor is most obviously essential for salmonids and other migratory fishes, it is also of critical importance to a host of non-migratory aquatic organisms. Individual responses to varying flow conditions and the need for food, shelter, and reproduction typically include movement up and downstream (i.e., longitudinally), up and down through the water column, and even into the porous streambed (i.e., vertically), and from the middle of the channel to the margins and off-channel floodplain features (i.e., laterally). The timing and direction of movement, and distance traveled vary with the species, age, and specific needs of the individual.

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. In addition to storing and routing matter in the downstream direction, these systems provide continuous habitat and migration corridors essential to many aquatic and terrestrial species.

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 et al. 1998) 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[32]. When habitat connectivity is lost, migratory species may be excluded, and disturbance can lead to local extinction of resident species (see **Figure 2.25**).

Figure 2.25. a) Natural fish passage barrier. b) Human-created fish passage barrier.

Lateral Connectivity
The lateral dimension of the stream corridor runs perpendicular to flow. Streams have a lateral structure that begins at the main channel and progresses through the channel margin and floodplain/riparian habitats to the adjacent upland environment. 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. 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 2.26** illustrates the simplification caused by diking.

Figure 2.26. 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 2.2.4 *Influence of Large Wood on Stream Morphology* the hyporheic zone is the volume of saturated sediment beneath and beside streams where ground water and surface water mix.

Recognition of the hyporheic zone and its importance is relatively recent and much is still poorly understood. According to a literature search by Edwards, 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.

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. The ecology of gravel-bedded streams appears to be heavily influenced by hyporheic functioning.

2.3.3 Flooding, Stream Habitat and Stream Ecology

Flooding is an essential ecological interaction between the river channel and its associated floodplain[33]. Flooding creates, maintains, modifies and destroys physical floodplain features such as bars, levees, swales, oxbows, backwaters, and side channels; floodwaters carry sediment, organic material, nutrients, and biota to and from the floodplain; flowing water sorts sediments, creating 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 gradient. This gradient, coupled with variations in soil structure, vegetation, and topography create a complex and dynamic network of habitats throughout the floodplain .

Floodplains alternate between aquatic and terrestrial environments and the change can be stressful, or even detrimental, to the affected biota. Organisms may be killed or harmed during the flood event (e.g., drowning, scouring of eggs from redds) or they may be affected by the resulting change in habitat conditions immediately following the disturbance and during the system's recovery. The biological response of biota to the dynamic floodplain environment varies with the regularity, frequency, and duration of inundation, the rate of change, the abundance and distribution of new and undisturbed habitat, and the abundance, distribution, sensitivity and adaptive capability of the surviving populations. Headwater streams are characterized by rapid, unpredictable changes in flow, as their hydrology is strongly influenced by precipitation events. In contrast, large streams and rivers with access to extensive floodplains typically have a more predictable flooding regime.

The intermediate disturbance hypothesis predicts that biotic diversity will be greatest in systems that experience moderate levels of disturbance[34]. Disturbances that are too frequent or too intense are thought to suppress biotic diversity by causing local extinction of certain species and/or dominance of colonizing species[35] [36]. In systems subject to infrequent disturbance, competitive interaction of species becomes the dominant force determining the structure of biological communities; superior competitors tend to dominate. Some moderate level of disturbance allows colonizing species to coexist with superior competitors, as neither species is favored.

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 to what degree ranges of natural variability can be tampered with before significant habitat simplification occurs; stream ecosystems have varying degrees of resilience. 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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STREAM HABITAT RESTORATION GUIDELINES
CHAPTER 3

STREAM HABITAT ASSESSMENT

****This Chapter is a draft version and the Aquatic Habitat Guidelines Program will be working to finalize it in the future****

Stream habitat is created and maintained by the dynamic interaction of multiple physical, chemical and biological processes that function at a range of 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 inappropriate spatial and temporal scales and did not address the processes that were limiting the production of habitat or species. Therefore, 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 to put towards restoration efforts, the risk of project failure, and the risk of unintended detrimental habitat and infrastructure impacts when watershed processes and conditions are not well understood, some degree of assessment should be conducted for all projects in order to maximize their long-term success. Assessment costs should be considered part of the cost of project implementation and should therefore be included in a project budget. It is usually more cost effective to adequately assess watershed conditions before project implementation rather than after a project has failed to meet expectations, 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's going on elsewhere in the watershed may influence the effectiveness of your 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 may allow one to determine 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 its cause, will provide only short-term localized benefit.

Reid (1998)[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 at which to implement restoration, rehabilitation, enhancement, and preservation efforts, and
- Developing monitoring strategies and objectives to determine the individual or collective effectiveness of restoration measures conducted throughout the watershed. Such measure

is necessary to monitor and adaptively manage the watershed's overall restoration strategy.

3.1.2 Reach Assessment

A reach assessment addresses 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, or sediment size[2].

Reach assessments can be used to collect information essential to project planning, development, and implementation. Reach assessments can 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 restoration constraints and opportunities within the reach. And they may identify limiting factors to the health and abundance of species that spend their entire life cycle within that reach. But their limited scope may not allow one to assess limiting factors to migratory species that spend some part of their life cycle outside the study reach. Their limited extent may also prevent the cause of any habitat deficiency from being revealed if the cause lies outside the study reach. As a result, treatment may only partially address the problem 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 their limited scope leaves them incapable of evaluating the cumulative watershed effects that lie outside the study area.

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. In addition to 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. And they can 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 are controlled by site, reach and 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.

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 may cause a series of channel and watershed responses that destabilize the stream or degrade habitat conditions, water quality, or fish and wildlife productivity. Degraded conditions may also result from natural disturbance (e.g., floods, landslides, fire, or debris torrents). Because the issues and cause and effect relationships vary both within and between watersheds, every assessment is unique, even if the reasons for conducting the analysis are the same. Assessments must be tailored to address the specific topics of interest and objectives of those conducting the analysis.

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. Note that it may be very difficult to collect historical data and its proper use is often problematic. For example, how far back in history do we have to go to get a look at natural habitat, and is that information still relevant to the species given the possibilities for restoration?

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 done in conjunction with landuse, land management, landowner, and infrastructure assessments. It is important to note that it can be difficult to establish clear causality between cumulative land use activities, 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 in to play. For example, it may take decades for sediment inputs associated with logging to accumulate in downstream sites[4].

3.2.1.1 Physical Habitat Assessment

A physical habitat assessment describes the structure and composition of a landscape. 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 (limiting factors) that limit fish, wildlife, and plant productivity within the stream corridor.
- Identifying potential constraints to ecosystem recovery and restoration.

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[5] [6] [7]:

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), calculations of road density, or identification of dams, reservoirs, and instream detention basins that prevent downstream sediment transport. Refer to Chapter 4.5.1, *Restoring 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. [8]

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 4.5.2, *Restoring Stream 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.[5 6]

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.[5 6 8]

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 :

- 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 4.5.4, *Restoring 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. 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 assessment

Biological assessment may encompass any and all life within the stream corridor, though it's scope is often limited to a particular species, group of species, or type of life form (e.g., vegetation, birds, reptiles, amphibians, fish, invertebrates). Biological habitat assessment may include [9]:

- 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 prevent recovery
- 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 harvest and harvest management over time

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, may also 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. For instance, the scale of assessment necessary to conduct population and limiting factors studies must equal the range of migration for the species of interest. 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 an 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, 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. An overview watershed analysis that identifies broader ecosystem problems is recommended prior to initiating isolated restoration activities. Note that such an analyses does not necessarily need to be extremely detailed or costly.]

Even watershed assessments can be conducted at multiple scales. A watershed is any area of land that drains to a common point. A watershed-scale assessment extends from the mouth of the stream to the far reaches of its drainage basin. Because the watershed of a small tributary stream is nested within the watersheds of successive larger streams, watershed-scale assessment 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. 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 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*. 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 4.0*[10]. 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 include:

> *State of Washington Guidance on Watershed Assessment for Salmon*. 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. 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)[11]. PFC was first developed by the Bureau of Land management, and 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. PFC's strength 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. 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 those conducting the assessment. 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 and credibility of its results 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.

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.[5] 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 (plus sign means it could extend beyond the indicated duration), variability in success, and probability of success (low = L, moderate = M, high = H) of common restoration techniques.

[Insert table 6 from Roni et al (2002)—need copyright permission]

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 in watersheds.

It is recommended that the following considerations be made 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. 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 much 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.

**** NOTE: THE REMAINDER OF THIS CHAPTER IS INCOMPLETE AT THIS TIME ****

[Discuss risk assessment as it relates to geomorphic condition of landscape (e.g., steep channels, entrenched channels, unstable channels (aggrading, incising, alluvial fans), urban watershed]

3.2.3 Necessary Level of Expertise for Conducting Assessments

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 of the following:

- Property ownership and access may limit the area of study.
- The type and resolution of data collected may be limited by time, money, or the limited objectives of those conducting the assessment.
- Scientific understanding of watershed processes is limited and comprehensive and reliable techniques for evaluating watersheds are lacking[12].
- Impacts to environmental resources are influenced by multiple factors and can accumulate through space and time, a fact that complicates the determination of cause and effect relationships and the evaluation of potential future impacts.
- No single discipline covers the many influencing variables, and thus, a study must involve an interdisciplinary team of professionals. This requires coordination and cooperation among the individuals involved.
- 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 may be insufficient to identify remote or historic causes.
- Lack of historical records may limit our understanding of past conditions.
- 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.

Consider these limitations when evaluating the level of confidence inherent to a study.

3.3 *Assessment Methodologies*

There is no single resource for the State of Washington that provides comprehensive guidance and instruction in how to conduct an assessment for stream habitat restoration.

3.3.1 Published Reviews of Assessment Methodologies

3.3.2 Published Assessment Methodologies

List the most common methodologies. Note that the list is not exhaustive, nor is it meant to limit the reader. For each, we will provide a citation and a brief description of the type of information to be gained.

Consider WDNR (1995)[13], Skagit Watershed Council (1999)[14], and Watershed Professionals Network (1999)[15].

3.3.2.1 Physical Habitat Assessment

3.3.2.2 Chemical Habitat Assessment

3.3.2.3 Biological Habitat Assessment

> Limiting Factors Analysis- if some sort of standardized protocol exists, need to get a reference and describe what it tells you—check with Conservation Commission--limitation is that it is very species specific

3.3.3 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. There may be considerable data available 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 assessment is conducted primarily for the purpose of implementing a project.

In addition to published assessments, there is a wealth of publicly available information that may be useful. [This list needs to be expanded. Can refer reader to Section 2.1 of Rapp and Abbe[16], in press, for more information, if appropriate.]

- Air photos
- GIS maps
- Satellite photos
- Historic records

- USGS stream gage and water quality data
- 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:

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

Is it of sufficient quality? Consider its accuracy, completeness, data collection, handling, and analysis methods.

The reader is encouraged to make the results of their assessment publicly available so that others may benefit and build upon it.

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STREAM HABITAT RESTORATION GUIDELINES
CHAPTER 4

DEVELOPING A RESTORATION STRATEGY

The term “restoration” is often used loosely to refer to any project that strives to improve habitat conditions or re-create specific habitat features. However, the actual definition of the term is much narrower and involves bringing something back to its previous condition[1]. The condition of a stream at any given time is a reflection of current and past events and activities occurring within its watershed. As such, stream ecosystems are dynamic in space and time. Long-term restoration of stream ecosystems requires consideration of how past, current, and future events and activities have and will continue to influence their structure and function.

The 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. Disturbance can come in a rare catastrophic event, such as a volcanic eruption, or in a more predictable pattern, such as the input of fine sediment by surface erosion off a steep hill slope. Disturbance may be from daily or seasonal events to events that happen on a geologic time scale. Spatially, disturbance may operate on a local scale, impacting an individual pool, or on a larger reach or watershed 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 diverse. Considering the dynamic nature of the stream environment, these guidelines echo the recommendations of numerous other researchers[2,3,4,5] 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. Restoration should strive to provide sustainable long-term benefits to the stream ecosystem, not just a target species, by addressing the cause(s) of habitat degradation and by supporting natural succession and disturbance regimes, which, in turn, support long-term habitat and biological diversity[1,6].

Although the ultimate goal of restoration is to return an ecosystem to a close approximation of its pre-disturbance condition, existing infrastructure, invasive species, limited native species abundance and extinction, and past and current land use may prevent full ecosystem recovery from being achieved. In such systems, rehabilitation (returning the system, or a fraction of the system, to a state of ecological productivity and useful structure, but not necessarily its pre-disturbance condition[7]) or enhancement (an improvement in habitat structure or function) may be the only achievable goals. Rehabilitation generally consists of restoring select ecosystem functions and characteristics (e.g., water quality) in order to support a “potential natural community” that can be accommodated within the given land use and ecosystem constraints. Its priority should be to establish a self-sustaining ecosystem that is resilient in its recovery response to its disturbance regime, rather than one that will require repeat intervention by humans. Enhancement, on the other hand, typically involves manipulation of habitat at a relatively small, microhabitat scale, such as an individual pool, riffle, or an isolated reach. As a result, enhancement achieves lesser benefits for the overall ecosystem, unless it happens to address the most significant feature to have been degraded and the principle cause of its degradation [8]. When conducted without adequate consideration and knowledge of watershed and ecosystem processes and conditions, any measure (whether intended to provide restoration, rehabilitation, or enhancement) will be prone to failure, providing only short-term benefits, and having unintended adverse effects [4 8 9].

4.1 A Coordinated Strategy

Restoration of the structure and function of stream ecosystems requires a coordinated and comprehensive strategy to reestablish and preserve the natural rates of physical, chemical, and biological processes and interactions that have been compromised by human activities. The reason for this is two-fold. First, aquatic and upland ecosystems are interconnected and interactive; the range for individuals of certain migratory species, such as ducks and whales, extends across entire continents. And second, the condition of wetlands, lakes, or streams reflects the cumulative effects of activities and events within their watersheds. As a result, ecosystem recovery efforts will be most effective when implemented on a scale that encompasses the entire range of affected species and the 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. Individual projects must be considered within the context of the overall restoration strategy to ensure their incremental gains will collectively achieve restoration goals.

The following steps are suggested for inclusion in any stream habitat restoration strategy. They are a compilation of key aspects described by the National Research Council, Federal Interagency Advisory Group[10], and Hobbs and Norton[11] (cited by Roper et al.). Select steps are further described in succeeding sections of this chapter.

1. Form an advisory group.
2. Define the problems and deficiencies within the watershed, stream network, or other appropriate landscape unit and identify their root cause(s).
3. Define and prioritize realistic restoration goals and objectives.
4. Develop performance indicators to measure the success of the restoration program.
5. Develop a monitoring program to accurately and reliably measure performance indicators (refer to the *Monitoring Considerations* appendix).
6. Identify, prioritize, and implement tasks or techniques to achieve restoration goals and objectives.
7. Monitor performance indicators to determine progress towards meeting restoration goals and objectives.
8. Modify the restoration strategy, as necessary, to better meet goals and objectives.
9. Document and communicate successes, failures, and lessons learned so others may benefit from the knowledge and implement better projects.

4.2 Defining the Problem and Identifying Its Cause

One of the first steps in the process of habitat restoration is to define the problem and the biological consequences of that problem. Habitat deficiencies may be expressed as a decline in the quantity or quality of specific types of habitat, a decline in habitat diversity, or as an accelerated rate of change. Habitat deficiencies are often revealed by their biological response. For instance, a decline in species' productivity, range, health, or population abundance is typically the driver for identifying whether or not habitat deficiencies exist within a watershed or ecosystem. Investigation into the nature and extent of habitat deficiencies may also be triggered by observed changes in the physical or chemical characteristics of habitat at a specific location (e.g., a change in channel bedform, characteristic size of streambed material, temperature, or dissolved oxygen level within a particular reach) or by perceived changes in stream or watershed stability (e.g., channel incision, aggradation, or migration rates; mass wasting occurrences in the watershed). As stream habitat is dynamic in space and time, even under pristine conditions, it is necessary to consider historic as well as current habitat conditions in order to draw conclusions with regards to the degree of change over time and whether the rate of change has accelerated, decelerated, or remained constant. One must also consider individual sites within the context of the overall ecosystem to determine if there is an actual net decline in the abundance of a specific habitat type (e.g., the number of acres of side channel habitat in a specific river system declined 85% in the last 50 years) or if the loss of an individual site has been offset by the creation of another (e.g., during a flood event, one side channel filled with sediment while another was formed).

Once the nature and extent of habitat degradation within an ecosystem has been clearly defined, the next step in the process is to identify the root cause(s) of degradation in order to develop a long-term solution. Rehabilitation measures that treat only the symptom of the problem and not the cause will provide only short-term benefit and will likely need to be repeated periodically to provide continued benefit in the long-term. Unfortunately, cause and effect relationships in stream environments can be extremely complex and are often difficult to define with certainty. A single habitat problem often has multiple causes, thereby confounding explanation. For example, stream incision may be due to an increase in the magnitude and frequency of peak flow events, a reduction in sediment supply, or a steepening of channel slope. And each cause or mechanism of habitat degradation may be attributed to a series of activities occurring with the watershed (urbanization, timber harvest, dam building). Similarly, a single activity can trigger a variety of channel responses. For example, channel straightening may cause a channel to incise or aggrade, depending upon the circumstances. Identification of activities and events that lead to a decline in habitat abundance, quality, stability, or diversity generally requires a thorough watershed assessment (refer to 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.

The cause of habitat deficiencies may be related to site-, reach-, or watershed-scale activities or events. Understanding the spatial extent of habitat deficiencies can often help identify whether causes are site-specific or systemic. Site and reach scale problems may have similar causes, but the extent of their impacts differ. For instance, the impact of removing one log from the stream may be limited to the loss of one pool. However, removal of all wood from a four mile reach of stream may significantly reduce cover, pool habitat, invertebrate populations, and overall habitat diversity; reduce the quality and alter the gravel size distribution of salmonid spawning beds; and cause channel incision or aggradation due to a reduction in channel roughness and scour mechanisms. These effects may extend upstream and downstream of the wood removal site.

Stream habitat degradation may be caused by:

- Direct physical modification of the stream corridor;
- Changes in channel boundary conditions upstream, downstream, or laterally;
- Physical constraints placed on natural channel adjustment; or
- Changes in watershed management or land uses.

Direct physical modification of the stream corridor includes, but is not limited to, such activities as deliberate alteration of a channel's planform (e.g., straightening), cross-section (e.g., widening), profile (e.g., dredging, gravel mining), or roughness (e.g., removal or addition of wood, rock, vegetation, or other instream roughness elements, armoring of the stream bed or banks). It may also include removal or modification of riparian vegetation or filling of off-channel habitats. Although direct modification of the channel may be limited to a particular site or reach, the impact may extend upstream, downstream, or laterally by changing boundary conditions.

The conditions of a particular site may be affected by changes to its boundary conditions; that is, changes that occur upstream, downstream, or otherwise outside the site. For instance, a stream reach may down cut (vertically incise) in response to downstream dredging or gravel extraction operations. Other examples of boundary condition changes that impact a particular stream reach include modification or removal of riparian vegetation and levee construction. Although these changes occur outside the stream channel, they influence its bed and bank stability, channel form, water quality, water depth, bed material, and other habitat characteristics.

Physical constraints placed on natural channel adjustment include any structure that limits the natural migration and adjustment of a river system, either laterally through bank erosion or vertically through scour and deposition. Such structures will likely reduce habitat diversity and connectivity, wood and sediment recruitment, and initiate adjustments to the channel planform, cross-section, or profile upstream and downstream. Constraints may occur as a result of bank armoring, grade control, or similar structures.

Land use affects habitat structure, function, and availability by altering or disrupting the processes that create, connect, and maintain habitat. These processes include the supply and transport of water, sediment, solutes (including contaminants, nutrients, dissolved oxygen), energy (i.e., light and heat), and organic material (ranging from large wood to detritus) to the stream, floodplain, and riparian corridor. Watershed-scale causes of stream habitat degradation or loss may not be as obvious as reach- or site-scale causes. They may, therefore, be more difficult to link directly to habitat problems and more challenging to remedy.

The reader should note that, in some cases, land use activities might not yet have manifested themselves in a habitat or biological response as a result of their relatively small scale or recent occurrence. However, an increase in the extent or longevity of the activity, or the occurrence of a flood or other natural disturbance event may trigger a system response. Implementing responsible land management now, instead of waiting until a problem develops, will minimize threats to ecosystem decline and protect healthy high quality habitat.

4.3 Development and Prioritization of Ecosystem Recovery Goals, Objectives, and Activities

Once the activities and events that have led to ecosystem decline have been identified, the next step is to develop a set of realistic goals and objectives to reverse or mitigate for the decline. The term realistic is emphasized here in recognition that past, current and future land use, water rights, species extinction, the presence of exotic species, and other factors may place physical, biological, or societal constraints on the outcome of ecosystem recovery efforts. The distinction between goals and objectives is subtle. Both define the purpose toward which restoration endeavors are directed. However, goals and objectives are generally considered to be hierarchal with goals being the most broad-based and over-arching of the two. Goals may be, for instance, to restore water quality or reduce the excessive sediment supply to the stream to a more natural rate. 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).

Most Washington watersheds and streams have been significantly modified and often suffer from channel instability and multiple habitat deficiencies. Because of limited resources, goals and objectives must be prioritized in order to target the dominant factors that prevent the reestablishment of pre-disturbance ecological conditions. Individual restoration activities implemented to achieve established short and long-term goals and objectives must also be prioritized so that effort is focused where and how it will yield the most benefit. Recent revelations concerning the important function of large wood in streams have spawned a multitude of wood placement projects. However, whether the absence of wood is the most pressing problem in a particular stream is not always given adequate consideration. Highly manipulated streams (such as those that were straightened, leveed, tide-gated, relocated, and dredged, or those in highly altered watersheds), where natural self-sustaining processes have been disrupted, may benefit more from projects that restore water quality, floodplain and/or tidal connectivity, natural channel location, pattern and configuration, riparian vegetation, or other self-sustaining processes and controls that have been altered or disrupted.

Restoration efforts should focus first on projects that offer the greatest potential for success and relatively rapid recovery[3 5 12]. Those projects that can do so at relatively low cost and risk to existing habitat, infrastructure, and the public will likely receive further priority. Roni et al. suggest the following stream ecosystem recovery prioritization.

1. 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 and provide access to isolated habitat, including instream, off-channel, and estuarine habitat made inaccessible by culverts, levees, or other man-made obstructions.
3. 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. 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).

The above priorities are not mutually exclusive. An actual recovery plan will likely include a combination of all four approaches in order to ensure that short- and long-term restoration and recovery goals are met. For instance, if there is an immediate need to establish specific habitat features to foster recovery of a threatened or endangered species, site-specific habitat enhancement work that provides immediate but short-term benefits could be justified. However, it must be done within the context of a watershed recovery program that will eventually create and sustain the desired habitat conditions naturally in the long-term.

4.3.1 Habitat Preservation

Preservation 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, preservation also offers a greater chance of success[3 12] and may be comparatively easier to implement. Preservation helps to conserve biodiversity, reference conditions, and a source of locally derived native plants, fish, and wildlife to recolonize nearby restored areas.

Doppelt et al. suggest that priority for preservation be given to:

1. Remaining healthy key biotic refuges, benchmark watersheds, floodplains, and riparian areas. Biological 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.

Candidate sites for preservation should seek to collectively represent all orders of stream within every ecoregion, all community types[13], centers of species richness, and habitats that support rare, endangered, or endemic species. Redundancy in the types of habitat and biological communities that are represented in reserves is essential to accommodate future natural and anthropogenic disturbances.

Preservation 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. But preservation 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 land use activities within the preserve and past, current, and future activities outside the preserve that can nevertheless impact the site. 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 preserves is secure, restoration activities should focus on improving the condition of land between individual preserves in order to eventually expand and link them.

4.3.2 Restoring Habitat Connectivity

Connectivity within a stream system refers to “the flow, exchange, and pathways that move organisms, energy, and matter through these systems”[14]. 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 between 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).

The focus of the following discussion is on physical, including hydrologic, barriers to habitat connectivity. But keep in mind that barriers may also be biological (e.g., invasive species, extinction of species) or chemical (e.g., water quality). 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[15].

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 (e.g., predatory pets, invasive weeds) also increases, along with the proximity between adjacent patches. As a result, mobile fish and wildlife traveling between patches of natural 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 maintain a viable population, and those opportunistic species capable of adapting to this new environment. Sensitive interior species will be most affected by the change.

Roni et al. identify three basic habitat types that are commonly isolated from the main stream channel:

1) Off-channel freshwater areas, such as side channels, sloughs, off-channel ponds and wetlands, perennial or intermittent streams and springs, and other permanently or seasonally flooded areas. A diversity of off-channel areas in various stages of succession increases the diversity of aquatic habitat available within a stream corridor. Off-channel

areas can provide reproductive, rearing, and foraging habitats for fish, amphibians, invertebrates, and selected birds and mammals. And they frequently offer aquatic species refuge from main stem conditions during floods and other events. Off-channel areas also provide a source and sink for sediment, nutrients, wood, organic matter, food, and vegetation to and from the stream.

2) Stream reaches. Access to entire stream networks is critical to species whose survival depends upon their ability to migrate to find suitable habitat and food, and to species whose survival depends on those migrating species. As of April 2002, a total of 2,324 WA State Department of Transportation (DOT) road crossings of fish bearing streams had been inspected[16]; more than a third of those examined were barriers to passage of adult salmonids. But DOT road crossings represent only a fraction of statewide barriers. Currently, there are an estimated 33,000 blockages to salmonid passage in the state of Washington (Paul Sekulich, WDFW, personal communication 4-12-02). The number of blockages is likely higher if other migratory fish and wildlife species are considered. In addition to fish and wildlife passage concerns, road crossings, weirs, and dams disrupt the flow of sediment and organic material from the upper watershed and alter nutrient cycling and energy distribution within the stream network.

3) Estuarine habitat. An estuary is “the zone between the fresh water of a coastal stream and the seawater of an ocean influenced by the tide”. As such, estuaries are interfaces between riverine, marine, and terrestrial ecosystems. Estuarine habitat includes the main channel, distributary channels, and tide flats. Collectively, these provide important foraging, reproductive, nursery, and refuge habitats for many species of fish, invertebrates, resident and migratory birds, and terrestrial, aquatic, and marine mammals[17]. They also provide physiological transition zones for salmon[18] and, presumably, other fish and aquatic organisms that move between freshwater and marine environments. Other functions provided by estuaries include groundwater recharge, flood desynchronization, sediment retention, shoreline erosion control, and water quality improvement[19]. Simenstad and Thom estimated that estuaries along the Pacific Northwest coast and in Puget Sound have lost approximately 42% and 71% of their tidal wetland habitat, respectively. Although the greatest magnitude of change occurred in the large, heavily urbanized river deltas of Puget Sound, the loss of estuarine wetlands to tidal action in agricultural areas is also significant.

4.3.2.1 Activities that Impact Physical Habitat Connectivity

Habitat isolation may be caused directly through barrier construction or indirectly through land use and other activities that alter the rate of water, sediment, or wood supplied to the stream and eventually leads to barrier formation. Typical causes of habitat isolation vary. They include, but are not limited to:

Off-channel freshwater areas

Direct causes

- Levee construction limits the extent and frequency of floodplain inundation
- Floodplain fill may eliminate or reduce the extent and depth of off-channel habitats such as ponds, side channels, and wetlands. It can also limit the extent, frequency, and depth of floodplain inundation that forms a hydrologic connection between habitats.
- Stream straightening typically reduces the length of interface between the stream and its floodplain. It also alters the proximity of the channel to off-channel habitats and may sever the physical and hydrologic connections between them.
- Screens and water control structures, such as tide gates, standpipes, weirs, and sluice gates limit or prevent passage of aquatic species to and from off-channel habitats.
- Development, roads, agriculture, and other floodplain land uses eliminate native vegetation and fragment quality habitat. Roads that parallel a stream may also create a barrier to the movement of nutrients from the channel to the floodplain by hindering animals that drag carcasses from the channel.

Indirect causes

- Instream and watershed activities that contribute to channel incision, physically isolating the stream from its floodplain and lowering the water level of nearby groundwater and surface water bodies. Off-channel areas may become dewatered or inaccessible, especially because shallowing can cause stagnation, heating, and thus evaporative water loss. The habitat in these areas may also become unsuitable. Refer to Chapter 4.5.5, *Restoring Incised Channels*, in this guideline for a discussion of activities that may lead to channel incision.
- Disturbance of the natural stream flow regime so that the extent, depth, duration, or frequency of flooding is altered, or the water level of nearby groundwater and surface water bodies is lowered. Off-channel areas may become dewatered or inaccessible. The habitat in these areas may also become unsuitable. Refer to Chapter 4.4.2, *Restoring Stream Flow Regime*, in this guideline for a discussion of activities that may impact the natural flow regime of a stream.
- Tide gates along the main stem that alter the frequency, depth, and duration of floodplain inundation and so may limit or alter the hydrologic connection between the main channel and off-channel habitats.
- Activities that prevent or minimize opportunities for the natural formation and maintenance of off-channel habitats, including:
    - Bank armoring or hardening
    - Activities that reduce the extent, depth, duration, or frequency of flooding (e.g., dam release management, water withdrawals, levee construction)
    - Activities that reduce the supply of large wood to the stream (e.g., timber harvest, land clearing, stream cleaning)
- Watershed activities that increase the sediment supply to off-channel areas, accelerating the rate at which off-channel areas fill in. Coupled with activities that prevent creation and maintenance of off-channel habitat, habitat lost through sedimentation will not be replaced or renewed.

Stream reaches

Direct causes

- Culverts, dams, tide gates, or other artificial obstructions or constrictions can create drop, velocity, turbulence, depth, or other physical barriers to upstream fish and/or wildlife passage. Outfall drops may also create a barrier to safe downstream fish and/or wildlife passage.
- Modified channels that are steep, shallow, devoid of roughness elements, or have artificial smooth channel linings can create velocity, slope, or depth barriers to upstream fish and/or wildlife passage and eliminate holding habitat that facilitates passage.
- Road crossings may create physically challenging and potentially dangerous conditions for organisms that must climb the embankment and cross the road to reach upstream and downstream habitats.

Indirect causes

- Instream and/or watershed activities that lower the streambed elevation, physically isolating a stream reach from its tributaries and upstream reaches where opportunities for vertical channel adjustment have been constrained.
- Watershed activities leading to debris flows and landslides that block the channel[20].

Estuaries

Direct causes

- Tide gates reduce the inflow and outflow of the tidal prism necessary to move sediment, organisms, and water and to maintain the temperature, salinity, nutrients and temperature characteristics of an estuary
- Dredging and dredge spoil disposal, estuary fill, levees, docks, bulkheads, log dumping and storage, and jetties eliminate or alter the configuration and type of estuarine habitat, substrate, surface cover, patterns of sedimentation and scour, and estuarine circulation.

Indirect causes

- Instream and watershed activities that contribute to accelerated estuary aggradation or incision resulting in the loss of estuarine function and habitat.
- Upstream water diversions, storage reservoirs, withdrawals, and other activities that disrupt surface and groundwater hydrology and limit or alter the influx of freshwater

4.3.2.2 Techniques to Restore Habitat Connectivity

Techniques used to restore habitat connectivity depend upon the type of habitat that has been isolated and the cause of its isolation. Providing a long-term, self-sustaining solution to the problem requires that the cause be addressed (e.g., removal of a barrier culvert) as opposed to simply treating the symptom (e.g., trap-and-haul fish to release them on the other side of the barrier culvert).

If habitat is in good condition, but is isolated from the main channel or adjacent reach by a direct cause, such as a man-made obstruction (e.g., a levee, dam, or culvert) or channel dredging, and the processes that otherwise maintain that habitat and its connection to the main channel are intact, then restoration efforts need only to address that direct cause of habitat isolation. Such techniques may include:

- Remove impassable culverts or replace them with non-barrier alternatives (see *Fish Passage* technique)
- Remove dams, diversions, and water control devices or modify them to accommodate fish passage
- Remove, breach, or relocate levees (see *Levee Removal and Modification*, and *Dedicating Land to the Preservation, Enhancement, and Restoration of Stream Habitat* techniques)
- Remove floodplain, estuary, or other fill that isolates the habitat
- Remove drainage systems that lower the local water table and drain nearby wetlands and ponds
- Stop dredging or otherwise manipulating the channel, remove artificial constraints on the channel (e.g., bank armor, channel lining, road crossings) and allow the channel to naturally recover to a self-sustaining condition (see *Bank Protection Construction, Modification, and Removal* technique). If recovery is unlikely to occur within the desired timeframe as a result of passive restoration efforts alone, or if land use imposes constraints on the outcome, planners may choose to accelerate natural recovery through actively modifying the channel to a more natural self-sustaining state (see *Channel Modification* technique). Note that if the original channel manipulation was conducted in response to channel instability, the cause of instability and its affect on the ecosystem and nearby land use will need to be assessed.

The probability of success for habitat reconnection projects such as those described above is moderate to high.

If the loss of habitat connectivity cannot be attributed to a direct cause, it is likely that the processes that naturally create and maintain the isolated habitat or the connection to that habitat have been disturbed. Restoration of habitat connectivity will require identification of disturbed processes (e.g., delivery of wood and sediment to the stream, stream flow regime) and the root cause(s) of their disturbance.

4.3.3 Restoring Habitat-Forming Processes

Restoration of degraded habitat requires that the root cause of degradation be identified and addressed if the treatment is to provide long-term, sustainable results[3] [4] . In doing so, benefits of the project can extend far beyond a target area or species and the probability of success in meeting long-term restoration goals is relatively high. Sometimes, the cause of degradation may be unequivocally attributed to a specific activity or occurrence within the stream reach (e.g., channelization, point-source discharge of contaminants). However, more often, habitat becomes degraded as a result of cumulative impacts from multiple activities and land uses occurring within the watershed. These activities collectively alter the habitat-forming processes, including the supply and transport of sediment, water, wood, solutes, and energy to streams. By focusing on restoring the processes responsible for forming, connecting, and maintaining stream habitat, rather than merely recreating a specific habitat feature, it’s possible to nurture the watershed’s recovery to a functional dynamic ecosystem that supports a range of habitat conditions and a diverse biological community over the long term .

Restoring stream processes requires an assessment to determine which processes have been altered, how, where, and to what degree [5 9]. This, in turn, requires knowledge of how an ecosystem functions and the dominant factors responsible for its structure, composition, and productivity[3 6] . Past, present, and future activities and conditions must be considered. Such an assessment must be conducted at a watershed scale, unless the cause of impairment is obviously limited to a smaller scale (refer to Chapter 3, *Stream Habitat Assessment*, in this guideline for further information on assessments). Consider whether disruption of each process is permanent (e.g., a dam) or temporary (e.g., mass wasting from a clear-cut hill slope that will recover over time). If temporary, how long will it take to recover (e.g., how long will it take for a forest to grow back to an adequate size, extent, and composition to become a functional source of shade, large wood, and bank stability to the stream)? Are further alterations expected under the current management plan (e.g., is the watershed subject to active, on-going expansion of development, timber harvest, or agriculture)? The reader should note that the interaction of processes and how they shape habitat is complex and often unpredictable. Our frame of reference is often limited. For instance, we may not have observed processes at play under particular flow events such as a flood with a 500-year recurrence interval. Similarly, we may not fully appreciate how significantly runoff patterns have changed with urbanization.

Once the activities causing habitat degradation are identified, the first step to restoring habitat is to halt those activities or modify them so as to minimize their impacts, prevent further degradation, and allow natural recovery to occur. This approach is referred to as “passive” restoration. It may include such activities as implementing best management practices 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.

Ecosystems have the ability to recover from disturbance. Native species evolved with the natural (historic) disturbance regime of their stream system and have developed a suite of adaptations for survival[21]. Their response to disturbance, and the rate and likelihood of ecosystem recovery, depends on the duration, intensity, extent, distribution, and frequency of the disturbance; the sensitivity of the channel[22]; the abundance and distribution of suitable habitat; and the abundance, distribution, sensitivity and adaptive capability of the surviving populations. As cited by Reeves et al., Yount and Neimi[23] describe two types of disturbance, “pulse” and “press”. A pulse disturbance occurs within the bounds of historic natural disturbance regimes and so, within the limits of conditions in which the ecosystem has evolved and from which it can recover. Press disturbance, on the other hand, pushes conditions to a state outside their normal range. A stream will respond and adjust to these new conditions and eventually reach a new equilibrium, provided it is not subjected to additional impacts and that the channel is allowed to evolve (i.e., the channel is allowed to migrate and its bed and banks to erode). Populations of certain affected species that are unable to adapt to these new conditions will decline while those of others that are favored by the new set of conditions will rise, thus fostering ecosystem succession. Ecosystem recovery to prior or a new set of conditions could take years, decades, or centuries depending on the extent and nature of changes in the watershed. Furthermore, the start time for recovery will be reset following every disturbance.

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 should be considered. Such activities may include road removal, reconstruction, and maintenance; revegetation; weed removal; reintroduction of species that have been extirpated from the area; removal of dams; removal of bank armoring; or removal or breeching of levees. Although some activities might occur instream (e.g., dam removal), the majority of activities necessary to restore stream habitat-forming processes will occur upslope.

In highly altered systems, the ability to restore all habitat-forming processes is limited. A more realistic goal in such environments is to restore as many processes as possible within given land-use constraints to create a self-sustaining potential biological community. Partial restoration of processes may have higher long-term costs if further activities are necessary to maintain habitat conditions in the long-term.

Because of limited resources, it is not feasible or necessary to restore all disrupted processes throughout all watersheds or ecosystems simultaneously to achieve long-term goals. Restoration will likely occur in stages. Prioritization of watersheds and prioritization of actions within each watershed is recommended in order to target the dominant factors that prevent the reestablishment of pre-disturbance ecological conditions. Kauffman et al. and the Natural Research Council suggest prioritizing target systems by focusing first on those with a greater potential for recovery at the least amount of risk and cost. Then focusing on those systems requiring greater intervention for recovery. Enhancement activities at sites that are incapable of restoration in the true sense of the word should be given lowest priority. The sequence suggested above is simply a guideline. Restoration, rehabilitation, or enhancement of degraded habitat for species near extinction, as well as locally-defined restoration priorities, may alter the actual sequence of restoration activities[3 9]. However, such considerations should not alter the types of activities undertaken in the overall restoration plan, as they are all necessary to collectively achieve the ultimate goal of reestablishing a dynamic, self-sustaining system.

Active and passive restoration of habitat-forming processes may or may not provide immediate habitat benefits, but should provide long-term benefits. This approach can be used in combination with direct modification or creation of habitat to provide immediate as well as long-term benefits.

4.3.3.1 Managed Inputs of Material to a Channel

There may be instances where processes that are essential to ecosystem health have been disrupted and cannot recover to pre-disturbance levels in the near-future (e.g., it will take decades for a newly planted riparian zone to provide a source of large wood to the stream), or in the long term (e.g., a dam will block downstream passage of bedload until it its removal, reduced numbers of salmon returning to their natal stream decrease the supply of nutrients provided by their rotting carcasses). Where this occurs, some processes may be artificially simulated through a deliberate, managed input of material to the stream. This approach is most commonly used to supplement the supply of sediment, wood, or nutrients to the stream, although instream flow

requirements could also be considered to fall under this category. For the purpose of this guideline, supplementation is defined as the direct feeding of materials, including gravel and wood, into a channel without specialized placement.
Material supplementation is only effective in situations where stream processes have not been altered to the point of impacting material transport and delivery. Material distribution often relies on flow events. Consequently, this approach will not provide immediate benefits to stream habitat. After a supplementation project has been implemented, 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. There is also a risk of undesirable consequences if the material gets deposited where it compromises infrastructure, property, public safety, or valuable habitat.

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. Supplementation should be suspended when the natural supply processes have recovered (e.g., the riparian zone is capable once again of providing a source of large wood to the system). 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.

4.3.4 Modifying and Creating Stream Habitats

Direct creation of habitats involves actively constructing a specific habitat feature to address an identified or perceived problem or deficiency in the system. For instance, it may involve constructing a salmonid spawning pad, excavating pools, constructing large wood complexes, reestablishing pre-disturbance channel morphology, or constructing a side channel or wetland. This approach is often undertaken for in-kind mitigation to offset the deleterious impacts of other construction projects or land use activities. It is also used to enhance, rehabilitate, or restore habitat conditions. But planners and designers should note that the success rate associated with creating habitats is highly variable[5 17]. There is a tendency with this approach to over-emphasize habitat benefits for a specific target species and to not give full consideration to the habitat needs of other fish and wildlife species also present in the system. As a result, the potential benefits of created habitats may be limited in comparison to natural habitats. Emphasis on *ecosystem* restoration, which *supports* target species may be more effective than creation of site-specific habitat elements that directly benefit target species.

Habitat modification and creation projects are sometimes implemented without regard to whether or not the constructed habitat is or was a natural feature in the landscape and, similarly, without regard to whether or not the processes that naturally create and maintain that habitat in the long-term are present. Consequently, the project may simply create form without function and benefits, if achieved, may be short-lived without regular, long-term maintenance. For example, constructing a salmonid spawning pad in a stream using optimal “spawning-sized material” will be a wasted effort if the material is too small to be maintained in the reach and gets transported downstream during the first storm event. Such measures may even harm the very resource they are intended to benefit if they lure fish to spawn there only to have all their eggs wash out. In addition to simply not providing the benefits being sought, projects undertaken without knowledge of the condition of the stream and watershed and without understanding of the relationship between stream variables (channel slope, width, sinuosity, velocity, sediment transport, etc.) may have unintended consequences by causing channel avulsion, meander migration, or bed and bank erosion or deposition. Such consequences may be advantageous, harmful, or have no significant effect on biota, infrastructure, property, and public safety, depending on the circumstances. Even where habitat-forming processes are considered, project success may be inhibited by a limited understanding of the complexity of process interactions; the limited accuracy of models, predictions, and estimates; the presence of non-native species; the unpredictable behavior of organisms; and unforeseen circumstances. In summary, it can be difficult to predict what a constructed habitat will be like and what species will benefit[24]. Developing and defining realistic goals and objectives is essential.

The value of constructed habitat will be enhanced when implemented in conjunction with other activities that address the root cause of habitat degradation. Constructed habitats complement efforts to restore disrupted habitat-forming processes by providing short-term benefits during the years, decades, or longer timeframes necessary for certain processes to fully recover. For instance, adding large wood to a stream channel in a historically forested watershed can provide short-term benefits while the riparian zone is recovering from past land use activities. However, if wood is added to the stream in the absence of activities that restore a long-term source of wood to the channel, benefits will last only until the wood decays or floats away.

Modifying or creating stream habitat may also be appropriate to enhance instream conditions when the natural processes that create and maintain habitat have been severely constrained or eliminated and cannot be effectively restored. This is most commonly the case in urban settings, but may also be a consequence of hydro-modification, tide gates, levees, bank armoring, or similar structures where current land use prevents their removal or modification. The longevity of created habitat in such settings will depend largely on the stability of the channel and the watershed. While some short-lived habitat enhancement measures in dynamic systems may be appropriate in certain circumstances, created habitat will provide the longest benefit to relatively stable channels and watersheds that are not undergoing rapid change.

The process of habitat creation, evolution, and destruction in a natural system is spatially and temporally dynamic. Therefore, the quantity, quality, and distribution of specific habitats are constantly changing. Creation of certain habitat types, such as plunge pools, using rigid, fixed instream structures, such as log weirs, constrictors, or deflectors, is less common in modern enhancement projects than in the past. Experience has demonstrated that such habitats are often short-lived and less sustainable than those created using "process-based" or "land use-based” recovery actions. Instream structures typically treat only the symptoms of the problem, not the cause. In addition, 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.

Habitat creation and modification techniques can provide immediate benefits to affected fish and wildlife. However, projects that rely on hydraulic forces to reshape the channel bedform and sort sediment may take months or years to achieve their full potential.

4.4 Factors to Consider When Identifying and Selecting Ecosystem Recovery Alternatives

Habitat restoration projects will be more successful at producing desired habitat and ecological benefits in the long-term if the implications of various alternatives are carefully considered during the selection process. Every watershed is unique in terms of its restoration objectives, limitations, and priorities. As a result, no single set of selection criteria can be developed and universally applied. Common factors to consider when selecting and prioritizing alternatives are described below and include existing or future watershed condition; project scale; the time frame necessary to achieve desired results; the longevity of benefits; operations and maintenance needs; risks associated with implementation; uncertainty of achieving desired results; and cost effectiveness.

Consider the "do-ability" and "durability" of the project. "Do-ability" refers to the degree to which an approach is technically and financially sound and feasible. Is the design likely to achieve restoration goals and objectives? Are equipment, materials, labor, and funding available for project implementation and necessary monitoring, operations, and maintenance (weed control, irrigation, repairs)? Has the responsibility for necessary post-construction operations, monitoring and maintenance been clearly assigned? Is the timing right? What permit conditions, bid package provisions, contract provisions, expert construction oversight, contingency planning, environmental monitoring, and inspection requirements are in place to assure the project is completed as designed, and that the desired future condition is achieved?

"Durability" refers to the probability that the desired future condition will occur and persist in the landscape. Can the design be supported by existing and anticipated future stream and watershed conditions? Will it promote or maintain a level of resiliency to disturbance or will it require repeat application to provide long-term benefits? Does the proposal address the cause of the problem or merely treat its symptoms? Have necessary complementary projects and land management been implemented to maximize the longevity of results (e.g., upland slope stabilization to reduce fines delivered to the stream prior to implementing salmonid spawning gravel cleaning)? Consideration of all aspects of do-ability and durability will help frame the possible alternatives from which final restoration projects and tasks may be selected.

4.4.1 Existing or Future Watershed Condition

Habitat restoration, ideally, will result in "natural" conditions where natural geomorphic and ecological processes maintain habitat function. However, "natural" conditions must be viewed in the context of current and future conditions of land use and development within a watershed. Natural, in the purest sense of pristine, pre-settlement condition, may be impossible to achieve given permanent or predicted landscape changes. Thus, desired conditions must be considered within the context of realistic rehabilitation of site, reach, and watershed landscapes.

When selecting projects 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 the creation of a channel system which promotes natural process and function under the new hydrologic and sediment regime.

4.4.2 Scale of Project

Stream habitat restoration may be implemented at virtually any scale, ranging from placement of a single habitat structure, to alteration of watershed-wide land use practices. The later will generally necessitate a conscious decision to alter land use and management practices, which have political, social, and economic implications.

The appropriate scale of the project or series of projects will be highly dependent upon restoration objectives, the size of the stream in question, and the scale of the problem and its cause. 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 some minimum 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 decline in fecal coliform levels expected in response to that 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.

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 an achievable project is dictated 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 properties, careful consideration must to given to whether such limited application of the treatment will be capable of achieving project goals. Logistics make it difficult to apply such a treatment on an incremental property-by-property basis as additional landowners choose to participate over time.

Consider the full extent of project effects and contact all potentially affected landowners early in project planning in order to address their concerns and document project constraints and ecological benefits. The effects of certain restoration actions may extend beyond the immediate localized area of treatment. For instance, a proposal to raise the profile of an incised stream to reconnect it with its floodplain may cause flooding of neighboring property; a fact that must be given careful consideration during project planning and deign.

The size of the stream will not likely determine the scope of the project. Either a small stream or a large river with systemic habitat degradation resulting from watershed scale impacts may require a watershed-scale approach to restoring disturbed processes. Alternatively, a site-specific problem on a large river or small stream may be appropriately remedied through a site-specific technique. Thus, the size of the stream or river dictates the scale of the effort, but not necessarily the scope of the project.

4.4.3 Delay to Results

Healthy natural systems are the product of complex interactions of multiple variables over time.

Restoration activities give a stream a starting point from which further interaction, and time, will bring about natural function and health. Realistic objectives for restoration activities will likely have to accept some lag time between completion of physical restoration activities and realization of full recovery potential, especially when passive restoration techniques are employed. Furthermore, different processes and functional components will recover or regenerate at different rates:

- Food (macroinvertebrate and plant) production may be restored on a scale of months to years following restoration activities (and associated disturbance).
- Physical habitat features (pools, rearing, etc.) may be immediately available or may depend on high flow events to achieve desired function (such as sorting or scouring of bed substrate). As a result, the desired function may not be achieved until after a number of seasons or years.
- Vegetation may require decades to centuries to recover. While riparian shrub species may reach maturity in both size and composition within decades, riparian forests may require centuries for full recovery.
- Geomorphic processes may be restored within a time frame of immediate recovery to years.

Oftentimes, passive restoration is all that is necessary for successful long-term ecosystem recovery and it 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 there may be lost opportunity for habitat function and value. 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.

4.4.4 Durability and Longevity

Varying approaches to habitat restoration will have varying durability and longevity. Durability refers to a specific feature's ability to withstand the various forces that it is subjected to. For example, a log jam may be designed to withstand a moderate flow (low durability) or an extreme flow (high durability). Longevity refers to the duration of benefit gained by restorative action, or quite simply, how long it will last.

The ideal objective is to strive for self-sustaining and adaptive projects, thereby creating indefinite longevity. Activities that restore the natural rates and types of habitat-forming processes rather than creating specific habitats will generally result in greater longevity. 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 which may destabilize them. Because the magnitude of hydrologic events is a largely unpredictable variable, 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. For example, a log jam placed to create scour, deposition and provide cover and spawning habitat may be left high and dry by a natural shift in channel location.

The functional life of restoration projects will be influenced by:

- Chance and random geologic and hydrologic events, including erosion, mass wasting events, and floods;
- Land use and land tenure arrangements, including changes in land use regulations, easements, and ownership; and
- Stream and watershed stability.

4.4.5 Operations and Maintenance Needs

An emphasis on self-sustaining habitat restoration will promote development of projects that are operation and maintenance-free in the long term. The best restoration project design and approach, however, may still require some period of operation and maintenance to maximize the rate and likelihood of recovery. Operations are activities that are anticipated and required by design for proper function of implemented projects. Examples of operations may include weeding and irrigation of planted materials, management of flows from impoundments, managed grazing of riparian corridors, inputs of gravels, wood, or nutrients in systems where the natural input of such material has been disrupted, or the removal of any temporary project construction components such as erosion control measures. Maintenance is any activity that becomes necessary through normal degradation or as a result of unexpected conditions before a project becomes self-sufficient. Examples of maintenance may include the repair or replacement of damaged structures or failed project components.

Operations and maintenance requirements are project- and site-specific considerations and will be dictated by both anticipated and unanticipated conditions and events. Typical operations and maintenance requirements are provided for each technique described in Chapter 5 of this guideline entitled *Designing and Implementing Stream Habitat Restoration Techniques*. Maintenance needs are highest when using a managed inputs approach or a direct habitat creation approach. Maintenance needs increase when the restoration design does not take into account existing and future watershed conditions, the location of the project within the stream network, or when design treats only the symptom and not the cause of a problem.

4.4.6 Risk Assessment

Different approaches to achieving a given project objective may involve varying degrees of risk to public safety, natural resources, property, or infrastructure. They may also offer varying certainties for success. These risks and the probability for success must be weighed against other project considerations when selecting and prioritizing projects.

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. The following detrimental environmental impacts commonly occur either on-site or off-site as a result of project implementation:

- Aquatic impacts associated with construction and equipment:
    - Water quality impacts such as increased turbidity or fuel spills

    - Disturbance of existing aquatic life and habitat.
  - Riparian and terrestrial impacts, particularly those associated with access and staging areas for any construction components of the project.
    - Soil compaction and disturbance
    - Removal of vegetation, snags, wood, and duff layer
    - Spreading noxious weeds
    - Disturbance of wildlife
  - Marine impacts may be realized if the project scale includes a significant portion of a watershed or if it is in close proximity to marine environments.

Disturbance can be greatly minimized if the project is properly designed and constructed, and if ongoing monitoring and maintenance is conducted. For example, access to a stream channel may require transport of materials and equipment across a healthy riparian plant community. In such a case, extreme measures may be necessary to minimize disturbance, and to reclaim all impacts, including soil decompaction, reestablishment of vegetation, and control of noxious weeds that colonize the disturbed soil.

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 log jam 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 in a stream may increase the roughness of the channel or constrict flow such that upstream sediment deposition and bank erosion occurs and compromises adjacent roadways through undermining and increased flooding. Risks that are commonly associated with specific techniques are discussed in the individual technique descriptions included in Chapter 5 of this guideline.

Certainty of success is the likelihood that a project will meet its objective. The possibility that a project will not meet its objectives can be considered a risk. Certainty varies among techniques, the level of design effort, the information available, and familiarity and experience of the designer with the technique.

Following are example situations that may result in higher risk or reduced certainty of success:
- Failure to perform thorough reach and watershed assessments can reduce the certainty of success and increase risk if stream and watershed conditions are not fully understood.
- Projects that address problem symptoms rather than their cause have less certainty of success compared with projects that address the root cause of the problem.
- Instream activities generally pose higher risks than those occurring outside the stream channel. Proximity to infrastructure can increase risk associated with instream activities.
- Certainty of success for passive or managed input approaches to restoration may be less than that associated with a more active approach.

4.4.7 Cost Effectiveness

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. A benefit-cost 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 value of the benefit. Costs can usually be readily determined in dollar units; however, benefits are often impossible to evaluate quantitatively. Benefits are usually based on anticipated recovery of habitat and production values that don't easily have a monetary worth. Additionally, there may be ancillary benefits, such as a stabilized channel that prevents the future need for rock armoring or dredging, that cannot be easily measured. In addition, not all projects are subject to cost effectiveness considerations; fish passage is required by law, independent of cost: benefit considerations, although cost: benefit will certainly be considered in project prioritization.

As an alternative to benefit-cost analysis, the National Research Council recommends using an opportunity cost assessment to determine the appropriate level of restoration. In an opportunity cost assessment, a comprehensive list of benefits is compiled for every restoration alternative under consideration, but no attempt is made to assign those benefits any particular value. Instead, interested parties responsible for evaluating and prioritizing proposed restoration projects make their decision by weighing the qualitative list of anticipated benefits against the estimated opportunity cost, risks, and other decision criteria associated with each project or restoration task under consideration. Opportunity costs are quantitative and include not only direct financial payouts (for assessment, design, construction, long-term monitoring, operation, and maintenance requirements), but also the current benefits derived from existing conditions that will be lost following implementation of the restoration project (e.g., land set aside for riparian restoration will displace that available for livestock grazing or other land use activities). The primary benefit of conducting an opportunity cost assessment over a cost-benefit analysis is that it is not necessary to seek agreement on a single method of assigning value to various benefits. The value placed upon each of these benefits may differ among stakeholders and change over time or from watershed to watershed in response to the needs of the resource, social preference, and lessons learned regarding the effectiveness of various techniques.

4.5 Approaches to Achieving Common Restoration Goals

Processes that determine the abundance, diversity, form, and quality of stream habitat are the supply and transport of sediment, water, solutes (including nutrients and contaminants), organic matter (ranging from large wood to detritus), and energy (light and heat) to the stream. For this reason, common restoration goals included in the following discussion are:

- Restoring Sediment Supply
- Restoring Stream Flow Regime
- Restoring Energy Inputs to the Stream, and
- Restoring Water Quality

Restoring large wood to the stream is discussed at length in the *Large Wood and Log Jams* technique.

Other more site- and species-specific restoration goals are also included to illustrate their dependence on restoring habitat-forming processes. These include:

- Restoring Incised Channels
- Restoring Aggrading Channels

- Restoring Salmonid Spawning Habitat, and
- Restoring Salmonid Rearing Habitat

The focus of the discussion is on addressing anthropogenic (human-made) causes of stream and habitat degradation. Potential causes of degradation that are identified in the text are not exhaustive but are meant to provide the reader with a sense of the variety and types of problems that may need to be addressed. It is also intended to reinforce the need to conduct a site, reach, and/or watershed assessment before proceeding to restoration design.

Many of the techniques listed below provide long-lasting benefits by restoring disrupted landscape processes while others provide immediate but short-term benefits. Some provide more predictable results than others. These techniques are broad suggestions offered as guidance and are not intended to limit the designer. Actual designs 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*. To achieve long-term stream habitat restoration, the root cause of habitat degradation must be addressed, not just the symptoms. All restoration work should be coupled with a change in watershed management to prevent further degradation and maximize the benefits and longevity of the restoration project.

4.5.1 Restoring Sediment Supply

Sediment is the product of erosion and may be derived from within a stream channel via bed and bank erosion and from sources outside the channel via surface erosion and mass wasting events (slumps, landslides, debris flows, and soil creep). Erosion tends to be episodic and linked to disturbance and weather. Erosion processes and rates (see Chapter 2 of this guideline) are controlled by climate, topography, soil type and organic matter content, soil depth, soil saturation, and surface cover. As a result of these factors, the type and volume of sediment delivered to a stream varies over both space and time.

Once sediment enters the stream, it is subject to transport, deposition within the channel or floodplain, and re-entrainment by flowing water. The sediment transport capacity of a stream is related to channel hydraulics and geometry. Moving water exerts a force on the bed and banks of the channel. That force, referred to as shear stress, moves sediment grains downstream. Shear stress is a function of the slope of the water surface and the hydraulic radius of the channel (cross-sectional area divided by the cross–sectional length of the wetted channel). In very wide shallow channels, the hydraulic radius approximates the depth of flow. Since the shear stress required for sediment transport increases with the size of the particle, smaller particles move more easily and can travel longer distances than larger particles. Shear stress and sediment transport are discussed more thoroughly in the *Sediment Transport* and *Hydraulics* appendices. The supply of sediment relative to the sediment transport capacity of the stream can affect the stability of a channel, causing channel aggradation if the volume delivered exceeds the available sediment transport capacity, and causing channel incision if the volume is insufficient[25].

The sediment load transported by stream flow is comprised of a suspended load and a bedload. The suspended load refers to sediment that is carried and supported by flow. It generally consists of relatively fine material (clay and silt sized particles). Bedload consists of larger particles that are pushed along by the flow but are supported by contact with the bed of the stream. Suspended sediment plays a significant role in water quality and affects the ability of fish and other organisms to live in the stream[26]. It also provides a source of nutrients, silt, and organic material to floodplains[2] [27]. Bedload transport dominates channel morphology; it determines the nature of the bed material and provides a source for its renewal.

Sediment size, sorting, volume, and transport dynamics exert a major control on channel form, which describes the pattern, cross-section, and profile of the stream as well as its internal relief. Channel form controls the physical state of the stream (e.g., temperature, depth, substrate, and velocity) that collectively influence the abundance and diversity of aquatic life[28]. The size and sorting of bed material influence plants, fish, macroinvertebrates, and other stream life. Coarse bed materials (e.g., gravel, cobble, boulders) have a higher porosity than fine sediments (e.g., sand, silt, clay); likewise, well-sorted materials have a higher porosity than materials that are poorly sorted. Higher porosities allow for higher rates of interstitial flow[29] and yield greater amounts of interstitial habitat. Such habitat is critical to macroinvertebrates, most of which spend the majority of their lives attached to bed material[30], as well as to fish and wildlife that feed on macroinvertebrates and that spawn or rear in the bed. The preferred substrate composition varies among species.

Sediment supply is also a critical element of marine and lacustrine habitats. It is hard to separate estuarine habitats from river processes so they are mentioned here. However, the focus of this guideline is riverine habitats. It is intended that a future guideline within the Aquatic Habitat Guideline program series will focus on marine and estuarine habitat restoration.

4.5.1.1 Activities that Impact Sediment Supply

The sediment supplied to a stream varies naturally over time due to climatic variability and periodic natural events such as landslides, debris flows, wildfire, wind, and volcanic eruptions. But anthropogenic influences, stemming from land use and stream alterations, can significantly alter the rate and types of sediment supplied to the stream and, thus, severely impact the stream and aquatic habitat. Such influences include human activities that affect the sediment supply from the watershed and those that affect the sediment supply and transport from upstream reaches and tributaries. These include, but are not limited to:

Direct Causes:

- Direct dumping or stockpiling of material in the active channel or floodplain increases the supply of readily erodible material to the stream.
- Removal of bedload material from the stream (e.g., instream gravel mining or dredging operations) reduces the supply of sediment to the downstream reach and may lower the baseline elevation for the upstream reach. These activities can cause upstream and downstream channel incision[31].
- Instream activities, such as operation of equipment and vehicles within a stream channel, yarding of logs through a channel, and foot traffic by livestock, people and pets, stir up sediment in the vicinity of the activity, increasing its availability for downstream transport.

Indirect Causes:

- Land-use activities that, through alteration of soil structure, vegetation, topography, and hydrology, significantly 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 **Table 4.5.2** for further information on land use activities that impact stream sediment supply.

- Riparian management practices leading to the removal or alteration of riparian vegetation. Vegetated riparian zones trap sediment contained in surface runoff and floodwater and provide streambank resistance to the erosive forces of flowing water. Loss of riparian vegetation may increase the supply of sediment to the stream via surface runoff and accelerated rates of bank erosion. Loss of riparian vegetation can also lead to channel widening that reduces the sediment transport capacity of the reach.
- Channel modifications that alter the slope or cross-section of the channel, thereby altering its sediment transport capacity. Increases in the sediment transport capacity of a reach (by channel dredging, narrowing, steepening, or straightening; levee construction; or removal of wood or other roughness elements) may increase bed and bank erosion in the affected and upstream channel reaches, resulting in an increased supply of sediment downstream. Decreases in the sediment transport capacity of a reach (by channel widening or flattening, installation of channel roughness elements, or by levee construction in tidal areas) may cause aggradation in the affected and upstream channel reaches, resulting in a decreased supply of sediment downstream.
- Land use change and flow management practices within the watershed that alter the flow regime of the stream, thereby altering its sediment transport capacity (by changing the depth of flow) and the degree of connectivity between the channel and its floodplain. Depending on their nature and scale, altered flow regimes (among other causes) may cause channel widening or incision, which can supply extraordinary amounts of sediment to the downstream channel, or they may cause channel aggradation, decreasing the downstream sediment supply. They may also alter the level of the surrounding water table that directly impacts the extent and species composition of riparian vegetation, which, in turn, influences the stability of the banks and sediment detention from surface runoff and floodwater. Land uses and flow management practices that may alter streamflow regimes are discussed under Chapter 4.5.2, *Restoring Stream Flow Regime*.
- Stream bank protection and armoring reduce the natural recruitment of sediment, including gravels, to the stream.
- Capping floodplain sediment sources by impervious surfaces prevents the natural recruitment of sediment during flood events.
- Activities that directly or indirectly reduce natural sediment storage sites within the stream corridor increase the supply of sediment to adjacent and downstream channel reaches. Such natural storage sites include floodplains, backwater areas, alluvial fans, bars, deltas, wood accumulations, and bank, bed, and floodplain vegetation.
- Installation or removal of channel obstructions and constrictions that increase channel roughness, create backwater, physically intercept downstream sediment transport, and reduce the supply of sediment to downstream reaches. Such structures include dams, undersized culverts, boulders, large wood, and beaver dams, among others.

4.5.1.2 Techniques to Restore Sediment Supply

The most effective long-term solution to restoring stream sediment supply must address the cause of altered supply, not just the symptom. Most causes of altered sediment supply are indirect in nature and many derive from non-point sources. As a result, restoration will likely need to occur upstream of the affected stream reach and/or outside the channel. Appropriate techniques used to restore the historic sediment supply to the channel may include:

- To restore sediment supply that has been lost
  - Stop instream and floodplain dredging and sand and gravel mining operations
  - Remove or modify existing bank protection. This may require land use modification (see *Bank Protection Construction, Modification, and Removal* and *Dedicating Land and Water to the Preservation, Enhancement, and Restoration of Stream Habitat* techniques).
  - Restore sediment transport from upstream reaches by removing or modifying upstream dams or by modifying their operation. Management of sediment stored in dammed reservoirs is a key element of dam removal design.
  - Artificially place bed material in discrete locations or implement a periodic or continuous gravel supplementation/feeding plan for an affected reach (see *Salmonid Spawning Gravel Cleaning and Placement* technique). Note that these techniques will provide only short-term benefits without periodic repetition. They do not address the source of the problem, only the symptom.
  - Restore the sediment transport capacity of a disturbed upstream channel. The sediment transport capacity may have been reduced by a decrease in channel slope, altered channel cross-section, altered streamflow regime, or by installation of channel obstructions and constrictions that create roughness, backwater or physically intercept downstream sediment transport. See *Channel Modification* technique, *General Design and Construction Considerations for Instream Structures*, and Chapter 4.5.2, *Restoring Stream Flow Regime*.
- To reduce the excessive supply of sediment to the stream
  - Stop dumping and stockpiling sediment in the active channel or floodplain
  - Prevent or minimize direct access of livestock, people, and vehicles to the channel
  - Implement upland best management practices for existing land use activities within the watershed and/or modify land use to increase upland stability and to reduce surface erosion and mass wasting events (see *Dedicating Land and Water to the Preservation, Enhancement, and Restoration of Stream Habitat* technique and Chapter 4.5.4, *Restoring Water Quality*). Road removal, reconstruction, and maintenance and replacement of undersized culverts with larger culverts or bridges reduce the risk of landslides, debris flows, and surface erosion.
  - Restore the sediment transport capacity of a disturbed upstream channel. The sediment transport capacity may have been raised by an increase in channel slope, altered channel cross-section, loss of floodplain connectivity, an altered streamflow regime, or by removal of channel obstructions and constrictions that create backwater or physically intercept downstream sediment transport. See *Channel Modification, Levee Removal and Modification*, and *General Design and Construction Considerations for Instream Structures* techniques, and Chapter 4.5.2, *Restoring Stream Flow Regime*.
  - Restore natural sediment detention within the stream corridor by removing

channel constraints (e.g., bank protection and levees) and ceasing activities (e.g., dredging, straightening) that simplify the channel; restoring natural channel geometry, large wood and other roughness elements to the stream, riparian vegetation, and historic floodplain connections; and reintroducing beavers to the stream corridor. See Chapter 4.5.2, *Restoring Stream Flow Regime* and the *General Design and Construction Considerations for Instream Structures, Large Wood and Log Jams, Riparian Restoration and Management, Channel Modification, Bank Protection Construction, Modification, and Removal, Levee Removal and Modification, Beaver Reintroduction,* and *Dedicating Land and Water to the Preservation, Enhancement, and Restoration of Stream Habitat* techniques.

- Construct sediment detention basins throughout the watershed or within the stream to intercept sediment transport. Note that sediment detention basins do not address the source of the problem, only the symptom, and will provide only short-term benefits without regular maintenance. Use of instream sediment detention basins has limited application (see *Instream Sediment Detention Basins* technique).
- Restore or increase the width and extent of vegetated riparian zone to increase the detention of sediment from surface runoff and floodwater and increase bank stability (see *Riparian Restoration and Management* technique).
- Implement bank protection techniques on severely eroding banks. Note that this technique is an acceptable habitat restoration technique only in limited applications (see *Bank Protection Construction, Modification, and Removal* technique).

4.5.2 Restoring Stream Flow Regime

According to the National Research Council, flow regime restoration is one of the most neglected aspects of stream restoration, despite the fact that streamflow is a driving force with regards to channel form and a key element of aquatic habitat and habitat connectivity. Stream flow provides the energy needed to transport water, sediment, organic material, nutrients, and thermal energy within the stream corridor[32]. The flow that transports the largest amount of bedload over time is referred to as the “effective” discharge. This discharge has the most influence on creating and maintaining alluvial stream channels and the physical habitat they provide. In streams that are neither incised nor actively aggrading, effective discharge typically fills the channel to the top of the banks[33] . See the *Hydrology* appendix for further discussion regarding effective discharge.

Streamflow 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 [14 21].

Flow determines the amount of available aquatic habitat. At its simplest, aquatic habitat is living space or volume; volume increases with flow. 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[14]. 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 may limit the amount of quality habitat available to fish and wildlife. Higher-than-normal flows can flush fish, wood, food, and substrate out of a reach. Lower-than-normal flows 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[34]. 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*.

In addition to the ecological benefits, streamflow serves humans in many ways. These include consumptive uses (such as irrigation and domestic and industrial water supply), hydroelectric power generation, navigation, and recreational activities (such as boating, rafting, swimming, water skiing, and kayaking). The flow level in a stream also influences aesthetic and scenic qualities of natural settings.

4.5.2.1 Activities that Impact Natural Stream Flow Regime

Land use and water management activities can alter the magnitude, timing, and duration of flow in streams. The most common causes of altered flow regime include:

Direct causes

- Controlled releases from dams that optimize the availability of water for power production, irrigation, water supply, recreation, or flood control.
- Water withdrawals from the stream and aquifer for power production, irrigation, and water supply. Where water withdrawn from the stream is stored for a period of time and later released back into it, flow regimes may shift in time[14], possibly causing high flows during historic low flow periods and low flows during historic highs. This can have a major impact on aquatic biota and riparian vegetation.

Indirect Causes

- Loss of water retention and acceleration of runoff in the watershed. Loss of retention combined with accelerated runoff typically increases the frequency and magnitude of flood peaks and reduces the availability of water to streams during low flow (base flow) periods. Loss of water retention and acceleration of runoff may be caused by:

  - Altered land cover (e.g., removal of native vegetation, increased impervious surface area) due to development, road construction, timber harvest, and agriculture, among others.
  - Compaction of soils throughout the watershed.
  - Construction of drainage networks to dry wetlands and floodplains for agriculture, development, and other land uses. This may also lower the water table and surface elevation of nearby waterbodies.
  - Traditional stormwater management practices that focus on getting water off the land and into the streams as quickly as possible to reduce localized flooding.
  - Loss of floodplains and isolation of streams from their floodplains due to levee construction, floodplain fill, channelization activities, and channel incision. These activities reduce floodplain storage during high flow events, thereby increasing flow within and downstream of the affected reach in non-tidal channels.

4.5.2.2 Techniques to Restore Stream Flow Regime

With the exception of flow regulation of dams, 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.

- Techniques to Increase Base Flow
  - Remove dams, modify dam impoundments, or modify the water release management plan
  - Reduce water withdrawal/diversion
    - Reduce water consumption
      - Reduce irrigation needs by replacing traditional crops and landscapes that require large amounts of supplemental water with ones whose needs more closely match natural precipitation patterns (including use of native plants)
      - Improve irrigation practices and systems to maximize their efficiency
      - Decrease energy demands (Washington is primarily dependent upon hydroelectric power) and use alternative energy sources
      - Improve soil water retention (organics, mulch)
      - Use water efficient appliances and reduce non-essential water use
    - Improve efficiency of water delivery systems (e.g., fixing leaks and using systems that minimize loss of water to evaporation and infiltration)
  - Increase stormwater retention and groundwater recharge
    - Improve stormwater management
    - Reduce and limit the amount of impervious surfaces in the watershed
      - Change land use practices and zoning regulations to limit the allowable percent of impervious surface in the watershed

      - Decommission roads
      - Use pervious pavement alternatives where feasible
    - Minimize the extent and degree of soil compaction
    - Restore stream connectivity to floodplains (see *Channel Modification, Levee Removal and Modification, Dedicating Land to the Preservation, Enhancement, and Restoration of Stream Habitat* techniques)
    - Revegetate denuded areas within the watershed
    - Protect, restore, and create wetlands and other infiltration areas
- Techniques to Restore the Magnitude and Frequency of Peak Flow Events
  - Remove dam, modify dam impoundments, or modify the water release management plan
  - Increase stormwater retention and groundwater recharge (as outlined above)
- Techniques to Restore the Natural Flow Regime (distribution of flow over time)
  - Remove dam, modify dam impoundments, or modify the water release management plan
  - Restore base flow (as outlined above)
  - Restore peak flow magnitude and frequency (as outlined above)

4.5.3 Restoring Energy Inputs to the Stream

[This section consists strictly of notes and is incomplete at this time.]

Sources of light and heat to the stream are controlled primarily by climate, the degree of shade (from vegetation, hillsides, buildings) and the source of water (groundwater is typically cooler than surface water in the summer, and warmer than surface water in the winter; the temperature of stormwater, irrigation returns, and other discharges may differ significantly from that of the stream). The effect of light and heat to the stream is controlled by water width, depth, velocity, substrate, and turbidity (as turbidity increases, light penetration decreases). Temperature of the stream may be elevated or suppressed by relatively warm or cool discharges from irrigation returns, industrial, stormwater, and other discharges, and temp of other waterbodies connected to the stream. Urban areas tend to be warmer than rural areas (pavement, concrete, brick, etc. retain heat). Loss of connectivity with hyporheic zone can also alter the temperature of the stream.

Reference: Spence, B. C., G. A. Lonnicky, R. M. Hughes and R. P. Novizki. 1995. An Ecosystem Approach to Salmonid Conservation, Volume 1: Technical Foundation. Prepared by Man Tech Environmental Research Services Corporation, Corvallis, Oregon, for the National Marine Fisheries Service, U.S. Environmental Protection Agency, and Fish and Wildlife Service.

4.5.4 Restoring Water Quality

Water quality, or the *physical, chemical, and biological characteristics of water,* is a critical factor to the existence, abundance, and diversity of aquatic life in a stream. Temperature, streamflow, turbidity, dissolved gases, nutrients, heavy metals, inorganic and organic chemicals, pH, and biota (pathogenic bacteria, viruses, etc.) are among many parameters that influence water quality. 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[35].

Pollution affects organisms in a number of ways. The toxicity of the chemical may cause an organism to suffer acute or chronic effects, depending upon the concentration and period of exposure of the chemical concerned, the condition of the organism at the time of exposure, and other factors such as water temperature, turbulence, and synergistic effects[36]. Substances that are acutely toxic cause death or severe damage to an organism by poisoning during a brief exposure period (i.e., ≤days). Substances that are chronically toxic cause death or damage to an organism by poisoning during prolonged exposure. Pollution may also affect organisms by creating conditions unsuitable for the organism; increasing the organism's susceptibility to disease and pathogens; changing metabolic requirements, behavior, rate of growth and development, or migration timing; or causing mortality from predation and competition with other organisms more tolerant of the change [37] .

Water quality standards for surface waters of the state of Washington are provided by the Washington Administrative Code (WAC) Chapter 173-201A and are summarized in **Table 4.5.1**.

In 2001, the Washington Department of Ecology reported that 48 percent of all river and stream reaches monitored did not meet state water quality standards[38]. The primary water quality problems identified were temperature, pH, and fecal coliform bacteria. For this reason, it is important to examine the water quality of a particular stream or reach being considered for restoration prior to project initiation. To learn more about the water quality and quantity issues within a particular watershed, consult the Washington State Department of Ecology's website at: http://www.ecy.wa.gov/programs/wq/watershed/index.html. Additional flow and water quality information can be obtained at the United States Geological Survey site at http://wa.water.usgs.gov/.

Table 4.5.1. Water quality standards for surface waters of the state of Washington.

Water Quality Parameter	Class AA Waters[a] (Extraordinary)	Class A Waters[a] (Excellent)	Class B Waters[a] (Good)	Class C Waters[a] (Fair)
Fecal Coliform Organisms	Geometric mean = 50 colonies/100ml	Geometric mean = 100 colonies/100ml	Geometric mean = 200 colonies/100ml	Geometric mean = 200 colonies/100ml
Dissolved Oxygen	>9.5 mg/L	>8.0 mg/L	>6.5 mg/L	>4.0 mg/L
Total Dissolved Gas	≤110% saturation	≤110% saturation	≤110% saturation	≤110% saturation
Temperature	≤16.0°C	≤18.0°C	≤21.0°C	≤22.0°C
PH	6.5 to 8.5	6.5 to 8.5	6.5 to 8.5	6.5 to 9.0
Turbidity	≤5 NTU over background	≤5 NTU over background	≤10 NTU over background	≤10 NTU over background
Toxic radioactive, or deleterious material	Concentrations shall be below those that have the potential either singularly or cumulatively to adversely affect characteristic water sues, cause acute or chronic conditions to the most sensitive biota dependent upon those waters, or adversely affect public health.			

[a] Classes of surface water are established based upon the characteristic use of the water body. See WAC 173-201A-030 and WAC 173-201A-130 for details.

Source: WAC 173-201A, Revised November 18, 1997

Note: Water quality standards 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[39].

4.5.4.1 Activities that Impact Water Quality

The water quality of a stream 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. Land use practices, if not managed effectively, provide the opportunity for pollutants to enter these transport pathways. Examples of non-point source pollution include groundwater infiltration and runoff from agricultural operations (nutrients, sediment, salts, bacteria, pesticides, and other chemicals), mining (acid drainage, sediment), urban stormwater runoff (increased peak storm flows, low base flows, heavy metals, sediments, lawn and garden chemicals, bacteria, temperature, petroleum products, and nutrients), roads (sediment, gasoline, oil, other fluids, litter), managed forestlands (sediment, temperature), construction sites (sediment), and septic systems (bacteria, nutrients). A further break down of pollutants commonly associated with various land use activities has been included in **Table 4.5.2**.

Table 4.5.2: Sources of Pollution by Land Use Activities

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						

Source: Green, W. P., W. A. Hashim, and D. Roberts. 2000. Washington's Water Quality Management to Control Non-point Source Pollution. Washington Department of Ecology Publication Number 99-26, Olympia, Washington. 583 pp.

As cited by Green et al.[40], the Washington Department of Ecology in their Report on Water Quality in Washington State[41] found "only 22% of the problems in [Washington] streams that don't meet water quality standards could be traced to point sources". The rest were attributed to non-point sources of pollution. While the majority of lake and groundwater pollution is also attributed to non-point sources, point sources are the dominant cause of estuary pollution.

Even if the magnitude of a pollutant source remains unchanged, the amount of pollutant reaching a stream can increase or decrease if the pollutant's pathway to the stream is altered. For instance, shortening the distance or travel time along a pollutant's pathway to a water body. This can occur through removal or modification of vegetation or wetlands along a flow path, resulting in the reduction of opportunities for interception, uptake, or degradation of the pollutant prior to its entering a water body.

Intact 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 sorbed to the sediment (e.g., phosphorus, heavy metals), and insoluble pollutants from overland flow and from flood flows . 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.

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 a stream not meeting water quality standards. Shallow flow is also more prone to temperature increases and, thus, reduced dissolved oxygen content.

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 (cited by Paul and Hall[42]). 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)[43] [44] [45] [46], backwater areas, alluvial fans, bars [45], log jams[43] [47] [48] [49] [50] [51], low gradient channel reaches[52], and bank, bed, and floodplain vegetation. 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[46] [53], and sediment supply[54], among other factors. 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. Such activities include straightening, dredging, and removing wood from streams; constructing levees; filling the floodplain; and altering the stream hydrology so that the channel becomes incised or is no longer subject to flows capable of accessing its floodplain.

4.5.4.2 Techniques to Restore and Improve Water Quality

If there are identified water quality problems in a stream, water quality restoration should be implemented prior to instream restoration measures. Ecosystem restoration plans that alter the physical form of the stream corridor are of limited use if the quality of water is inadequate to sustain life.

4.5.4.2.1 Point Source Pollution

Within the state of Washington, pollution caused by point source discharges of wastewater and stormwater to surface water are controlled through National Pollutant Discharge Elimination System (NPDES) permits issued by the Washington State Department of Ecology. NPDES permits are required for wastewater discharges to surface water from industrial facilities and municipal sewage treatment plants, and for stormwater discharges from industrial facilities, construction sites of five or more acres, and municipal storm sewer systems that serve populations of 100,000 or more[55]. For further information on point source discharges within a particular drainage, consult the Washington State Department of Ecology's website at http://www.ecy.wa.gov/programs/wq/permits/index.html or contact their Water Quality Program.

4.5.4.2.2 Non-point Source Pollution

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.

Treating the Source

Preventing the introduction of a pollutant to the environment is the most effective means of avoiding its detrimental impacts and should be a priority in any pollution management plan. Effective management of non-point source pollution can best be achieved through a combination of: 1) thoughtful 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 (measures implemented to control and minimize the source or transport of pollution) that minimize the impact of an activity. 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. Many resources are available for guidance on the prevention and management of non-point pollution. Some are listed below. Consult the U.S. Environmental Protection Agency and the Washington Department of Ecology web sites for further information.

- *Guidance Specifying Management Measures for Sources of Non-point Pollution in Coastal Waters*[56] provides management measures and fact sheets for agricultural sources; forestry; urban areas; marinas and recreational boating; hydromodification; channelization and channel modification, dams, and streambank and shoreline erosion; wetlands, riparian areas, and vegetated treatment systems.
- *Washington's Water Quality Management Plan to Control Non-point Source Pollution* describes a holistic approach to controlling and cleaning up non-point source pollution. The plan reflects current efforts and creative, practical new ideas from all partners and interested citizens. The recommendations focus on how to improve existing efforts through stronger implementation, increased funding, or alternative techniques. 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 Manual for Western Washington*[57]. 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. The Department Ecology believes that when the standards and recommendations of this manual are properly applied, stormwater runoff should generally comply with water quality standards and protect beneficial uses of the receiving waters. Local governments and businesses statewide use the manual to help design their stormwater programs. The manual is useful for anyone needing guidance on sediment and erosion control for construction sites. Operators, or engineers, representing industrial facilities will benefit from the technical volumes.
- *Stormwater Management Manual for Eastern Washington*—in development http://www.ecy.wa.gov/programs/wq/stormwater/eastern_manual/index.html
- *Management Recommendations for Washington's Priority Habitats*. Management recommendations for riparian habitat were developed to meet the goal of maintaining or enhancing the structural and functional integrity of riparian habitat and associated aquatic systems needed to perpetually support fish and wildlife populations on both site and landscape levels. These recommendations consolidate existing scientific literature and provide information on the relationship of riparian habitat to fish and wildlife and to adjacent aquatic and upland ecosystems. Recommendations on major land use activities commonly conducted within or adjacent to riparian areas are provided, including those relative to agriculture, chemical treatments, grazing, watershed management, roads, stream crossing and utilities, recreational use, forest practices, urbanization, comprehensive planning, restoration, and enhancement.
- *On-site Sewage Treatment and Disposal Information Tool Kit*[58]. This tool kit demonstrates to homeowners how they can easily participate in preventing water quality degradation by informing themselves about their on-site sewage disposal systems. The materials included in the kit illustrate what action individuals can take to protect the water supply by properly maintaining and utilizing their on-site sewage disposal systems. Further information, including Homeowner's Manuals for the Operation, Monitoring and Maintenance of On-Site Sewage Treatment and Disposal Systems are available on line at http://www.wsg.washington.edu/outreach/mas/water_quality/onsite_sewage_treatment/maintenance.html#manuals

Controlling Transport

Controlling a pollutant's transport to the stream involves 1) intercepting the pollutant before it reaches the stream, and 2) controlling the capacity of surface runoff, wind, or other transport pathways to carry pollutants from their source to the stream.

Intercepting the pollutant before it reaches the stream includes such activities as establishment and preservation of vegetated riparian zones, upland vegetation, and wetlands between the source of the pollutant and the stream. As discussed above, vegetated buffers and wetlands delay transport of a pollutant, thereby providing further opportunity for interception, uptake, or degradation of the pollutant. However, the pollutant may still harm the ecosystem within the buffer or between the buffer and the pollutant source.

Controlling the capacity of transport pathways to carry pollutants from their source includes such activities as creating “wind breaks” to minimize the capacity of wind to blow soil and airborne pollutants from fields and construction sites; or implementing stormwater management techniques to limit the rate of surface runoff and, thus, its capacity to transport waterborne pollutants from the watershed.

Resources available for guidance on limiting the transport of non-point pollution from the source to the stream are the same as those for addressing the source of non-point source pollution. See also *Riparian Restoration and Management* and *Dedicating Land to the Preservation, Enhancement, and Restoration of Stream Habitat* techniques in this document.

Instream Treatment

Water quality improvement techniques that focus on a pollutant’s fate are those that minimize the effect a pollutant has on stream water quality once it reaches the stream. Such techniques may focus on:

- Removal of the pollutant once it reaches the stream (e.g., dredging, pump and treat systems).
  This approach is a short-term enhancement technique that treats the symptoms of the problem rather than the cause. As a stand-alone treatment approach, it will require repeat application until the source of water quality impairment has been addressed. It is generally less cost effective and more disruptive to the ecosystem than addressing the source or transport of a pollutant. However, depending on the contaminant, its toxicity, and the removal method employed, used in combination with techniques that control the source and transport of pollutants, it can accelerate ecosystem recovery and minimize harm.
- Counteracting the effects of the pollutant. This includes such activities as buffering acidic water or aerating water depleted in oxygen. This approach is also a short-term enhancement technique that treats the symptoms of the problem rather than the cause. As a stand-alone treatment approach, it will require repeat application until the source of water quality impairment has been addressed.
- Increasing streamflow to minimize a stream’s susceptibility to temperature increases and to dilute pollutants already in the stream. This approach is an acceptable stand-alone treatment when it fully addresses the cause of water quality impairment. It may include such activities as minimizing and eliminating water withdrawals (e.g., for irrigation or domestic or industrial water supply) or restoring stream base flow through modification of regulated flow regimes and by restoring and preserving groundwater recharge in the watershed during precipitation and snowmelt events. (See Chapter 4.5.2, *Restoring Stream Flow Regime* for further information.) If this approach does not fully address the cause of water quality impairment, it is best used in combination with techniques that address the source and transport of pollutants to the stream. Note that dilution does not modify the load of pollutant. Impacts to aquatic life downstream may still occur even if problems within the reach are reduced.
- Restoring storage sites within the stream corridor for sediment, organic matter and the nutrients and contaminants adsorbed to them. Note that, depending on the pollutant, it may impact fish and wildlife within the storage site or it may be released back into the stream through overland flow, flood flow, groundwater transport, and desorbtion.

Restoration activities that increase sediment storage within the stream corridor are described in Chapter 4.5.1, *Restoring Sediment Supply*.

4.5.5 Restoring Incised Channels

Channel incision is the progressive lowering of the channel bed relative to its floodplain elevation. Incised channels are transitional forms which are unstable for a period of time and result in erosion of the bed and banks, the transport of considerable quantities of sediment to downstream reaches, dewatering of the riparian zone[59], destruction or degradation of existing aquatic habitat[60], and the undermining of infrastructure such as bridges and utility crossings. Schumm and others [61] describe an incised channel-evolution sequence that consists of five successive stages, assuming that the base level for the channel does not change and that land use in the watershed remains relatively constant. These stages are Stable (Stage I), Incising (Stage II), Widening (Stage III), Stabilizing (Stage IV), and a new, dynamic equilibrium (Stage V). Once channel incision has been initiated, the channel will become increasingly isolated from its floodplain as bed erosion proceeds. Higher flows are contained within the channel, which further accelerates erosion. This process usually continues until a more resistant layer, such as bedrock or clay hardpan, is exposed. Tributaries to incised channels erode in the upstream direction (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. The deepening of the drainage network causes more rapid draining of the soil mantle and a lowering of the water table.

After an incised channel reaches vertical stability, the erosive power of high flows is expended on the banks. Often the channel has incised below the root zone of the riparian vegetation, exposing bank material that is not stabilized by root strength and lowering the water table to a depth that no longer supports the riparian community. Channel widening proceeds until the stream has developed enough width to begin depositing and stabilizing sediment. When vegetation is able to persist within the incised cross-section and stabilize sediment through high flow periods, floodplain rebuilding at the new base level (i.e., channel recovery) has begun. A more detailed look at the process and restoration of channel incision can be found in Schumm *et al.* and Harvey and Watson, the latter includes a comprehensive bibliography.

4.5.5.1 Activities that impact channel incision

Channel incision may be initiated by lowering the base level of the affected channel reach (e.g., by dredging or downstream incision), removal of bed stabilizing features (including grade control, large wood, and boulders), decreasing the sediment supply to the reach (e.g., by the presence of an upstream dam), or when the erosive forces and transport capacity of stream flow exceed the resistance of the bed materials. The later may occur as a result of an increase in the magnitude and frequency of high flows to which the channel is subjected or channel modifications that increase the slope or depth of streamflow. Channels with erodible beds may downcut in response.

Incision may occur on a watershed or reach scale. Reach scale channel incision is generally initiated by the removal of grade control, roughness elements (including large wood), dredging 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 climate, land use or base level change, which force the channel over the threshold to the new, distinct state. With the exception of land use, watershed factors are largely outside our control, and in some instances, land use is difficult to control. For instance, in highly urbanized areas and in stream reaches with water regulated by active dams, it may be impossible to modify existing land use sufficiently to restore the flow and sediment regime to pre-disturbance conditions. As a result, remediation of incised channels is often a reach level activity. What follows is a list of human activities that impact channel incision.

- Booth[62] clearly linked impervious surface area to incision. As runoff per unit watershed area increases, the stream channel, accustomed to lower flows, must increase its cross sectional area. If the bed is readily eroded, incision occurs.
- Channelization (straightening, confining, or shortening a channel) is singled out as a major cause of incision.
- Dredging and gravel mining may trigger incision, sending the upstream channel into a condition not easily reversed[63].
- The removal of large, channel-stabilizing wood results in lowering of the bed and release of stored sediment[64] [65] [66], a potentially reversible impact.
- Dams may lead to incision by halting the natural flow of sediment from the upper watershed.
- Culverts act as control points in channel incision and may affect the immediate reach, although the general cause of incision will remain regardless of the treatment at the road crossing. Undersized culverts may cause localized downstream incision.

4.5.5.2 Techniques to restore incised channels

Incised channels are a transitional form between one dynamic equilibrium and another[67]. A stream's progress through time is punctuated with periods of disequilibrium, some more so than others. On a geologic timescale vertical instability was found to be common in one study looking back over 7,000 years of channel history. In this context, applying techniques to stabilize stream elevation amounts to human meddling in a natural process. While channelization, gravel extraction and land development are artificial causes of incision, the general tendency toward equilibrium is not precluded, baring bank hardening, which prevents the channel from widening and reestablishing equilibrium.

Rosgen[68] points out that incised channels may be in geologies or land forms that are naturally associated with entrenched channels. We must recognize the naturally occurring channel type before planning projects to restore wide flood plains to endemically entrenched channels.

When possible, efforts to restore incised channels should address the root cause of incision, rather than only the symptoms. For instance:

- If incision is caused by altered flow regime, take measures to restore a more natural flow regime (see Chapter 4.5.2 *Restoring Stream Flow Regime*);
- If incision is caused by interruption to sediment flow, take measures to restore that flow (see Chapter 4.5.1 *Restoring Sediment Supply*).

Major objections to allowing natural stream evolution to bring about equilibrium include the length of time required to reach equilibrium (considered to be decades[69]) and the increase in width necessary for the reestablishment of a functioning channel at the new elevation. There are many situations in which allowing the channel to evolve to a new equilibrium creates unacceptable risks to property, infrastructure, and habitat[70]. These factors lead to active channel modification to restore a more acceptable equilibrium more quickly.

There are a variety of well-documented channel restoration projects in incised channels.

- Shields *et al.* uses stone weirs as grade control to arrest the erosion process and elevate the stream bed. Later, Shields *et al.*[71] uses large wood to accomplish similar goals with greater ecological benefits and lower cost.
- Rosgen uses his channel classification scheme to guide restoration efforts. He recommends first identifying the cause of instability, then recognizing the appropriate stream classification for the channel, finally selecting a reference reach with the characteristics of the intended channel. For stream types that are not naturally entrenched, the key is to restore floodplain connectivity through the use of grade control or to construct a new channel at a higher elevation to bypass the incised channel. See *Channel Modification*, *General Design and Construction Considerations for Instream Structures*, *Large Wood and Log Jams*, and *Drop Structure* techniques for design guidance.
- In a recent article, Watson *et al.* [72], used an incised channel evolution model to guide the selection of design alternatives. Two dimensionless ratios define a channel stability diagram that contains the five phases of incised channel evolution. One is a bank stability ratio where the existing bank height is divided by a critical bank height for that geology and vegetation. When bank height exceeds the critical bank height it is considered unstable. The other is a hydraulic stability number, defined as the ratio of sediment transport capacity to the target sediment supply. Watson *et al.*[72] discuss the merits of various remediations on the basis of this analysis. This process recognizes the evolution of incised channels and attempts to select measures that compliment the morphologic phases.
- Some incised streams in western Washington may not follow precisely the same recovery sequence outlined in Schumm *et al.* and other references. These streams show a resistance to bank erosion atypical of those studied by researchers in other parts of the country and, as a result, they may remain in an entrenched condition for a considerable amount of time. A typical situation in western Washington: a stream that lacks large wood, becomes entrenched in a coarse glacial soil during an exceptional storm event, or due to the lowering of base level (as opposed to the chronic entrenchment in fine grained soils as found in other parts of the country). Over time, riparian vegetation recolonizes and hardens the banks, and repeated smaller storms winnow fine bed material to armor the channel bottom. This channel will remain entrenched (a Rosgen F or G channel[73], entrenchment ratio <1.4) and stable since it is not actively widening or lowering, nor is it sending a large sediment load to the downstream channel. We would consider it incised during a field inspection and note a lack of habitat, poor channel complexity with low residual pool depths. One restoration strategy that has successfully restored channels like this is to add large wood. This will trigger channel widening, renew the recovery sequence common to other incised channels, and restore a diverse fish habitat (pools, spawning gravel, delivery of wood and nutrients). Large wood placements occupy channel cross-section, increase velocity and turbulence thereby increasing local scour and

channel widening. They also encourage sediment deposition and reestablish floodplain connectivity (See *Channel Construction and Modification*, *General Design and Construction Considerations for Instream Structures*, *Large Wood and Log Jams* techniques for design guidance).

The response of a given reach to incision restoration techniques depends on the peculiarities of that geomorphic system. Sediment supply and the availability of large wood or the use of large wood in the restoration effort is especially important. Some sections of the Murray River, Australia are still adjusting 54 years after constructing weirs to correct for incision, an observation that should make us realize the role of time in restoration activities.

4.5.6 Restoring Aggrading Channels

Aggradation is the progressive accumulation of in-channel sediment resulting in increased channel bed elevation. The characteristics of aggrading streams are covered in the *Geomorphology* appendix. Generally, bed material from upstream sources is transported by flow and deposits:

- at a grade break (transition from higher to lower gradient),
- at an expansion (from a narrow to wider channel cross section),
- upstream of a constriction (upstream of an undersized bridge, culvert or natural channel constriction),
- or at the confluence of a river and a tributary.

Change is inherent in aggrading reaches. The channel widens as material is deposited, often forming a delta or area of increased slope. The resulting shallow depth reduces the capacity of the stream to transport sediment, which leads to more deposition. An aggrading channel commonly evolves in one of two ways. In one scenario, the leading edge of the deposited material increases slope with time until it reaches a critical threshold and a head-cut trench works back through the aggraded bed, cutting a channel that flushes out a portion of the alluvial deposits and the cycle is renewed. The cycle may be repeated on a yearly basis or it may take hundreds of years to complete[74]. The other scenario is where aggradation continues to a point where the channel elevation increases high enough to force an avulsion, the channel rapidly moves laterally, cutting a new bed in the adjacent soil, abandoning the aggraded reach.

Both scenarios can become a problem when they 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.

4.5.6.1 Activities that impact aggrading channels

As outlined in the *Geomorphology* appendix, increased sediment supply and reduced stream power are the primary causes of aggradation. Aggradation is part of the natural valley-building process in a watershed context, ultimately the consequence of hill slope erosion and valley deposition[75]. On a reach scale, local sources of sediment (*e.g.*, avulsion) are deposited a short distance downstream (fluvial fan). Human activities that affect aggrading channels come under three main headings.

- Increased Sediment Supply:
  - Increased erosion caused by development, agriculture, and land clearing on erodible or unstable soils, concentration of overland flow into discrete channels, or re-routing of runoff into other drainages (often caused by road building and culverts);
  - Increased number and extent of debris flows and mass-wasting events as a result of land clearing, saturation of unstable soils on valley walls (often caused by routing stormwater onto steep slopes), or road failure;
  - Upstream channel incision.
- Decreased Sediment Storage, primarily the isolation of the channel from the flood plain:
  - channelization;
  - Levee construction.
- Decreased Sediment Transport:
  - Channel widening from livestock grazing [76], riparian vegetation removal, or other causes;
  - Decreased channel slope as a result of channelization or installation of channel obstructions that raise the channel bed;
  - Channel and floodplain constrictions, such as bridges, road fills that backwater the upstream channel,
  - Reduced stream flows caused by water withdrawals and managed water releases from reservoirs.

If manipulations such as these lead to aggradation, then watershed and channel restoration techniques can be used to restore the channel to pre-disturbance conditions.

As a word of caution, keep in mind that many streams do not have equilibrium channels and that periods of aggradation leading to widening and flooding may be normal[77] and do not attention for the sake of the resource.

4.5.6.2 Techniques to restore aggrading channels

Past methods for dealing with aggrading channels included channelization, sediment basins and dredging. Channelization has generally proven unsuccessful and dredging unreliable[78]. These techniques have yielded only short-lived benefits without repeat treatment and resulted in severe detrimental impacts to stream health and geomorphology. We are now charged with developing more acceptable solutions.

If the effects of aggradation are intolerable, then sediment continuity should be examined at the site, looking at it in a watershed context. Through this process one can identify source, transport and response reaches and how each contributes to the problems at the site[79]. It is important to recognize that channel mechanisms are complex and episodic so that conditions may lead to aggradation one time and then scour the next. The time scale of these trends may be short or very long and determining this scale leads to different management approaches.

- Anthropogenic channel aggradation may be caused by poor land use practices that yield excessive sediment supply to the stream. Solutions should focus on watershed-wide land use management (see Chapter 4.5.1, *Restoring Sediment Supply,* Chapter 4.5.4, *Restoring Water Quality*, and *Dedicating Land to the Preservation, Restoration, and Enhancement* *of Stream Habitat* technique).

- Aggradation may also be caused by intensive flow modification through water withdrawals or dam management, issues that should be addressed in conjunction with any instream restoration measures (see Chapter 4.5.2 *Restoring Stream Flow Regime*).
- A sediment pulse or wave, such as from an isolated landslide, creates a one-time increase in sediment that moves through a stream system creating local aggradation. If the short-term effects of such a wave are unacceptable, then a sediment trap may be approved where it can be shown that it will solve the problem and the site can be effectively restored. This option in thoroughly explored in the *Instream Sediment Detention Basins* technique.
- Channel incision or chronically unstable hill slopes, on the other hand, can supply an endless stream of bedload that may deposit in ways that interfere with developed lands and fish and wildlife habitat, requiring long-term solutions. Schumm describes the formation of natural alluvial fans, a study that can help planners incorporate natural patterns into engineering solutions. In two papers Parker *et al.*[80 81]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 a grade break (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.
- Purchase land or easements to remove valuable infrastructure or impacted uses from areas surrounding an aggrading reach. Cost analysis may reveal that such purchases are cheaper than sediment management or chronic bank repair. Aggrading reaches are inherently unstable and incompatible with development. See *Dedicating Land to the Preservation, Enhancement, and Restoration of Stream Habitat* technique.
- Large instream wood plays a significant role in the staging and storing of sediment in mountain streams [65 66]. Storage in many of these channels has been eliminated through stream cleaning, salvage operations, splash damming, as well as harvesting large logs from riparian forests. Aggradation in valley bottoms may be reduced through the placement of large wood in source and transport reaches. See *General Design and Construction Considerations for Instream Structures* and *Large Wood and Log Jams* technique.

4.5.7 Restoring Salmonid Spawning Habitat

Adequate high quality spawning habitat is key to preserving native salmonid populations in our streams. Spawning habitat requirements vary among species but in general all salmonids need stable, relatively clean and appropriately sized gravels that are supplied with an adequate flow of clean, cold, oxygen-rich water. Restoring or creating these conditions can increase salmonid reproductive efficiency (fry per female).

According to a literature review conducted by Schuett-Hames and Pleus[82], favorable spawning sites often form upstream of obstructions to flow, such as bedrock outcrops, boulders, and large woody material, and in the tail-outs of scour pools. These scour pools may be associated with instream structures (e.g. large wood and boulders) or with stream meanders. The relative importance of these two features in spawning habitat development depends on the morphology of the stream. Low gradient channels with meandering pool/riffle morphology often have abundant deposits of gravel in pool tailouts, riffles, and point bars. Whereas in steeper channels, spawning habitat is often limited to small patches of coarse gravel associated with obstructions. Characteristics used by salmonids to select spawning sites include 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 .

4.5.7.1 Activities that Impact Spawning Habitat Quality, Quantity, and Availability

Spawning habitat may have been lost or degraded for a number of reasons, both natural and anthropogenic. Anthropogenic impacts to salmonid spawning habitat availability include:

Direct Causes:

- Replacement of natural streambed materials with hardened structures like concrete linings and riprap or scoured structures like undersized culverts and flumes.
- Impassable culverts, dams, weirs, tide gates, sluice gates and other objects that limit or eliminate access to spawning habitat (see Chapter 4.3.2, *Restoring Habitat Connectivity*).
- Loss of channel length and complexity from realignment and straightening.
- Unregulated access by livestock, people, pets and vehicles which collectively reduce the amount of cover, compact and vibrate the beds, greatly reduce water quality, and smother the beds with fine material, reducing inter-gravel flow. All of these impacts can significantly reduce the survival of eggs in the gravel.
- Removal of instream and overhead cover available to adult fish including wood, boulders, and riparian vegetation.
- Activities, such as filling or draining of off-channel habitat, which eliminates the existence or quality of spawning habitat.
- Changes in the natural flow regime from activities such as upstream diversions and hydroelectric operations that alter the amount, accessibility, stability, and physical characteristics (e.g., water depth, sediment size and sorting) of spawning habitat.

Indirect Causes:

- Land use change within the watershed that alters the type or amount of sediment delivered to streams (see Chapter 4.5.1, *Restoring Sediment Supply*). A decrease in sediment supply may reduce the amount and stability of suitable spawning substrate. An increase in supply may bury redds or cause channel instability through aggradation.
- Land use change and unregulated stormwater runoff within the watershed that alter the flow regime and sediment transport capacity of the channel, causing subsequent change in the amount, accessibility, stability, and physical characteristics (e.g., water depth, sediment size and sorting) of spawning habitat.
- Channel modification and removal or addition of instream and shoreline roughness elements that alter the channel’s sediment transport capacity, stability, flow depth, and velocity, all of which impact the stability and suitability of spawning habitat.
- Manmade structures such as dams and road crossings with undersized culverts that create large-scale backwatered conditions unsuitable for salmonid spawning upstream (however, they may be suitable for rearing).
- Undersized culverts or other obstructions to flow that produce relatively high velocity jets that scour downstream reaches.
- Watershed modifications that degrade water quality creating unsuitable conditions for salmonids and other aquatic life (see Chapter 4.5.4, *Restoring Water Quality*). High

turbidity levels reduce inter-gravel flow and can smother or suffocate incubating eggs.

- Timber harvest and other land use practices that remove vegetation from the riparian zone so recruitment of large wood to the channel and overhead cover is effectively eliminated for many years, and water quality is degraded.
- Ramping rates from flow regulation that dewater and strand redds.
- Poor quality forest practices that yard logs across and along stream channels scouring and/or eliminating natural instream cover and altering overhead cover that eliminates shade and protection from predators.

4.5.7.2 Techniques to Restore, Enhance, and Create Spawning Habitat

Due to the many possible causes of salmonid spawning habitat degradation, no single technique is applicable to every situation. The most effective long-term solution is to address the cause of salmonid habitat degradation, and not just the symptoms. For instance, if a channel has been narrowed, deepened, and made steeper to the point that the resulting increased water velocity does not allow spawning sized material to collect and remain stable in the reach, then the artificial placement of spawning sized gravel may serve to lure salmonids to spawn there only to have their eggs and the gravel washed out during periods of high flow.

Because of the high risk of producing only short-term benefits or even negative effects, spawning habitat creation as a mitigation or enhancement technique has limited application and should be done only with a clear understanding of the physical processes involved and the specific habitat needs of the target species. Planners must determine whether lack of suitable habitat may be limiting the population recovery and what can be realistically done to improve conditions. True restoration of salmonid spawning habitat requires reestablishment of the physical processes that naturally create and maintain spawning habitat. An approach that restores these natural processes and habitat diversity will produce long-lasting, high quality salmonid spawning habitat, and benefit other fish and wildlife species as well. Rigorous enforcement of forest practice rules, stormwater management guidelines, critical areas ordinances, agricultural setbacks and similar protective measures can correct many deleterious activities associated with land use activities.

Techniques to consider include:

- Stop operating equipment and vehicles within the stream and exclude livestock, people and pets with durable fencing and rerouting of traffic and use areas. Use alternative methods to skidding logs through a channel.
- Increase Spawning Gravel Availability—
    - Restore the natural gravel supply that has been lost (see Chapter 4.5.1, *Restoring Sediment Supply*). Where the supply of gravel cannot be restored, consider on-going gravel supplementation and spawning pad construction, if warranted and appropriate (see *Salmonid Spawning Gravel Cleaning and Placement* technique).
    - Encourage gravel stability
        - Restore the balance between sediment transport capacity and sediment supply. The sediment transport capacity may have been raised by an increase in channel slope, altered channel cross-section, loss of floodplain connectivity, removal of channel obstructions and constrictions that create

    backwater or physically intercept downstream sediment transport, or by an altered streamflow regime (see *Channel Modification* and *Levee Removal and Modification* techniques, *General Design and Construction Considerations for Instream Structures,* Chapter 4.5.2, *Restoring Stream Flow Regime*, and Chapter 4.5.5, *Restoring Incised Channels*).
    - Restore channel features that naturally encourage the deposition and maintenance of spawning gravel, including meander bends, instream wood and other roughness elements, and riparian vegetation. See *Channel Modification, Riparian Restoration and Management, Dedicating Land and Water to the Preservation, Enhancement, and Restoration of Stream Habitat, General Design and Construction Considerations for Instream Structures*, *Large Wood and Log Jams*, *Boulder Clusters,* and *Porous Weirs* techniques.
  - Increase available spawning area
    - Pursue opportunities to restore a diverted stream to its former channel or to restore a straightened channel to a more natural meander and length. Adequate consideration will have to be given to site-specific hydrology, channel hydraulics, geomorphology and similar issues to develop a practical and durable design (see *Channel Modification* technique)
    - Restore fish access to isolated spawning habitat through such actions as culvert, tide gate, bank protection, and levee removal or modification. See Chapter 4.3.2, *Restoring Habitat Connectivity* and *Fish Passage Restoration, Bank Protection Construction, Modification, and Removal, Levee Modification and Removal* and *Dedicating Land to the Preservation, Enhancement, and Restoration of Stream Habitat* techniques.
    - Remove structures that create artificial surfaces unsuitable for spawning (e.g., culverts, concrete liners)
    - Remove constraints that prevent creation and maintenance of new side channels, restore access to existing side channels, and restore processes that maintain existing and new side channels. Where such activities cannot occur, constructing a new side channel may be an option. See *Side Channel / Off-Channel Habitat Restoration, Bank Protection Construction, Modification, and Removal* and *Levee Removal and Modification* techniques, and Chapter 4.3.2, *Restoring Habitat Connectivity*.
    - Restore natural flow regime. Streamflow at the time of spawning determines the available amount of submerged spawning habitat, the ability of fish to access spawning grounds, and the water depth and velocity over the spawning bed. Flow regulation and ramping rates from hydroelectric dams can be changed to prevent redd dewatering and stranding. See Chapter 4.5.2, *Restoring Stream Flow Regime*.
- Improve the Quality of Spawning Habitat
  - Reduce excessive supply of fine sediment (see Chapter 4.5.4, *Restoring Water Quality* and Chapter 4.5.1, *Restoring Sediment Supply*)
  - Sort and clean gravel—

    - Restore channel features that naturally encourage the sorting and maintenance of spawning gravel, such as instream structures (including large wood) and meander bends. Structures form obstructions to flow causing local scour pools to form. The velocity gradient around and downstream of the obstruction forms pool tailouts comprised of naturally sorted spawning gravel. In low gradient channels with pool/riffle morphology, velocity differences between pools and riffles during peak flows result in sorting of sediments and deposition of coarse gravel in bars and riffles[83]. Note that a pool-riffle morphology is not appropriate for all stream reaches. See *Channel Modification, General Design and Construction Considerations for Instream Structures, Large Wood and Log Jams, Boulder Clusters,* and *Porous Weirs* techniques.
    - Artificially clean gravel (e.g., Gravel Gertie) (see *Salmonid Spawning Gravel Cleaning and Placement* technique). It should be noted that if the source of fine sediment is not identified and corrected prior to gravel cleaning, the benefits would be short lived without repeated maintenance.

  - Improve water quality (see Chapter 4.5.4, *Restoring Water Quality*)
  - Restore or increase instream and overhead cover (see *General Design and Construction Considerations for Instream Structures, Large Wood and Log Jams, Boulder Clusters,* and *Riparian Restoration and Management* techniques)
  - Restore flow regime and channel morphology to ensure that adequate water depth and velocity and sediment conditions are present during spawning and egg incubation (see *Channel Modification* technique and Chapter 4.5.2, *Restoring Stream Hydrology*)
  - Eliminate or reduce human-caused channel aggradation to increase the stability of spawning habitat and egg survival (see Chapter 4.5.6, *Restoring Aggrading Channels*)

4.5.8 Restoring Salmonid Rearing Habitat

Abundant well-dispersed rearing habitat appropriate to the salmonid species that inhabit a stream is essential to the maintenance and recovery of depressed populations. Without adequate rearing habitat, preferably near desired spawning habitat, survival and health of emergent fry and juvenile fish will be reduced as these fish are forced downstream to find suitable areas. If downstream areas are already at or near carrying capacity, these fish may be lost from the system altogether and not able to help in stock maintenance and/or recovery.

Prior to evaluating the need for restoring rearing habitat quality and quantity, however, there must be an assessment of the habitat requirements for the species to be enhanced. For example, since pink and chum salmon have such a short freshwater residence time, measured in just a few days or a couple weeks at most, little can be done in the freshwater environment to enhance rearing conditions and improve survival. The predominant rearing area for these species is the estuarine marsh, beach and near-shore marine areas that can be protected and oftentimes recovered through improved fish passage at tide gates, setback of levees, removal of bulkheads, island creation and similar projects. By contrast, Chinook and coho salmon and steelhead rear anywhere from a few months up to several years in the riverine system and freshwater enhancements are possible. However, each species generally uses a different part of the system to avoid competition and these specific habitat needs must be understood to assess whether lack of suitable habitat may be limiting the population recovery and what can be realistically done to improve conditions. Where rearing habitat requirements do overlap, such as in the estuary for Chinook and chum salmon, single projects can have multiple species benefits.

Efforts to improve conditions for spawning may also increase the amount of rearing habitat depending on species-specific requirements. Reactivating an abandoned slough, for instance, with some gravel supplementation to provide off-channel spawning habitat for coho salmon will likely improve and/or restore high quality rearing habitat for the juveniles since these are the preferred rearing locations as well. However, these ancillary benefits may not always be realized. In the Big Qualicum River in British Columbia, specific flow improvements for coho spawning did improve conditions with increased egg-fry survival but there was no subsequent increase in the number of rearing juveniles[84]. Apparently, the amount or volume of slack water and/or pools, the needed rearing habitat, did not change. Careful evaluation of the probable outcome(s) of the proposed enhancement action can be very useful in deciding whether the desired habitat objectives will be achieved.

Generally, freshwater rearing habitat for salmonids tends to be the lower velocity areas either mid channel, along the bank, or in active sloughs often associated with either overhead and/or instream vegetative or wood cover. Since different species use different areas, enhancement options can vary widely. Juvenile Chinook, for instance, tend to rear over shallow bars and along natural banks in the main stem making for few types of improvement opportunities. Projects may be restricted to restoring natural bank lines through removal of bank hardening and reactivation of major river channels. Enhancements for steelhead can be even more challenging since they often prefer the faster water of streams and tributaries in association with large cobble or wood for velocity breaks where small eddies make for energy efficient holding and capture of forage items that wash by. Opportunities for steelhead may only exist in higher gradient streams that are devoid of wood or fast rocky pools that can be enhanced to provide these rearing conditions. Juvenile coho, though, prefer slower moving pools and flowing backwaters and sloughs in association with in and out of stream cover and these preferences do offer many types of effective improvement opportunities with proven techniques. The cover element, whether it is large rock, wood, emergent and submergent vegetation, exposed root bundles, a bubble screen, or any combination is needed for protection from predators and often provides an important substrate for invertebrates that can be a vital food supply.

The amount of rearing area and the number of juvenile fish that can be accommodated will often be dependent on channel length in a given reach and the structural complexity within that length. Restoration of both features could be goals of restoration.

Estuarine and near shore rearing habitat has not been as well studied but is believed to be very important for some species even though the use period may be relatively short, perhaps only weeks or several months at most. Since most of these areas have been severely altered or lost altogether, almost any recovery work will likely be beneficial. But local knowledge and information will be very important in designing any project to maximize its success. Some of the best information to date is coming from the Skagit River delta in Washington State by the

Skagit System Cooperative that has been carefully evaluating estuary use by salmonids.

4.5.8.1 Activities that impact Rearing Habitat Quality, Quantity and Availability

Rearing habitat, like spawning habitat, may have been lost or degraded for a number of reasons both direct and indirect.

Direct Causes:

- Loss of natural stream reaches by replacement of normal streambed materials with hardened structures like concrete linings and riprap or scoured structures like undersized culverts and flumes.
- Loss of channel length and complexity from realignment and straightening.
- Changes in the natural flow regime from activities such as upstream diversions or hydroelectric operations that alter the amount, accessibility, stability, and physical characteristics (e.g., water depth, sediment size and sorting) of habitat.
- Loss of channel complexity and cover from significant removal of both instream and overhead cover, sometimes referred to as “stream cleaning”.
- Unregulated access by livestock, people, pets and vehicles that can reduce the amount of cover, cause major disruptive disturbance and greatly reduce water quality.
- Activities that reduce access to habitat such as impassable culverts, dams, weirs and levees.
- Wood removal operations in the estuary that significantly reduce habitat complexity and carrying capacity for juvenile salmonids and their prey organisms.
- Levees that eliminate off-channel and side channel habitat.
- Bank armoring with materials such as large rip rap rock that eliminate natural stream margins characterized by wood accumulations, protruding root masses, alcoves and similar natural conditions.

Indirect Causes:

- Timber harvest and other land use practices that remove the riparian zone so recruitment of large wood to the channel for both instream and overhead cover is effectively eliminated for many years and water quality is degraded.
- Ramping rates from flow regulation that strand juvenile fish in otherwise good quality habitat or expose them to excessive predation.
- Unscreened diversions such as those for irrigation or other types of water withdrawal like pumps.
- Land use changes such as urban development with increased hardened surfaces that reduce infiltration and storage leading to increased high velocity winter flows and reduced summer flows.
- Permanent reduction in water quality from land use activities that increase turbidity above background levels and introduce toxins from industry and runoff.
- Poor quality forest practices that yard logs across and along stream channels scouring and/or eliminating natural instream cover and altering overhead cover that eliminates shade and protection from predators.
- Long-term seasonal turbidity increases from perennial slope failures, landslides, surface erosion, and similar sources.

4.5.8.2 Techniques to Restore, Enhance and Create Rearing Habitat

Restoration and recovery of high quality rearing habitat will depend on the requirements of the target species. As for spawning habitat, an effort should be made to understand the ultimate cause for the loss of quality or quantity of the appropriate rearing habitat feature(s) and ensure it is being addressed either prior to undertaking instream work or in coordination with it. In some cases, such as permanently hydro-modified reaches (i.e. hydroelectric dams), the natural processes of channel meander, wood accumulation and seasonal flow will never be restored and specific focused measures will be required to restore valuable rearing areas.

Correct direct and indirect causes as listed above to the greatest extent possible. For example, flow regulation and ramping rates from hydroelectric dams can be changed to allow fish redistribution that avoids stranding. Livestock and people can be excluded from streams with durable fencing and rerouting of traffic and use areas. Shading cover can be re-established with riparian plantings of appropriate species (see *Riparian Restoration and Management* technique). Culverts can be replaced that not only restore access to habitat but can also provide habitat inside if they accommodate a natural channel bed with capability for some limited wood accumulation (properly sized and placed culverts should be able to provide this benefit without threat to the structure, see *Fish Passage Restoration* technique).

Other specific measures will depend on the target species and can vary greatly in expense. Techniques to consider include:

- 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 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. See *Side Channel / Off-Channel Habitat Restoration* technique.
- Instream structures that create depth, velocity and substrate variation, scour pools and backwater ponds or restore wood accumulation can be built using a variety of techniques as long as they consider the existing and anticipated flow regime of the system. See Section *General Design and Construction Considerations for Instream Structures* and the *Large Wood and Log Jams*, *Boulder Clusters*, and *Porous Weirs* techniques). A summary of criteria and methods for this type of enhancement can also be found in Slaney and Zaldokas[85]. Generally, this type of work will be easier to implement in small streams. In large streams or main river channels, planning, permitting, design and construction will be much more complex and liabilities considerably greater. Large-scale implementation of this technique can be very expensive with less certain outcomes, although it may be the only way to restore holding and rearing areas in the main channel preferred by Chinook salmon, for example.
- 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 (see *Levee Removal and Modification* technique). Tide gates can be modified or replaced to be open longer during each tidal cycle and with reduced velocities to provide a wider window of access that can match the swimming abilities of juvenile fish. In several cases, tide gates were removed entirely and an appropriately sized culvert installed that by careful

design of its size controlled the amount of water inside the diked area on each tidal exchange. Evaluation has shown juvenile salmonids readily migrate through the culvert and rear in the slough. Dike removal, breaches and setbacks can restore natural freshwater and estuary processes and channels increasing the total amount of freshwater and estuarine area available. Dike or levee modification may require additional work in the slough to hasten recovery.

- Near shore 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. Near shore islands can also be built to provide shallow water habitat rich with eelgrass that mitigate for permanent loss of high quality shoreline habitat.
- Hardened bank protection can be removed to not only restore a natural channel bank dominated by native vegetation but also restore flow to side channel and back water areas that can be of critical importance to some species. It can also lead to the natural creation of new channels (see *Bank Protection Construction, Modification, and Removal* technique).
- Rigorous enforcement of forest practice rules, stormwater management guidelines, critical areas ordinances, agricultural setbacks and similar protective measures can correct many deleterious activities associated with land use activities.
- Occasionally, opportunities exist to restore a diverted stream to its former channel or to restore a straightened channel to a more natural meander and length that can greatly restore rearing capability of the reach. Adequate consideration, though, will have to be given to site-specific hydrology, channel hydraulics, geomorphology and similar issues to develop a practical and durable design (see *Channel Modification* technique).
- Where increased pool habitat is desirable for high quality rearing areas and beavers have been exterminated, they can be successfully re-introduced. Beavers and their dam activities were often extremely important in maintaining stream stability, capturing wood, storing water and promoting a well-developed riparian corridor in the pre-European era (see *Beaver Reintroduction* technique).

4.5.8.3 Monitoring

Monitoring will be an important part of the enhancement effort to measure project success and learn what features either need to be changed and/or included or modified in the next effort. The method and timing of evaluation will depend on the species and nature of the habitat. Options include snorkeling, electrofishing, trapping, seining or other safe-capture methods. Levels of use should be evaluated relative to parent escapement to the vicinity and/or river basin, seasonal or annual hydrology in the year of evaluation, degree to which the project has been functioning, and similar factors that can strongly affect findings of fish use.

4.6 Glossary

Benchmark watershed – remaining undisturbed watersheds that may be used to research, compare, and monitor stream ecosystems over time[12]

Biological hot spot – relatively small intact riverine habitat patches that provide critical functions for the stream or biodiversity. Hot spots can include deep pools for fish habitat, a cold-water tributary junction that provides a small thermal refuge for biodiversity, or a small section of complex, healthy Riverine habitat.[12]

Passive restoration - cessation of anthropogenic activities that are causing degradation or preventing natural recovery[3]

Refugia – areas with relatively undisturbed healthier habitat and processes that serve as refuges for biodiversity

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STREAM HABITAT RESTORATION GUIDELINES
CHAPTER 5

DESIGNING AND IMPLEMENTING STREAM HABITAT RESTORATION TECHNIQUES

Chapter 5 is a compilation of techniques that are commonly applied to restore, rehabilitate, enhance, or create stream habitat. 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. It is recommended that before proceeding to this chapter, the restoration practitioner should have already completed a site, reach, or watershed assessment (Chapter 3, *Stream Habitat Assessment*), as appropriate, to determine limiting factors to ecosystem recovery and to identify restoration opportunities and constraints. They should also have identified realistic restoration goals and objectives and developed a restoration strategy to meet those goals and objectives (Chapter 4, *Developing a Restoration Strategy*). In addition to the techniques presented in this chapter, appendices to this document and related Aquatic Habitat Guidelines white papers (http://wdfw.wa.gov/hab/ahg/ahgwhite.htm) 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.

The intent of the following techniques is not to provide a “cookbook” that walks you through every analysis that may be required. 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.

The techniques present what the authors consider to be the best available science for each method. The information provided represents the integration of that available through other guidelines and the literature, as well as the experience of the authors and contributors to this document.

5.1 Techniques Included in this Guideline

The optimal goal of stream habitat restoration is to restore the natural processes that create, maintain, and connect stream habitat, including sediment transport, scour, deposition, channel migration, riparian development, nutrient cycling, flooding, etc. However, some of the techniques presented below do not work towards that goal. They 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.

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
    a. General Design and Selection Considerations for Instream Structures
    b. Boulder Clusters
    c. Large Wood and Log Jams
    d. Drop Structures
    e. Porous Weirs
11. Bank Protection Construction, Modification, and Removal
12. Instream Sediment Detention Basins

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:

- A wide range of watershed management techniques, including Best Management Practices, that address point and non-point source pollution, slope stability, and changes in sediment supply, large wood supply, and flow regime, many of which may be necessary to address the root cause of habitat degradation as outlined in Chapter 4.5, *Approaches to Achieving Common Restoration Goals*.
- Many techniques that treat the symptoms of habitat degradation, rather than the cause, and whose detrimental impacts to the ecosystem typically outweigh any benefits that they provide. For instance, dredging a stream channel that has aggraded due to an increase in sediment delivery to the stream from a denuded watershed may increase the depth of flow and prevent fish stranding within the floodplain. But it provides only a short-term solution unless the cause of increased sediment delivery is addressed. It is also very disruptive to existing habitat, it may sever the connection between the channel and its floodplain and riparian habitats, and it may cause upstream and downstream channel incision. Some techniques that address only the symptoms of habitat degradation (e.g., instream sediment detention, gravel cleaning, bank stabilization) are included here because they are in common use and they have some application to stream habitat restoration under limited circumstances or when used in conjunction with other techniques.
- Techniques that have been used in the past that have not been successful, or which inhibit or impede natural habitat-forming processes. This includes any form of hardening of the channel or banks that will ultimately restrict the channel’s ability to adjust to changing

inputs.

- Techniques that may be appropriate but whose utility has not been demonstrated to date or is not known to the authors at this time.
- Land use planning and establishment of protective regulations that is critical to the long-term success of restoration.
- Wetland restoration
- Estuary Restoration (topic of a proposed future Washington State guideline)

5.2 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, 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 Considerations* 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 Considerations* 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.

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.

5.3 Design of Techniques

Once the tasks or techniques necessary to achieve overall restoration goals and objectives have been identified and prioritized, planning and design of individual projects can begin. The process involved is similar to that outlined for developing a restoration strategy in Chapter 4 of this guideline. It typically includes the following steps:

1. Identify stakeholders and interests (discussed below in this introduction)
2. Identify project constraints (discussed below in this introduction)
3. Define project goals and objectives
4. Develop design criteria to meet those goals and objectives (discussed below in this introduction)
5. Collect data and conduct necessary assessments and baseline monitoring (discussed in each technique)
6. Evaluate the risks to the environment, infrastructure, property, and public safety that are associated with both project installation and failure (risks are described for each technique)
7. Develop project designs (design components and methods are presented for each technique)
8. Develop a construction plan (refer to the *Construction Considerations* appendix)
9. Develop drawings, specifications, and contracting documents (example drawings are provided for most techniques)
10. Construct the project
11. Conduct post-construction monitoring (monitoring considerations are discussed briefly in each technique and in greater detail in the *Monitoring Considerations* appendix)

5.3.1 Expertise Required

Restoration, rehabilitation, enhancement, or creation of natural stream channels and habitat is a relatively young and developing science. Techniques are numerous, and many are unproven. In addition to often-complicated social and political considerations, the ecological and physical complexity of stream systems requires an understanding and appreciation of many disciplines within the natural sciences and engineering. As such, it is commonly the subject of debate among academics and practitioners from many disciplines and organizations. Early phases of project planning, including identification of project objectives and alternatives analysis, will benefit from an interdisciplinary approach and may require expertise from several related scientific and engineering disciplines, including:

- Hydrology. Hydrologists determine the impact of watershed change on the hydrologic regime and can help identify causes related to hydrologic impacts, and evaluate alternatives with respect to altered hydrologic regimes.
- Geology and fluvial geomorphology. Geologists can identify geologic inputs and controls to the channel, such as sediment sources and natural grade control. Geomorphologists evaluate the stability and form of the stream channel and the inputs and processes that control them.
- Fish biology and aquatic ecology, including aquatic entomology. Aquatic life scientists are essential to evaluating habitat condition, conducting population studies, and limiting factors analyses.
- 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.

They are 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. Landscape ecologists compile and evaluate broad-scale ecological and land use data using remote sensing, GIS, and other technology. Such data is useful to determine the extent and distribution of habitats and problems within a watershed or ecosystem, to identify likely causes to those problems and threats to habitat, and 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.
- Construction. Individuals familiar with construction are skilled at evaluating access availability, equipment requirements, and construction feasibility.

5.3.2 Identify Stakeholders and Interests

Successful restoration requires involvement from numerous stakeholders early in the process of planning a restoration project. Stakeholders may include:

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

Inclusion of all impacted, interested, and involved parties will help develop project objectives that are achievable. Each stakeholder brings to the table their own set of objectives, some of which may benefit fish and wildlife while others may not. Early stakeholder involvement and the negotiation among them will provide the designer with an opportunity to address all concerns and to maximize benefits to fish and wildlife in a cost-effective timely manner. It may also yield a project that addresses multiple objectives and provides opportunities to further expand restoration work. 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 the project. The longer stakeholder involvement is delayed, the more likely the project will be rejected and design modifications will be required to proceed.

5.3.3 Identify Project Constraints

There are many possible societal, political, and logistical project constraints to address. The myriad of stakeholders contributing to the development of project objectives will facilitate the identification of potential hurdles and roadblocks in the path to implementation. The earlier these roadblocks are identified, the earlier they can be addressed. Project implementation may be limited by:

- Permitting. Numerous federal, state, and local permits may be required to implement a project, even though the goal is to restore stream habitat. Permits sometimes take years to obtain, especially if endangered species may be positively or negatively impacted by the project. Permit requirements may sometimes conflict, causing further delays while these conflicts are resolved. See the *Typical Permits Required for Work In or Around Water* appendix for more information on permitting.
- Regulatory authority. When a number of regulatory entities are involved, the degree of authority of each agency is sometimes unclear. Delays in project development or implementation may result, especially if restoration priorities and recommendations conflict among agencies.
- Resistant stakeholders. Unwilling stakeholders may prevent any project from proceeding or limit the extent of the project such that certain restoration objectives cannot be met.
- Funding. Project funding may be insufficient to cover the design, implementation, maintenance and monitoring costs. Funding may also have sunset dates or only be available for specific types of work.
- Resource management policy. Current management policies and protocols may conflict with restoration goals.
- Infrastructure. Existing infrastructure may limit the spatial extent of treatment such that certain restoration objectives cannot be met.
- Private landowner concerns. Private landowners often pose significant restrictions on activities on their property, and their land management preferences may be inconsistent with restoration goals.
- Time. There may not be sufficient time for the project to work through the development steps needed to achieve implementation to meet the criteria of funding, availability of key personnel, scheduled development activities or other limitations.

While significant constraints to restoration opportunities may exist, stakeholders should consider whether these constraints are perceived or absolute, and if they can be overcome through negotiation, mitigation, procurement of additional funding, or development of additional alternatives. Stakeholders should consider whether these constraints allow the project to restore habitat or whether they limit it to enhancement only. Where limitations to complete restoration exist, there may be alternative rehabilitation or enhancement projects that can meet many stakeholder goals and objectives.

5.3.4 Design Criteria

Design criteria are specific, *measurable* attributes of project components developed to meet project objectives[1] and are typically developed by the project implementation team as a means of clarifying project objectives. Design criteria are acceptable benchmarks for individual components of a design, providing numeric allowable limits of performance and tolerance. Criteria for habitat restoration and design define the spatial and temporal aspects of project objectives. They also address any constraints to fully achieving project objectives that may be imposed by social, political or jurisdictional boundaries.

Ideally, design criteria are developed with stakeholder review and feedback, such that they clearly represent the intent of the project and identify the risk associated with various design components. Perhaps equally important, design criteria provide a framework by which to measure project success. Design criteria can provide the ideal framework for establishment of a monitoring plan that is directly related to design objectives and is capable of evaluating the success of a project. (For further discussion of evaluation criteria to measure success, refer to Kondolf and Micheli[2].)

5.3.4.1 Examples of Design Criteria

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 whether the channel location is allowed to deform over time, the degree to which it is allowed to migrate within a defined corridor, and what channel pattern (braided, meandering, or straight) will be applied.

- Floodplain function: Design criteria define the frequency, timing, and duration of floodplain inundation as it relates to stream stability, riparian vegetation composition and health, and fish and wildlife habitat development and connectivity.

- Aquatic habitat: Design criteria define what species or life stages 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.

There are two classes of design criteria – 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"[3].
Examples of performance criteria include:
- Create spawning habitat for 10 additional pairs of spawners per given length of stream,
- Provide off-channel rearing habitat for 10,000 juvenile fish for 10 years, and
- Provide upstream passage for adult chum during all flows up to the high fish passage design flow.

Examples of prescriptive criteria that relate to the above performance criteria include:

- Create X square feet of spawning habitat per given length of stream
- Create X acres of off-channel rearing habitat
- Create X number of drop structures of 1-foot or less at all flows up to the high fish passage design flow.

The difference between the two types of design criteria can be illustrated by considering the project objective of increasing cover and spawning habitat by installing large wood in a channel. Performance criteria may include a target minimum volume of cover habitat and area of spawning habitat directly associated with large wood after a given period of time, without dictating how this will be achieved. Prescriptive criteria, on the other hand, may dictate the size, volume, number and location of large wood complexes, and the method of installation. While performance criteria may be better suited to ensuring that project objectives are achieved, they must be carefully articulated such that they are reasonable, achievable, and measurable.

5.3.4.2 How Design Criteria Relate to Monitoring

As described above, design criteria can be developed as either performance criteria or prescriptive criteria. Those 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 Considerations* appendix.

Prescriptive criteria can also be used as the basis of a monitoring plan, though such monitoring is better suited to evaluating durability and longevity of design components rather than success of meeting overall project goals and objectives. Post-implementation monitoring based on prescriptive design criteria entails measuring physical attributes of an implemented project, rather than its outcome. For example, prescriptive criteria may dictate the number of pieces of large wood placed and the period of time over which they are expected to perform. (In contrast, performance criteria associated with large wood may specify fish use of habitat created by the wood.) To evaluate the success of a project relative to these prescriptive criteria, a monitoring plan must include a count of the number of pieces of large wood installed at the end of the prescribed time period. By comparing post-project measurements to pre-project prescriptive design criteria, the success of individual project components can be evaluated (e.g., that the structure withstood the 50-year design flood event and still persists). But only performance criteria can be used to determine if the project objectives related to fish usage of habitat created by the structure were achieved.

Consider again the example of project objectives including improved aquatic habitat through increased numbers of log jams. With prescriptive criteria dictating the form and number of log jams, a project may be deemed unsuccessful if the jams became dislodged before the end of the intended project life. Yet the jams may reform in another location, with the same wood, in the same reach and continue to provide desired function. Thus, monitoring conducted using a plan that is based on performance criteria may indicate project success; while monitoring conducted using a plan based on prescriptive criteria may indicate a failed project, even though project objectives (increased habitat associated with log jams) were achieved.

5.3.5 Levels of Design

Project design typically occurs in a number of phases, including conceptual design, detailed design, and development of plans and specifications. Conceptual designs are commonly presented to identify and illustrate select alternatives and to identify project components. They often include schematics of each alternative, with basic design considerations to address project feasibility. This level of design provides a platform for the project owner, project designer, 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 thorough assessment, topographic information, analysis of hydrology, as well as basic hydraulic evaluation to establish feasibility of selected alternatives.

The design process that follows typically requires detailed analysis to develop designs that address all established criteria. The required level of analysis in design will depend greatly upon the technique selected, site conditions, project goals and objectives, 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.

Plans and specifications represent the end product of the design process. 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 30 to 50% of the bankfull channel, stabilize the logs by burying 1/3 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 crew or supervisor to select the specific location and orientation of each individual log and the installation methods. Alternatively, a large log jam 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, 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.

5.4 References

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CHANNEL MODIFICATION

1 DESCRIPTION OF TECHNIQUE

As described in Chapter 2, *Stream Processes and Habitat*, of the Stream Habitat Restoration Guidelines (SHRG), the physical structure of alluvial streams is a reflection of interactions among available energy, water, sediment and structural elements (such as large wood). These processes are mediated by the stabilizing influence of vegetation, and, sometimes, the extent of available floodplain. Where inputs of sediment and water have been altered from their natural rates, or where the form or structure of the channel or floodplain have been modified by human activities, channel instability and degraded habitat conditions are likely to exist.

As part of an overall management plan that addresses the underlying causes of degradation on a watershed scale, 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 of a channel in map view and is defined by sinuosity and meander characteristics)
    - cross-section (the shape, width and depth of channel from bank to bank and across the floodplain)
    - profile (the slope, and variability of the slope, along the channel bed)
- Location of the channel

Planform, cross-section, and profile are integrated 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. Functional habitat is dependent upon variability in all three of these channel components.

Modifications may include direct restoration (reconstruction of a channel) or incremental process restoration (installation of a structural feature to induce change in a channel). Modifications often employ instream structures that reduce bank erosion and reduce or control channel migration, at least during the period of vegetation recovery.

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

When properly applied, channel modification techniques can result in a cost-effective, comprehensive fix, preferable by far to the periodic and chronic-fix approach that treats problems symptom by symptom. However, without a thorough understanding of the complexities of channel modification techniques and of the stream channel in question, problems may arise. Channel modification alters the way energy is dissipated as water flows through the reach, which has effects on:

- Size distribution and volume of sediment transported
- Velocity, shear stress, turbulence, and other hydraulic variables
- Scour and fill processes
- Water surface elevations at all flows, including flood flows
- Recruitment, transport and retention of large wood

Thus, 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, affecting channel stability, habitat features, and floodplain interactions there as well as locally.

Channel modification projects often provide immediate benefits by creating improved habitat. However, the purpose of channel modification is to accelerate recovery to a stable, sustainable channel form that is in dynamic balance with its sediment, large-wood and flow regime. Successful modification of a stream channel to a more stable, natural shape should create conditions of flow hydraulics and sediment mobilization, transport and storage that sustain this shape and in doing so, sustain high quality, diverse habitat. The long-term benefits will be dependent on the degree to which the reconstructed or modified channel is able to adjust over time to maintain equilibrium.

Successful channel modification may result in any of the possible benefits normally provided by a natural channel system. Benefits may include the following:

- Improved stability and sorting of gravels for spawning habitat
- Improved water access to floodplain
- 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 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)

Channel modification can be part of a process-based restoration strategy. For example channel modification may be utilized as a tool to assist in reconnection of a channel with its floodplain, reestablishment of natural streambank erosion and channel migration rates, reestablishment of natural sediment storage and mobilization patterns, or natural large wood recruitment and retention patterns. Successful restoration of a stream to a more stable, natural shape can have tremendous benefits for fish and wildlife by providing natural diversity of habitat, and natural in-channel and riparian zone disturbance regimes.

Because of the spatial scale of construction-related disturbance associated with channel modification projects, the risk of unanticipated impacts can be very high. 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. 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 of the inadvertent consequences of channel modification may include:

- Incision or aggradation of upstream, downstream or local channel reaches and tributaries
- 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 intervening floodplain)
- Out-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

In addition, short-term impacts that occur as the system recovers from construction-related disturbance must be considered, especially where at-risk species are present. These short-term impacts, which can be minimized but not eliminated, 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 Considerations* appendix. These impacts must be weighed against long-term benefits in the context of species and habitat resiliency.

3 APPLICATION OF TECHNIQUE

Before selecting channel modification as a technique to address channel instability or degraded habitat, a context for both the symptoms and the technique is needed. Disruptions to channel equilibrium typically fall into two categories:

1. *Reach specific impacts resulting 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 the resistance of the bank to erosion.
2. *Reach impacts that result from watershed-scale disturbance*. 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-specific impacts are the cause of degradation, simply removing the cause of degradation and allowing natural recovery to take place (passive restoration) may be a cost-effective, low-risk solution, particularly if much of the potential degradation has already occurred. If, however, the rates of channel change are still high or accelerating, channel modification can be an effective tool to boost natural recovery (active restoration).

In the case where watershed-scale disturbance is the root cause of degraded conditions, these causes must be addressed first. 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 designs are unlikely to be sustainable over the long term. Furthermore, the spatial scale of channel degradation when watershed processes are the cause is sufficiently large that use of channel modification on a significant portion of the affected reaches becomes economically infeasible. Greater benefits for cost may be obtained by addressing land-use-related disturbances and then allowing for natural recovery.

If land use has been corrected, 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. If 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 regime can be accurately quantified and accommodated in the design.

By nature, channel modification is an invasive technique, involving substantial on-the-ground and in-channel disturbance. As such, it should not be a first choice in restoration, but should be used only when restoration goals cannot be obtained using less invasive techniques (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 natural, sustainable rates. A stable channel is not an immobile channel, but rather one that maintains its form over time as it moves all of 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 not 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 important to note that while an equilibrium channel is pleasant to look at and falls within expected parameters, habitat-forming mechanisms may not be present[2]. 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 taking 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. A partial list would include:

- Transitional areas, such as alluvial fans, where high stream power, decreasing sediment transport capacity, and convex topography drive 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 virtually any scale, from site-specific to multiple continuous reaches of a river, and on any size stream. However, the risk of failure increases with increasing stream size and stream power (i.e. discharge and slope). Site-specific channel modifications may include bedform modifications or removal or installation of structures to improve fish passage or increase habitat complexity. Reach-scale modifications may include channel relocation or planform, profile, and cross-section modification. Large-scale modifications may include removal or setback of levees through long reaches of a valley (refer to the *Levee Modification and Removal* 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. In some instances, such as when a channel has been straightened, rerouted, or otherwise dislocated, complete relocation of the channel may be appropriate. However, it is important to recognize that changing one component of a channel usually results in changes to, or necessitates changes to other channel components. For example, significant changes to channel planform often result in changes to channel profile. A channel cannot be lengthened without reducing its slope. Modifying the elevation of the channel requires slope alteration at either the upstream or downstream end of the modified reach, or both.

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. Physically, the main objective of altering channel profile is to alter energy dissipation patterns. Specifically, this will alter:

- 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)
- Volume, extent and pattern of hyporheic flow

These physical objectives are clearly linked to biological objectives as well, through effects on habitat complexity, riparian zone function, habitat connectivity and water quality. Reach-scale channel profile alteration is often proposed specifically to address the degraded habitat which has resulted from past river management, including:

- Straightened, incising (eroding) channels
- Widened, aggrading (depositional) channels
- Man-made fish passage barriers

Specific channel profile changes implemented to improve habitat include:

- Installation of large wood, drop structures or channel fill (i.e., roughened channel bed) 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

Since channel profile governs the energy dissipation pattern of a stream, knowledge of stream channel response to these altered energy patterns is essential. Physical responses, in turn, have biological implications. Factors to consider include:

- 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
- Steps, which cause abrupt drop in elevation, dissipate energy locally and thus break up the channel profile. This has the effect of:
  - Making less energy available overall to transport sediment through the reach
  - Creating a localized scour and associated deposition area;
  - Reducing the longitudinal extent of high-velocity zones.
- Proper channel profile is needed for equilibrium sediment transport processes
- Channel profile influences the passage of fish and other aquatic organisms through the channel and into adjacent floodplain habitats
- 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 stream bed elevation can cause water to spill onto the floodplain at relatively lower discharges

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. Most channel planform modification efforts are focused on restoring single-thread, straightened channels to a more sinuous pattern. Physically, the main objectives in doing this are:

- To increase the proportion of the stream’s energy which is dissipated by friction (as the water is made to turn around bends) rather than erosion
- To establish a natural pool-riffle pattern and channel migration dynamics

Since planform change is impossible without altering the slope or profile, it is difficult to discuss effects specific to the planform alone. Nevertheless, increasing sinuosity is generally accompanied by:

- Increased 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.)
- Increased vertical topography
- Bedforms, such as point bars
- Increased volume of hyporheic flow
- Establishment of a channel migration process due to differential erosion at outer bends, which results in:
  - Gravel recruitment
  - Large wood recruitment
- Diversity of edge habitat (undercut banks, etc.)

Planform modification is often proposed to address the same reach-scale habitat degradation syndromes discussed under profile change, including straightened, incising channels and widened, aggrading channels. Disruptions to natural planform can also result from:

- Activities which increase bank erosion rates, such as:
  - Removal of large wood from channels
  - Removal or modification of riparian vegetation
  - Upstream modification of channel banks (including armoring) or upstream constrictions (levees, road grades, landfill, etc.)
  - Aggradation (deposition) and widening caused by downstream flow restrictions (e.g. at road crossings)
- Land use which confines whole reaches of channel, such as:
  - Confinement by levees
  - Impinging floodplain fill or road grades
- 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 changes implemented to improve habitat include:

- Reconnection or reconstruction of historic meanders in straightened (channelized) reaches
- Removal or modification of levees, bank armoring, and infrastructure that artificially confine the channel (see *Levee Modification and Removal)*
- 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)

Relocation of stream channels is particularly effective at restoring channel stability in the case of:

- Aggraded channelized streams if the channel is perched above the surrounding landscape making it susceptible to avulsion, and stranding of fish when flood flows leave the channel and go to the low point in the land, abruptly reducing the sediment carrying

capacity of the remaining flow in the channel;
- Aggraded channelized streams that were lengthened from their historic planform in order to follow human-imposed boundaries, reducing their slope and sediment carrying capacity.

Relocation of stream channels can also be an effective way to restore incised channelized streams, reestablishing bank stability, floodplain connections, and riparian functions. However, establishing a stable transition from the reconstructed reach to the downstream reach is often a weak point in such designs.

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.

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 modification of floodplain elevation or features such as levees (refer to the *Levee Modification and Removal* technique for discussion of levee modification). The main physical objective of cross-section changes is to alter the channel depth, and thus alter the hydraulic forces acting on the bed and banks. In particular, making the cross-section narrower and deeper has the effect of:
- Increasing the volume and particle sizes of sediment transport for each given discharge
- Increasing average velocity, while
- Maintaining water volume capacity

Other important effects on physical habitat include:
- Increasing the chances that large wood is retained and interacts with the water at all flows
- Reducing surface area for solar heating
- Promoting habitat complexity and hydraulic diversity
- Altering the physical habitat suitability for various species, which is a function of substrate type, velocity, depth, and bank characteristics

Cross-section modifications can be accomplished by:
- Encouraging the channel to narrow itself by restoring vegetation and/or large wood, porous weirs, or other in-stream structures that redirect flow
- 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.
- Excavating a new floodplain for an incised channel to accelerate the natural recovery process, which typically involves initial incision, channel widening and enlargement, and eventual deposition of floodplain within the incised and enlarged channel[3]

- Excavation of depositional materials from discrete aggraded reaches
- Removal of levees (for further discussion of levee removal, see *Levee Modification and Removal*)

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. There are three general approaches to rehabilitation of incised channels[4,5]:

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 (but not at the original level), which is a proactive acceleration of the natural progression of incised channels listed previously. Variations include:
    a. Partial excavation of a new floodplain, such as by excavating material on the inside of meander bends and creating floodplain or bankfull "benches"
    b. Creation of a different, but more stable, stream type within the incised channel, such as a step-pool system
3. Restore the historic channel grade and 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

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 offers little in terms of habitat value or long-term stability. Such an approach does not constitute restoration.

Restoring the historic channel grade (the third approach listed above) involves installation of drop structures, grade control, or channel fill to restore the elevation of the channel bed following incision. An increase in bed elevation 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 (one- to five-year return-interval events), channel erosion may be minimized. Therefore, raising the elevation of an incising channel bed should be considered as an effective means of stabilization. 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

4.1 Risk to Habitat

Channel modification projects should be designed to provide aquatic and terrestrial habitat benefit. However, large-scale channel modification may result in significant short-term adverse impacts to, and loss of, habitat, fish and wildlife due to disturbance. Months to years may be required for full recovery of some habitat components and recolonization. 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. There is also a risk that a poorly designed channel modification project 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 and Property

Channel modification may result in risk to infrastructure if inappropriately designed due to the complexity of accurately predicting relationships among various channel attributes in design and implementation (e.g. raising the channel bed elevation can increase the local flood risk). However, the intent is to improve channel stability and, thereby, reduce risk to infrastructure. Some desirable channel characteristics for habitat may be at odds with land use. For instance, flooding is a natural and beneficial feature of healthy channels. In-stream wood increases roughness and flood elevations. Wood, as with any in-stream obstruction, may redirect flow, collect additional wood, and influence scour and deposition, all of which may impact bank erosion or cause channel migration or avulsion.

4.3 Risk to Public Safety

Because channel modifications are typically relatively comprehensive reconfigurations of the channel, public safety should be considered in design, and if adequately addressed, risks can be avoided or minimized. Complementary techniques that may be implemented simultaneously, such as large wood placements, may present additional safety concerns. Refer to discussion of risk for each complementary technique.

4.4 Reliability/Uncertainty in Technique

Because all channel modification techniques will potentially alter hydraulic variables (depth, shear stress, velocity, turbulence) and sediment transport, there is a risk that an inappropriate design or unanticipated conditions will cause a project to fail. It is difficult to predict the response of channel modifications to the hydraulic character of the reconstructed and adjacent reaches as well as the sediment transport through the reach. A thorough understanding of fluvial geomorphology is an essential component of developing channel modification projects. Refer to SHRG Chapter 2, *Stream Processes and Habitat*, and the *Fluvial Geomorphology* appendix for further discussion of channel planform, profile, cross-section, and channel stability and equilibrium.

Channel modification design requires consideration of many design components, including sediment mobilization and transport, habitat, bed substrate, bank material, vegetation, channel hydraulics, and hydrology, and an understanding of many disciplines, including geomorphology, biology, hydrology and engineering to name a few. The risk and uncertainty associated with conducting a channel modification project can be greatly reduced by adequately accounting for many interdependent design components and by involving specialists from all related disciplines.

5 METHODS AND DESIGN

5.1 Data and Assessment Requirements

Channel modification should be integrated with fluvial geomorphic processes. These processes act on the stream channel to determine its form and character, which then influences the processes themselves, creating an evolving system. Watershed inputs to the stream that determine channel form include flow, sediment, and large wood inputs. These inputs, and the character of boundary materials of the channel, including bank vegetation, determine channel form, and available habitat and habitat quality. Stream habitat design will benefit greatly from consideration and evaluation of the geomorphic processes shaping the stream and the resultant form (slope, planform and cross-section characteristics) of the stream. Concepts in fluvial geomorphology that are pertinent to channel design are discussed in SHRG Chapter 2*, Stream Processes and Habitat*, and detailed in the *Fluvial Geomorphology* appendix.

As such, data collection and assessment in support of project design and monitoring should include elements that allow for this geomorphic approach. Data and assessment needs will be highly dependent upon the availability of existing watershed assessment information, the intent of the project, the nature of the channel, and the modifications to be implemented. However, 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.

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 the root cause of those problems. For instance, assessment required to narrow a short reach of stream that has been over-widened due to grazing of riparian vegetation and uninhibited livestock access to the stream will require assessment of the affected reach and a stable reference reach. In contrast, a watershed scale assessment will likely be necessary to modify an incised reach of stream in order to correctly identify and address the cause of the problem. For further discussion of assessment, refer to SHRG Chapter 3, *Stream Habitat Assessment*.

The following are minimum factors to be considered for modifying stream channels:

- What is the root cause of the problem? Has it already been addressed or will it be fully addressed by this project? If not, the project will likely address only the symptoms of the problem and it may reoccur.
- How has the stream or watershed been altered from historic 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?

- Are in-stream and watershed activities and conditions likely to have additional impacts to the project site? If so, how will they impact the project's success? Where there is a moderate to high risk of detrimental impacts or project failure, consider implementing watershed recovery projects prior to channel modification or wait until the watershed naturally recovers.
- Evaluate whether or not the modified channel will be self-sustaining. Items to consider include:
    - Is the channel in a natural setting or has it been moved to an unnatural location (e.g., it is perched or has it been lengthened or shortened making it susceptible to aggradation or incision)?
    - 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 naturally available bed material?
    - How will the proposed modifications respond to recruitment of large wood? Will instream large wood need to be actively managed?
    - Will channel migration be accommodated by the proposed design? Are there structural elements that will need eventual maintenance and replacement?
- If the proposed design will not create a naturally self-sustaining channel, is there a self-sustaining design alternative? If not, are there staff and funding to support permanent monitoring and maintenance of the project?
- 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?

Elements of a reach-scale analysis generally include:

- 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)
- Evaluation of sediment transport volumes and size distribution (see Section 5.1.3, *Sediment Transport Capacity*). Any channel modifications must be able to accommodate the sediment load without unanticipated adjustments.
- Determination of pertinent aspects of site hydrology (see Section 5.1.1, *Hydrology*). This includes channel forming discharge, low flow and flood discharges.
- Hydraulic conditions (see Section 5.1.2, *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)

- Documentation of physical, regulatory, social, and economic constraints and project limits
- Documentation of property, infrastructure, and land use activities that may be at risk by implementing or not implementing the project
- Evaluate access and materials availability. What access routes and staging areas are available? Will they limit the type of equipment, and therefore, the type of material that can by utilized?
- 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.
- Document baseline conditions necessary to support any planned monitoring activities at the site. The scope and nature of an assessment depends upon monitoring objectives. It may include documenting existing pool: riffle ratios, width: depth ratios, permanent cross-sections, photo documentation of site from permanent benchmarks that will not be disturbed by the project, or the frequency, extent, and depth of overbank flows, among other things.

In addition, some projects may require watershed-scale analysis elements, such as:

- 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)
- Large wood recruitment, transport and retention
- Riparian function (shade, temperature)
- 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)
- Trends in watershed land management and response to past management

In relatively small, stable, low energy streams where there is minimal risk to infrastructure, habitat, and public safety, elements of the design, if not the entire design, may be based on reference site conditions. For instance, if a new channel has a similar size, slope, and degree of entrenchment as a stable reach located immediately upstream, it can be assumed that the gradation of bed material necessary to maintain stability of the new channel is equal to that upstream. Many of the highly technical elements mentioned above would then not need to be quantified.

However, high risk projects, high cost projects, high maintenance projects (those that will not be self-sustaining), those where no reference reach is available and those on vertically or laterally unstable channels will require all or most of the reach assessment elements for proper design and evaluation.

5.1.1 Hydrology

There are three ranges of flows to account for that may influence design of channel modifications. The *Hydrology* appendix includes further details on these flows, and how to determine appropriate values for a given project.

1. *Dominant discharge* is the discharge that over time does the most work in the form of sediment transport, erosion and deposition within the channel. In streams in equilibrium, this discharge is commonly equivalent to bankfull discharge. As such, it is the discharge that should be used to determine the size of the bankfull channel dimensions. Refer to the *Hydrology* appendix for a detailed discussion of dominant discharge and its derivation.
2. *Low flow* is the base level of flow in the channel when the stream is not subjected to runoff from storms or snowmelt. Low flow should be used to design and size many habitat components including refuge, pools, and fish passage.
3. *Flood flow* is any low-probability flow that exceeds the capacity of the channel and inundates the floodplain or other adjacent areas. Flood flows, such as the 100-year flow, may be the basis of design for some channel components that are otherwise unrelated to habitat, but which may be required for regulatory purposes. Certain in-channel structures that artificially limit a stream's range of motion, such as grade control, should have associated design discharges to clearly outline risk to the project, infrastructure and general stream health, and future maintenance commitments if such structural controls are not self-maintaining or eventually superseded by natural processes. In many urban areas, channel modification projects will not be permitted to increase water surface elevations during flood flows. It is common to evaluate the 5-, 10-, 25-, 50-, and 100-year flow events.

In addition to the in-channel flows, hydrologic considerations for habitat design may include hyporheic and groundwater flow and interaction. The hyporheic zone is the transition area between surface flow and groundwater and is important for:

1. Supply and sink of nutrients within the channel
2. Temperature regulation within the channel
3. Moderating variations in stream flow
4. Regulating intra-gravel water quality.

While the importance of this zone is acknowledged, the opportunity to actively account for and manage the influence of this zone in habitat projects is very small due to the limits of understanding and the extreme variability of hyporheic conditions spatially and temporally. Bed substrate composition, particularly fine sediment content and surface embeddedness, has a large influence on hyporheic flow conditions. Channel complexity, including topographic variations in the streambed elevation, large wood and sinuosity also influence (promote) hyporheic flow. Refer to SHRG Chapter 2, *Stream Processes and Habitat,* and the *Hydrology* appendix for further discussion of hyporheic conditions.

5.1.2 Hydraulics

Hydraulics refers to the forces generated by moving water within the channel. Consideration of hydraulics is essential to successful design of stream habitat, 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 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 also 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* appendix.

5.1.3 Sediment Transport Capacity

Sediment in the context of channel modifications includes everything from boulders and gravel to sand, silt and clay. Channel modifications can include components designed to manipulate existing sediment transport and deposition within a channel reach and 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). Characterization and design of sediment transport is an integral component of channel modification design. The size and shape of the channel will determine to a large extent what size material will be transported and sorted within the channel, and thus will influence the viability and quality of habitat, particularly spawning habitat and aquatic food production.

Channel modifications require consideration of existing bed substrate and sediment supply. In alluvial channels (those built from material moved and deposited by the river), equilibrium conditions depend on both bed substrate size gradations and the size and volume of sediment moving into the reach. Channel modifications must ensure that:

- Appropriate size bed material exists to prevent incision but allow mobility and sorting of gravels, or where supply is limited, that bed material is sufficient in size to withstand mobilization
- The channel is capable of transporting all sizes and volumes of material delivered to the reach, without incising or aggrading
- Appropriate size gradations are available to meet habitat objectives, particularly for spawning

5.2 General Approaches to channel modification design

There are three general approaches to channel modification designs: Analog, Empirical, and Analytical[7]. Skidmore et al.[7] provide a detailed discussion of the applications and limitations of these varying approaches. Channel modification design may use any of the approaches described above, or a combination of the three. Project objectives, site conditions, and availability of an appropriate reference reach or sediment data 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).

1. *Analog design* involves replicating channel characteristics from historical data on the project site or from information gathered from a similar, stable channel and assumes those reference channels are in sediment and hydrologic equilibrium. This is sometimes called the Reference Reach Approach. It is best suited to cases where watershed hydrologic and sediment inputs have not been significantly changed. It is a relatively intuitive and simple approach, but this advantage can lead to its use in inappropriate situations.
2. *Empirical design* uses equations that relate various channel characteristics derived from regionalized or "universal" data sets, and also assumes equilibrium sediment and hydrologic conditions. Regional relationships are seldom relied upon as the sole design tool, but are useful to confirm design elements obtained by other means, or to help in evaluation of channel condition. Like the analog approach, empirical design is a relatively intuitive and simple process, which can lead to its use in inappropriate situations. Careful evaluation of similarity between characteristics of the stream and watershed in question, and those comprising the dataset used in the regional relationships must be exercised.
3. *Analytical design* makes use of the continuity equation, roughness equations, hydraulic models, and a variety of sediment transport functions to derive equilibrium channel conditions, and thus is applicable to situations where historic or current channel conditions are not in equilibrium, or where applicable analogs or empirical equations are unavailable. Application of the analytical approach generally requires access to engineering expertise, which can lead to a bias against its use due to cost or availability. The approach is particularly appropriate for cases where watershed sediment dynamics and hydrology are changing, where no reliable analog reaches exist, and where the assumption of equilibrium conditions cannot be applied.

Careful analysis of the watershed should accompany any channel modification work to determine if there has been significant alteration of the watershed hydrology. 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 historic 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

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. 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*.

Although each project requires a unique sequence 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 above. 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
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. Go back to Step 3 if sediment mobility is insufficient
9. Design grade control and/ or hydraulic bank protection
10. Develop bank designs
11. Add habitat features consistent with geomorphic function
12. 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.

Note that 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.

Note also that 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).

Note that 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 there is a strong relationship 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. Small changes to various design components are necessary in a backwards and forwards process to achieve the desired end design product. There is no single linear series of design tasks that can be followed to arrive at a final design.

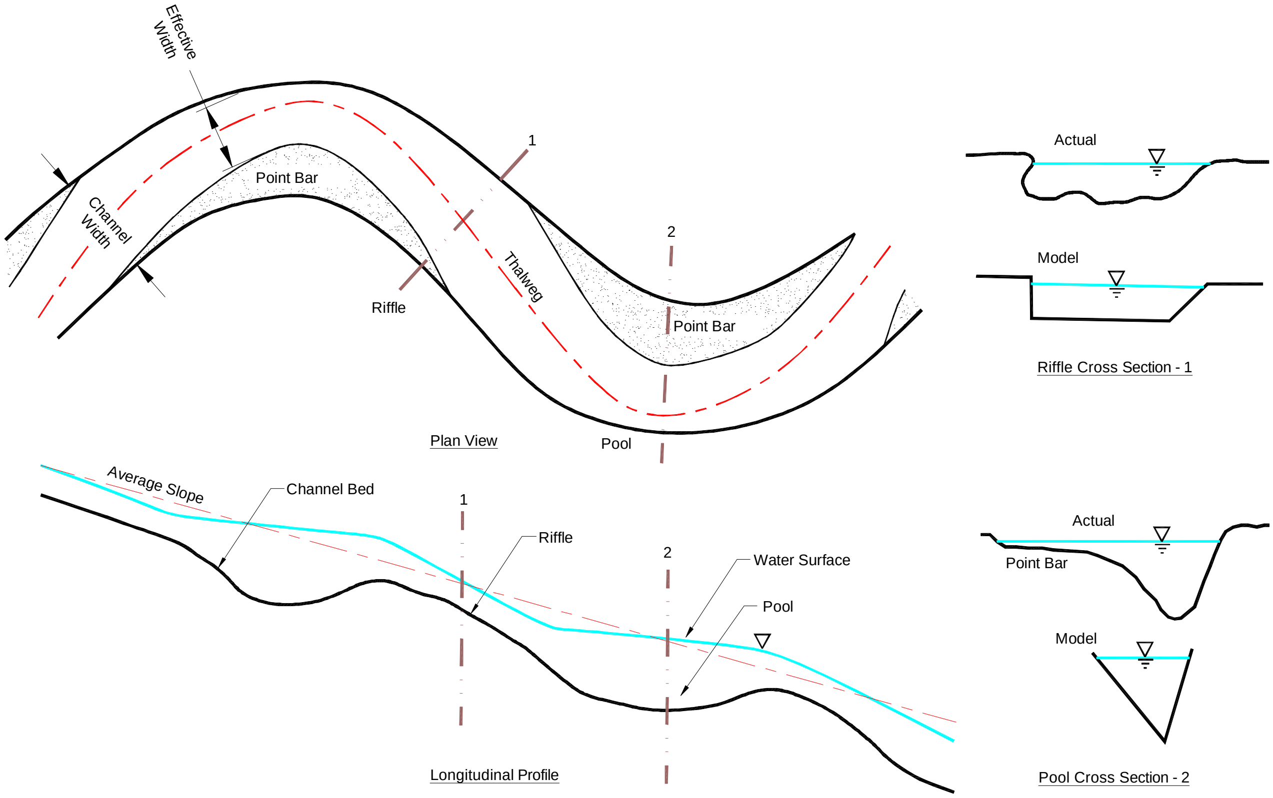
5.3.1 Cross-Section Considerations

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, upstream and downstream channel 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), though 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 **Channel Modification 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.



Channel Modification Figure 1: Channel cross-section in relation to position on longitudinal pool-riffle sequence. 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 use idealized cross-sections and average slopes, as shown.

The analog and empirical approaches emphasize a cross-section shape appropriate to the stream type being considered. For example, typical width: depth ratios can be obtained through measurements from a reference reach or from regional relationships. These shape parameters will depend on the type of stream being modeled (e.g. gravel-bed pool-riffle system, moderately-confined step-pool system, Rosgen Type C4 versus Type E6, etc.).

Channels come in various shapes. Familiarity with a channel classification system can help in deciding which shapes fit which stream types and which stream types are appropriate for which settings. 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). These numbers are not random or based solely on engineering hydraulic models. .

5.3.2 Channel Profile and Bedform Considerations

The primary design considerations when modifying or designing the channel profile are:

- Overall channel slope
- Bed elevation relative to floodplain elevation, existing bed elevation at the upstream or downstream limits of the modified reach, existing water table, or other design parameters
- Bedform characteristics (longitudinal variations in the channel bed) that mimic stable natural channel configurations and provide habitat diversity
- Transitions in slope between reaches upstream and downstream of the project

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. The modified channel (and upstream channel) will likely incise without stable grade control (e.g., drop structures or immobile bed material). 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), though 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 historic channel may be indicated by the depth of buried alluvial material within the soil profile.

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 **Channel Modification Figure 1**). Bedforms, such as pools, pool tailouts, riffles, chutes and other variations in the bed topography are three-dimensional features, and are therefore incorporated in both profile design and cross-section design.

In streams undergoing restoration or modification, channel profiles typically fall within one of the following types of sequences, which are further discussed in the *Fluvial Geomorphology* appendix:

- Pool-riffle sequences consist of steep armored riffles and deep slow pools, and are most common at slopes of less than 2 percent. Scour patterns form pools on the outside of

meander bends and in association with large wood, rock, or other obstructions to flow. Pools typically have tailouts of mobile gravels, which slope up to the head of the next riffle. The riffle gradually deepens and transitions into the next pool. Pool riffle sequences typically occur at an interval of 4 to 10 channel widths[8].
- Step-pool sequences consist of steep drops formed by large wood or boulders, and scour or backwater pools. Step-pool sequences commonly occur at slopes of greater than 2 percent. Step-pool sequences typically occur at an interval of 1 to 4 channel widths.

The channel type found at any location is determined by channel slope, available bed material and large wood, and the surrounding landform. Channel types that occur in Washington State, other than those described above, are described in the *Fluvial Geomorphology* appendix.

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 related. Slope may be constrained by sediment transport characteristics.
- Site constraints on meander amplitude and wavelength may exist due to valley width or placement 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 (Rc) can be varied considerably in most situations and can provide valuable opportunity for variability in planform. The ratio of Rc:W (radius of curvature to channel width) has been studied extensively and found to correspond to susceptibility to erosion, both in nature and in labs. This ratio, therefore, can be used to define limits for planform characteristics. Meandering alluvial channels tend to have an

Rc:W ratio of between 2 and 3[9]. 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[10]. 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. In such instances, larger Rc:W ratios (3 to 4) may reduce erosion potential initially. Here, it is worth noting that the design channel type must be appropriate for the slope, substrate and valley setting. Design of meandering, pool-riffle type channels are not appropriate at slopes greater than about 2 percent.

Sine-generated curves may also be used to design planform, but 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 of the location of the new channel relative to the old channel. Construction can be greatly complicated when the new channel alignment crosses the old channel alignment repeatedly, as each crossing will require fairly complicated construction sequencing and careful design of plugs in the old channel. Crossings do, however, provide opportunity to create off channel rearing habitat. Leaving the downstream portion of a previous channel open where it connects with the new channel can provide low velocity off-channel habitat. Channel plugs should consist of compacted earth (not porous rock) and they should be of sufficient length to minimize risk of headcut and avulsion into the old channel during high flow events. A 40-foot minimum plug length is recommended on relatively low gradient small streams (<20’ wide); longer plugs may be necessary for larger or steeper channels. It may be best to break up lengths of old channel into segments, forming a string of ponds, to reduce avulsion risk. 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 (e.g., 5H:1V) on the downstream end of the plug and heavily mulching and/or vegetating it may also suffice. Likewise, potential headcutting at places where floodplain water enters an old channel from the side must be carefully considered to avoid a channel avulsion.

Finally, subtle valley topography may exclude some proposed channel locations. Channels naturally form in low areas. However, relocated channels are sometimes perched above the surrounding land with levees, making them susceptible to channel aggradation, avulsion, and fish stranding when high flows leave the channel or spill over the levee. Perched stream reaches thus present a high risk of failure, necessitating a long-term monitoring and maintenance commitment to keep them within their constructed channel. Creating or sustaining perched channel conditions should be avoided.

5.3.4 Control of Streambed Elevation

Control of streambed elevation, often called grade control, is often used in order to:

- Provide a gradual transition from a reconstructed reach to a downstream reach

- 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 a dam or pond that traps sediment)
- Prevent channel incision where the sediment transport capacity is higher than that in the upstream channel (e.g., if the new channel has a greater slope, depth, or degree of confinement than the upstream or existing channel)

Methods commonly used to fix streambed elevation include:
- Drop structures (see the *Drop Structures* technique)
- Buried large wood or large rocks
- Placement of coarse streambed material.

Grade control is often incorporated at the downstream and upstream ends of a newly constructed channel (see **Channel Modification Figure 2**), and in longer reaches at regular intervals along the reconstructed reach. Drop structures should be designed and constructed to be flush with the channel bed elevation, unless there are other habitat objectives incorporated in the control. Drop structures may be rigid or deformable (designed to eventually deform through gradual mobility of materials). The advantages and disadvantages of using drop structures, and design guidelines and considerations necessary for drop structures to control grade are described in the *Drop Structure* technique. In many cases, grade control structures must extend far up into the floodplain to avert potential channel avulsion. Design teams must be forthright about the fact that grade control structures may be necessary to hold some projects together. Thus, long-term project success depends on commitment to monitor and maintain these structures, replacing them in the future as necessary. The best designs will include restoration of processes (such as large wood recruitment and retention) that ultimately eliminate dependence on structures. Refer to the *Porous Weirs* and *Drop Structures* techniques for further information on habitat value associated with these structures, and for design guidelines.

Channel Modification Figure 2: Step-pool drop structures are often employed as streambed elevation (grade) control in transitional zones at the ends of newly constructed reaches. This is particularly common at the downstream end of a restored incised channel.

5.3.5 Bed Material Considerations

In alluvial channels, modifications can often be implemented within existing substrate and alluvium. Channels are 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 part of the initial design, or even part of the long-term maintenance activity. These cases include:

- Reaches with very low sediment input from upstream, as indicated by:
    - Analysis of existing bed substrate and sediment mobilization and transport both in the project area and upstream
    - The existence of dams, ponds or other sediment traps upstream
    - Artificial stabilization of dominant upstream sediment sources, such as pervasive bank armoring
- Where bed material enhancement is needed to temporarily stabilize the bed and provide spawning gravel until natural recruitment provides the supply, as when relocating a gravel-bed stream onto floodplain deposits (silts and sands)

In circumstances where the natural supply has been eliminated, supplementation may be a part of a regular maintenance program. Supplementation of gravels is discussed in detail in the *Salmonid Spawning Gravel Cleaning and Placement* technique. Regular supplementation is costly, but may be justified where resource values are high. Commitment to gravel supplementation requires careful consideration of geomorphic processes, since not all reaches, even within alluvial settings, are conducive to persistence of stable spawning gravel deposits. Supplementation is most effective in response reaches that are not in the gravel-to-sand transition zone (refer to the *Fluvial Geomorphology* appendix for further discussion).

The science of sediment transport straddles the disciplines of engineering and fluvial geomorphology. Typically, engineers conduct the methods and models used to analyze sediment transport at short time scales. Geomorphologists identify dominant sediment dynamics over long time spans and larger spatial scales. Both long (decadal) and short (storm or annual) time scales may need to be considered. The *Sediment Transport* appendix presents methods for measuring and quantifying sediment transport, and for applying these methods to design of channel modifications.

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? If not, grade control may be necessary to prevent channel incision.
- 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 substrate within the newly constructed channel and run it part way up the banks.

5.3.5.1 Gradation of material for constructed channel bed

Gradation refers to the range of particle sizes present, and their proportions in the bed material mixture. Bed substrate provides both habitat and channel stability. In natural systems, substrate character (size, gradation, porosity, and depth) can vary substantially through a reach. 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 Fish Passage Design at Road Culverts manual[11] provides further discussion and resources for design of bed substrate gradation.

Habitat value (e.g., for spawning) is dependent primarily on size, depth, and porosity, while streambed stability is dependent primarily on scour depth and material gradation. 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. In some instances, 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 degradation. Protection of the channel will have to be balanced with the need for mobile spawning gravels. Ideally, selection of the gravel size distribution for instream placement should be based upon a particle size distribution from an appropriate reference reach. However, in many instances appropriate analogs are not available, in which case detailed hydraulic and sediment transport analyses are necessary to determine 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[11]. Thus, at bankfull conditions, nominally 84% of the bed substrate material would consist of a size that could mobilize, and 16% would be immobile. The surface particle size distribution will differ for different channel bed features.

Also, in practice, a substrate 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 much coarser substrate than non-riffle portions of the channel, and should be constructed to be largely immobile 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. 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. Other methods for determining substrate mobility are presented in the *Hydraulics* appendix and the *Sediment Transport* appendix, the Fish Passage Design at Road Culverts guidance manual, 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 eggs within gravels. “Spawning” sized material is not appropriate in all situations and shouldn’t be forced into a design. The value of adding it may be short lived if it blows out of the new channel in the first storm. Unless it can remain naturally stable in system, it should only be used to supplement other more stable material.

Depth of substrate. Where imported bed substrate material included in the reconstructed channel 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 depth of scour is discussed in the *Hydraulics* appendix. It can also be estimated by measuring pool depths in a reference reach. But keep in mind 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, the thickness of the installed material should be approximately 10 to 20% greater than designed 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. Most channel modification activities will require reconstruction of channel banks on one or both sides. 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. In other cases, hydraulic structures or even judicious use of bank armoring locks the new channel in place for an indeterminate time period. This may be part of a strategy to regenerate a mature vegetative buffer zone that ultimately serves to accommodate channel migration. Or, it may be that social concerns preclude channel migration and the bank protection may need to be maintained in perpetuity.

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 long-term stability to the lateral channel boundaries, nutrients, and detritus to the stream, shade and acts as a source of wood. Revegetation should be an integral part of most channel modification projects, particularly where bank reconstruction is involved, and is often 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 management actions. 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 tends to be a natural magnet for fish, and tends to promote physical processes such as 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 them can be incorporated in channel modifications. Large roughness elements and habitat features can substantially affect the hydraulics of the stream by reducing velocity, shear, and sediment transport and by increasing water surface elevations at all flows. The design process should consider the degree of habitat and roughness that is appropriate and intended such that these elements don’t 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 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 (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;
- Diverting stream flow;
- Rescuing fishes from areas to be dewatered;
- Dewatering;
- Constructing the channel bed, streambanks and installing habitat features; and
- Redirecting flow into the modified channel.

Further discussion of these components can be found in the *Construction Considerations* 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 Considerations* 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 Considerations* appendix.

8 COST ESTIMATION

Channel modification project costs are site and design specific and vary according to the size of the channel. Reconstruction and relocation projects may range from as little as \$20 to well over \$1000 per foot of channel (including reconstructed banks and dewatering), 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 historic 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

Because channel modification projects generally involve impacts to the channel and banks, they will require comprehensive monitoring of both channel and bank features, in addition to particular attention to habitat monitoring. For a comprehensive review of habitat-monitoring protocols, refer to Johnson et al., 2001[12].

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 Considerations* 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 doesn't work, and what are the benefits and impacts of various 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 occur on time and spatial scales 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.

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[13].

9.2 Habitat/Fish/Wildlife monitoring

Fish and wildlife populations are determined by numerous biological and abiotic factors besides physical habitat[14]. An increase or decrease in fish and wildlife populations following a stream channel restoration project therefore may be completely unrelated to geomorphic changes effected by 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[15]. 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[14]. 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.

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. While the intent of channel modification is to create a stable channel, 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.

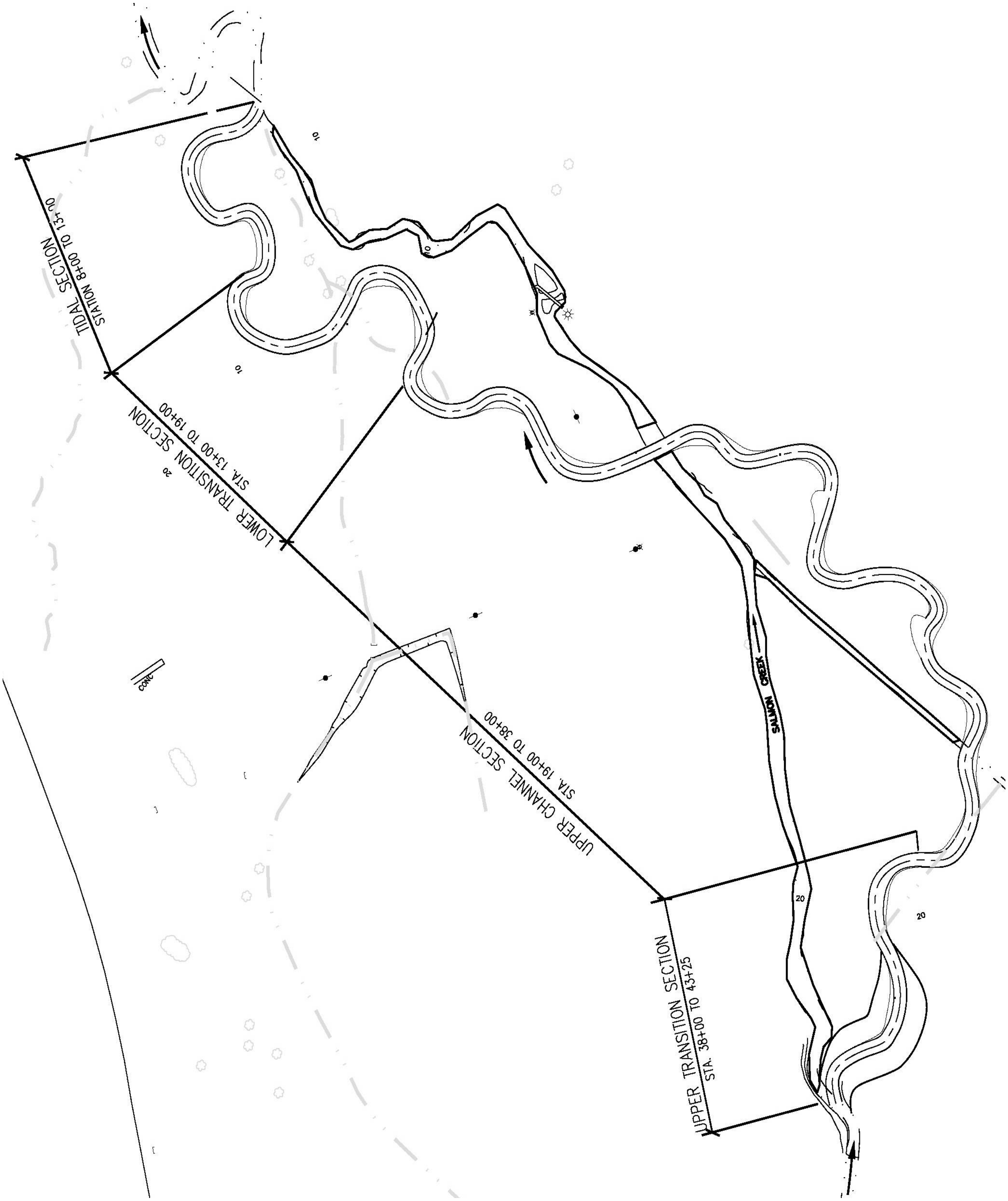
11 EXAMPLE

Salmon Creek Restoration Project

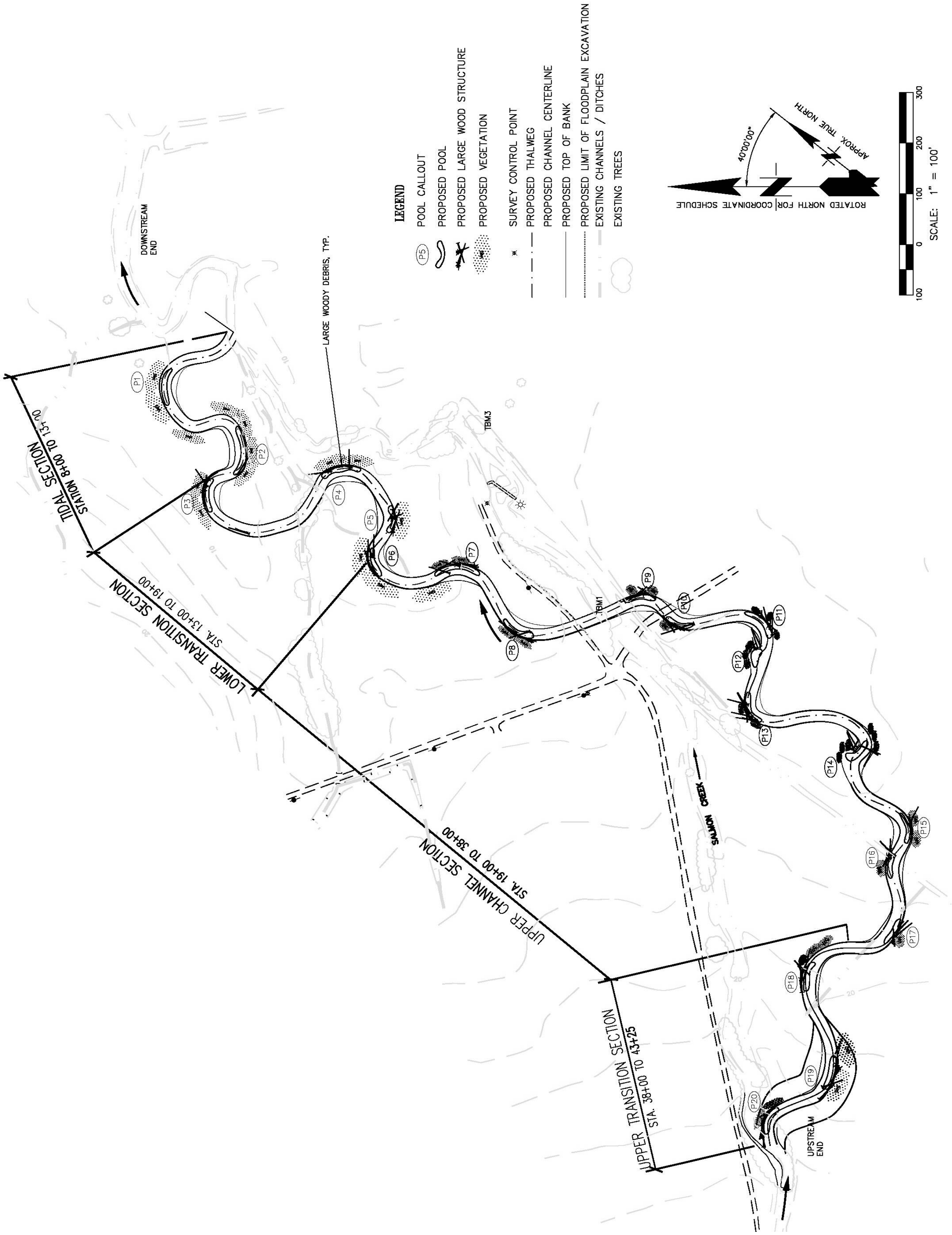
The objectives of the project were 1) to restore an approximately ½ mile reach of Salmon Creek (from river mile 0.25 to river mile 0.75) to a self-sustaining configuration to prevent the need for periodic dredging, and 2) to enhance fish habitat throughout the reach, with a particular focus on endangered summer chum salmon. Salmon Creek is located in Jefferson County and is a tributary of Discovery Bay. 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 aggradation, high water temperatures, lack of channel complexity and in-stream cover, and excessive levels of fines in the gravel.

Aggradation occurred as a result of several factors. The reach lies in the valley bottom; sediment transported from the hill slopes tends to deposit in the break in slope. Sediment supply upstream is elevated above historic levels as a result of extensive timber harvest as well as a pulse of sediment from a large landslide associated with an upstream tributary which was rerouted in the past and now falls over an approximately 25 foot high bluff. A third contributor to channel aggradation is that the stream was relocated such that portion of it are now perched above the surrounding ground. Relatively frequent high flow events jump the right bank levee and leave the channel. The competence of the remaining flow to carry sediment substantially decreases, and the sediment drops out. Lastly, a fish weir is located at approximately river mile 0.3. The fish weir severely constricts the channel and backwaters the upstream reach, encouraging upstream sediment deposition. The reach was maintained in its current configuration by levees and periodic dredging. 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.

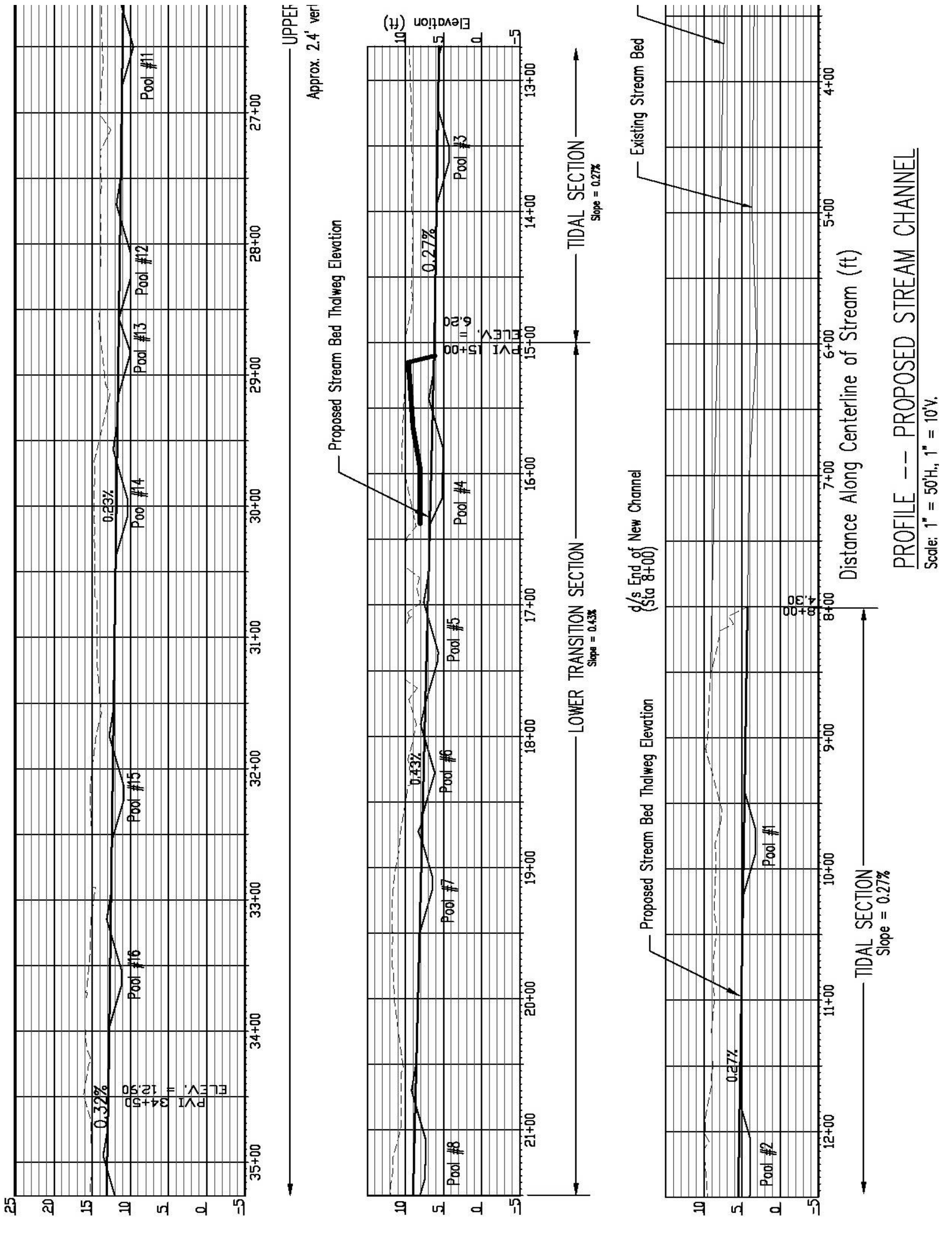
The project entailed constructing an approximately 3,500 foot long new channel with a more natural configuration. **Channel Modification Figures 3 and 4** show the existing channel and the channel modification design in plan view. The designed channel lies closer to the topographic low point in the valley, 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. These features are evident in the longitudinal profile (**Channel Modification Figure 5**). Riffles were constructed with imported bed material wherever gravel was not found during construction, as shown in more detail in **Channel Modification Figure 6**. **Channel Modification Figure 7** is a detailed plan and profile view of a typical mid-reach segment, including cross-section designs and large wood structures. **Channel Modification Figure 8** shows one of these structures under construction. Finally, **Channel Modification Figure 9** 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.



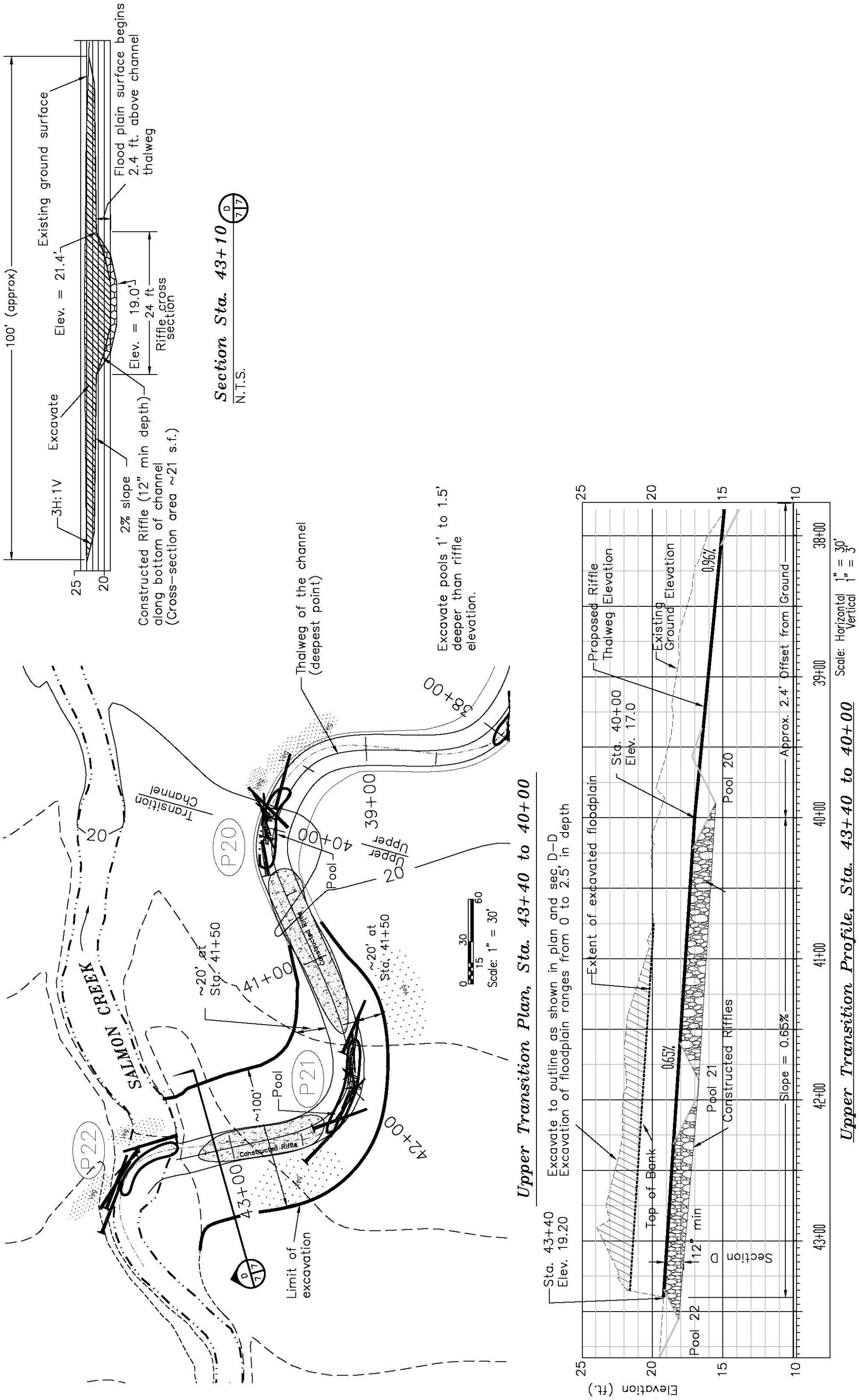
Channel Modification Figure 3: Channel modification example: Salmon Creek, Jefferson County, Washington. Plan view, showing existing channel and new channel design.



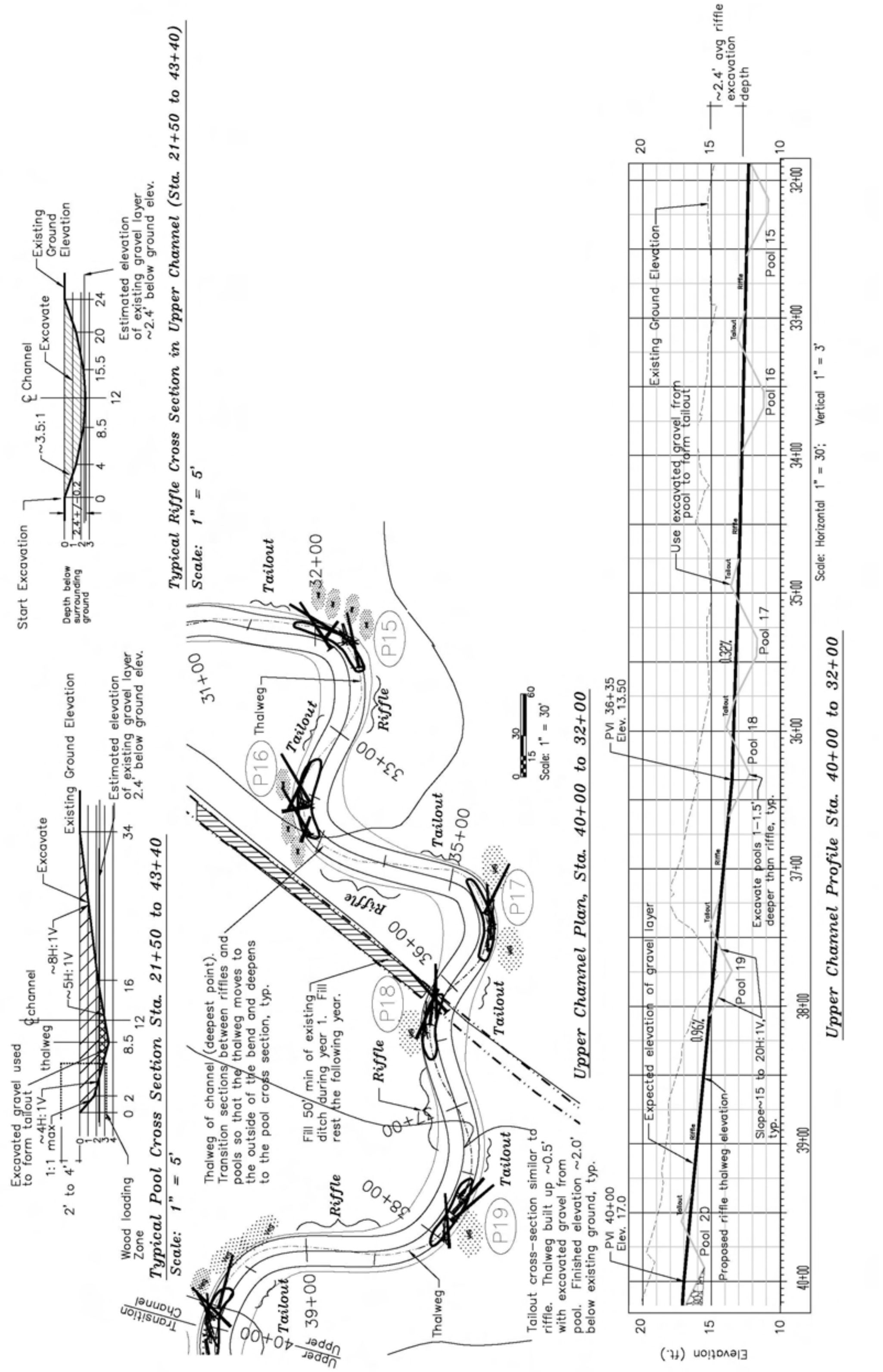
Channel Modification Figure 4: Channel modification example: Salmon Creek, Jefferson County, Washington. Plan view, showing reach delineation, locations of pools and large wood complexes.



Channel Modification Figure 5: Channel modification example: Salmon Creek, Jefferson County, Washington. Longitudinal profile.



Channel Modification Figure 6: 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.



Channel Modification Figure 7: Channel modification example: Salmon Creek, Jefferson County, Washington. Close-up details of profile, cross-sections, and large wood complexes.

Channel Modification Figure 8: Construction of a large wood complex.

Channel Modification Figure 9: Aerial view of Salmon Creek project under construction. Photo provided courtesy of the Jefferson County Conservation District.

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LEVEE MODIFICATION AND REMOVAL

1 DESCRIPTION OF TECHNIQUE

This technique describes the full or partial removal, breaching, lowering, and/or relocation of artificial stream and tidal levees for the purpose of habitat restoration. Levee Modification and Removal 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. Levees directly affect floodplain extent and connectivity with the stream channel, which affects available habitat and complexity. Undeveloped, natural floodplains provide stream energy dissipation and flood storage by allowing flood flows to dissipate, thus reducing velocities and providing areas for organic and inorganic sediment deposition. These low velocity areas provide refuge areas for aquatic species during floods and are excellent habitat for a wide variety of species. From a restoration perspective, it is preferable to have an entire levee removed, but where complete removal is not feasible, the use of setback levees or carefully placed breaches can provide excellent restoration opportunities.

Because most levee removal or setback projects will result in some changes to channel and floodplain processes, a thorough understanding of fluvial geomorphology is essential. Refer to the *Fluvial Geomorphology* appendix and to Stream Habitat Restoration Guidelines *Chapter 2: Stream Processes and Habitat*, for further discussion of channel stability and equilibrium.

1.1 Background

The United States has over 25,000 miles of levees, dikes, embankments, and floodwalls, but despite this relatively high level of "protection", flood losses continue to increase. The use of levees for flood protection generally results in, and even encourages, increased development of floodplain areas because of the public perception that the area will not be flooded. 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. In fact, 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]. Often the loss in floodplain storage from dikes results in increased flood water elevations, and thus increased flooding, elsewhere in the watershed.

Levees or dikes are defined as artificial embankments, usually of random earth fill, built along the bank of a watercourse or an arm of the sea and designed to protect land from inundation or to confine streamflow to its floodway[2]. Accordingly, the Natural Resources Conservation Service (NRCS) uses three classes of dikes designated by the type of land use they are protecting. Class I dikes are constructed in areas where levee failure may cause loss of life or serious damage to homes, businesses, or transportation networks. Class II dikes protect areas where failure may result in damage to isolated structures, some infrastructure, and high value crops. Class III dikes are constructed in rural areas and protect lower value agricultural land. Each of these dikes has specific design criteria depending upon the level of protection provided by the levee[3]. There are various types of levees used for flood protection, which include:

1. Lateral levees – built adjacent to a stream channel to confine flows within the active channel. Often used in conjunction with channelization and/or dredging projects. Generally requires a high structure to reduce flooding due to the limited cross-sectional area. Revetments and other types of bank armoring are common with this type of structure.
2. Setback levees – generally parallel to the stream but placed far enough from the active channel to allow overbank flooding and some natural floodplain function. The degree of setback is variable, however, narrow setbacks may result in erosion on the surface of the newly established floodplain due to high flow velocities. Structures are generally lower than lateral levees and require less maintenance.
3. Perimeter levees – used primarily to protect individual structures, groups of structures, and wells. Often called “ring dikes”, these levees protect small areas from flooding rather than confining flood flows within the stream channel or floodway. Levees are generally broad in cross-section to accommodate equipment and vehicle access and other land uses.
4. Cross-floodplain levees – generally perpendicular to the stream and used to redirect flood flows back into the active channel or floodway. They allow floodplain storage of water but no flow parallel to the stream. For instance, road fill across floodplains can inadvertently function like cross-floodplain levees by creating constrictions that cause localized scour, channel down-cutting, and backwater conditions upstream. Cross-floodplain levees may be required at the upstream and downstream limits of a levee removal or setback project, so that adjacent land outside of the project area is not flooded.
5. Tidal levees – used to protect land specifically from high tide and saline water. This results in the conversion of tidal marshes into other habitat types. Tide gates are often used in conjunction with tidal levees. Fresh water can be trapped on the landward side of these levees increasing the salinity gradient at the tide gate, which may impact species that migrate through the freshwater/saltwater interface.
6. Deflecting levees – the objective of deflecting levees is for “river training” rather than flood protection. Structures are used to control flow direction during floods. Deflecting levees need not be continuous.

In the early 1900s, many lateral and tidal levees were constructed or authorized by the U.S. Army Corps of Engineers (Corps), which is consistent with other Corps dredging and navigation projects during this period. For example, in a delta area a typical Corps project would focus the river’s flow into one main channel to establish a navigable river channel. Many of the sub-channels in a river’s delta would be closed and training dikes would be installed to guide the channel, whereupon dredging would ensue to establish the channel to the appropriate navigation depth. Dredged materials would typically be side cast for use in construction of the adjacent dikes.

1.2 Geomorphic Consequences of Levees

Natural levees are found along the margins of many alluvial stream channels and are formed by the deposition of the coarser part of the sediment load when stream flows exceed channel capacity and the water flows onto the floodplain[4]. Artificial levees, however, 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. While initially effective in reducing inundation, levees have numerous drawbacks.

Levees constrain stream flow to a smaller cross-sectional area, thus velocity and stream power are higher after levee construction for similar discharges. Increased stream power results in more pronounced erosion and depositional sequences, often causing channel incision and over-steepened streambanks. In turn, channel incision can lead to accelerated bank erosion and the introduction of additional sediment into the stream system from the mechanical 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 stream bed is armored, or a resistant layer is encountered, the channel may preferentially erode its streambanks.

Vegetation is often removed from the levees to preserve structural integrity and is also removed from areas within the levees, referred to as the “floodway”, in order to decrease roughness, increase velocities, and hence lower flood stages. This reduction in energy dissipation further increases stream power and flow velocities, reinforcing the processes responsible for channel boundary erosion and channel incision.

The loss of available floodplain reduces areas in which channels respond to changes in watershed inputs (water, sediment, wood). By reducing sediment storage adjacent to the channel (in the floodplain), deposition of sediment occurs within the channel during low flow periods, potentially resulting in aggradation. 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). 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. 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. In contrast, during high flows stream power 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) that are described below.

2 PHYSICAL AND BIOLOGICAL EFFECTS

Levee removal can potentially restore a more stable cycle of erosion and deposition by allowing the channel to access its floodplain. 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). By restoring floodplain functions and channel processes, levee removal has many potential physical and biological benefits. In contrast, levee removal may also cause further instability if the channel has adjusted to the presence of the levee. In summary, the potential physical and biological effects of levee removal include:

Potential physical effects:

- Change in energy distribution within the channel (usually decrease) and on the floodplain/floodway (usually increase), which more closely mimics natural conditions.
- Reduction of water surface elevation at the site and upstream during floods.
- Increased overbank flow resulting in greater potential for increases in groundwater recharge in the floodplain.
- Reduced flood potential to downstream areas by increasing storage of flood water.
- Attenuation of sediment transport downstream by providing sediment storage.
- Greater channel complexity and/or increased shoreline length.
- Increased floodplain flows and thus floodplain channels, diversity and interaction with the active channel.
- Stabilization of the channel reach from chronic erosion or instability due to sediment deposition.
- Short-term and/or chronic instability if the channel has evolved to the hydraulic condition of the presence of the levee.
- Changes in channel geometry as the newly unconfined channel evolves to its new hydrologic situation.
- Restoration of estuarine functions of temperature, tidal currents, and salinity in the case of tidal levee removal.
- Increased habitat abundance from distributary channels, which increase in size after tidal flows are allowed to inundate on a twice daily basis and scour.
- Increased width of the riparian corridor.

Potential biological effects:

- Increased riparian function including:
    - increased shade and hence moderated water temperatures and microclimate,
    - increased abundance and retention of wood,
    - increased organic material supply,
    - water quality improvement,
    - filtering of sediment and nutrient inputs,
    - nutrient cycling,
    - seed dispersal, and
    - wider, more effective migration corridor for terrestrial species.
- Restoration of flood-flow refuge for aquatic species.
- Reduction of fine sediment in-channel and downstream, including estuary filling by providing low energy, overbank storage areas for fines.
- Restoration of fish and wildlife access into tributaries, floodplain habitats (side channels,

off-channel ponds and wetlands) main channels, estuaries or ocean by reestablishing historic channels.
- Restoration of saline-dependent plant species and thus increased drainage (tidal levees).
- Increased primary productivity.
- Restoration of estuarine food production (tidal levees).
- Restoration of an estuarine transition zone (tidal currents, temperature, salinity) for species migrating through the tidal zone.
- Shift in vegetative community composition and distribution.
- Shift in wildlife species composition and distribution.

An example of a biologic effect is the existing dike structures in the Deepwater Slough area of the Skagit River delta that create a system of disconnected habitats. The lands behind the existing dikes provide habitat for a variety of invertebrate, amphibian, and plant species. These habitats produce an important food source to a variety of predators; however, the great majority of the biomass and organic nutrients inside of the dikes cannot be transported out of the area due to the blockages. With the dikes in place, there is no hydraulic connectivity between these habitats and the river and estuarine environment. It is hypothesized that the lack of biomass and nutrient transport to the river and estuary has become an ecosystem function-limiting factor in this system.

3 APPLICATION OF TECHNIQUE

Levee removal or setback applies to all stream systems that have artificial levees in place, but is most beneficial in streams that are not incised and are still capable of accessing their historic floodplains at relatively frequent flows (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. Accordingly, implementation of levee removal or setback in incised channels is augmented with in-channel grade control in order to reverse the incision process.

Focus should be placed on streams where infrastructure and floodplain development is minimal, but 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, agricultural areas, public lands, and parks; these areas favor restoration of natural floodplain vegetation, flood channels, and active side channels. By restoring floodplain functions and processes, Levee Modification and Removal can be used in conjunction with many other techniques including but not limited to: Channel Modification, Log Jams, Bank Protection, Land Preservation and Buy Back, Riparian Restoration and Management, and Side Channel Habitats. Accordingly, floodplain restoration work should often begin prior to modification or removal as long as access is retained for actual construction work.

4 RISK AND UNCERTAINTY

Flood damage typically results from levee failure rather than levee overtopping. If flood stage exceeds levee height, then overtopping is imminent. The overtopping may cause levee failure by cutting back through the levee at the point where it is overtopped, however, it is much more common for a failure to occur before overtopping. Because of the hydraulic pressure gradient (the difference in water surface elevations on either side of the levee), seepage occurs through the levee and discharges on the “dry” side. This increases overall pore pressure, which reduces shear strength in cohesive materials. Increased velocity can cause piping, or excavation of material from the inside of the levee, which leads to failure. Once a levee is breached, water shoots through the opening at very high velocities, entraining material within 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.

The Levee Modification and Removal technique has a low technical uncertainty, assuming the analyst completes the appropriate analysis and modeling. Overall, the analyst should have access to hydraulic and sediment transport modeling software that allows quantitative analysis of the risk incurred by levee modification or removal. Accordingly, risk analysis must include:

1. Assessment of changes in channel stability resulting from levee removal or setback.
2. Assessment of the hydraulic effects on upstream and downstream reaches and on the floodplain within the project area.
3. Assessment of changes to flood hazards.
4. Assessment of stream channel response within the project area.

Stream, estuary, and tidal system adjustments to levees may be complete or on-going, and they must be addressed before levee modification is undertaken. For instance, the cross-sectional geometry or longitudinal profile of a stream channel may be significantly altered due to a levee on one or both banks. Therefore, a geomorphic analysis is required to determine potential stream adjustments after the levee is removed. In some situations, it may be necessary to restore some floodplain functions, such as topography, roughness, and structure, before a levee is removed.

The primary hydraulic effect of levee removal is restoration of overbank flows. Accordingly, the designer should estimate the effects of levee removal in situations where the channel has evolved to the presence of the levee. Levee removal may actually decrease channel capacity in streams that have aggraded in response to the constraining effect of the levees. In some cases there may be no channel capacity at all. In these situations, without mature flow channels in the floodplain, this situation can result in years of chaotic channel evolution as it tries to develop a suitable alignment, shape, and slope.

Additionally, hydraulic effects of levee removal or setback include changes in channel and floodplain roughness and a potential change in channel length and slope, which in turn affect velocity and shear stress. Generally, velocity and shear stress will decrease causing a loss in sediment transport capability through the levee removal reach. For instance, the reach upstream of a levee removal project may experience increased velocity and shear stress as the backwater of the levee during flood events is eliminated. Sediment deposition on the floodplain should be expected. Hydraulic models are available to help predict these changes. Many analytical tools are available for flood routing (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. Likewise, sediment transport models (HEC-6 and GSTARS) are helpful for addressing issues associated with sediment deposition within the project area and in the upstream reach, but should be used with caution as sediment transport modeling is an inexact science with large margins of error.

4.1 Risk to habitat

Risk to habitat is generally low for levee modification or removal. Primary risks include longer and more frequent inundation, which may result in changes to vegetative communities and hence animal assemblages. Localized scour and increased velocities may impact existing habitat. 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. If a levee setback is not extensive enough, there may be scouring flows over the floodplain essentially resulting in an over-widened channel. Hence, vegetative success would be low and the area would have minimal value for aquatic and terrestrial species.

Another risk to habitat is land subsidence due to disconnection of the floodplain from the source of sediment, dewatering, compaction, and peat decomposition. 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 may avulse through the floodplain. Eventually the floodplain will regain its former elevation if sediment is available, but the initial plant community may be representative of a much lower elevation than expected.

4.2 Risk to infrastructure and property

Risk to infrastructure can be very high depending on site conditions. For levee removal, flooding and channel erosion may pose a significant threat to infrastructure and buildings. Geomorphic and hydraulic evaluations of flood elevations, inundation periods, and potential patterns of channel migration are essential for evaluating risk. There is a lower risk to infrastructure and property with levee setback if the flood capacity is maintained, except for the property on the streamside of the levee. Levee setback can actually improve flood protection for adjacent infrastructure and property because the flood capacity is often increased due to 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 others 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 Integrated Streambank Protection Guidelines[5], for information regarding streambank protection and avulsion risk reduction.

Flood risk can be evaluated using available models, which calculate backwater curves during flood events (HEC-RAS). Flood risk is usually decreased for adjacent areas by the removal or setback of a levee except for the area directly impacted by the activity. Long-term flood risk is generally reduced for all areas if the floodplain and channel are returned to a condition in which overbank flows are more predictable and the channel and flood stages are not super-elevated above the surrounding floodplain by being confined by levees.

Local zoning may need to redefine the extent of the 100-year floodplain to better represent the areas at risk of inundation.

4.3 Risk to public safety

Risk to public safety can be either increased or decreased depending on the project. Because flood elevations are actually lower with levee removal or setback, and risk of levee breaching is reduced, public safety is enhanced. If, however, proper analysis of flood stage and routing has not been completed, inadvertent flooding in previously non-flooded areas could decrease public safety. Areas that have historically been protected by levees may be perceived as “safe” by the public, even during large flood events. 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 planning and design. Projects may require several years of coordination and planning to obtain environmental clearances, landowner permission, easements, and adequate analyses and designs before they are 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 quantifying the hydraulic and geomorphic effects of modifying or removing levees (refer to Stream Habitat Restoration Guidelines *Chapter 3: Stream Habitat Assessment*). Projects implemented at the reach scale are preferred over site-specific projects because they restore more floodplain functions and amplify beneficial effects. They also potentially reduce the cost per acre because cross-floodplain levees are not required to protect adjacent lands. Accordingly, watershed-level assessments are necessary at some level to account for potential actions and effects to the reach in question.

In evaluating levee modification or removal, determining the relative elevation of a channel or estuary to the floodplain surface is a critical component for project feasibility and planning. For instance, areas protected by levees may subside due to the disconnection of the contributing water body, which results in significant decreases in organic and inorganic sediment deposits, increases in soil compaction, and decomposition of organic materials in the soil. Because subsidence in conjunction with instream deposition may result in a perched channel condition, modification or removal of a levee 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 to an artificial condition in response to the levee confinement.

In a second example, many levees provide bank stabilization due to artificial armoring of the levee bank, therefore removal of the levee results in removal of the armoring, and a potential increase in erosion. Accordingly, short-term bank protection may be necessary to stabilize bare, erodible banks until native vegetation has become effective. See the Integrated Streambank Protection Guidelines for further guidance.

In summary, the degree of risk and uncertainty dictates the amount of data collection and assessment required for a given project. If possible, compare current channel geometry to pre-levee geometry to assess the extent of channel change, and determine the rate of change, in order to predict the rates of future channel change. Aerial photography is an excellent tool for determining the rates of change for channel planform, but is not helpful for channel geometry changes, hence the need for cross-section data over time. For most levee modification or removal projects, the following data collection and assessments are required.

Data Needs:

- Hydrology (high flow frequency, magnitude, timing, and duration) for analysis of flood and sediment effects.
- Topographic survey with cross-sections (including in-channel, levee, floodplain, and surrounding area which will potentially be impacted) for analysis of flood effects and for potential realignment design.
- 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 infrastructure at risk for analysis of flood risks, to help minimize risks, and to investigate channel alignment alternatives. Levees are structures that may have specific legal constraints due to flood hazards and flood elevations as mapped by the Federal Emergency Management Agency (FEMA). Determining who owns and maintains the levee is critical before an analysis for modification or removal is undertaken. Even if levees are located on private land, the jurisdiction may fall to the US Army Corps of Engineers, local flood control district, or other entity. Modification or removal of small levee systems owned and built by a private landowner may be easier to accomplish, although impacts to adjacent lands should still be investigated. This becomes more feasible if a levee has breached during a high flow event, and the breach is not repaired.
- Channel bed and bank materials for sediment and scour analyses.
- Floodplain characteristics (including soils, potential flow paths, vegetation, roughness, infrastructure and natural constraints to channel migration).
- Sediment load and sediment transport characteristics.
- Channel and floodplain cross-sections and floodplain characteristics of a reference channel may be needed if those parameters are not defined at the project site in post-project condition.

Assessment:

- Assess habitat benefit of specific levee modification or removal in terms of specific biological effects that were generally described previously.
- Hydraulic modeling of impacts to river stage during high flow.
- Sediment transport analysis.
- Scour analysis, especially for levee breach and setback options.
- Risk to infrastructure (i.e., roads and bridges) located upstream and downstream.
- For levee removal, some form of channel migration hazard study may be needed for establishing potential migration risk (low, medium, high) (this is more likely an issue on medium and large-sized rivers).
- Evaluate upstream and downstream effects of levee removal/setback including flood and sediment storage and rerouting through the floodplain and channel profile changes upstream.
- Evaluate how the stream has responded to the levee over time, and possible permanent or temporary secondary restoration activities needed, such as grade control, realignment of channel, and/or revegetation efforts.
- Assess value of various levels of setback. Setback design is often ultimately based on the longevity of sediment storage and channel migration zone rather than quantifiable hydraulic changes to the channel.
- Assess trends in channel movement, specifically channel incision – has the channel achieved a state of quasi-equilibrium, or is it still incising?

The following is a sample design process, which covers the main components required for a levee modification or removal project.

Design process:

1. Define goals and objectives.
2. Develop topographic maps and hydraulic model of existing condition.
3. Model various scenarios of removal, setback, and breaching including setback distances in terms of sediment storage, scour, flood storage, flood stage, and channel migration.
4. Engineering design for setback levee.
5. Engineering design for any accommodation of levee modification such as channel alignment, grade control, floodplain restoration, and protection of setback levee and/or infrastructure.
6. Bank design as necessary to repair disturbance to banks.
7. Design drawings, specifications, and contracting information.

5.2 Channel and Floodplain Modifications

Levee modification or setback projects are intrinsically linked to a linear system that transfers energy and mass. It is essential that a levee project be evaluated within the context of this system and not extracted into a hypothetical closed system with known variables and assured outcomes. The scope of a project should be expanded well beyond the footprint of the project when evaluating impacts, benefits, and risks.

With this more global scale in mind, it may be necessary to modify the channel upstream and/or downstream from the project site and the floodplain behind the levee before the levee modification is constructed to reduce negative impacts such as erosion or avulsion. Specific guidance on modifying in-channel characteristics is provided in the *Channel Modification* Technique.

An early project task includes an assessment of floodplain characteristics, which is essential for evaluating the vegetative, structural and topographical changes that are needed to complete the project. For example, converting an agricultural field to a floodplain may require placing 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. Accordingly, a floodplain assessment and a channel assessment are critical for evaluating the risk of avulsion. For instance, if flow velocities over the floodplain are high enough to entrain sediment, and there is low roughness due to prior land management activities, then the potential for channel avulsion is high. Unless avulsion is an acceptable and anticipated channel process, precautions may be required to manage for this potential. For example, regulating flow at levee breaches may reduce the risk of avulsion and contain most of the flow in the primary channel; depending on the project, log or dense plantings of vegetation may adequately meter flow into the floodplain. In evaluating avulsion hazards and flow regulation, the elevation of the breach is critical in establishing when the floodplain will become active. In some cases, it may be desirable to leave a low levee along the channel in order to mimic natural levees.

Additionally, restoring floodplain topography is often a high priority in restoration projects. However, this may not be necessary or even desirable in some situations. Florsheim and Mount[6] documented floodplain topography changes after intentional levee breaches along the Lower Cosumnes River in California, and found that excavation of floodplain ponds and other depressional features actually trap incoming sediment and retard the development of floodplain topography.

5.3 Levee Removal

Levee removal has a number of considerations that relate to the excavation and removal of the structure itself. Unlike a levee breach, a levee removal project must consider the amount of sediment to be removed and the distance to a disposal site. Implementing a levee removal project includes:

- Establishing entry and exit points. Entry and exit points are often on the levee itself, given the surrounding land may remain saturated for extended periods. This may require clearing vegetation for access and establishing a turnaround area.
- Determining haul road locations,
- Removing and/or trimming vegetation,
- Excavating and removing material. Excavation and hauling costs will comprise the majority of the budget. The approximate volume of a levee is easily calculated, which allows for a relatively accurate estimate of removal costs since excavation costs per cubic yard and hauling distances will be a fixed value.

- Ripping the footprint area of the levee in compacted areas. 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 should be stockpiled for later use on these mineral soil areas.
- Recontouring of the site.
- Revegetating the site.

Given the cost of removal and disposal of levee materials, complete levee removal is most feasible in areas that have relatively low and/or short levees denuded of vegetation. For highly sensitive areas, or areas that have very mature vegetation, consider either remnant islands of vegetation or carefully placed breaches as opposed to full levee removal. Leaving islands of mature vegetation intact will provide a seed source and some habitat during the reestablishment period. Natural channel avulsions often leave higher upland areas within an active floodplain.

5.4 Levee Setback

Levee setback is an excellent option for areas where levee overtopping is common (such as along coastal streams), and where significant land use changes are unlikely to occur. Levee setback requires the same construction components as removal, in addition to rebuilding the levee itself. Accordingly, this requires separating the organics from the excavated levee material if it will be used in the new setback levee. A temporary storage area to stockpile soil material will also be required until 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.

One of the great advantages of a levee setback is that it allows for seasonal use of land within the newly established floodway, and greater flood protection. Generally, greater beneficial impacts are associated with wider setbacks (discussed in previous sections). While setback distances will vary greatly and are often dictated by landowners and land managers, to restore the majority of floodplain functions, the minimum setback distance should be 7 to 10 channel widths[7]. However, setback distances do not need to be equal on both sides of the stream or longitudinally along the stream. At a minimum, the setback levees should be on the edge or outside of the meander belt width. Since it is unlikely that a levee would be setback on two separate occasions in the same location, maximum setbacks should be obtained on each and every project. Setbacks become like default easements since flooding is allowed which will generally curtail development.

5.5 Levee Breach

Levee removal and setback projects can be unfeasible 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 an excellent option. On a local scale, and generally for individual projects, levee breaches can be used as a low cost alternative to complete levee removal. Levee breaches still allow for some level of inundation of the floodplain, floodwater storage, sediment deposition, and refuge areas for terrestrial and aquatic species, although not to the same extent as removal or setback.

An analysis for levee breaches will be similar for removal or setback, but on a more site-specific scale. Localized scour is of greater concern because of the concentrated energy of the flow at the breaches. The size and location of breaches should be carefully evaluated to minimize the risk of scour due to flow constriction and channel avulsion in areas where levees are used as river training structures. It is fairly easy to calculate breach size using expected volumes and critical flow velocities; if breaches are too narrow, flows are constricted and may result in bed scour and floodplain channel development, which could lead to avulsion. Narrow constrictions may also limit fish passage. Where scour is anticipated, it may be necessary to add energy dissipation in the form of vegetation or large wood, which can be incorporated into the design to dissipate energy and reduce flow velocities near the breach area. If a single breach area cannot be adequately enlarged, consider adding multiple breaches to reduce shear stress and flow velocities; multiple breaches will also help reduce the risk of channel avulsion and will provide alternative channels if one of the breaches plugs with wood or becomes inoperative.

Since many levees were also designed to provide river training, 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 flow events without allowing channelized flow access to the historic floodplain. For backwater breaches, generally the lower half of the inside of a meander bend, where natural deposition is expected, is a good place for the breach, which allows for some floodplain function, flood storage, and reduces hydraulic gradient between the floodplain and channel. Another benefit for landowners with land in some type of production is the ability for the land to naturally drain after a flood event. Many areas that are leveed become large stagnant pools of water after floods overtop the levees and there is no method for drainage.

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 placed through the levees to allow some connectivity to the historic floodplain while maintaining the access road. While this is not the preferred alternative, it can still have beneficial effects for aquatic and terrestrial habitat. Maintenance for culverts and bridges should be factored into the overall cost of the project.

No matter what type of breach is used, all 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. It is even possible to clear some vegetation to help set the stage for a natural breach without actually using equipment; while the certainty is much lower, so is the cost.

6 PERMITTING

Various permits will be required at the local, state, and federal levels depending upon the location of the existing levee system and who owns and/or maintains the levee. Refer to the *Typical Permits Required for Work in and Around Water a*ppendix for further information. Counties generally require grading permits and also have regulations regarding work in floodplains (check with the appropriate county and/or city for requirements). Any changes to flood elevations will require additional permitting from the state and county. Construction related permits, including sediment control, spill response, reclamation, and a safety plan, will also be required.

If the work is in a riparian area, permits may be required from the state and the federal government. For lateral levees, the work may actually impact a water body and may be restricted to the in-water work window as designated by the state for protection of aquatic species. In-water work requires a US Army Corps of Engineers Section 10 or 404 permit with a Section 401 certification for water quality usually obtained from the Department of Ecology.

The applicant should contact the U.S. Fish and Wildlife Service and NOAA Fisheries to determine if there are threatened/endangered species on the property or in the area. Incidental take permits may be required.

7 CONSTRUCTION CONSIDERATIONS

Consider the following elements when constructing new setback levees or removing existing levees:

- Requires large equipment in potentially sensitive habitats. Clearly designate entry and exit points and access roads. Minimize the number of roads and the number of trips by large equipment.
- Minimize clearing and grubbing. Instead trim vegetation to the ground level and cover with a geotextile during construction.
- Removal of mature riparian vegetation may be necessary to open up the floodplain. Consider saving islands of vegetation to serve as a natural seed bank and to provide at least remnant 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.
- Floodplain wetlands may be impacted by construction activities. Try to route construction equipment through less sensitive areas.
- Stockpile fertile topsoil for later use. Be cautious to keep soil piles small to minimize composting which will reduce the available seed bank.
- The footprint of an old levee will need to be ripped (decompacted) prior to vegetative establishment.
- To reduce soil compaction, special equipment for operating on soft ground may be required. If this equipment is not appropriate or available, ripping of the construction access areas following construction to decrease soil compaction is recommended.
- Refueling should occur outside of the active floodplain area.
- If invasive species are of concern, steam clean the equipment before it is brought on-site.
- A spill response plan should be developed and available for the construction crew.
- Construction timing should be related to soil moisture conditions, hydrological trends of the contributing water body, and to sensitive plant and animal species.

8 COST ESTIMATION

Actual unit cost estimation for Levee Modification and Removal includes but is not limited to the following items:

- Feasibility studies including hydrologic, hydraulic, geomorphic, biologic, and specific habitat studies. Costs will vary depending upon the size and scope of the project.
- Conceptual or preliminary designs.
- Contract plans and specifications.
- Permits including NEPA, ESA, Corps, state, and county permits.
- Land acquisition. Costs vary widely depending upon current land use and local land prices. The proponent should investigate within the area to determine appropriate land values. Inquiries should be made to the county auditor 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 and bank stabilization generally require mobilization and demobilization of equipment, pollution control, clearing, recontouring, and excavation, 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 is required for the spoil material. Mobilization and demobilization costs will typically be a percentage of the total contract cost (generally 12 to 18%).
- Bank stabilization and other structures.
- 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.
- Construction management. A critical component for project success, construction management generally costs between five and ten percent of the total project cost. This insures that someone is onsite during the entire construction period and that the project is built as designed.
- Pollution control. A relatively set cost based on the type of equipment on-site and site conditions (up to 20% of excavation cost can be used as an estimate).
- Excavation, hauling and disposal. Cost is based on the volume of material to be moved. Excavation and handling costs will range from one to three dollars per cubic yard ($1 – $3/cy). Hauling cost depends on haul distance, but general estimates can be made based on rental rates for dump trucks. A 10 to 12 cubic yard dump truck rents for approximately $30 – $50/hour. The cost for material disposal will vary greatly depending upon the condition of the material. For clean, uncontaminated material, disposal costs may be very low, or free. Contaminated soil will significantly increase cost.
- Operations and maintenance. Costs vary greatly and are project specific. Once a project design is developed, these items can more effectively be estimated.

- Monitoring and tracking. Costs vary greatly and are project specific. Once a project design is developed, these items can more effectively be estimated.

9 MONITORING

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 (DTM's), satellite imagery, LIDAR, etc. Since the reconnection of streams to their floodplains can be extensive, aerial photos allow 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. Aerial photos can be taken during various seasons to allow for evaluation of flood extent, ephemeral habitat, and plant communities. For smaller projects, photo points may be sufficient to evaluate general trends.

Specific monitoring items may include:

- Installing a simple water level recorder to determine when a floodplain becomes activated. This gage can be calibrated to other gages within the basin.
- Supplemental information may include sediment and debris lines on vegetation.
- 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), total stations 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.

10 MAINTENANCE

Operations and maintenance applies primarily to levee setback or breaching. Full levee removal, accompanied with appropriate restoration of the floodplain, should require very little or no maintenance beyond the establishment of native vegetation.

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

- Prompt repair or replacement of damaged components.
- Removal of obstructions from inlet and outlet facilities.
- Periodic check of earth 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.

11 EXAMPLES

Although removing, breaching or setting back levees has substantial potential for restoration, these projects appear to be relatively uncommon and not well monitored. Simenstad and Thom[8] describe two examples located on the Salmon River estuary along the coast of Oregon, and the Elk River estuary located in Grays Harbor County on the Washington Coast.

11.1 Salmon River Estuary

The Salmon River estuary is a small (<2 km^2), drowned river valley estuary located on the Oregon coast immediately south of Cascade Head, and is considered one of Oregon's most pristine estuaries[9]. Watershed and estuarine land use moderately affect the Salmon River estuary by increasing turbidity and surface water temperatures as well as reducing freshwater flows[10]. Diked in 1961 for pastureland, a 21 ha segment of brackish marsh was reconnected to tidal inundation in September 1978. Frenkel and Morlan[11] assessed vegetation and soil characteristics at the restored estuarine marsh 11 years after the breaching of the dike. Frenkel and Morlan used two 15-ha marsh habitats occurring on either side of the dike-breach marsh as reference sites for interpreting the vegetative recolonization of the restoration site.

The sequence of vegetative recolonization did not mirror the vegetative communities present at the reference sites. Instead, the restored marsh developed into a low marsh dominated by *Carex lyngbyei* due to 35-40 cm of subsidence over the 17 years of use as pastureland. According to Frenkel and Morlan, sedimentation of the restoration marsh averages between 5 and 6 cm y^{-1} (range, 3-9 cm y^{-1}), compared to an average of 4 cm y^{-1} (range 2-9 cm y^{-1}) in the control marsh. Frenkel and Morlan also found that sediment accretion in the restored marsh was measurably higher at lower tidal elevations than at higher elevations. Frenkel and Morlan used net primary production (NPP) as the principle index of wetland function; however, other functions (e.g., fish and wildlife utilization, benthic infauna or epibenthos, nutrient cycling, etc.) were not assessed and monitored.

11.2 Elk River Estuary

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. Like the Salmon River site, 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, while subsiding 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). The restoration strategy for this site could be modified to promote more favorable results by restoring historical topography (via supplementing sediment to the landward side of the levee), removing the entire levee, and transplanting high marsh vegetation.

11.3 Other Projects

Lockwood Creek (tributary to the EF Lewis River) in Clark County, WA. Levee removal with some floodplain excavation to improve fish habitat. Project sponsor is the Clark Conservation District. Implemented in 2000.

Spencer Island Wetland Restoration in Snohomish County. Built a cross levee and breached an existing levee to recreate a tidally-influenced, freshwater wetland on 400 acres in the Snohomish River Estuary. Sponsored by Snohomish County Parks. Designed by Entranco.

Deepwater Slough Section 1135 Restoration Project near Conway, Washington[12]. Levee breach, levee removal, new dike construction and dike augmentation by the U.S. Army Corps of Engineers. Constructed in 1999.

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SIDE CHANNEL / OFF CHANNEL HABITAT RESTORATION

1 DESCRIPTION OF TECHNIQUE

Side channel habitats are generally small watered remnants of major river meanders across the floodplain. They are most common in those floodplains that have been strongly glacially influenced leaving a relatively flat valley floor. They include areas that may or may not be actively influenced at any one point in time by the main river. These sites include naturally abandoned river channels, oxbows, flood swales and sometimes the lower ends of terrace tributaries flowing out onto the floodplain. They also include constructed channels and connecting ponds that could have been built specifically for aquatic habitat or indirectly for some other purpose such as gravel mining. This technique includes construction, restoration and reconnection of side channels to the main channel and protection of these areas by controlling river and flood flow from the main river and capitalizing on availability of floodplain groundwater.

The focus of this technique is on restoration or creation of self-sustaining habitats. Self-sustaining is not synonymous with maintaining static conditions. Side channels may succeed into drier habitats as part of their natural evolution. Sustainability normally depends on channel processes including floods, channel migration, and aggradation. In some cases, sustainability will be more determined by fish activity than hydraulic conditions. Intense annual or biennial spawning by large numbers of salmon can keep some natural and/or created side channels active and functioning where without this natural activity they would soon succeed into ephemerally wetted swales.

There are also opportunities for restoration that are not self-sustaining that should not be foregone. For example, the only opportunities for side channel restoration in some areas might be to connect the river to relic side channels that have been isolated from the river by armored banks or levees that protects infrastructure or development. These sites may not be self-sustaining if the river is not allowed to flood through them. This type of side channel restoration might be a valuable exception to designing habitat restoration purely by restoration of natural processes. The types of side channel restoration discussed in this guide are the following:

- New side channel habitat. This focuses on the creation of self-sustaining side channels, which are maintained through natural processes.
- Reconnection of existing side channel habitat, which focuses on restoring fish access and habitat forming processes (hydrology, riparian vegetation).
- Restoration of side channels includes the restoration of habitat within an existing channel.
- Connection of side channels refers to restoration of hydraulic and hydrologic connection to the mainstem by restoring the relative elevation of the channel to the mainstem or removing flow blockages such as levees and sediment plugs.

The side channel technique is often used in conjunction with other techniques in this guideline such as *Levee Removal and Modification*, *Dedicating Land and Water to Stream Habitat*

Preservation and Restoration, and *Riparian Restoration and Management*. Removal of floodplain fill and bank protection, restoration of stream hydrology, and channel modifications may also be necessary to restore habitat forming processes to the side channel.

Restoration of fish access to side channels that have been blocked by roads, culverts, and dams can be a critical factor driving recovery of populations. Fish passage is mentioned in this guideline generally and discussed more thoroughly in *Fishway Design Guidelines* and *Design of Road Culverts for Fish Passage*[1] guidelines.

This side channel technique does not include artificial spawning channels, which generally include formal water supply structures, formal structures to supply upwelling water, and/or fish holding or segregation devices. Artificial spawning channels are generally not a self sustaining technique but are intended to provide a highly regulated and controlled spawning environment as an alternative to, or to supplement, hatchery production. Bell (1990)[2] includes a description and criteria for spawning channels.

1.1 EVOLUTION OF NATURAL SIDE CHANNELS

In unconfined natural alluvial river systems, side channel habitat is constantly created and abandoned as the river migrates laterally and changes course. Naturally formed side channel habitat is usually associated with former stream channels abandoned through natural process, or the landward side of gravel bars formed during high flow events within the active channel area. Side channels generally evolve over time from being an active channel to a backwater, then perhaps to an isolated oxbow intermittently connected to the main flow during floods, and finally to a wet depression on the floodplain. This evolution might occur over decades. Interrupting the processes of channel evolution with activities such as bank protection can lead to loss of fish habitat over the long term (Roni et al. 2002)[3]. As long as the stream is creating new side channels, all successional stages of side channel development will occur within the stream corridor, providing a niche for all successive plant and animal communities.

Side channels often derive a major portion of their flow from either groundwater or seepage from the adjacent stream/river. The role of surface water in side channel habitats varies depending on mainstem and groundwater hydrologies, channel topography, and physical features. Peterson and Reid (1984) describe three types of side channel habitat within a river floodplain: overflow channels, percolation-fed channels and wall-based channels.[4] This technique also includes floodplain ponds.

> *Overflow channels* are flood swales, and often-relict mainstem channels, that are directly connected to the main river channel during high flows or at all times. They are often very dynamic as a result of the periodic influx of water, sediment, wood, nutrients, and organic material from the main channel. Fish habitat associated with overflow channels is often unstable and typically prone to flooding and channel shifting though possibly on an infrequent basis. Periodic floods through these channels can help maintain their productivity, cleaning and redistributing spawning material and creating new habitat as other habitat is destroyed. Restoration of overflow channels might include reconnection of the channel to the mainstem and placement of habitat features within the channel. Without the natural hydrology and disturbance regime, keeping habitat functional often requires a high maintenance effort. The level of utilization may depend on the frequency

of inundation by the mainstem. Entrapment of fish can occur if surface flow stops.

Perc channels are relict river and/or flood channels and are primarily supplied by groundwater of the hyporheic zone. The hyporheic zone is the area beneath and next to a river channel that contains some proportion of water from the surface channel. See **Figure 1**. Frequently, they are better protected from floods than overflow channels and so have relatively stable flows. Groundwater channels provide winter and summer refuge for juvenile fish, larval and adult amphibians, and a suite of invertebrates; spawning habitat for adult fish, some amphibians, and some invertebrates; and foraging habitat for many bird and mammal species.

Wall-based channels can be groundwater fed but are often fed from springs or surface water from an adjacent terrace. They are usually higher in elevation relative to percolation-fed channels. Habitat projects might include providing fish access to them and enhancing habitat within the channels.

F*loodplain ponds* are natural or constructed ponds in or above the floodplain such as abandoned gravel pits, mill ponds, ponds, and river oxbows. They might be supplied by groundwater or surface water from streams or springs and may or may not be connected to the river. Habitat projects might include providing fish access to them and enhancing habitat within the ponds. Though the origin and hydrology of floodplain ponds may be different than a wall-based channel, in this guideline they are described together.

The type of side channel (overflow, percolation-fed, wall-based, floodplain pond) has direct bearing on the approach to a restoration project and potential fisheries benefits. These general categories of side channels are used in this guideline for convenience. Although specifically defined, individual projects and work sites will likely include several of these channel types. For example a spring channel might be constructed as a tributary to a surface flow side channel and the spring channel may include connections to floodplain ponds or wall-based channels. The design of any side channel should consider using the attributes of all of these side channel concepts.

1.2 Side Channel Habitat

Side channel wetlands and ponds have been found to provide critical habitats for both juvenile salmonids (Peterson 1982; Cederholm and Scarlett 1982)[15, 42, 5] and a variety of wildlife species (Zarnowitz and Raedeke 1984)[6]. Species that frequent these areas and the attendant riparian community include amphibians, reptiles, birds, mammals, and mollusks (FEMAT 1993)[7].

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 frequently offer aquatic species refuge from adverse mainstem conditions. Juvenile coho are known to actively and preferentially migrate from mainstem rearing locations to side channel habitats in both fall and spring for protection from winter freshet activity and low summer flow stranding where they experience high survival rates. Though residence times vary, they migrate back to the mainstems generally in the spring. Side channel habitats have been constructed and studied by Swales and Levings (1989)[8] and

Cederholm and Peterson (1989)[9] to determine behavioral and physiological responses of coho salmon in these habitats.

Side channel wetlands and ponds have been found to provide critical habitats for juvenile salmonids (Peterson 1982; Cederholm and Scarlett 1982)[15, 42, 5] and a variety of wildlife species (Zarnowitz and Raedeke 1984). When these areas are more regularly and permanently available, as in larger stream basins, they can provide additional benefits such as high quality protected spawning habitat especially for coho and chum salmon that actively seek these areas. In many larger stream systems, side channels are important spawning areas, particularly for chum and coho salmon. They are also recognized for their value as summer and winter rearing habitat for coho salmon and cutthroat trout. Lister and Finnigan (1997)[10] provide a more thorough description of the use of natural and constructed side channels by various life stages of several species of salmonids.

Such projects also have significant benefits for a suite of wildlife species that either use or indirectly benefit from such habitats (e.g., amphibians as refuge and reproductive habitat, birds as foraging habitat). Bird and mammal scavenger species feed on spawned out salmon carcasses that tend not to be washed away as they might be in the mainstem. Use of side channels by fish and wildlife depends on connectivity (access) between the mainstem and side channel and the presence of suitable habitat characteristics.

Although side channel habitats may only be available intermittently or seasonally, they can still provide critical refuge for juvenile coho and other salmonids. Intermittent values can be reduced by losses to fish stranding depending on outlet escape conditions or the extent to which isolated pools area still can support fish life. For fish to survive in isolated pools there must be adequate shading cover and ground water exchange to keep temperatures low and sufficiently oxygenated.

The quantity, quality, and longevity of side channel habitat depend on the frequency, magnitude, timing, duration, and source of its flow. A channel that is fed primarily by groundwater provides a more stable environment for incubation and rearing than does a channel that relies solely on surface flow. Spawners of many species of salmon and trout select redd locations associated with groundwater (hyporheic) flow (Geist and Dauble, 1998)[11]. Additionally, groundwater specifically attracts spawners of some salmonids that prefer these conditions. As mentioned previously, the more stable conditions in these sites, reduced turbidity, warmer winter and cooler summer temperatures, limited scour and sediment deposition, and generally high invertebrate production for feeding juveniles make them very attractive to species adapted to this type of habitat. The most productive side channel sites are likely those with year-round fish access to allow rearing fish to benefit from optimal conditions whether in the main channel or side channel and to minimize likelihood of stranding if the outlet dries up.

Side channel habitats are commonly used by various salmonid species.

Blackwell et al (1999) summarize the use of side channels as follows:

> “Anadromous coho (Oncorhynchus kisutch; Sandercock 1991)[12], chum (O. keta; Bonnel 1991), sockeye salmon (O. nerka; Burgner 1991)[13], and resident salmonids (Brown and Mackay 1995)[14] often select off channel habitat to spawn. Resident species and

> anadromous species with extended freshwater residency periods, rear in hydrologically stable off channel areas (Peterson 1982a; Nickelson et al. 1992; Richards et al. 1992)[15, 16, 17].
>
> Lister and Finnigan (1997) continue the description of off-channel use as follows: Among the salmon species, chum and coho are most commonly associated with off-channel habitats. These species are apparently attracted to sites fed largely by groundwater. Late-run chum stocks, throughout their range, have been noted to spawn in groundwater-fed channels or seepage areas (Salo 1991)[18]. Coho spawn in groundwater channels to some extent (Sheng et al. 1990)[19], but most coho spawning occurs in relatively small surface-fed streams (Sandercock 1991). Coho juveniles, on the other hand, make widespread use of off-channel habitats, often gaining access to small stream and pond environments that are either inaccessible to adult coho or unsuitable for spawning (Peterson 1982a).
>
> Chinook salmon do not spawn in off-channel habitat, but interior stocks make some use of off-channel ponds and side channels, often associated with tributaries, for juvenile rearing and overwintering (Anon. 1987; Swales and Levings 1989).
>
> Of the trout species, coastal cutthroat (O. clarki clarki) are most likely to be found in off-channel environments. Adult and juvenile coastal cutthroat can be expected to cohabit many off-channel sites with juvenile coho (Cederholm and Scarlett 1982; Hartman and Brown 1987)[20].
>
> Steelhead trout do not commonly spawn in side channels, and juvenile steelhead apparently use such habitats to a much smaller extent than coastal cutthroat. Steelhead are not abundant in off-channel ponds (Cederholm and Scarlett 1982; Swales and Levings 1989). In coastal stream steelhead underyearlings and parr prefer small surface-fed tributaries to groundwater environments for rearing and overwintering (Cederholm and Scarlett 1982). Some coastal groundwater channels do, however, overwinter significant number of parr and pre-smolt steelhead[21] and a groundwater channel at Deadman River, in the British Columbia interior, attracted significant numbers of underyearling steelhead for rearing and overwintering (Sheng et al. 1990). Adequate velocity and habitat diversity were likely requisites for juvenile steelhead use of these sites.
>
> The stream-dwelling species of char, Dolly Varden, and bull trout, have not been commonly observed in off-channel habitats.

Though Lister and Finnigan (1997) report that sockeye use of side channels for spawning is not common in B.C., there is extensive use of overflow side channels and floodplain ponds by sockeye spawning in the Cedar River, Washington[22]. Sockeye spawn in the outlet channel of Newhalem Ponds side channel restoration project on the Skagit River.[23]

Use by chum salmon tends to be high. Large numbers of a mass spawner such as chum, can annually clean the gravel by suspending and flushing out accumulated debris and fines maintaining percolation inflow and flow through the gravel. Chum salmon tend to seek side channel habitats within the active floodplain.

The diversity of use is beneficial; for example chum carcasses can produce a high level of biomass and nutrients that are retained on the site because they aren't washed away during floods. Salmon carcasses are an important source of nutrients to the food chain supporting stream-rearing species such as coho, cutthroat and steelhead (Bilby et al. 1996)[24] and distributed through the hyporheic zone to benefit other ecological functions in the floodplain. Samuelson (1990)[25] showed coho and Chinook grew faster in Wynoochee River abandoned floodplain gravel pit ponds than in the river and fish grew faster in ponds that had been fertilized with salmon carcasses. Average lengths of coho and Chinook in the river were 30.38 and 41.25 mm respectively. In the unfertilized pond they were 46.38 and 56.61 mm. In the fertilized pond they were 49.60 and 66.52 mm. Body weights of Chinook improved with fertilization, coho did not. Egg-to-fry survival in groundwater channels has been three to five times greater than that of mainstem spawners.

Side channel projects have significant secondary benefits for a suite of wildlife species that either use or indirectly benefit from such habitats (e.g., amphibians as refuge and reproductive habitat, birds as foraging habitat). Side channels may function as spawning, rearing, and overwintering habitat for fish as well as providing a refuge from floods. In many larger river systems, side channels are important spawning areas, particularly for chum and coho salmon. They are also recognized for their value as summer and winter rearing habitat for coho salmon and cutthroat trout.

Restrictions and constraints imposed on the system, such as levees, dikes, bank protection, and channelization, often isolate existing side channels from the main stem and prevent or limit natural channel meander shifts that create new side channels. As a result, this valuable habitat has often been lost or has become inaccessible to the fish and wildlife that use it. These are lost opportunities and likely limit production of salmon on many large rivers systems in the Northwest. The best restoration is usually to remove such constraints. The value of some of the techniques within this section is the creation of habitat to replace lost opportunities where the constraints cannot be removed.

During the last few decades, habitat enhancement programs in British Columbia and Washington State have developed off-channel spawning and rearing habitat, primarily to benefit salmon.[26] 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. The projects are summarized by watershed in **Table 1** and specific projects are listed in **Table 2**.

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%

Table 1. Project smolt production by watershed.

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.

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 spine rays. (Scherer et al, 1999)[27] Access of fish to side channels may also affect native amphibians[28].

2 PHYSICAL AND BIOLOGICAL EFFECTS

The physical effects of reconnecting or creating side channels likely include a short-term increase in turbidity at and downstream of the site, both during excavation of the connection with the main channel and following introduction of water to the side channel. Increased flow to side a channel may present an increased risk of aggradation of the mainstem. When flow is split, it reduces the competence of the flow remaining in the main channel to carry its sediment load. This may cause the sediment to deposit in the main channel. This effect can only occur if a substantial portion of the mainstem flow is diverted through the project, which is not the objective of the project and has not been experienced in Washington project history.

Excavation of a new side channel will likely result in removal of riparian vegetation in the vicinity of the new channel and displacement of flora and fauna adapted to the current setting. It may also result in lowering the local groundwater level, decreasing the amount of water available to nearby wetlands, ponds, wells, and vegetation. Project sites have a significant quick colonization by emergent wetland vegetation along the channel margins that is not only good habitat for juvenile fish but wetland associated wildlife as well. Usually, this wetland area did not exist in the pre-project site.

A side channel project might cause a redistribution of fish away from existing areas thus creating a situation in which there is more competition for limited resources. It might also cause fish to be more vulnerable to predation until riparian vegetation matures at a site.

3 APPLICATION OF TECHNIQUE

Roni et al (2002)[3] suggest that restoration of side channels may be more effective than other techniques for coho. Though it is not always restoration of natural process such as channel migration, this technique can be considered restoration in reaches that are confined by armoring or other measures to protect infrastructure and property. There are opportunities for creation of habitat where none exists now in upland and floodplain areas. Side channel habitats might be used as habitat restoration or as mitigation for other projects that confine a channel (e.g.; bank protection, bridges). Enhancement and restoration of existing side channel habitat and construction of off-channel spawning and rearing habitat may provide mitigation for the future loss of this habitat type, or lost opportunity.

Culverts and other road crossings of side channels often block access for juvenile fish and therefore may present restoration opportunities.

Channels downstream of dams and urbanized areas can become lowered by the change in sediment and/or hydrology regime. The channel degrading can potentially leave associated side channel habitats perched above the active channel elevation. Restoration of the grade of the main channel or lowering the side channel might be restore side channel function.

Side channels should be created where they will be self-sustained through natural processes. Created channels should mimic those locations to maximize longevity. Part of self-sustainability is the probability that a created channel will be naturally overtaken by erosion or avulsion from the mainstem. If that process leaves habitat in its wake, the habitat is self-sustaining.

Side channel habitat exists in nature on virtually all sizes of alluvial streams and can be up to thousands of feet in length. The scale of side channel reconnection or creation projects implemented however depends on the objectives of the project and available resources.

Side channel habitats might be used as habitat restoration or as mitigation for other projects that confine a channel (e.g.; bank protection, bridges). Enhancement and restoration of existing side channel habitat and construction of off-channel spawning and rearing habitat may provide mitigation for the future loss of this habitat type, or lost opportunity.

4 RISK AND UNCERTAINTY

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. There is short term risk to adjacent and downstream habitat 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, there is a potential that the water level in nearby wetlands and ponds will be lowered and the extent and that the type of riparian vegetation will change. There may be some risk of avulsion into the side channel 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 5.2 *Design Considerations.*

There is a risk of the bed and banks of an overflow side channel shifting during the first few years following construction 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 though new habitat may be created at the same time. 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 depression on the floodplain.

4.2 RISK OF CHANNEL CHANGE

There is some risk 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 <u>Integrated Streambank Protection Guidelines</u> [29] An avulsion is caused by concentration of overland flow that scours or headcuts a new or enlarged channel. If the flow capacity of a side channel were greatly increased, it might cause enough water to flow through it that the upstream connection to the mainstem could scour during a flood, increase the flow to the side channel, and eventually divert 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.

There may also be an increased chance of avulsion into the side channel if large flow events that reach the side channel cause a headcut through to the main stem. The chance of avulsion increases if aggradation occurs in the mainstem. The presence of a side channel subject to overflow from the mainstem may reduce the flow and scour in the main channel. 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. Separation of the constructed channel from the river channel by distance, elevation, or a maturely vegetated floodplain will reduce risk of avulsion. Control of high flow into the side channel will also limit the risk of an avulsion. Flow can be controlled by constrictions that limit the flow or spillways that protect against headcuts. See the section 5.2 *Design Considerations* for more details of these techniques. Risk of avulsions can also be managed with techniques such as floodplain roughness, floodplain drop structures, flow spreaders, and buffer management practices. See the Integrated Streambank Protection Guidelines for details of these techniques. If there is even a moderate risk of avulsion, a hydraulic analysis of avulsion should be conducted.

There may be some level of risk that of the mainstem shifting away from a side channel project 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 5.2 *Design Considerations*. 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 1980's 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 be realize a benefit in a short project life.

4.3 RISK TO INFRASTRUCTURE, PROPERTY, OR 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. Channels with deep pools and high, steep banks can potentially trap people or wildlife. Generally channel and pond banks that are configured with slopes to optimize habitat benefits, such as shallow benches and gentle bank slopes for riparian structure and diversity, are least risky to people and wildlife.

4.4 Uncertainty of Technique

The certainty of habitat gain varies among the objectives and types of projects. Roni et al (2002) 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; the variability of success among projects was low. Projects that involved creating off-channel habitat had a moderate probability of success; variability of success among projects was high. The high variability appears to be at least partially due to the wide variety of off-channel projects constructed and reported.

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 (Blackwell et al 1999). Because of this Blackwell et al suggest 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. Preliminary results of studies to evaluate constructed side channels in Northern Puget Sound region of Washington suggest that production of coho from constructed channels is greater than natural channels though they have less relative abundance of other species (evenness of species)[30].

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) to species targeted by the project, 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

5.1.1 Site Selection and Inventory

A key to successful side channel creation or restoration is site selection. Side channels should be created where they will be self-sustained through natural processes or where they have been lost because natural processes have been curtailed. 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 flood hazard management planning that may also contemplate actions that will confine the mainstem channel. Potential sites should be identified from aerial photos and USGS quad maps and then confirmed by field inspection. See **Figure 2**; aerial photos of abandoned gravel pits and pond site near Satsop River for an example. Things to look for at the scale of maps are geologic conditions that will create hyporheic upwelling, multiple river channels, oxbows, relict channels and evidence of them in vegetation patterns, wide undeveloped floodplains, wall-base channels, abandoned gravel pits, and areas of shallow groundwater. Just as many sites are identified by ground investigation. In the field, look for gravel in riverbanks that imply porous floodplain, flood swales, water sources, relative elevation of the floodplain to the river, levees that isolate the floodplain, road fills that either isolate the floodplain as a levee or that prevent floodplain flow such as a bridge approach fill, and existing side channels.

Hydrology of the mainstem should be considered. Potential sites associated with a mainstem that has a relative constant normal water level and high spring flows may be easier to develop and have less risk than sites with great water level fluctuations and low spring water levels. Sites below storage reservoirs might have hydrology that works well for these projects.

Fish utilization in the reach should be considered . 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 most spawning, juvenile recruitment into the project may not be adequate and it may take some time for fish to find it and build a loyal population through imprinting of its progeny.

Some side channel projects involve construction on large pieces of ground. Ownership of the land is a consideration. Projects are much easier to coordinate at sites in public ownership or in a single private ownership than multiple ownerships or land that is developed.

Search parameters depend on objectives of the project. For example, chum spawning objective may capitalize on hyporheic flow conditions; a coho rearing project may focus on wall-based channels and side channels that have low risk of flooding from the mainstem. The following describes the minimum effort required for a rough inventory-level assessment of side and off-channel habitat opportunities.

- Natural floodplain constrictions may be topographic and geologic evidence of hyporheic upwelling and downwelling and may also be depositional zones with multiple natural channels. See **Figure 3**.
- Meander scars, multiple channels, and oxbows may indicate natural side channel opportunities.
- Alluvial fans often force hyporheic upwelling as well as multiple side channels that may be opportunities for restoration.
- Channel junctions where a tributary carries bedload that a mainstem cannot transport might have associated side channels.
- Degraded channels may have associated side channels that are perched.
- Wall-based channels, ponds, and abandoned gravel pits may offer restoration opportunities.
- Look for railroads or highways that have truncated or confined channel meanders. There are often side channel opportunities on the landward side of these facilities that might be restored by reestablishing flow from the mainstem and/or restoring fish passage by replacing culverts or providing other fish passage improvements.
- Be aware of likely land use changes adjacent to sites that might affect water quality.
- Be aware of access needs for heavy construction equipment. The cost of access is an important consideration for project feasibility.
- If the prime objective is spawning habitat the inventory should cover the current range of spawning activity unless the intent is to increase the range of a species by supplementation.

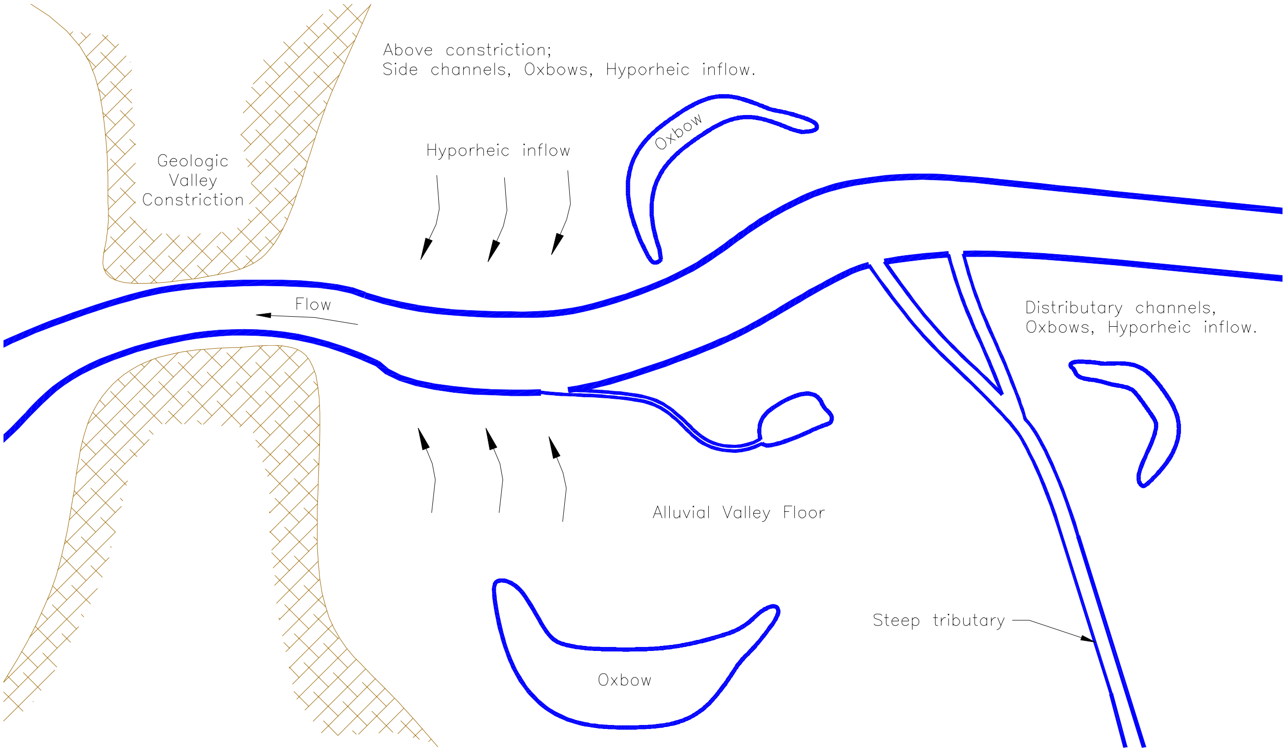


Figure 3. Natural floodplain constrictions may be topographic and geologic evidence of hyporheic upwelling and downwelling.

5.1.2 Project Data

Data collection and assessment for specific projects vary and 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 impacts and effects. The following data might be needed for specific projects. Monitoring of individual sites to evaluate site conditions and project effects should be done for several years before a project is built. More thorough explanation and application of some of these data are described in section 5.2 *Design Considerations*.

5.1.2.1 Data needs for all side channel projects

- Current fish use of the site.
- Topography and cross-sections of project area including river and floodplain.
- High and low flow hydraulic profile of the mainstem through the project reach and adjacent reaches. Recent high-water marks of the mainstem.
- Characteristics of the mainstem as evidence of aggrading or degrading
- Static water levels wherever available in the project site.
- Profile and representative cross-sections of likely and/or existing channel alignments.
- Sources and paths of overbank flow or additional surface flow during heavy runoff events.
- Characterization of floodplain roughness, woody vegetation, and large wood that will spread and moderate overbank flows.

- 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.
- Calibrated water level rating curves of mainstem near upstream and downstream ends of project channel from low to high flow.
- Site constraints and project limits (e.g., existing infrastructure, preservation of floodplain conditions, property limits)
- Baseline monitoring data, which may include photo documentation of site from permanent benchmarks that will not be disturbed by the project
- Elevation reference points should be set at least at three locations near the channel alignment, and tied together in a survey that includes elevation reference points for other fieldwork on the project site.
- Flow measurements in flowing channels. A flow measuring weir can be installed but be aware that a slight change in water surface elevation caused by the weir can significantly change the volume of measured flow.
- Any evidence of standing water and/or wetlands in the project area.

5.1.2.2 Data needs for design of perc channels

- Groundwater
    - Profile of static water levels
    - Estimate of perc flow potential based on pump tests or calculated transmissivity
    - Assessment of quality of perc water
    - Topographic, geologic, and direct observations of evidence of hyporheic upwelling and downwelling in and near the project reach.
    - Perc water supply quantity.
    - Quality of perc water
- Soils
    - Potential loss of flow around drop structures.
    - Quality of bed material for use as project spawning material.
- Surface water
    - Quality and quantity of flow, sediment and pollutant risks.
    - Reliability of flow.
    - Assessment of flooding potential from the river mainstem

5.1.2.3 Data needs for restoration of wall-based channels

- Flow and reliability
    - 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
- Quality and quantity of surface water sources to the side channel and risks to water quality.
- Current aquatic and riparian habitat features and restoration opportunities.

5.1.2.4 Data needs for enhancement of floodplain ponds

- Topography and bathymetry of ponds
- Flows – springs and low flow stranding
- Water quality especially during low flow periods
- Flooding potential
- Current fish utilization including likely predators such as centrachids.
- Current aquatic and riparian habitat features and restoration opportunities.

5.1.2.5 Data needs for reconnection of side channels to mainstem

- Assessment of existing habitat for fish and other wildlife within the side channel including spawning gravel.
- Sediment
- Instream and riparian sources (mainstem and side channel) of large wood that will affect side channel point of diversion from mainstem.
- Stability of side channel considering increased flow and risk of high flows.
- Risk to infrastructure or other properties due to increased flow through side channel or on floodplain.
- Current aquatic and riparian habitat features and restoration opportunities.

5.2 Design Considerations

Design considerations are generally broken into four types of projects; 1) construction and restoration of groundwater channels, 2) reconnection of overflow channels to the mainstem, and restoration of 3) wall-based channels and 4) floodplain ponds. These general categories of side channels are used in this guideline for convenience. Most projects will actually include more than one if not all four of these concepts. The designer should refer to all channel types for attributes that might be included in a design regardless of the specific character of the intended project.

The primary objective of most side channel reconnection or creation projects that have been built to date is to provide habitat for salmonid spawning and/or rearing. 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 allocated and designed solely to function as spawning sites, whereas other sites may incorporate juvenile rearing and adult holding habitat into the design. Though most side channel reconnection and creation projects have targeted salmonid habitat enhancement, they provide benefits to many other fish and wildlife species as well. The number of species and age classes benefited theoretically increase with the diversity of habitats built into the design. Rearing habitat projects can rely entirely on recruiting juvenile fish from the mainstem. To optimize benefit of rearing habitat, try to include some spawning habitat even in rearing habitat projects, especially at projects high in the range of spawning that may not recruit a large number of fry from upstream. It is recommended that perc channels be designed with diversity so they benefit a variety of organisms. 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.

5.2.1 Hydraulics

General considerations of water supply and reliability, risk of channel change, and channel and hydraulic grade apply to all projects. The supply of water to off-channel habitats may include surface water supply from the main channel, overbank flooding, groundwater upwelling, and/or isolated springs. Most sites are really a combination or several of these sources. A channel may have an overflow source from the river during high flow seasons, a perc source during low flow seasons, and be supplemented with flow from a wall-base source. The sources of water control the amount and type of sediments, nutrients, and organic matter supplied to the habitat, water temperature, flow and flow stability, and the diversity and longevity of physical features within the habitat. Upslope influences are much more likely to create water quality limitations. Be aware of potential source runoff from roads or agricultural practices that may affect the project.

The quantity, quality, and longevity of side channel habitat depend on the frequency, magnitude, timing, duration, and source of its flow. A channel that is fed primarily by groundwater provides 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 run warmer and clearer in the high flow season than the main channel, providing better prey production and feeding opportunities, and a less harsh over-wintering habitat than the mainstem. Groundwater-fed side channels are also less subject to sediment deposition than those that are subject to overflow from the main stem, maximizing their longevity.

A potential site associated with a mainstem with a great range of normal water levels will be more difficult to develop than one associated with less variation. Excavation will have to be deeper and/or the site may be backwatered more frequently. A site associated with a mainstem with high spring flows during fry and smolt outmigration will have less risk of stranding fish in the spring due to low water.

Backwatering may affect the extent of spawning habitat in the channel. Backwater is the pooling of floodwater from the mainstem back up the side channel. It occurs when the mainstem water surface at the confluence of the side channel is higher than the normal water surface in the side channel. Backwatered portions of the channel will tend to become a pond instead of a channel during high flows. There may be increased deposition of fine sediment in the ponded area. The ponding and sediment together reduce the value of spawning habitat in the backwatered area. Adequate channel flow following the backwater condition may flush fines from the channel. Backwater effects should be estimated as part of the design. Effects are estimated by knowing the stage-discharge relationship of the river at the confluence with the side channel relative to the profile of the project where the channel enters the mainstem river relative to the project elevations.

The amount of flow can be a controlling factor for adult usage, juvenile recruitment, and objective of a project. Furthermore, the amount of inter-gravel flow is also closely related to egg-to-fry survival[31].

5.2.2 Channel Entrance and Fish Passage

Channel entrance conditions are important for attraction and access of fish into the side channel.

The desired situation is one that maximizes the opportunity of recruiting adult and/juvenile fish and is self-sustaining. Fish that strategically use side channels may have an innate ability to sense groundwater sources. Peterson (1985) stated that the point where the egress channel joins the stream is the most critical aspect of project design. Nickelson et al. (1992) 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.

If flow from a 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. Channel outlets have been designed as a wide alcove in the bank of the mainstem. Large rocks and/or wood have been situated to maintain the alcove and provide physical and hydraulic cover for the fish. Beaver activity will also often benefit channel entrance conditions.

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. See **Figure 1**. They may also follow the toe of a terrace. Channel entrances in these locations are helpful because they are less vulnerable to deposition that may block the entrance more than other locations.

Beavers that use side channels 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. Without the beaver pilot channel, sediment deposited in the alcove or eddy may result in wide, shallow sill at the channel junction.

Whether a project is intended for adult spawning or juvenile rearing, fish access into the site is obviously required. There are several situations that may block fish access. If a perc channel isn't low enough in any area, water may go subsurface leaving no surface flow for access. See the section on channel profile for perc channels.

Large wood and/or beaver dams can block fish passage at times. Before modifying a beaver dam to improve fish passage, evaluate whether it is in reality a barrier. Juvenile and adult salmonids often pass through beaver dams with drops of three feet or more that otherwise appear to be barriers; they are often passable at higher flows. There are often multiple paths 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 Fishway Guidelines for Washington State and Powers[32]. These documents are available at http://www.wdfw.wa.gov/hab/ahg.

Road culverts or small dams can block passage. If a channel is perched above the low water level of the mainstem, there may be a drop that blocks access. These situations may necessitate the removal of the obstruction or modifying the channel to step it up over the barrier. Design of fishways and culverts for fish passage are described in other guidelines see http://www.wdfw.wa.gov/hab/ahg/

The depth of water may have to be controlled to provide fish passage, create habitat, and/or reduce the risk of breaking a seal in the bottom of a channel and losing flow. Drop structures are often required to create adequate depth; otherwise a project could become a long continuous riffle. Drop structures might be built to raise the hydraulic profile rather than excavating the channel into the groundwater. Drop structures must be very low, about a half of a foot, and they must be sealed deep into the bank and bed so flow is not lost around them through the permeable native soil. Drop structures are commonly made of logs so they can be well-sealed and so the water surface elevation can be precisely controlled; details for log controls and other drop structures are provided in the WDFW guideline Design of Road Culverts for Fish Passage . Drop structures should be notched or vee-shaped for fish passage at low flow. With a low flow or wide channel there will only be a thin film of water over a control structure. A hydraulic profile of the designed channel including high and low channel flow and backwater is prudent for design. Another benefit of control structures, assuming hydraulic conditions are appropriate for them, could be the reduced volume of excavation saving time, money, and space for disposal of spoils.

5.2.3 Managing Risk of Channel Change

Increasing the capacity of a side channel or removal of floodplain vegetation may increase the risk of an avulsion. A site that is associated with a mainstem channel that is aggrading is vulnerable to an avulsion. If there is even a moderate likelihood of increasing risk of avulsion, measures should be considered to manage the risk. Measures should include the consideration of the restoration project as a short-term project.

Separation of the constructed channel from the river channel by lateral distance, non-erodible soils, control of flow to side channel, control of flow entering the side channel, and/or mature floodplain vegetation, all reduce risk of avulsion. 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. See the Integrated Streambank Protection Guidelines techniques on floodplain roughness, floodplain drop structures, flow spreaders, and buffer management for ideas that can supplement side channel construction to manage the risk of avulsion.

There may be some level of risk that shifts in the mainstem may capture the side channel or migrate away from it and leave it disconnected from the mainstem. Capture or disconnection may occur gradually and naturally due to lateral channel migration or capture may occur due to an avulsion exacerbated by the presence of the side channel.

5.2.4 Perc channels

Groundwater and spring-fed channels have year-round flow from springs or groundwater and may exist naturally, or may be created. Perc channels are constructed by excavating a channel in the floodplain to a depth that intercepts groundwater. Because of limitations of scale, land ownership, and flooding potential there are a limited number of opportunities for construction of perc channels. Those opportunities should be optimized with the best design. The success of perc channels especially depends on pre-design data, design considerations, and construction sequencing. It is recommended that anybody undertaking such a project consult with individuals with experience in such work and visit previous-constructed sites. A list of WDFW side channel projects is included with this technique.

Perc channel design is the most intensive because it usually entails the creation of a new channel so everything from location and alignment to design details of habitat structures is important. Many of the details in this section will apply to portions of other types of off-channel projects.

Excavation of an entirely new channel can be a large intrusion onto the floodplain landscape. Every feasible effort should be given to minimizing the effect by designing the alignment of the project, access and storage routes, disposition of spoils, processing of excavated materials and large wood, compaction of floodplain soils, and general restoration of the site. Clearing should be minimized by potentially working from one bank of the channel, alternating banks, or from the channel itself.

5.2.4.1 Water supply, quality, and reliability

Perc channels derive a major portion of their flow from groundwater, the source of which is usually the adjacent stream/river. Many abandoned natural channels exhibit year-round flow from groundwater or springs. The quantity and quality of side channel habitat depends on the volume and timing of groundwater and/or surface water flow delivered to these areas. A hydraulic gradient is created when a channel or pond is excavated into the water table with the channel outlet and water level control elevation below the static water level. This hydraulic gradient and permeability of floodplain soils control the amount of surface water flow and important parameters in the success of a project. Water source may also change between seasons. 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 groundwater.

Success of a perc side channel is much more likely if it is associated with hyporheic flow. The hyporheic zone is the area beneath and next to a river channel that contains some proportion of water from the surface channel. Hyporheic zones strongly influence sub-surface and surface water flow, temperature, dissolved oxygen, chemical composition and nutrients. All of these variables can affect spawning success. Channels with predominantly river-source water supplies are generally reliable when designed with the appropriate elevation and profile. They have water that is generally saturated with oxygen, nearly saturated with total gases, and experience mild seasonal temperature fluctuations making them excellent sites for restoration.

There are geologic, geomorphic, hydraulic, and biological indicators that can indicate presence, general rate, and direction of hyporheic flow. Edwards (1998)[33] describes several scales of hyporheic indicators; large-scale geological features, watershed and valley-segment scales, and channel unit scale.

Stanford and Ward (1988)[34] describe changes in channel constraint by bedrock or other soils that create basin or valley-scale distribution of hyporheic zones. Water is forced to flow to the surface at the transition between an unconstrained reach upstream and a constrained reach downstream. Types of bed material influence the channel reach scale. Alluvial reaches are more porous than colluvial or bedrock channels. Floodplains are usually a combination of seemingly random patterns of alluvium and colluvium often bounded by bedrock or consolidated sediments. The randomness is created as the floodplain evolves by the transport and sorting of alluvium in the active channel and gradual filling of relic channels with fine sediment and colluvium. The patterns of buried relic channels and colluvium deposits create locally variable hyporheic flow conditions. Reach-scale gradient and topography can greatly influence hyporheic flow.

5.2.4.1.1 Assessment of Flow Potential

Topographic, geologic, and direct observations of evidence of hyporheic upwelling and downwelling in and near the project reach.

The amount of water that will flow as surface water in a perc channel is proportional to the depth the design water surface is below the static water level, the porosity of the substrate and surrounding soils, and the area of contributing flow. A profile of static water levels through the length of project and across the floodplain at the project site and including the mainstem will show the direction and gradient of groundwater flow. River and groundwater levels and/or flows should be monitored during a wide range of river flows and seasons. Monitoring during low flow and dry seasons is especially important since water supply may be most limited during those periods. This usually requires a period of at least a year to cover seasonal groundwater levels. These measurements are used to determine hydraulic profile and flow of the channel.

A correlation of soils, static water surface profiles, and pump test results provide a best estimate of groundwater flow potential. An evaluation of soil characteristics and percolation capabilities is necessary for the design of perc channels. Test pits should be dug and percolation tests performed to determine soil types, the potential of groundwater flow, and water temperature and quality. Soil conditions will vary through the project site so a number of test pits should be dug. Test pit spacing of about 500 feet or at about quarter-points of the portion of the channel that will contribute perc flow near the project alignment is recommended to best estimate perc channel flow. The subsurface conditions can be highly variable as a result of sediment sorting and old channels being filled as the floodplain developed. Apparent strata of clean gravel or fine sand may be just pockets. In either case, added certainty is gained with additional test pits.

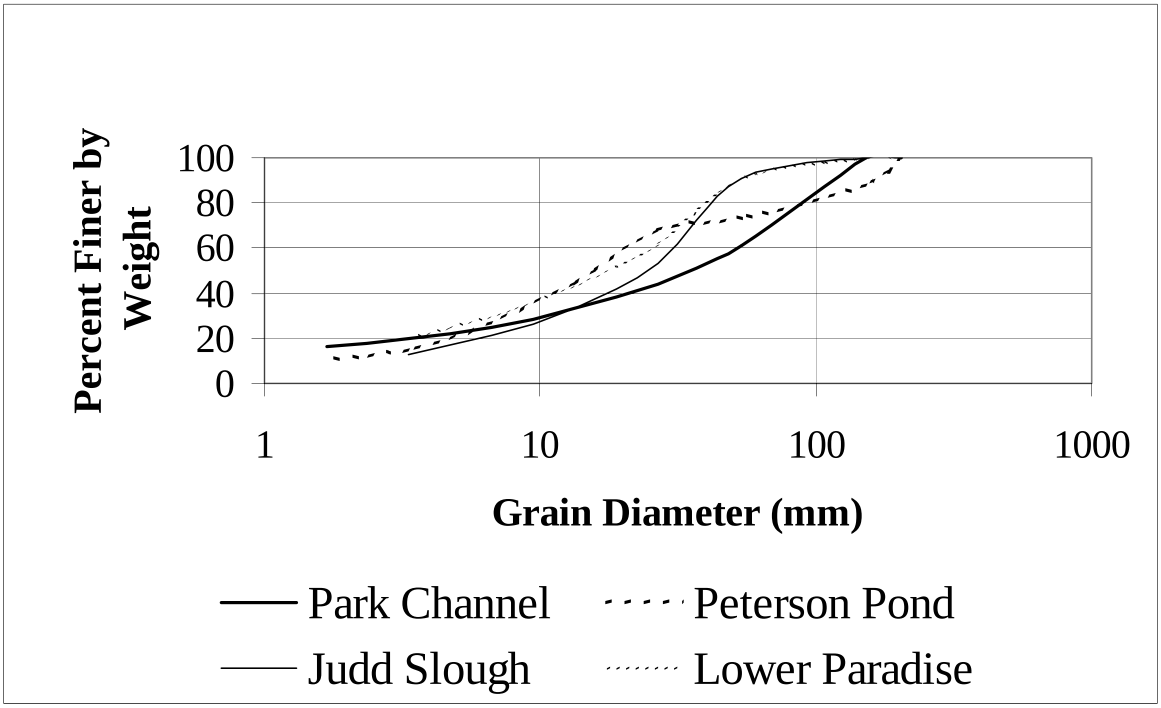


Figure 4. Four gravel samples associated with successful projects.

Descriptions of the soils should be recorded and elevations of soil strata in the test pits should be surveyed as the test pits are excavated. Soil samples should be collected to compare with those of other successful constructed side channels. **Figure 4** shows four typical gravel samples of in situ gravel associated with successful projects. The Park Channel and Peterson Pond are projects constructed by WDFW [23, 35], and the Judd Slough and Lower Paradise by Bonnell (1991).

Pump tests may be necessary to more accurately predict percolation rates. To accurately quantify groundwater-flow potential, an extensive aquifer test with several high-capacity wells and a long period, high-capacity pump test would be required. Such a test is not practical for this scale of project. As an alternative, the Washington Department of Fish and Wildlife has developed a simple pump-test method to calculate relative aquifer permeability and relative aquifer supply rates among sites[5]. This pump test procedure simplifies the description of the groundwater by making the assumption that the aquifer has no impermeable boundaries. Pump tests should be conducted during low flow season when river and groundwater levels are near their lowest levels. A description of the standard pump test is attached to this technique as *Appendix A.*

Water is pumped from a test pit excavated with a backhoe to about three feet deeper than the static water level. Two parameters are used to analyze the groundwater potential: drawdown index and apparent velocity. The drawdown index is the pump rate divided by the drawdown rate. The apparent velocity is the pump rate divided by the wetted area of the test pit. These parameters have been measured for 12 different projects, and comparative ratings have been developed with correlations to flow in the constructed channel.[36] Piezometers should be installed in the test pits as they are refilled to monitor static water levels during subsequent seasons. Piezometers can be PVC pipe buried in the backfill with a perforated section at the bottom and wrapped with filter fabric and capped.

There is some risk in excavating to expose or increase flow from groundwater. The groundwater can be perched on relatively impermeable strata of silt or clay that acts as a seal to contain the flow and keeps the level of groundwater relatively high. The seal has been broken at several sites during excavation of a channel or pond and flow has been lost through it to a deeper aquifer. Assessment of the risk may be difficult. Test pits might show water above consistent layers of silt or clay and loss of water may be directly observed. If monitoring of water levels in piezometers indicates the groundwater is very consistent regardless of changes of river flow and is at an elevation higher than expected relative to the mainstem or with an unusual direction of flow (other than downstream and/or towards the mainstem) the water might be perched.

5.2.4.1.2 Water Quality Assessment

Water quality should be evaluated. Water samples should be taken from test pits 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, it is important to evaluate these parameters so a fish hazard is not created. Piper et al (1986)[37], Senn et al (1984)[38] provide water quality standards for salmonids aquaculture that have been used for assessment of perc channel quality. Lister and Finnigan (1997) 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[39]. Total gases have been observed to vary with seasons as water source naturally changes between hyporheic and groundwater sources but not enough to be a problem. Ultimately water quality hasn’t been a driving issue in any of over forty perc channels constructed by WDFW in the last 20 years.

5.2.4.2 Channel and hydraulic grade

The design of a groundwater channel requires balancing the optimum water surface elevation for maximum groundwater flow against the potential that the channel will be backwatered too frequently from the river mainstem and the cost of excavation. For groundwater to flow as surface water, the design water surface of the channel has to be below the static water level. The amount and reliability of flow is directly related to the head differential of the hyporheic water level to the water level in the channel. The deeper the channel is into the groundwater, the more flow will be produced but the more frequently and extensively the channel will be backwatered from the mainstem. Head differential is much more important than surface area of the channel bed or deep pools within the channel. Pools might be effective in increasing flow if they connect the channel to more porous substrate. On the other hand, if a segment of a channel is too high, surface water will not flow or be present, especially during low flow and dry seasons. Deepening a pool within the channel will not increase flow through the channel though it may create flow through the pool itself. If the water infrequently becomes too low or the temperature high, deep pools distributed through the channel may provide refuge and year-round rearing.

Lister and Finnigan (1997) recommend that the designer avoid the temptation of maximizing the channel length to gain the largest possible habitat gain. 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. Excess slope can often be mitigated by the addition of drop structures or constructed riffle section. Ultimately slope depends on flow potential, groundwater level, and excavation quantities.

The channel should be designed to not lose surface flow during low flow seasons. This is especially critical for perc channels because they are designed at or near the static water elevation. If there is a risk of breaking a seal in the bottom of a channel and losing flow, drop structures might be built to build the hydraulic profile up rather than excavating the channel into the groundwater. The depth of water in a perc channel can be controlled by drop structures but they must be very low; drop is commonly no more than 0.4 feet. They must be sealed deep into the bank and bed so flow is not lost around them through the permeable native soil. Seals should extend well into the bed and banks. Low porosity geotextiles are commonly used for sealing. The depth of the seal depends on the porosity of the native material; generally ten feet into the bank is appropriate. More than three feet into the bed is impractical. Portions of a perc channel intended for spawning habitat should normally operate without backwater effects from the river unless strong upwelling is expected to continue. Percolation flow, and therefore upwelling intergravel flow, is reduced when the channel is backwatered. Strong upwelling will maintain inter-gravel flow and prevent clogging with fines to aid egg incubation.

A water surface profile of the mainstem and designed channel including pump test elevations and high and low channel flow and backwater is prudent for design.

5.2.4.3 Special issues with construction of perc channels

Construction of a perc channel may require substantial excavation and handling and/or hauling of spoils, which can be a substantial project cost. Depths of excavation can be as much as ten feet. If the spoils are left on the site, careful consideration should be given to their effect on the constructed channel as well as the hydraulics of the floodplain. The spoils might be used to create a flow-spreader in the floodplain. Flow spreaders are explained in Integrated Streambank Protection Guidelines. A flow spreader might dissipate energy of overbank flows and clarify the water by spreading the water out across the floodplain. A flow diversion berm might be constructed to prevent floodwaters from directly entering the constructed channel. Containment berms might constrict the mainstem channel, relocate floodwaters to areas of the floodplain that were not naturally flooded, and/or ultimately increase the risk of flooding by increasing the head differential between the floodwater in the floodplain and the water level in the constructed channel. Any restoration plan should include an aggressive program of protecting existing vegetation and revegetation of the disturbed riparian area.

Various strategies have been used to enhance substrate of perc channels. If the channel is protected from floodwater intrusion, there may be no natural sorting of fines and gravel. Placing spawning gravel over filter blankets or layers of filter gravel has enhanced substrate; channel beds have been mechanically and/or hydraulically cleaned, and channels have been over-excavated and replaced with imported gravel. Replacement has been the most commonly effective and efficient strategy but the preferred strategy at any site depends wholly on local conditions of gravel availability and access. The economics of perc channel construction is benefited at large or multiple projects in a vicinity that make the acquisition and operation of mobile gravel screening operations practical. A common strategy is to screen large and small material out of pit run gravel supplied near the restoration site. Washing material may not be practical or necessary considering the logistics entailed. Screening and washing material excavated from the channel makes sense but may not be practical; moving and screening wet material is more complicated and has greater impact on riparian areas than screening dry material at another location. Logistics and sequencing are also complex if material has to be excavated, processed and then replaced in the channel. The depth of spawning gravel depends on what is beneath it. If the natural base is very unsuitable for spawning, at least eighteen inches of spawning substrate should be placed so it can be redistributed by spawning fish and still have a useful spawning bed. If the natural bed is marginal or better spawning habitat, less imported material may be needed. A veneer of rock may be placed over material that is marginally acceptable as spawning gravel so as the fish spawn it becomes mixed providing a suitable bed. Usually imported material is only needed for riffle sections of pool-riffle sequences.

Lister and Finnigan (1997) 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.”

Experience has shown that armoring the bank toe of an excavated perc channel is beneficial for several reasons (Lister and Finnigan, 1997)[10]. Spawning fish are very active in areas of upwelling flow, which is most concentrated at specific locations at the toe of the channel. Their spawning activity eventually excavates into the bank causing it to collapse and a loss of the focused upwelling and spawning area. A riprap toe will buttress and ballast the bank to prevent failure. Fractured rock is often used because it provides a better structural base. If the rock is placed irregularly and with a thickness of at least two layers, the interstices of the rock provide cover for juvenile salmonids (Lister and Finnigan, 1997)[10]. It is believed that the interstices allow greater density of fish rearing because fish are visually isolated from one another. Habitat features are further described later in this section. The rock toe can be placed into the bed and covered with large wood or logs from the site to support the bank and hide the rock. A bank can also be constructed with benches or terraces to minimize risk of bank sloughing due to spawning activity. A bench immediately behind the rocked toe can provide an ideal wet area for establishment of water-dependent vegetation.

Constructed banklines of perc channels are generally on slopes of 2:1; steeper slopes tend to slough especially when saturated with high groundwater. In areas with substantial spring flow and sandy soils, slopes of as much as 4:1 may be required. Flatter slopes may also be required in situations where there is rapid drawdown after high flow events and therefore rapid drainage from the banklines and thus bank sloughing. Access for efficient construction may necessitate clearing a substantial area around the channel. Considering the depth and width of the channel, slope of the banks and general need for access roads along the banks, the width of affected corridor is often as much as fifty or sixty feet.

The quantity of groundwater flow in perc channels is important, so it is desirable to make pre-project estimates of the flow potential. 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 can be effective. Lower flows might be effective in projects built with special equipment or by hand. Channel bed width is based on constructability, equipment used, and desired total habitat. Drop structures are often used to create a nominal depth of 0.7 to one and a half feet; pools are also excavated in the bed. There generally is not enough perc flow available to maintain the hydraulics most desired for spawning conditions based on open channel flow so it is usually not practical to design channel width and slope for those characteristics. Flows in perc channels have commonly varied from 2.8 to 7.1 cfs creating average channel velocities of 0.2 to 0.5 fps (Sheng et al. 1990; Cowan 1991) [19, 40].

Large pools have been excavated at the very upstream of perc channels. Spawning fish often move as far upstream as they can and accumulate at the head end of the channel. The pool gives them a safe place to accumulate. A pool might be eight to ten feet deep. It should include cover and be designed as a holding area rather than spawning habitat. 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 add diversity to the channel. A good place to add pools in a channel is immediately downstream of any grade control weirs. The weirs create some aeration that acts as cover and fish may need a pool to help them negotiate passing the weir. As mentioned elsewhere, deep pools do not appreciably create additional surface flow unless they connect to more porous layers of substrate. Pools with large wood cover are useful in capturing and retaining spawned out carcasses keeping nutrients inside the project and sometimes providing forage for scavengers.

5.2.4.4 Manage the Risk of Avulson

The risk of avulsion was mentioned in the section on project risk and uncertainty. All types of side channels have some such risk. Spring channels can have a unique risk because a channel might be created where there was none before and substantial floodplain clearing and channel capacity might be necessary. Natural avulsions and channel changes are, on the other hand, important processes that create side channels.

Perc channels have been constructed commonly with the spoils used to construct a berm parallel to the side channel to marginally protect it from flood flows from the mainstem. Berms (or levees) can restrict natural processes and can have confining and constricting hydraulic effects on the mainstem (see the technique on *Levee Removal and Modification*); all such implications should be well understood if such a design is pursued.

There are several techniques that can be used to manage the risk of avulsion. Floodplain techniques, separation of the constructed channel from the river channel by distance, elevation, and control of high flow into the side channel will limit the risk of an avulsion. Floodplain techniques such as flow spreaders, drop structures, and avulsion sills are described in Integrated Streambank Protection Guidelines. Flow can be controlled by constrictions within the channel that limit the flow. Constrictions can be rock or wood structures that create headloss and thereby limit the flow in the channel to a safe discharge. To protect against a headcut as water spills from the floodplain into the channel, a spillway can be constructed in the banks of the channel at places where floodwaters will enter the channel. A spillway can be constructed of riprap, then buried and revegetated.

5.2.5 RECONNECTION OF SIDE CHANNELS TO THE MAINSTEM

The design components described in the following sections are important to the development of successful projects to reconnect existing side channels to the mainstem. The intent of this type of project is to restore surface water supply from a mainstem channel to a side channel. Surface flow may supply water at all river flows or at just high flows if perc flow water supply will continue at lower flows. Disconnection of a side channel often occurs at the upstream end due to several causes. If the side channel doesn't have the capacity to transport sediment delivered to it, sediment may block flow to the channel. Such deposition can be exacerbated by wood accumulation in the entry to the side channel. If the mainstem degrades, it may leave the side channel perched and therefore isolated from the mainstem at least at low flows. Mainstem channel patterns may result in the thalweg moving away from where the side channel feeds of the mainstem channel. The mainstem may also migrate towards the side channel and threaten to entirely divert into it. Artificial levees may also isolate a side channel from the river. Reconnection of the side channel is discussed here; the hydraulic effects of levee removal must be evaluated and are described in the Levee Removal technique.

Side channels with consistent surface water supply from the mainstem are the only side channel discussed here that are subjected to the hydraulics of surface water flow and floods. It is important to create processes within the side channel that will create and maintain habitat. Processes might be created or enhanced by combinations of channel layout, cross-section, elevation, and slope, structures, bed material, and large wood. Refer to the technique on *General Design And Selection Considerations For Instream Structures*.

5.2.5.1 Water supply, channel grade and elevation

Reconnection of water supply is all about water supply. A sediment deposition that plugs a side channel can be removed or modified but is only practical if it won't recur. The connection can be self-maintained in some situations by a constriction at the junction of the channels that maintains a scoured thalweg and therefore a low flow water supply. 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. Part of a common evolution of side channels is for debris to accumulate at the junction and meter flow into the side channel. The constriction of the debris maintains low flow water supply by scouring a thalweg and controls high flow by restricting floodwater flow into the channel. The constriction might be created with rigid structures; a pair of large boulders has been used in some projects. 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.

Large wood can be used to manage migration of the mainstem channel into the side channel. If there aren't naturally mature trees available in the right locations, logs can be placed across the side channel near the junction or downstream. The mainstem can then break into the side channel mimicking the trees that would have fallen as the mainstem migrates. See **Figure 5**.

There's not much practical recourse, so to speak, in the case of a mainstem channel that has migrated away from the side channel. Side channels are commonly created as a mainstem channel migrates or avulses across the floodplain; those processes shouldn't be interrupted. If a side channels is perched because the mainstem channel has degraded the solution may be to raise the mainstem channel back to its previous elevation. Such a project then becomes a channel modifications project; see the *Channel Modifications* technique.

Levees, road, and railroad fills often isolate side channels from the mainstem or confine channel meanders. Sites that will be protected from floods and channel migration by these infrastructures often have opportunities for restoration by reestablishing flow from the mainstem and/or restoring fish passage by replacing culverts or providing other fish passage improvements. Since natural processes of floods and channel migration won't occur, maintenance may be necessary.

Additional flow that is diverted into the side channel depletes the mainstem. Be aware of any habitat risk due to the depleted flow, especially in small streams.

Formal intakes have been constructed to enhance flow to side channels (Lister and Finnigan 1997)[10] 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 there is a railroad or road fill that separates the side channel site from the mainstem.

Flow can also be controlled in a side channel with a simple culvert 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 of flow control and a risk associated with formal intakes and control culverts of blocking upstream passage of fish.

5.2.6 ENHANCEMENT OF FLOODPLAIN PONDS AND WALL-BASED CHANNELS

The difference between floodplain ponds and wall-based channels is that wall based channels and ponds are usually higher in elevation relative to percolation-fed channels. They are usually located along the base of higher terraces. Floodplain ponds are generally constructed ponds, often by extraction of gravel for commercial purposes; they may be located closer to the mainstem channel; they are likely flooded more frequently by overland flow from the mainstem; and they are more likely to have porous gravel substrate.

Water sources for both can either be hyporheic inflow similar to perc channels, groundwater sources similar to wall-based channels, provided artificially from the mainstem or a combination of these sources. For these reasons, they might be restored for both spawning and rearing functions.

Habitat might be gained in floodplain ponds and wall-based channels by increasing the water depth, increasing the water level to add area, excavating within or next to a channel or pond, or by improving fish access to the channel. Restoration of wall-based channels and floodplain ponds often entails providing fish passage for juvenile fish. Bates (1992)[41] describes 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 there is little or no bed material transport that might affect a fishway operation. Any fishway, however, requires continued inspection and maintenance effort.

The layout and bathymetry of the ponds can affect its productive capacity. There may be benefit also in reconfiguring a pond. Shaping the pond to optimize production is easiest if the gravel pit is shallow. Some pits are excavated only down to the groundwater level where the excavation is limited by excavation equipment. See **Figure 6**. Gravel mining operations within the floodplain could be reclaimed either as part of the gravel mining operation or subsequent to it. Lister and Finnigan (1997) [10] and their sources describe pond geometries.

> "Studies of juvenile coho utilization of off-channel ponds for overwintering have indicated that while shallow, less than 0.75 m deep, may be beneficial to coho in terms of benthic insect food production, the presence of deeper areas (to 3.5 m) tends to maximize survival for smolt emigration (Peterson 1982b; Cederholm et al. 1988)[42, 43]. 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."

Peterson (1982) found greater survival of coho in deeper ponds (78%) than shallow ponds (28%). Swales and Levings (1989) suggest that shoreline perimeter and shallow areas are key to coho survival. Experience in Washington has been that the most efficient way to increase habitat in floodplain ponds has been to increase cover habitat within the pond or to improve fish access to it[35,39].

Predation is more likely a significant factor in floodplain ponds than other side channels. Zarnowitz and Raedeke (1984) attributed 43 percent of the mortality to coho in an over-wintering pond to bird and mammal predators. To minimize predation, they suggest a pond size less than 2.5 acres with steep sides that drop to greater than two feet in depth with two feet also 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. The beaches were planted with plugs of slough sedge (Carex Obnupta) at 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.

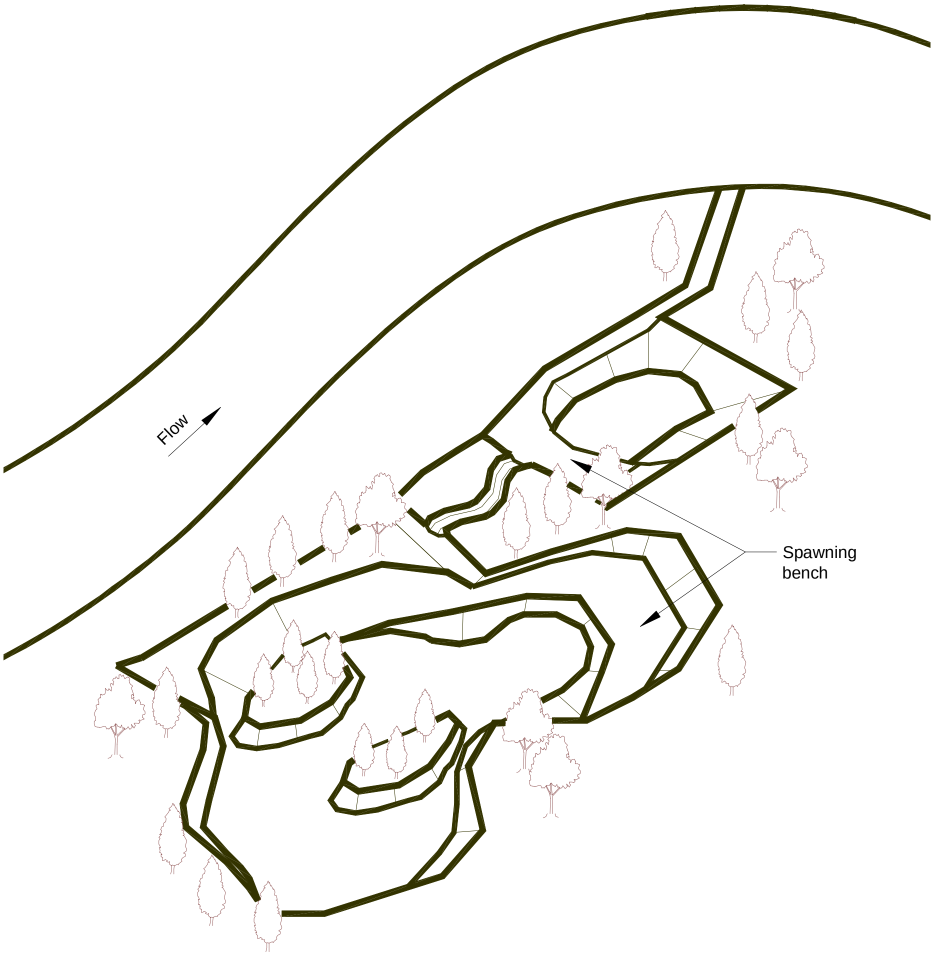


Figure 6. Pond layout and bathymetry can affect its productive capacity.

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 pond. The revegetation could be started whenever a potential restoration site is identified and long before additional work is accomplished. Creating a bench around the pond 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.

Explosives can also be used to add diversity to existing ponds or wetlands. Additional depths in areas can create over-wintering or low flow refuge that might not otherwise be available and to provide the diversity suggested by Lister and Finnigan to optimize food production and rearing habitat. This type of project has obvious safety and potential implications to wetland functions that must be addressed. Explosive pressure waves kill fish so may not be suitable for areas that are already inundated or near them. Explosives may not be permitted.

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 predator species. 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 there is significant perc inflow to the pond.

Water supply to wall-based channels is usually either groundwater other than hyporheic or surface water independent of the mainstem river stage. Those sources may have low dissolved oxygen levels and/or high total gas content.

Odors of hydrogen sulfide have been apparent in the winter at several floodplain pond sites implying there was 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. It could be exacerbated by heating of the pond surface and excess pond depth.

Spawning often occurs in floodplain ponds especially along the upstream edge of the pond where upwelling is very conducive to spawning. Constructing a series of ponds, as shown in **Figure 6**, can maximize spawning habitat. If there is adequate head throughout the site and between each pair of ponds, upwelling at the upstream side of each pond can create additional spawning area. Connecting six abandoned gravel pits with surface water channels restored Countyline Pond on the Skagit River in Washington State. There is substantial risk of dewatering the surface water connections between the ponds and stranding fish 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. A series of ponds can also help to manage risk of avulsion.

Additional shallow water can be provided along the upstream edge of ponds to increase spawning potential though spawning in gravel pits has been observed in water up to fifteen feet deep.

Additional water supply has been added to floodplain pits by culvert with a control gate that connects to the mainstem.

Public safety and the safety of wildlife are concerns at floodplain pits. If the banks are too steep, it is difficult for anybody or animal that falls into a pond to climb out. Shallow beaches, sloping banks at 2:1, and large wood reduce the risk.

A simple and common enhancement of floodplain ponds is to construct or lower a channel from the river to the pond to provide access for adult and juvenile fish. Access to provide spawning opportunity for adults, rearing habitat for juveniles, to prevent fish from being stranded in the pond, and to allow escape of fish stranded in the pond as a result of overbank floods from the river. Lowering the water level of a floodplain pond can add to the risk of avulsion. Though constructed floodplain ponds can be reclaimed as habitat, the practice of floodplain gravel mining may have risks that exceed these benefits at least in some cases. Bates (1992), Norman et al (1998)[44] and Kondolf (2002)[45] describe consequences and risks of floodplain pits including avulsion, entrapment of fish, and colonization by warm-water species and hydraulic effects on the floodplain.

5.2.7 HABITAT FEATURES COMMON TO ALL DESIGNS

A variety of habitat features can be included in side channels. These habitat features are described within other habitat restoration techniques in this guideline. These habitat features may not function the same as when they are built in mainstem channels. Relatively constant flow in perc channels and from floodplain ponds and wall-based channels may not scour under habitat structures, sort bed material, and carry large wood that will create log jams. Those features may have to be constructed where flood processes don't exist and they won't develop naturally.

5.2.7.1 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 overwinter juvenile survival. Without adequate cover, predators such as diver ducks can literally consume the entire supply of wintering fish obviating any values of the project. Once diver ducks find easy prey, they will commonly take up residence until the food resource is gone. The more complex and submerged the cover the better to make it as difficult as possible for the ducks to swim into the areas where fish will hold in efforts to escape.

Intermittent deep pools should 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 provide rearing/refuge habitat. Rock can also be used as described in the perc channel section.

Refuge alcoves are ponds excavated into the bank of a channel as refuge and rearing habitat. They are commonly dug deeper than the channel and loaded with large wood. Holding pools are also built into the upstream end of some channels and are described in the perc channel section.

If new large wood will not be replenished into a site, constructed wood structures might be anchored in place in portions of a channel that is backwatered. Otherwise, the backwater effect floats the wood out of the channel, either into the mainstem or up onto the floodplain. Anchoring might be done by use of appropriately sized wood that will form a natural jam or by mechanical means such as pins and cables. A site that is being cleared for a new channel may offer the opportunity to use material of the size that cannot normally be imported to another site.

5.2.7.2 Spawning substrate

Perc channels are generally constructed by excavation into the floodplain. If they are intended as spawning habitat, the spawning substrate may either be the native soil, cleaned native soil, or replaced with higher quality spawning gravel. Replacement of bed material with spawning gravel is described previously in section 5.2 *Design Considerations*.

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.

Substrate in a channel that periodically experiences flood flows from the mainstem may by rejuvenated by hydraulic sorting and recruitment from the river. Flood flows may also fill and scour to create diversity and specific habitats. These floods may be beneficial or they can potentially alter habitat conditions, scour the streambed and physically destroy incubating eggs.

Features such as spawning gravel should be incorporated into the design. Exposed gravel in the channel may be used or processed material may be imported into the site. Many channels have provided successful spawning habitat using existing substrate. An evaluation of the presence and quantity of potential spawning gravel can be conducted during excavation of the initial project 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 there is a high proportion of the desired size in the mix. Otherwise, the screening operation will extend the duration of the project since so much material will have to be sorted. Recent experience on a specific project found the desired fraction needed to be at least one third of the source material to be economical. The economics of processing substrate compared to importing it of course depends on the source and location of imported material. Using on-site materials, construction costs may range from as little as $6 to $8 per cubic yard of material excavated, which includes bed controls, habitat structures and revegetation. However, imported gravel may cost $40 to $60 per cubic yard installed. See the section on Special Considerations for Perc Channels.

Appropriately sized gravel is critical to the success of a groundwater fed spawning channel. Rounded rock provides ideal spawning habitat for many salmonids. For most species, 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). 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 such abrasion of the spawning adults. Recommendations of spawning gravel sizes are summarized in literature reviews (Keeley and Slaney 1996)[46]. 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 spawning technique in this guideline for additional information on spawning gravel mixes.

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, etc. The work can disrupt habitat and water quality at the site and downstream. The work also can be very 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

Off-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. Although, excavation is often done in deep water, and pumping down of the groundwater is sometimes needed to allow construction of some channel features. If a channel is to be constructed in a surface water channel or in a spring channel with substantial flow, a thorough plan for project sequencing and care of the water must be developed. It might include temporary closure berms to isolate work areas, pumping water onto the forest floor or settling basins, and substantial filter devices to clean water that will discharge to the main river. Factors such as access, materials availability, equipment and labor, and sediment control must be considered. Further discussion of these elements is provided in the *Construction Considerations* appendix.

Sequence the project so equipment doesn't have to be driven on the channel bed. Additionally, special low bearing pressure equipment may have to be used for at least part of the excavation. During construction of the channel, a layer of sand will likely accumulate on the gravel bed. It may have to be cleaned with a gravel-cleaning machine.

Excavation of perc channels may result in conditions not anticipated. The subsurface conditions can be highly variable as a result of sediment sorting and old channels being filled as the floodplain developed. Pockets of fine sand are often encountered during construction. It may be impossible to mechanically to excavate the fine, saturated material; it is essentially quicksand. Several strategies have worked in this case. If the channel realignment is flexible, investigate the lateral extent of the fine material to see if the alignment can be moved to miss the sand pocket. The material might be dredged by pumping it out leaving a pool for rearing habitat. It might just be left in place though if there is a strong upwelling current through the material that keeps it suspended, it might be washed downstream and contaminate spawning placed there. It might be left in place and protected with a layer of larger rock.

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 the site restoration. Gravel might be sorted and/or screened for use as spawning material. Clayey material might be used as a hydraulic seal at drop structures within the project. Large wood, trees and rootwads should also be stockpiled for use in the project as habitat features.

Floodplain ponds were constructed in the 1980's 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. Blasting technique was used at sites that had no access for equipment. ANFO explosives were carried to the site. Explosives precluded much 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.

7.1 Timing Considerations

Timing considerations are less of an issue in the establishment of off-channel habitat because the projects are usually somewhat removed from nearby bodies of water. Construction should be conducted when potential impacts to migrating or spawning fish are minimized. Additionally, construction should occur during seasons of low groundwater levels.

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 for perc channels, location of spoil piles, the need, availability and delivery of spawning gravel, large wood, and site access. The experience of the construction crew and the design team may also affect project costs. An economical option might be to sort gravels near the project site as describe previously.

9 MONITORING

Biological monitoring provides the ultimate measure of project success. Annual spawner counts and redd surveys are the most direct measures of salmonid spawning utilization. Trapping and counting adult and juvenile fish entering and leaving a site may be used to evaluate the total productivity including rearing use of a channel. If an estimate of project benefit is desired, this work should be done for several years prior and after the project and again after several generations of fish have used the site.

Smolt production is not always the total measure of success. Some sites are documented to have a great density of parr but with little smolt outmigration the next spring. It is expected that parr relocated to other habitats in the summer either due to competition or to a history strategy inherent in the stock of fish. This might be especially true at sites high in the watershed that, because of their headwater location and high energy conditions, have historically produced fry that relocated to downstream habitats and don't recruit fry from upstream. Look at both parr and smolt production, especially if high in the area of spawning distribution. Parr and smolt evaluations are a big commitment that should only be undertaken with specific objectives and experienced personnel and supervision. Evaluations can be very intrusive and damaging. Significant mortality can occur. It is also very expensive and must be undertaken with specific objectives and an overall program goal. It is a big commitment.

Biological monitoring for non-fish wildlife will depend on the local fauna. A local habitat biologist should be consulted for determination of what may be important or feasible species to monitor to effectively measure project success. 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*.[47]

In addition to biological monitoring, the monitoring of physical conditions is important to the documentation of project success. Periodic flow measurements in the channel will determine whether the flow 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 done after large floods occur that are high enough to enter the channel.

Effects of the project on groundwater and implications to wetlands should be monitored. Piezometers installed for the initial site assessment should be maintained and monitored for at least several years to see how the project affects groundwater levels and flows.

10 MAINTENANCE

Maintenance should be minimal with this type of project, although fine sediment and organic material may gradually accumulate in the gravel bed. Succession and maintenance of natural side channel habitat occurs by flood velocities and scour, channel migration, spawning fish that clean and sort substrates, wood, and debris. If these natural conditions are not present at a site, maintenance operations may be needed to remove sediment, clean fishways, open beaver dams, replace wood, and other actions. Periodic cleaning of gravel and/or supplementation with new gravel may be required to maintain or restore full habitat potential. Regular inspection and maintenance is necessary for formal fishways. If sedimentation or channel migration risks indicate a need for a high level of maintenance, the project feasibility should be questioned.

11 EXAMPLES

The Washington Department of Fish and Wildlife has constructed a number of groundwater channels in recent years. Good example projects that incorporate the latest design information include Young's Slough, Nolan Channel, and Peterson Pond on the Hoh River in Jefferson County; Rainier Channel on the Bogachiel River in Jefferson County; and Taylor Channel, Park Slough, Illabot Slough and Park Slough Extension on the Skagit River in Skagit County.

The following tables show most of the off-channel habitat projects constructed by WDFW in the last two decades.

Table 3. WDFW Off-channel project sites.

PROJECT SITE	RIVER BASIN	YEAR COMPLETED	HABITAT BENEFITTED	COST	PROPERTY OWNER
Airport Pond	Clearwater	1988/89	30,000 m5	$16,900	Rayonier
Rayonier Pond	Hoh	1988	4,048 m5	$19,000	Rayonier
Barlow Pond	Hoh	1988/89	8,100 m5	$26,600	Private
Anderson Ponds	Hoh	1988/89	10,150 m5	$45,900	Private
Pole Creek	Hoh	1988/90	6,100 m5	$45,300	Forest Service
Peterson Pond	Hoh	1989	2,000 m5	$22,500	Private
Dismal Pond	Hoh	1989	4,048 m5	$25,700	Rayonier
Anderson Cr. Channel	Hoh	1990	3,000 m5	$16,500	Rayonier
Nolan Pond	Hoh	1990	8,000 m5	$ 3,200	State
Wilson Springs	Bogachiel	1990	3,200 m5	$41,600	Private
Tall Timber	Bogachiel	1990	800 m5	$10,000	Rayonier
Smith Road Pond	Bogachiel	1990	2,000 m5	$15,600	Rayonier
Dahlgren Springs	Bogachiel	1990	600 m5	$ 7,300	Private
* Morganroth Springs	Bogachiel	1991	14,100 m5	$13,400	Forest Service
* W.F. Dickey	Dickey	1991	23,000 m5	$28,000	Rayonier
* Mosley Springs	S.F.Hoh	1991	4,048 m5	$21,000	State
* Lear Springs	S.F.Hoh	1991	800 m5	$18,100	State

PROJECT SITE	RIVER BASIN	YEAR COMPLETED	HABITAT BENEFITTED	COST	PROPERTY OWNER
* Upper Mosley	S.F.Hoh	1992	690 m5	$23,000	State
Bogey Pond	Bogachiel	1992	13,640 m5	$24,700	Rayonier
Falcon Walrus	Bogachiel	1992,1995	740 m5	$20,600	Rayonier
Calawah Springs	Calawah	1992	900 m5	$50,300	John Hancock Ins.
Colby Springs	Dickey	1992	9,200 m5	$13,500	Rayonier
Elkhorn Pond	Dickey	1992	5,400 m5	$ 9,100	State
W.F.Marsh Ck.	Dickey	1992	3,000 m5	$ 6,200	Rayonier
* Hoh Springs	Hoh	1993,1995	3,450 m5	$86,000	Rayonier
Soot Cr. Springs	E.Fk.Dickey	1993	2,100 m5	$64,000	Rayonier
T-Bone Springs	Dickey	1993	745 m5	$33,000	Rayonier
* Young Slough	Hoh	1994	3,000 m5	$158,000	John Hancock Ins.
* Lewis Channel	Hoh	1994	2,000 m5	$135,000	State
Tassel Springs	Sol Duc	1994	600 m5	$16,000	Private
Laforrest Pond	Bogachiel	1995/96	2,520 m5	$133,000	Private
*Nolan Channel	Hoh	1996	1,800 m5	$151,000	Rayonier
*Huelsdonk Creek	Hoh	1996	12,000 m5	$18,000	DOT
Manor Springs	Clearwater	1996	960 m5	$21,550	DNR
*Cascade Springs	W.Fk.Dickey	1996	3,000 m5	$42,000	Rayonier
*Powell Springs	Sol Duc	1997	2,000 m5	$76,000	Rayonier
Rootstock Springs (I)	Calawah	1997	200 m5	$12,000	Rayonier
Rayonier Channel	Bogachiel	1998	1,700m5	$135,000	Rayonier
Tyee Pond	Sol Duc	1998	2,800m5	$80,000	Rayonier
Rootstock Springs (II)	Calawah	1998	600m5	$22,000	Rayonier
*Eagle Creek Springs	Sol Duc	1999	2,200m5	$84,000	Private
Thomas Springs	Sol Duc	1999	2,800m5	$20,000	Private
Big Beaver Springs	E.Fk. Dickey	1999	7,400m5	$35,000	Rayonier
*Prairie Fall Creek	Sol Duc	2000	4,700m5	$148,400	Clallam County
*Labrador Creek	W.Fk.Dickey	2000	2,000m5	$37,800	Green Crow Timber
*M & R Springs	Sol Duc	2000	700m5	$59,900	Merril & Ring Timber
Mosley Springs Ext.	S.Fk.Hoh	2001	900m5	$68,000	DNR
Lear Ck. Springs II	S.Fk.Hoh	2001	700m5	$35,000	DNR

* Cost share projects with timber companies, DNR, DOT, Salmon Coalition, Counties and/or Tribes.

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

12 PHOTOS

(d) **Figure 2.** Abandoned gravel pits and pond site near Satsop River.

Figure 7. (a) Dismal Pond site prior to construction.

(b) Dismal Pond site during construction.

(c) Dismal Pond site after construction.

13 FIGURES

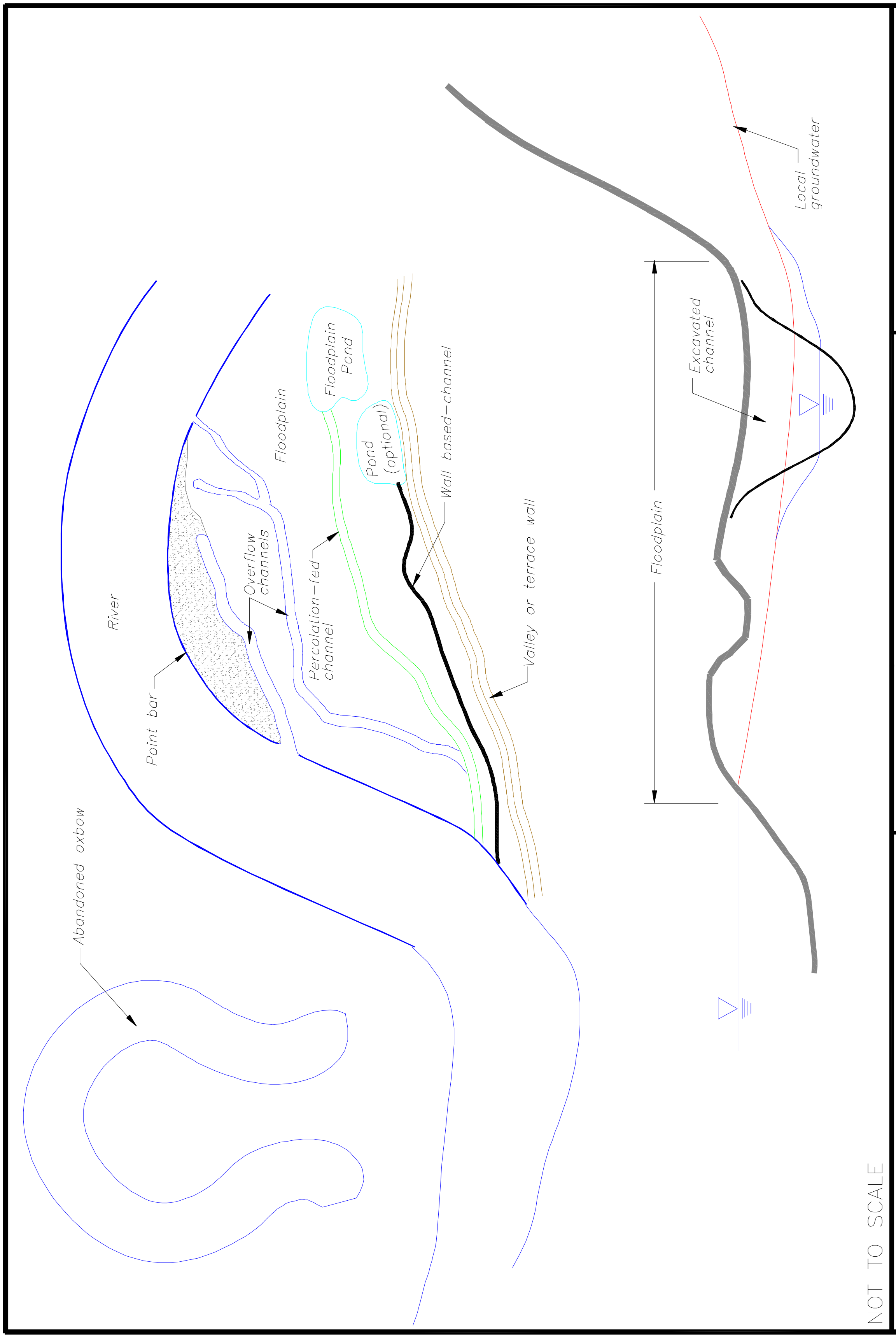
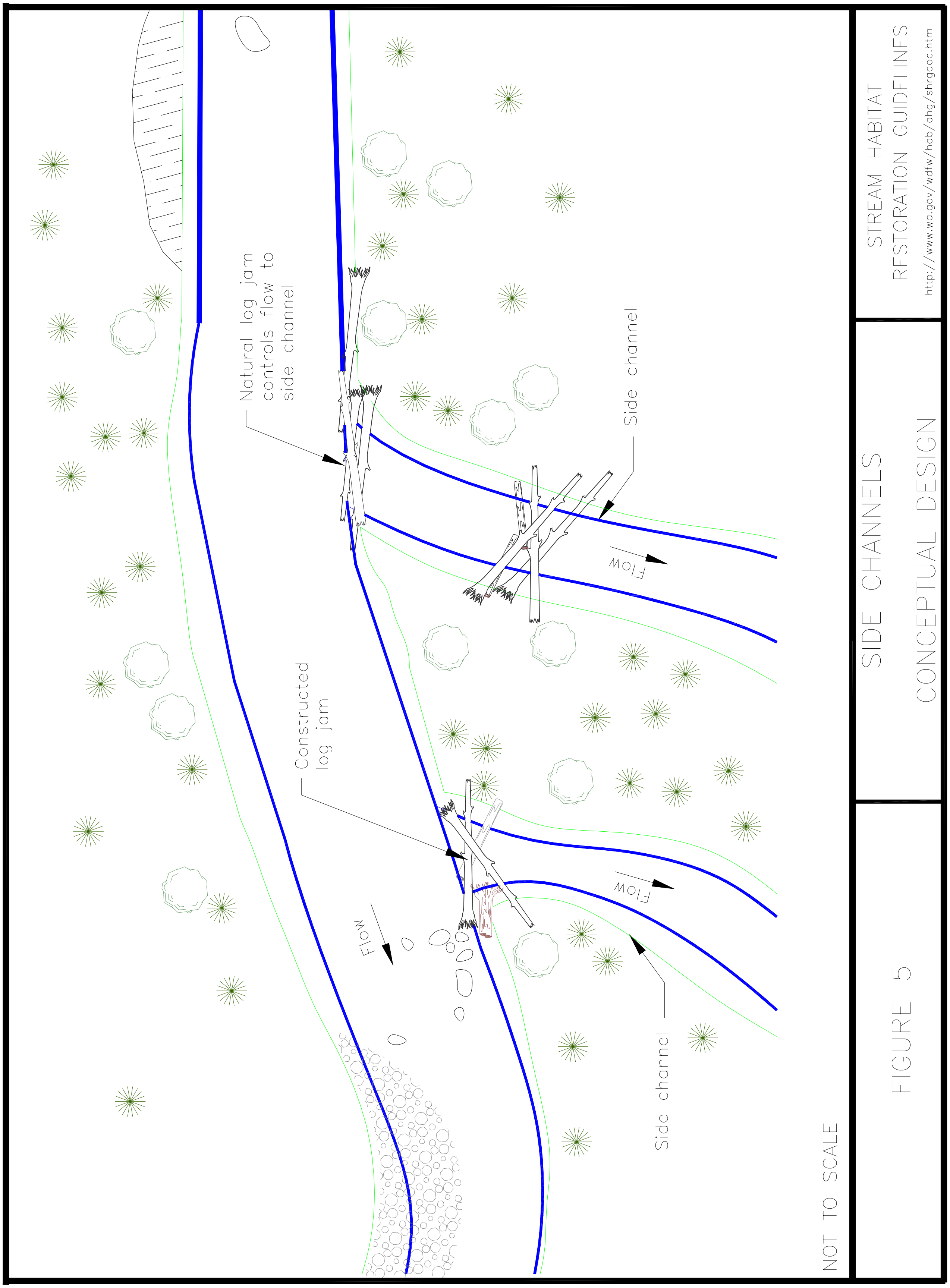


FIGURE 1

OFF-CHANNEL SPAWNING & REARING HABITAT CONCEPTUAL DESIGN

STREAM HABITAT RESTORATION GUIDELINES
http://www.wa.gov/wdfw/hab/ahg/shrgdoc.htm


STREAM HABITAT
RESTORATION GUIDELINES
http://www.wa.gov/wdfw/hab/ahg/shrgdoc.htm
SIDE CHANNELS
CONCEPTUAL DESIGN
FIGURE 5
Natural log jam controls flow to side channel
Side channel
FLOW
Constructed log jam
FLOW
FLOW
Side channel
NOT TO SCALE

14 APPENDIX A

PUMP TEST PROCEDURES FOR DEVELOPMENT OF GROUNDWATER CHANNELS

1. Survey the site and set a project benchmark and temporary benchmarks (TBM), on the river at the proposed channel outlet and upstream adjacent to the upper end of the proposed channel location. Set TBMs near selected test pump sites. Sites should be near the proposed channel centerline, and at the middle, and upper ends of the channel. All elevations recorded during pump tests are tied to the project benchmark. To minimize required volume of excavation, select pit locations at a low ground elevation near the proposed project alignment. The pump site should be outside of the alignment in order to preserve it for studies following construction.

Equipment Needed: Excavator with 15 foot reach, 50 to 200 gpm portable pump, 100 feet hose, 20 ft intake hose, bucket for priming pump, stopwatch, 30 gal container of known volume, survey rod and level, 4 inch PVC standpipe 10 feet long with/cap (lower 6 feet with 3/8 inch holes, 4 inches on center and filter fabric to wrap lower 6 feet), 5 gallon bucket for soil sample and debris net.

2. Dig test pit about 3 feet below static water level. Select cleaner granular material while digging and store separately for backfill. Slope banks to prevent material from falling into the pit as it is pumped down.

3. Select a 5 lb soil sample representative of soil near static water surface level to develop a grain size distribution curve.

4. Record static water surface level relative to TBM. Record the radius of the hole at the water surface. Record the bottom elevation of the hole. Analysis of results requires the computation of contributing flow area, which can be estimated by a parabolic shape.

5. Record soil descriptions and strata through depth of cut. Record strata elevations relative to TBM.

6. Record river water surface elevations. Record time of measurement. If available, read nearby stream gauges.

7. Record the initial (static) water surface elevation.

8. Pump the test pit at a minimum 200 gpm.

9. Record the water surface elevation and time as the water surface drops. Record at 30-second intervals if there is a rapid water level response. If the drawdown exceeds 0.5 feet in one minute, stop pumping; allow the water level to recover to its initial static level and resume pumping at a rate about half the first pumping rate. Continue pumping for four hours or until the water elevation stabilizes for at least 30 minutes, whichever comes first. It is important to continue pumping for at least 30 minutes after the water surface has apparently stabilized.

10. Measure the radius of the hole at the drawn down stabilized water surface.

11. Stop pumping and record time. Record water surfaces and times as the hole refills at a frequency similar to the drawdown procedure described above.

12. Collect appropriate water samples if lab analysis is required.

Secure a 4-inch PVC standpipe with the lower portion covered with filter fabric. Backfill and cut off the pipe one foot above the ground surface. Record the elevation of the top of the standpipe for future measure downs.

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RIPARIAN RESTORATION AND MANAGEMENT

1 DESCRIPTION OF TECHNIQUE

Riparian zones are defined as the land adjacent to streams, rivers, ponds, lakes, and some wetlands, whose soils and vegetation are influenced by the presence of the ponded or channelized water[1]. 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. They are transitions between aquatic and upland habitats and contain elements of both ecosystems. As such, they provide a rich and vital resource to fish and wildlife. Approximately 85% of terrestrial vertebrate species in Washington use riparian habitat for essential life activities[2]. Since the arrival of settlers 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, altering soil conditions, and disrupting natural disturbance cycles (e.g., fire, floods). In addition, channel incision and the diversion or impoundment of water for irrigation, hydroelectric power generation, domestic and industrial water consumption, and similar uses may alter the depth of the water table and patterns of floodplain inundation, which also impact the health and composition of the riparian zone. Techniques to re-establish native plant communities may be passive or active. Passive restoration involves halting those activities that degrade the riparian ecosystem or prevent its recovery (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, restoration of bank and floodplain vegetation may require channel modification, levee modification or removal, water management modification, or landuse changes to succeed (refer to the *Channel Modification* and *Levee Modification and Removal* techniques and Stream Habitat Restoration Guidelines, Chapter 4.5.2, *Restoring Stream Flow Regime*). Regardless of the specific technique employed, when restoring native riparian plant communities, it is essential to identify and address the cause of riparian degradation, or else restoration efforts are likely to fail. Both active and passive approaches to riparian restoration require years or decades for benefits to be fully realized due to the relatively long growth and establishment periods for many plant species.

Riparian restoration is most effective when riparian areas can be protected from deleterious landuse activities for the long term through land purchase, formal conservation easements, or similar agreements (see the *Dedicating Land and Water to the Preservation and Restoration of Stream Habitat* technique). Other complimentary techniques to consider when restoring riparian zones include removal of floodplain fill, levee removal and modification (see the *Levee Modification and Removal* technique), and reconnecting, restoring, or creating side channels and other floodplain features (see the *Side Channel / Off-channel Habitat Restoration* 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[4]. These habitats offer feeding, reproduction, and refuge habitat for invertebrates, fish, waterfowl, amphibians, birds, and mammals. In addition, they also have a significant influence on instream habitat. Depending on the type, extent, and density of riparian vegetation, riparian areas may provide the following critical functions to streams, even if they never come in contact with floodwater:

- Provide shade, which helps to moderate stream temperature, providing relatively cool water in summer and warm water in winter. This, in turn, influences the dissolved oxygen content of the water.
- 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 to the stream, 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 a source of roughness to the stream.
- Provide leaves, twigs, and insects to streams. These are important food and nutrient sources for fish and other aquatic life.

When riparian areas are accessible to floodwater, they have the additional benefits of reducing 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 the buoyancy of wood. Vegetated floodplains reduce flood flow velocities so as to limit scour and encourage sediment deposition on the floodplain.

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.[5] for more information on the fish and wildlife benefits associated with riparian zones.

Large-scale riparian restoration projects may require the acquisition and procurement of large amounts of plant materials. Local stocks of native plants will be best suited to site conditions. Some of the required plant materials can be transplanted or cut from adjacent healthy donor sites near the project area. They can also be obtained from nursery suppliers. In either case, source material should be carefully researched to ensure it was legally and responsibly collected (i.e., donor sites were not adversely affected), and that 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.

3 APPLICATION OF TECHNIQUE

Riparian restoration may be employed as a stand-alone technique or used in conjunction with other stream restoration and enhancement efforts. However, it is only applicable where short- and long-term landuse, management activities, and site conditions are compatible with the establishment and growth of 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.

Use of passive land or water management changes alone to improve riparian condition will be most successful where land uses such as poor livestock management, recreational foot traffic, logging, or mowing have degraded but not entirely eliminated desired vegetation and soil structure. Sites affected by more 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 landuse changes), the cause of the instability needs to be assessed and addressed prior to active riparian restoration or else new plantings will likely be lost to bank erosion or water table changes. However, passive approaches to riparian restoration may still be appropriate.

Since a well-established riparian corridor can buffer a stream from adjacent land uses and promote channel stability, it should be incorporated into all stream restoration work. This includes construction or modification of channels (see the *Channel Modification* technique); installation or removal of bank protection (see the *Bank Protection Installation, Modification, and Removal* technique); reconnection, restoration, or creation of side channels and other floodplain habitats (see the *Side Channel / Off-Channel Habitat Restoration* technique); and addition of large wood to the stream or floodplain (see the *Large Wood and Log Jams* technique).

4 RISK AND UNCERTAINTY

4.1 Risk to Habitat

Risks to existing habitat are limited in riparian restoration, since it is generally implemented where there is little or no natural habitat value. However, in some instances, potential risks to existing habitat include:

- Disturbance of existing habitat during weed control due to herbicide drift or large scale removal of existing vegetation in preparation to planting
- Disturbance to adjacent habitat to gain access to project areas
- Loss of existing habitat where plant material is salvaged for transplant
- Introduction of disease or pests by plants that are imported to the site

These and other risks to habitat must be considered and avoided where possible through careful planning. Where such disturbances are unavoidable or could potentially occur during the course of project implementation, efforts to restore or replace damaged habitats should be implemented, either as part of the original project plan or as a contingency measure.

4.2 Risk to Infrastructure and Property

Riparian restoration and management may pose an increased risk of flooding or damage to infrastructure and other property located in the floodplain when undertaken on a large scale. This 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.

4.3 Risk to Public Safety

Since large riparian planting projects that restore woody vegetation across the floodplain can increase the risk of flooding, public safety may be at risk. This risk may be minor if the affected area is only seasonally or occasionally used, such as a park, or it may be substantial if any infrastructure is affected. Chemical weed control may also pose a risk to the public.

4.4 Uncertainty of Technique

Riparian vegetation can rapidly reestablish under proper landuse 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 risks that can 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, and plant disease or pest infestations. 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, destruction from mowing, and unregulated uses such as off-trail motorized biking and unmanaged camping may also be a problem in some areas. Only some of these physical and biological constraints to vegetation establishment can be controlled.

There is also a risk 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 seral stages that ultimately will provide all 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, placing large wood directly in the stream or floodplain will provide immediate, though short-term benefits while the riparian vegetation matures.

5 METHODS AND DESIGN

Riparian restoration may be accomplished using passive means that involve halting or modifying deleterious landuse and water management practices that degrade the riparian plant community or prevent it from recovering. Alternatively, restoration may involve active measures ranging 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, consideration must be given to site-specific conditions such as soil type and exposure to drought, floods, sediment deposition, wind, and sun.

5.1 Data Collection and Assessment

Successful planting requires sufficient planning, site evaluation, monitoring, and maintenance to ensure that long-term goals are met. Plant materials must be carefully selected with regard to site conditions and constraints. 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 is less certain.

- Conduct a site review including nearby analogs of the desired future condition;
- Identify site constraints;
- Identify needed changes in land management
- Develop design criteria;
- Select plant species;
- Select plant-material types (e.g., woody, herbaceous, bare-root, seed, potted);
- Determine planting density and layout;

- Schedule timing of plantings;
- Consider site-preparation requirements;
- Determine planting techniques; and
- Define procedures to monitor and maintain project

5.1.1 Site Review

Riparian areas are often characterized by diverse site conditions. Flowing water sorts sediments, creating 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, coupled with variations in soil structure, vegetation, and topography create a complex and dynamic network of habitats throughout the floodplain[6]. As a result, site reviews are essential to ensuring site conditions match the needs of the selected plants.

The site review should include 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. Look for and identify any good sources for local cutting collection and/or plant salvage. Usually this must be done at a reference area since the area you are working on often doesn't 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 unvegetated channel to annual plants to perennial plants. If possible, note how this elevation relates to river discharge. See Information Series 16, Riparian Planting Zones, Riparian/Wetland Project, at http://www.Plant-Materials.nrcs.usda.gov/idpmc/
- *Depth to Groundwater* – ideally, this is determined using test pits or monitoring wells; but, in the absence of such tools, it is often 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. Are shallow soils or till present? Additional information that can be helpful but is not often collected includes soil pH, salinity and nutrient status. This information can be obtained by sending a sample to a soil lab or by testing it with a home soil test kit.

- *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.
- *Geographic Characteristics* – determine the elevation, slope and aspect of the site. Plant species harvested for revegetation projects that come from high elevations on the slope 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 possibly save money.

Below are some possible site constraints, many of which are specifically related to natural riparian processes.

- Weed and grass competition for water, sun, and space;
- Heavy shade;
- Direct sun exposure;
- Over-compacted soils;
- Overly drained soils;
- Poorly drained soil;
- 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 sunny open fields);
- 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;

Consider also landowner desires 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 its proximity to utilities, to address safety concerns, or to preserve views.

When installing structures such as fences, offsite watering facilities, irrigation systems, and other features in the riparian zone, consider the effects that high water events and flood flows may have. This would include deposition of sediments and debris as well as scour. It may be best to locate these structures outside the flood prone area whenever possible.

5.2 Changes in Landuse or Water Management

Changing landuse or water management to foster natural recovery of riparian vegetation or to complement revegetation efforts includes cessation or modification of current activities that limit the species, diversity and extent of the riparian community. Such activities may include, but are not limited to, 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 purchase or lease of the land (see *Dedicating Land and Water to Stream Habitat Preservation and Restoration* technique) or water rights, regulation of development, or a legally binding commitment by the landowner (e.g., a conservation easement. Restoration of riparian habitats through changes in landuse and water management requires a long-term commitment to be effective. This commitment should also extend to maintenance and repair work whenever applicable.

If relying on landuse and water management change as a stand-alone treatment (i.e., without supplemental planting), consider the likelihood and time period for natural regeneration of desirable vegetation and the potential for weed invasion. This is particularly important if the landuse 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[7], factors that affect the natural distribution and propagation of riparian plant species include:

- Spatial and temporal variation in the “seed bank”. Is there a natural source of seeds of the desired plant species available to the site? This may be a difficult question to answer. 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). 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.
- Variation in scour and deposition. These affect the ability of seeds and plants to germinate and establish, and the distribution of water-borne seeds.
- Inundation depth, frequency, extent, and duration. Many plant species are

adapted to, and depend on, flooding for propagation. Flood disturbance can revitalize riparian ecosystems by producing sunny, bare soil sites that lack competition from other plants and have high moisture availability. Such sites are ideal for the establishment of colonizing vegetation such as red alder, black cottonwood, and willow species.

- Elevation, drainage area, geology, and flow regime. These affect seed availability and dispersion.
- Characteristics vital to species' germination and growth, including water availability, soil condition, physical and biological constraints, flow regime.

Knutson and Naef[2] recommend specific best management practices to control or limit the adverse impacts to riparian habitats from various landuse activities, including agriculture, grazing, forest practices, roads, recreation, and urban development.

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. The Washington Department of Fish and Wildlife recommends the following minimum widths for riparian habitat associated with streams[2]

Riparian Restoration and Management Table 1: Recommended Riparian Habitat Area widths. Source: K. L. Knutson and V. L. Naef. *Management Recommendations for Washington's Priority Habitats: Riparian*[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 applied to 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 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[8].
- 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 **Riparian Restoration and Management 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 landuse or management alone is not sufficient to recover the riparian zone, a planting plan will need to be developed and implemented.

5.4.1 Design Criteria

While not necessary for all projects, revegetation planning should generally begin with development of 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, the development of objectives is the most important part of developing a plan. The development of clear objectives will help keep the project on track by limiting actions to those that will help meet the objectives. Refer to Stream Habitat Restoration Guidelines, Chapter 5.3.4, *Design Criteria* 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. In an unpublished 2001 study conducted by WDFW on ten channelized stream restoration projects in western Washington[9], 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, the most common cause of failure is inadequate assessment of available moisture and inundation patterns (Chris Hoag – 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 resistant to local insect infestations, and provide food and habitat for native wildlife. Use the reference site as a tool to aid in designing a planting plan for the project area, but be sure to consider the role of succession in achieving the reference plant community. For instance, a nearby site with similar conditions to the project area might be dominated by a relatively mature stand of western red cedar trees and an understory of salmonberry. But planting those same plants at a project site that is has just been denuded by construction and is fully exposed to sun and wind will likely result in high plant mortality unless the plants have access to lots of moisture. Cedar seedlings and salmonberry 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.

Historic plant communities at the site are also helpful when developing planting plans. Again, the role of succession must be taken into account. 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, re-establishment of historic vegetative communities will not be possible and other native vegetation or even non-native vegetation may have to be used.

Riparian Restoration and Management Table 7 provides a list of native species one might consider using on riparian restoration projects. This list is not exhaustive, but it does provide helpful information to consider during the plant selection process. Consult plant guides, local references[10] [11] or native-plant nurseries for further information on specific plants. There are over 40 native-plant nurseries in the state of Washington[12]. As with any purchase, when choosing a source of plant material, assess the quality of the plants; cheaper is not necessarily better. Plants grown in western Washington may not do well on the east side and vise versa. Make sure you know where the plants were collected, and match the elevation, soils, latitude, etc. as much as possible to your planting site. Usually, nursery staff can assist in plant selection.

Plant species should be selected with an emphasis on the following:

- Suitability for anticipated climate, hydrology, elevation, soils and constraints of the planting site;
- 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 consist of a variety of species and successional stages, which is important to support diverse fish and wildlife populations. In naturally forested areas, a mix of deciduous and coniferous trees exists. 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.
- *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*. Choosing native plants grown with seed or cuttings collected from sites in local watersheds will preserve the genetic integrity of the local stock and will have the highest likelihood of success.
- *Exposure tolerance to*:
    - *Sun, wind and low soil nutrients*. 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[13]. 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, offering at least partial shade.

- *Grazing*. Planting species capable of stump sprouting or suckering from roots (identified in **Riparian Restoration and Management Table 7** 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 are most often found on flood prone surfaces above the 10-year return interval flood level.

The plant community will likely change over time from the original planting plan 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.

5.4.3 Plant-Material Types

Plant-material types include cuttings, seed, containerized, bare-root stock, and ball and burlap 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. Most 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 tend to be strong and deep, mechanically reinforcing soils by adding tensile strength.[14] Large riparian trees 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.

Cuttings. Cuttings consist of harvested stems of dormant shrubs and trees. They are capable of developing both roots and shoots if planted in proper conditions. A short list of riparian shrubs or trees native to Washington can reliably and consistently root from cuttings. For the best chance of success, cuttings must be harvested during the dormant season, preferably fall or spring[6], and planted within days of collection. Expect up to 80 per cent mortality if the buds on the cuttings have begun to open as plant respiration will begin prior to root development and limit the degree to which new roots can form, if at all. By far, willow species (*Salix* spp.) are the most commonly used and successful cuttings. Other species commonly used in Washington with good success include red-osier dogwood (*Cornus stolonifera*) and black cottonwood (*Populus balsamifera trichocarpa*). Species that are less commonly used, but root well from cuttings, 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*), syringa (*Philadelphus lewisii*) and spirea (*Spiraea* spp.) [7]

Not all of the species listed above are appropriate in live-stake applications due to their relatively small, flexible branches, but they are appropriate as components of fascines and brush layers. Few other riparian shrubs or trees native to Washington reliably and consistently root from cuttings. Cuttings are popular in bank-stabilization projects because they are inexpensive and can be collected in long lengths capable of accessing moist soils in the vicinity of deep (10- to 12-foot) water tables. Whether installed as live stakes, fascines, or brush mattresses, cuttings provide excellent erosion control and bank stabilization. More detail on cuttings is provided later in this technique under *Planting Techniques*.

Containerized. Containerized plants are nursery-grown plants in any one of dozens of different sizes and shapes of containers. They are distinguished from most other types of plant materials by their well-developed soil/root mass, allowing planting to occur throughout much of the year, provided adequate water is available. If plants are irrigated, they can be installed in the dry summer months, which is an advantage when construction occurs during summer low-flow. Another advantage of containerized plants, especially in contrast to cuttings, is that many riparian plant species native to Washington State are commercially available in this form. Conifers such as cedar, spruce and hemlock are usually acquired as containerized plant material. On the down side, the root systems of containerized plants are initially established within commercially available potting soils. These soils typically have characteristics much different than that of the planting site and often the root systems of the plant do not readily leave the potting soil despite removal of the container and several years of growth. Care must be exercised during planting to encourage root migration into surrounding native soils. More detail on this is provided later in this technique under *Planting Techniques*.

Although conventional landscaping nurseries typically provide containerized plants in one-, two-, or five-gallon containers, some native-plant nurseries make use of a much wider array of containers better suited to streamside conditions. For example, a deep but narrow container known as a tubeling or plug has dimensions of approximately one inch wide by six inches deep. 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. Other innovative containers include, but are certainly not limited to, 14-inch-deep treepots®, PVC pipe four to six inches wide by one to two feet long, biodegradable burlap "socks" and biodegradable coir (coconut-husk fiber) containers.

Bare-root. Bare-root plant material is a nursery-grown, woody plant-material widely used in riparian restoration. Bare-root plants consist of rooted plants sold with the soil removed and packaged with damp sphagnum moss or sawdust and sold in bundles. Bare-root plant material generally requires smaller planting holes than comparatively sized containerized plants because you don't have to make room in the hole for soil packed around the roots. Although much less expensive (one-tenth the cost of container stock), bare-root plants have a lower survival rate if stored or planted incorrectly. Bare-root plants require special handling so that their roots are not exposed to sun or wind for more than 30 seconds to a minute. This requires keeping the bare-root plants covered and their roots moist at all time and not delivering more plants to the site in a day than can be planted. Bare root plants must be planted in a dormant condition. On the other hand bare-rootstock is planted directly in soils native to the site and roots more readily migrate out of the planting hole and into the surrounding soil. With proper storing and handling survival rates can be 80 to 90%. Bare-root plants are becoming increasingly available, both in number and species diversity, at native-plant-material centers, nurseries and local conservation districts. Locally collected material is harder to find, but some nurseries can accommodate special requests with advance notice. Contract growing is an increasingly available option and often does not cost more than regularly stocked bare root plants, but will need to be ordered 12 to 18 months prior to planting. The main limitation of bare-root plants is their narrow planting window (late winter/early spring dormant season), which will require proper planning and, possibly, use of a larger planting crew.

Ball and Burlap. Ball-and-burlap plants consist of mature trees and shrubs ranging from six to 12 feet tall. Plants are shipped from nurseries with their roots "balled-up" and wrapped in burlap and wire. Their large size makes ball-and-burlap plants less likely to become stressed and die as a result of animal damage and weed competition. Their large size also adds an element of structural diversity to a revegetated area. However, ball-and-burlap plants are considerably more expensive than other plant materials and their large size and bulk make handling difficult, requiring guy wires and staking for stability during the first one to two years after planting. They also provide many of the structural requirements much faster like shade, fish habitat, cooling, source of large wood, etc.

Salvaged. Ideally obtained on-site, salvaged shrubs and trees are those that otherwise would be destroyed or disposed of during the construction phase of a stream restoration project or another nearby construction project, but are instead salvaged and replanted. If carefully coordinated, excavators or tree spades can cost effectively transplant a large number of seedlings, saplings and, sometimes, mature 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. In addition to great cost savings (provided equipment and transportation costs are low), salvaged plantings can provide immediate benefits to bank stability, structural diversity, cover and aesthetics compared to smaller plant materials. Their large root mass may also make them resistant to flood flows.

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 excavation of a sufficient portion of the soil root mass to support the aboveground foliage. On small plants, the entire root mass may be obtained with the use of a shovel or backhoe. On larger shrubs or trees, excavators and tree spades are required; however, some trees may have root masses too extensive to allow for salvage and transplant. When salvaging plant material, keep in mind that 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 the process, 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 following transplant. To reduce the shock of transplanting, dormant plant materials are preferred, but if flood or winter conditions require non-dormant salvage, irrigation may be needed to maintain soil moisture until late fall[8]. Pruning woody stems and branches may help reduce drought stress. Willow clump plantings can be planted with the root systems and collar much deeper than the soil surface (as much as 3-4 feet below the surface). This allows the roots to be placed in the saturated zone rather than above it.

According to the Thurston County Master Gardener Foundation[7], native plants that are easily salvaged in western Washington include:

Vine maple (*Acer circinatum*),
Bigleaf maple (*Acer macrophyllum*),
Red alder (*Alnus rubra*),
Beaked hazelnut (*Corylus cornuta*),
Oregon ash (*Fraxinus latifolia*),
Nootka rose (*Rosa nutkana*),
Indian plum (*Oemleria cerasiformis*),
Pacific ninebark (*Physocarpus capitatus*),
Douglas fir (*Pseudotsuga menziesii*),
Cascara (*Rhamnus purshiana*),
Clustered rose (*Rosa pisocarpa*),
Red elderberry (*Sambucus racemosa*),
Snowberry (*Symphoricarpos albus*),
Western red cedar (*Thuja plicata*)

There isn't a similar document for eastern Washington, but the following species, native to the eastside, are likely easily salvaged:

Red alder[12]
Nootka rose
Willows
Thinleaf alder[15]
Wood's rose
Western red cedar
Snowberry
Douglas fir

<u>Seed</u>. Seed is a commonly used and inexpensive material for revegetation projects. However, the establishment of woody plants from seed alone can be difficult, and is often less successful than efforts using other types of woody plant materials. Whenever possible, seeding should be combined with materials such as cuttings, bare root, or containerized plants. On some sites, there may be interest in experimenting with western red cedar using direct seeding, as discussed in the Soil Rehabilitation Guidebook[16]. Similarly, most cottonwood species rely on seed distribution and moisture regimes associated with high flows to be successful, and therefore can be appropriate for seeding depending on site-specific conditions.

5.4.3.2 Herbaceous Plant Material

Herbaceous plants are grass and grass-like plants including rushes, sedges, ferns, legumes, and forbs. They 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, although some species tend to be more clumped. Their fine root mats and dense cover provide excellent 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.

<u>Seed</u>. Seed is the most common type of herbaceous plant material because it 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 it is 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 immediately following floodplain reconstruction. Care must be exercised in the selection of erosion control fabrics as 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 may use less expensive techniques such as sterile, seed-free straw or cellulose fiber mulch in less frequently flooded areas. Mulches can be used where necessary to protect newly sown seed from moisture loss, wind displacement, and competition from weeds. Seed is also available in pre-seeded erosion-control mats. This product may be beneficial 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, the need to protect a seeded surface with fabric should be weighed against the acceptable risk of loosing all placed seed and significant soil erosion if the floodplain is inundated prior to establishment of vegetation.

When only native grasses and herbs will be allowed in replanting programs on some lands (i.e. National Park Service) and they are not available, sterile seeds can be used. Sterile grasses, especially, are becoming increasingly available.

<u>Containerized</u>. Nursery-grown herbaceous species are widely available in containers similar to those described under the previous discussion on *Woody Plant-Material Types*. Keep in mind that very small plugs are difficult to plant, grow and maintain. NRCS research[17] shows that the best results were obtained using 24in^3 plugs. This size will have a good root system and above ground biomass to allow rapid establishment allowing it to compete with weeds and not drown during flood events. For sites requiring local material, contract growing of herbaceous species is widely practiced. If nurseries are supplied the local seed, contract-grown plug costs are often less than regular stock costs. Plugs are generally planted in a non-dormant state and have a wider planting window than bare-root stock.

<u>Bare-root</u>. Emergent, wetland, herbaceous plants such as bulrush (*Scirpus spp*.) are available in bean-sized, bare-root fragments. Easy to install and far less expensive than containerized plants, streambank and riparian zone plantings of bare-root herbaceous plants are appropriate. Growth from a bare-root fragment will be much slower than from a containerized plug and like woody bare-root stock, herbaceous bare-root stock must be planted in their dormant season (late winter to early spring) and may require supplemental irrigation.

<u>Salvaged</u>. Salvaged sod, if available, is an outstanding type of herbaceous plant material. It has a dense soil/root mass that is relatively resistant to erosive forces; it establishes quickly; it's cost effective, and it makes use of 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. Moist soil, even soils temporally moistened through irrigation, is necessary as dry soils result in sod blankets that break up during handling.

<u>Pre-vegetated Mat</u>. Similar to salvaged sod in terms of its advantages, pre-vegetated coconut mats resemble conventional turf sod. The mats have dense root systems that quickly penetrate the soil once installed. The coconut mat provides temporary erosion control until the vegetation gets established. Available from some Washington native plant nurseries, these products can 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. **Riparian Restoration and Management Table 2** provides general density recommendations for different plant materials. Remember that these recommendations are only 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 establishment of hydraulic roughness and anticipated time to maturity.

Riparian Restoration and Management Table 2: Recommended Densities for Plant Materials.

Plant Material Type	**Planting Density (highly site dependent)**
Cuttings	1-2 ft on-center or planted in bundles, dense rows, brush mattresses[18] or other bioengineering method
Containerized herbaceous plantings	1.5 to 2 ft on-center
Containerized shrub	3 ft to 5 ft on-center depending on the species
Containerized tree	10 ft on-center (435 plants per acre). This is species related. Too close and the plants can be overstressed.
1.5inch-diameter stem, ball & burlap tree	20 ft on-center
Bare-root stock	5 to 10 feet on-center for shrubs; 10 to 20 feet on center for trees
Seed mix	Seeding rate depends upon species

A small increase in planting density can increase the number of plants per acre substantially. For example, decreasing plant spacing from five feet on-center to three feet on-center increases plants per acre from approximately 1,792 to 4,840. **Riparian Restoration and Management Table 3** provides planting-density conversions.

Riparian Restoration and Management Table 3. Planting density equivalencies.

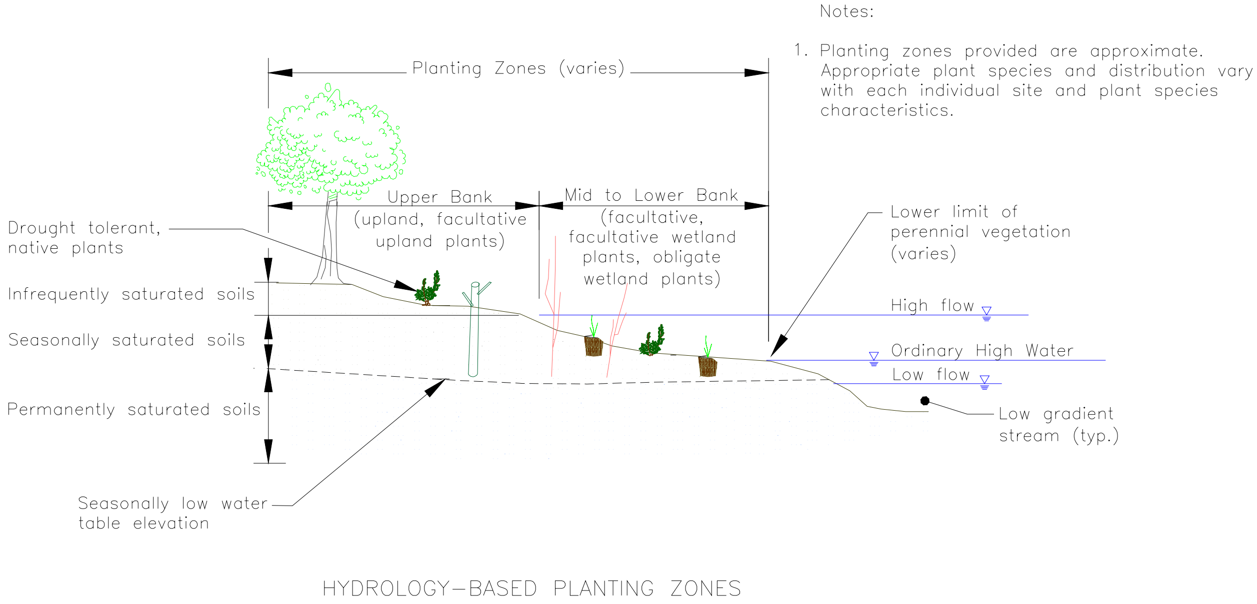
Ft on center	**Sq. ft per plant**	**Plants per acre**
1	1.0	43,560
2	4.0	10,890
3	9.0	4,840
4	16.0	2,722
5	25.0	1,742
10	100.0	435
15	225.0	193
20	400.0	109
25	625.0	70

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 easy installation 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-year to 10-year return flood elevation
- 10-year to 25 year return flood elevation
- above 25 year return flood elevation.

Plants have specific inundation preferences. Creation of flood inundation maps, for larger projects, assists in determining appropriate placement. Refer to **Riparian Restoration and Management Figure 1**.



Notes:

1. Planting zones provided are approximate. Appropriate plant species and distribution vary with each individual site and plant species characteristics.

Riparian Restoration and Management Figure 1: Hydrology-based planting zones.

Planting by hydraulic zone alone does not necessarily optimize fish and wildlife habitat and aesthetics. One should also base the planting layout on the size and type of material, the individual plant species habits, and the habitat needs of fish and wildlife. For example, low-growing shrubs or herbaceous plantings might be distributed uniformly across a streambank, while 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. This will mimic natural plant distributions, making it more aesthetically pleasing. Plants that tend to form thickets, such as salmonberry (*Rubus spectabilis*) or hardhack (*Spirea douglasii*), should be planted close together. Plants that tend to grow as solitary individuals, such as many tree species, should be planted further apart.

When planting the riparian zone above the top of the bank, future maintenance requirements should also be considered. Grasses and weeds surrounding new plants often need to be mown or otherwise suppressed for three years or more to minimize competition until the plants are firmly established. New plants often need supplemental water during the first year (and sometimes through the second summer) following planting. Maintenance will likely be easier if plants are spaced far enough apart to allow a mower to operate between them, or if plants are grown in distinct clusters or bands. Clustered planting offers the advantages of making the plants easier to find, and of limiting the area requiring weed-whackers or other hand-held tools to within and immediately outside of the cluster or band. Mowers or tractors can be used between plant clusters, if necessary. Heavy mulch between plants within the cluster or band will suppress weeds and conserve moisture so as to minimize the necessary 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. Maintenance issues are of less concern on the streambank because the desired uniform coverage will likely happen if the newly planted vegetation is left alone.

5.4.5 Timing of Plantings

Each plant material type has an optimal planting window, summarized in **Riparian Restoration and Management Table 4**. 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.

Riparian Restoration and Management Table 4. Recommended Planting Window

Plant-Material Type	**Recommended Planting Period**
Seeding	Spring/fall is best; summer seeding needs irrigation
Dormant cuttings	Spring/fall is best; possibly winter
Containerized/rooted plantings	Spring/fall is best; summer plantings need irrigation
Bare-root plantings	Late winter/early spring only
Salvaged trees/shrubs	All year where the ground isn’t frozen, but dormant season (November to March) is best; irrigate and prune summer transplants
Salvaged sod	All year where the ground isn’t frozen and soils remain sufficiently moist; irrigate summer/fall transplants
Ball and burlap trees	Spring/fall is best

Note that the Washington Department of Transportation’s (WSDOT) standard planting window for non-irrigated material is September 15 to March 31, although a more realistic time frame would be between mid October and mid March. WSDOT allows irrigated plant material to be installed throughout the growing season provided that the irrigation system is operational prior to installation.

5.4.6 Site Preparation

Site preparation is conducted prior to installation of 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 instance, techniques used to control competing vegetation in uplands, such as weed mats and mulch, although often beneficial in areas with low short-term risk of flooding, may be washed away if used in frequently 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 instance, the required maintenance at a site dominated by dense thickets of weeds may be lower if aggressive site preparation techniques are employed. 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 necessary site preparation and short- and long-term maintenance, as well as 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, employing 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 requiring use of a weed-whacker throughout the entire site. These planted areas can then be expanded as more funding becomes available.

5.4.6.1 Soil Amendments

Soil fertilizer that is regularly applied in uplands may not be appropriate in riparian zones for several reasons. Many riparian species naturally thrive in relatively sterile soil, 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.

If soil amendments or supplements such as compost, topsoil or fertilizer are to be used, they should be organic products with slow-release characteristics, and they should not be applied to the surface of the soil. Rather, they should be mixed into the rooting zone with existing soils. Amending existing soils and physically incorporating these amendments into the rooting zone increases their retention under flood flows and may encourage deeper rooting than if amendments are placed on the soil surface.

An amendment that may be worth considering in droughty sites, at least on an experimental basis is a product referred to as “water crystals.” Water crystals are synthetic polymers added to the rooting zone that can improve moisture retention and thereby allow plants to better withstand drought. Although some studies have not found this amendment to provide conclusive benefits[13], variation in application rates and techniques may be worth investigation[19].

5.4.6.2 Topsoil Salvage and Irrigation

If excavation is occurring on site, separate topsoil from sub-soil during excavation and stockpile for later use. Following excavation, the native topsoil can be reapplied to the new surface prior to planting. If restoration activities include use of a temporary irrigation system, the irrigation system should be operational prior to plant installation.

5.4.6.3 Soil Scarification

On sites with heavily compacted soils or large patches of invasive weeds, soil scarification may be required to promote plant rooting, growth, soil drainage, and reduce competition. Common techniques include disking, scalping, bedding and plowing. All aim to change or construct different physical properties that may influence seed germination and seedling establishment and survival. Be aware however, that if flood prone soils are scarified excessively they may be more susceptible to erosion. Site preparation techniques to control undesired vegetation are discussed below under *Weed Control*.

5.4.7 Weed Control

Weed control and monitoring will be an essential component of any riparian restoration project, particularly during the early plant establishment phase. Invasive non-native plants can doom a revegetation effort as they compete for light, moisture, and space (both aboveground and below). This can be especially true where aggressive species such as reed canary grass or blackberry dominate an area. Aggressive continued control is necessary until new desirable riparian vegetation is firmly established.

Riparian areas dominated by invasive non-native plants are often targets for restoration because they 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, a native substitute community capable of surviving and suppressing weed growth in the long term may be the best option. The only 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. Unfavorable site conditions may include shading of sun-loving weed species or periodic flooding of flood intolerant species. For instance, encouraging the establishment of native conifers may suppress weeds in time as canopy closure reduces light penetration to the understory and reduces the number and extent of non-native plants[5].

Weed removal 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 employed. Nevertheless, suppression or successful eradication of weeds often provides significant long-term benefits.

The method of weed control should be carefully selected, its benefits weighed against potential negative impacts. For instance, removal of 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 down-stream of the dredged area.

Before implementing weed control, a thorough understanding of the following considerations is recommended:

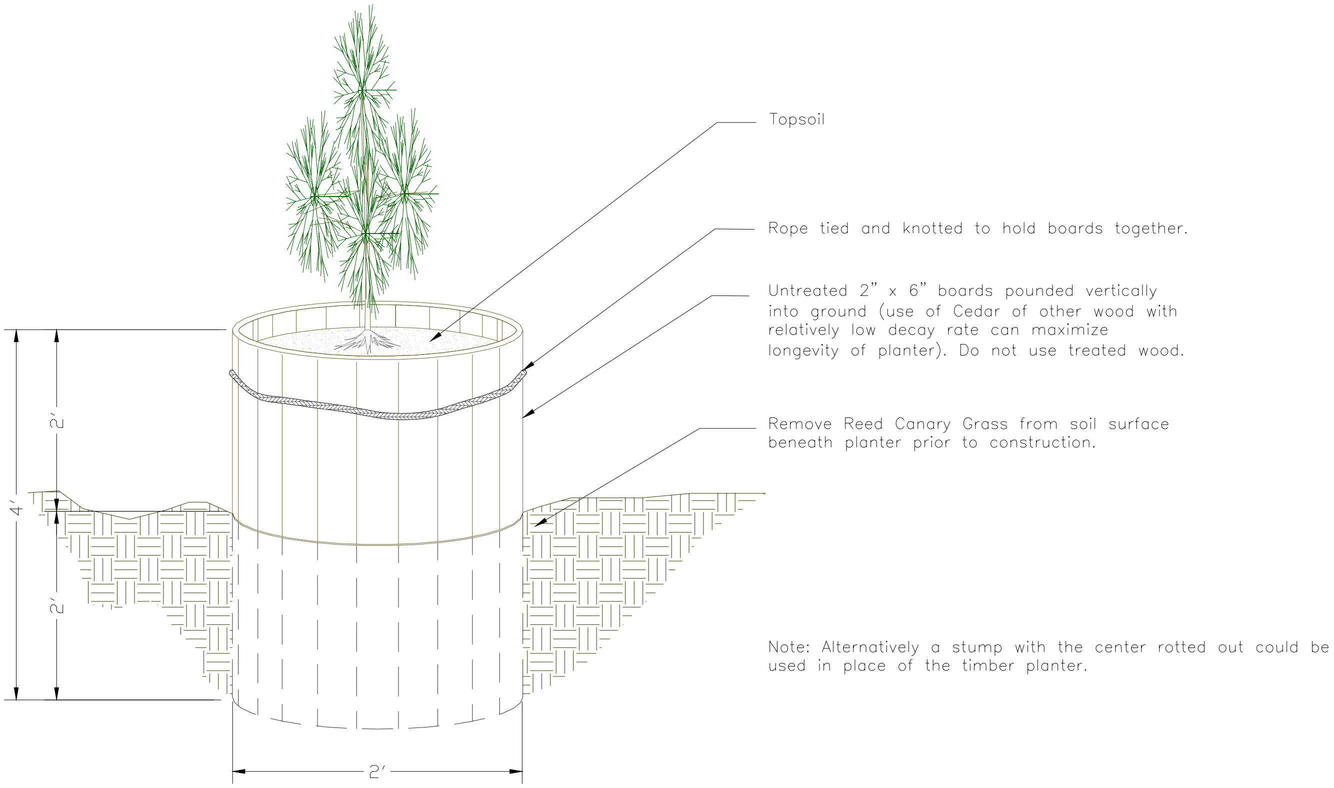
- Biology of the targeted species;
- Short- and long-term effectiveness and limitations of control efforts;
- Risk to non-target species and the ecosystem as a whole; and
- Long- and short-term availability of funds and work crews.

While the only long-term methods of weed control are to eliminate it seed source and to create conditions unfavorable for weed propagation, establishment and survival, a variety of techniques can be used to temporarily control and manage weeds including:

- Manual and mechanical control
    - Pulling by hand or with tools such as a Root Talon or Weed Wrench, girdling, mulching, mowing, tilling, plowing, surface soil scalping or disking, dredging, singeing with hand held torches, flooding, and solarization,
- Controlled grazing with cattle, sheep, goats, and even 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, and
- Controlled herbicide applications at appropriate times of year[20].

These techniques often work best when used in combination (i.e. mowing followed by disking, or removal of weeds by hand followed later by controlled herbicide application). Some of these techniques will be required to prepare the site, prior to planting; while others will be required as part of a short- and long-term maintenance plan. Often, there is somewhat of 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 or knocked back by mowing immediately prior to 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 the need for long-term maintenance. Alternatively, weeds may be initially removed only around the immediate vicinity of each new plant; frequent mowing around each plant will be necessary to suppress weed growth and minimize plant competition. Consult your state or local weed control board, conservation district, or Washington State University Cooperative Extension office for specific information and recommendations to control common weeds found in Washington. The Nature Conservancy has a very comprehensive “how to” manual for a variety of weed control techniques[16], another reference is by Leigh[21], both are available online (websites are provided in references). A common riparian weed in Eastern Washington that can be very difficult to remove is Russian olive. The NRCS has an excellent pamphlet on techniques to remove this specie[22]. 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.

One experimental method of reed canary grass control that may not be found in references is the creation of artificial hummocks or planting mounds in the surrounding riparian zone using heavy equipment. Various versions of this concept have been employed in western Washington. One version, employed 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 (see **Riparian Restoration and Management 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[9]. Further study is necessary to determine the long-term effectiveness of this technique and the hydrologic and hydraulic impact of the mounds. 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.



Riparian Restoration and Management Figure 2. Example of artificial planting hummock.

5.4.8 Planting Techniques

Proper storage and planting is critical to the success of stream revegetation projects. All plants used on site should have a healthy, vigorous appearance, free of dead wood and disease. Properly store plants prior to planting by protecting them from sun, wind and physical abuse. The appropriate planting technique in streambank settings depends on the type of plant material. If planting in an area that's heavily vegetated, such as a pasture or meadow, remove vegetation from at least a three-foot-diameter circle where the new plant will be set to minimize competition for light, water, and space. All plants should be watered immediately after planting to eliminate air pockets and to ensure that moisture around the root ball is at or near field capacity.

5.4.8.1 Seeding

Developing Seed Mixes. Seed mixes are combinations of grass, forb and occasionally woody plant seeds, intended to provide both short- and/or long-term cover, depending upon the specific project. Some suggestions follow:

- More species are not necessarily better. Select three to five species with a range of seed sizes that are biologically suited to your site.
- Do not specify hard-to-find or unavailable species unless you intend to collect them yourself and have them contract grown to supply sufficient seed the next year.
- To the extent possible, use locally collected seed.
- When purchasing seed, select seed certified weed free and inspected by the Washington State

Department of Agriculture.

- 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% desirable. 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.
- 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 try 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. On surfaces that are considered droughty, the use of annual cover species may result in poor establishment of perennial species. Annual species may consume soil moisture early in the establishment period stressing slower establishing perennials. The result is that perennial species may take longer to establish or need several seedlings to compete effectively with annuals.
- More seed is not necessarily better. Instead, focus on getting good seed-to-soil contact by firmly compacting seeded streambank areas with excavator tracks, 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.
- Have 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.
- After applying a simple seed mix containing three to five species, add diversity by separately seeding a wildflower mix in scattered locations across the seeded area. Use caution when buying wildflower seed mixes. Make sure all species are listed and all are native to the project area.

To maximize survival, seed should be planted during the correct planting season as recommended by the seed supplier. 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, even if the straw later washes downstream. 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 in conjunction with or in place of straw mulch to prevent straw and seed from washing downstream. It is recommended that only fabric comprised entirely of natural material be used. Fabrics that uses a plastic netting or mesh can easily get blown or washed into the adjacent stream or watercourse and act as a gillnet for fish. It may also be harmful to wildlife that ingest or become entangled in it. Generally, plastic netting also has a long life and may not be aesthetically appropriate. If using plastic bound mulch, select a variety that decays quickly. Clear plastic covering can be useful to prevent erosion of seed (and mulch if applied) from fall rains and enhance establishment with the "greenhouse effect" but should be removed once growth is underway. If growth is not monitored and the plastic removed when appropriate, the new growth will become overheated and smothered.

Preferred Seeding Methods.

There are three primary seeding methods: drilling, broadcasting and hydroseeding (see **Riparian Restoration and Management Table 5**). The most appropriate method for a particular site will depend on 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 if water levels rise above the seeded area before germination and seedling establishment, the mulch, binder, and seed will float and wash away. It should, therefore, be limited to steep, inaccessible areas. Prior to seeding an area, consider risks from wind displacement or rising water levels, which can displace and wash away seed/seedlings, mulch and binders, particularly when using hydroseed.

Riparian Restoration and Management Table 5: Advantages and Disadvantages of Various Seeding Methods.

Drill Seeding	**Advantages**	**Disadvantages**
	Proven high revegetation rate	Cannot be used on rocky soils or steep slopes
	Most successful on slopes 3:1 or flatter	Unless specially modified drills are used, all seeds, regardless of size will be planted at the same depth; the smallest seeds are likely to be planted too deep
	Seed depths and seeding rates can be closely controlled	Seeds drilled in rows may suffer from high inter-seedling competition
	Seed to soil contact is high, maximizing germination	Leaves rows, which often persist for many years, which may be visually unacceptable.
Broadcast seeding	Can be used on slopes that are steep, rocky, remote or inaccessible	Germination and establishment tends to be lower
	The variable planting depths that result from broadcast seeding allows better establishment of small seeds lower seed to soil contact without some kind of packing or dragging	Requires double or triple the seeding rate of drill seeding and seeding rate calibration is less precise.
	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	Dependent on local water supply

Tips for drill seeding:
- Seed to a depth of 0.25 to 0.5 inches. This is dependent on the size of the seed (based on grass species). Larger seeds should be planted ¾ inch deep.
- Seed along the contour to avoid erosion from water flowing down drill furrows

Tips for broadcast seeding:
- Before seeding rake or harrow soil to eliminate crusting
- After seeding cover the seed by harrowing, chaining, or raking
- Do not seed on windy days

Tips for hydroseeding:
- Do not mix seed and mulch together in a single slurry
- Do not use hydroseed containing fertilizer
- 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 in overbank flooding events that occur before seeds germinate and take root.

5.4.8.2 Collection, Harvest and Installation of Cuttings

Live cuttings are the most common type of plant material used on streambanks. There are many on-line and published planting guidelines, but some additional tips related to collection, storage and installation are described below:

- Best survival occurs with dormant collection and planting, but anecdotal reports suggest that successful establishment is sometimes possible from cuttings planted in early summer and early fall, especially 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%.
- Collect cuttings from healthy vigorous stock; those collected from stressed plants root poorly. Collect cuttings from male and female plants, if applicable. One- or 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. A general rule of thumb is to take no more than 1/20 of an individual plant[7]. When harvesting cuttings, don't clear-cut the source area.
- Cuttings should be at least one half inch in diameter, relatively straight, 12 to 48 inches long, and include two or more nodes (buds). One (or more) node is for the roots of the new plant and one (or more) is for the leaves. Some plants have very long sections between nodes so your cuttings may need to be longer than 18 inches. Longer cuttings may also 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 ½ of the total length of the cutting in the ground[23]. Experiment with a variety of cutting diameters, since literature on the most successful stem diameter is not consistent and varies depending upon species under consideration[7]. Cutting diameters less than one half inch may be necessary for species with relatively small diameter stems (e.g., *Spirea* spp.).
- Harvest cuttings with a clean, diagonal cut, and make sure the base of each cutting is inserted into the ground. Cutting the bottom with angled cut and the top with a straight cut and dipping the tops in latex paint will help identify the top from bottom. Upside-down cuttings become established much slower if at all!
- Cuttings should be kept moist, relatively cool, and shaded until planting. Even on a cold day, exposure to direct sunlight will stress them. Soak cuttings (at least that portion of the cutting that will be underground) in water for 24 hours to 10 days (soaking longer than about 14 days for most species will allow the root tips to emerge from the bark. This will cause problems when planting because they are easy to break off) prior to planting to improve survival. This is also an excellent, temporary, on-site storage method. Water should be changed daily. Cuttings will be most successful if harvested and planted in the same day.
- If cuttings cannot be installed within days of collection, consider long-term storage (up to several months) under cool, damp (not wet. Don't cover with wet burlap or wet shredded newspaper, store dry and hydrate by soaking), dark conditions (refrigeration).

- Never plant cuttings into dry soils.
- If the site is not irrigated, the bottom of the cutting must reach a depth where the soil is permanently damp. The literature is not conclusive on what percentage of the cutting should extend above ground. One quarter is often recommended (especially for arid areas), no more than one half, but experiment with variations and monitor results. If more than one half of the cutting extends above the ground, there will likely be too much shoot growth for the short sprouting roots to support. The plant will become quickly desiccated and die. When planted, at least one node should be buried and one node left exposed to establish roots and shoots, respectively.
- When planting cuttings in relatively loose, friable soil (i.e. sandy loam), tamp them in using a "dead blow hammer" (i.e., a hammer with a head filled with shot or sand)[24]. However, driving cuttings into hard or rocky coarse soils in this manner tends to peel back the bark and they have a reduced chance for survival. Instead, use rebar, an iron bar, or similar tools to develop 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.
- Consider planting dense willow "rows" (3-5 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.

5.4.8.3 Installing Containerized Plant Materials.

The success of planting techniques for containerized plants depends in large part upon the specific container size and dimension, making generalizations difficult. For example, narrow "tubeling" containers can be planted through erosion-control fabric with minimal fabric cutting, but larger containers require cutting fabric strands that can potentially weaken the fabric. On particularly erosive sites where erosion control fabric is employed, the advantages of larger material should be weighed against the potential for compromising fabric strength and integrity.

Depending upon the situation, planting holes can be hand dug with shovels and dibble bars, or with a variety of mechanical equipment including augers, excavators and backhoes, or a tree-planting machine. The planting hole should be roughly twice the diameter of the container. Loosen and uncoil or slice circling or twisted roots to encourage root growth outside of the potting soil. All container plants need to have the top of the soil/root mass planted flush with or slightly higher than the soil surface, and have a suitable backfill material firmly compacted around the root mass. 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 dry. Irrigation is recommended in many cases, but is generally not required for dormant-season plantings – plants are adapted to growing following dormant season when soil moisture is either high due to winter rain or snowmelt, or from spring rain and wicking from the stream channel during spring or summer high flows. If using mulch, avoid letting the mulch come in contact with the stem.

Mechanized planting machines should be considered to facilitate large-scale revegetation efforts and those occurring in rocky soil. Refer to the *Construction Considerations* section of this technique for more information.

5.4.8.4 Planting Bare-Root Materials.

Bare-root plants must be planted during the later winter/early spring dormant season. If irrigation is available, the planting season may extend into late spring and possibly early summer, but survival will be extremely low if the buds have broken or begun to open. Roots should be fresh and plump, not dry and withered. Store bare-root plants in a cool, shaded environment with roots covered by moist (but not soggy) mulch or sawdust and not exposed to air. Most nurseries sell bare-root shrubs packed in a silica gel and stored in a special bag with an evaporation barrier, which helps prevent desiccation. In theses cases, the bare-root plants should not be placed in sawdust but kept in their original container. Roots must be kept moist and protected from sun and wind exposure at all times. Installation requires attention to detail to make sure that all roots are directed downward so that none bend up towards the surface, and to make sure that the soil is firmed tightly around the roots so that there are no air pockets. A planting bar can be used to create a slit in the soil that the roots are placed into; the slit is then closed using the planting bar. Roots must be cut to the length of the planting bar to prevent bending the roots at the bottom of the slit. Bending the roots, or “J-rooting” will kill the plant.

If circumstances dictate, create a trough or low soil berm around the planting hole to encourage retention of water. However, care should be taken to keep the trunk base dry. Irrigation is recommended during the first, and sometimes second, growing season following planting, but may not be needed if seasonal, natural precipitation or moist soil conditions are anticipated. If using mulch, avoid letting the mulch come in contact with the stem. As in the case of large, containerized plants, bare-root trees and shrubs planted through erosion-control fabric require fabric strands be cut, thereby weakening the fabric. For this reason, on particularly erosive sites, the advantages of bare-root stock over cuttings should be weighed against the potential for compromising fabric strength and integrity.

5.4.8.5 Planting Salvaged Materials.

Heavy equipment such as a backhoe, excavator or tree spade is advised. While storage and/or transport of salvaged materials are possible, the increased handling, especially for woody materials, tends to increase cost and reduce survival rates. The following sequence is recommended:

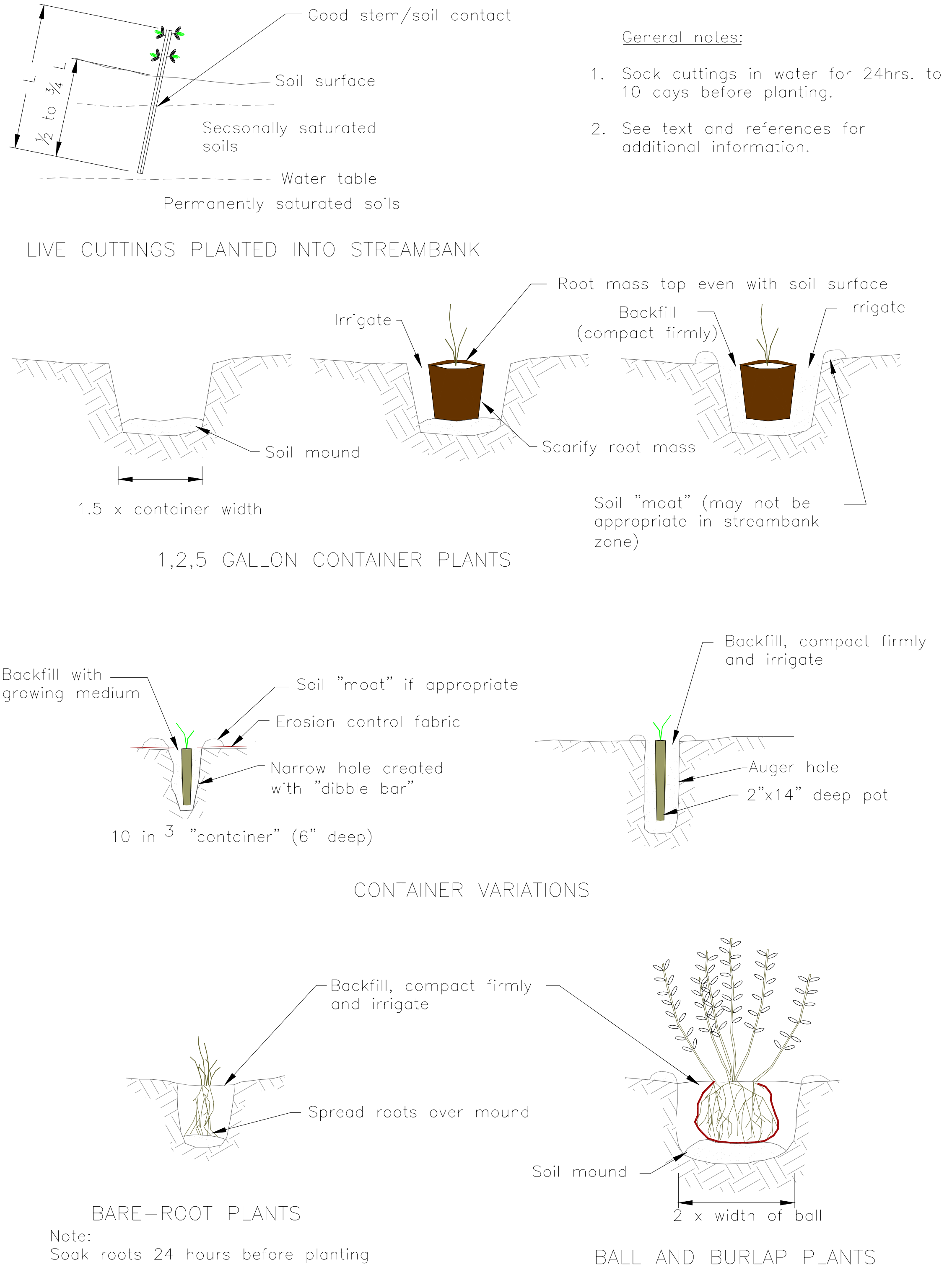
- Prepare the planting site (including digging holes if needed);
- Salvage plants, by excavating as much of the root mass as possible and directly transferring the salvaged plant to the planting site with the soil and root mass intact; and
- Install the salvaged plants in moist soil immediately.

Minimizing transport of salvaged materials is key to their success and survival. Make sure the roots stay damp; they will dry out in seconds if exposed. If the plants must be stored before replanting, they should be handled as ball-and-burlap plants. Transfer the plant from the ground with the dirt around its roots still intact onto a strip of burlap placed alongside the plant. Tie the burlap around the root ball with twine, keeping the dirt intact. To properly store the newly created ball-and-burlap plants, cover the root mass with moist mulch or sawdust. Following planting, irrigation is always advised, and pruning of woody stems and branches will help reduce drought stress[7]. Again, if they will be out of the ground for a while, use the terra-sorb to coat the roots.

Dormant-season salvage is best (November through March) although this is often not possible in eastern Washington due to frozen ground, but if irrigation is available and the risk of somewhat lower survival is acceptable, salvage can take place even in dry or hot seasons. 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.

5.4.8.6 Installing Ball-and-Burlap Plants.

The success of planting techniques for ball-and-burlap plants depends in large part upon the dimensions of the soil ball, making generalizations difficult. Depending upon the situation, planting holes can be hand dug with shovels and dibble bars, or with a variety of mechanical equipment including augers, excavators and backhoes. The planting hole should be roughly twice the diameter of the soil ball. The burlap surrounding the upper one-third of the ball must be peeled back and removed. All ball-and-burlap plants need to have the top of the soil/root mass planted flush with or slightly higher than the soil surface, and have a suitable backfill of native material firmly compacted around the root mass. 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 dry. Irrigation is recommended in many cases, but is generally not required for dormant-season plantings is surrounding soil moisture is sufficient. If using mulch, avoid letting the mulch come in contact with the stem. Nurseries that supply these types of trees and shrubs can provide excellent planting guidelines. Remember, the large size of the planting hole and the potential for guy wires to collect flood debris limit the application of this plant material type on streambanks. These planting requirements may be less of a concern on floodplains.



General notes:

1. Soak cuttings in water for 24hrs. to 10 days before planting.
2. See text and references for additional information.

LIVE CUTTINGS PLANTED INTO STREAMBANK

1,2,5 GALLON CONTAINER PLANTS

CONTAINER VARIATIONS

BARE-ROOT PLANTS

Note:
Soak roots 24 hours before planting

BALL AND BURLAP PLANTS

Riparian Restoration and Management Figure 3: Conceptual drawings of plant installation.

6 PERMITTING

Any construction activities in wetlands associated with placement of fill (e.g., creation of hummocks in a reed canary grass stand) or instream work is subject to federal, state, and local permitting including Section 404 of the Clean Water Act, Washington State Hydraulic Project Approval, and potentially Endangered Species Act (ESA) and Shoreline Management Act approval. Development of 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* appendix 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 Considerations* appendix for more details

7.1 Equipment

The project’s scope and site conditions will determine the types of tools required for the installation of riparian vegetation. Where soils are fine-textured, moist and not overly compacted, plants can be effectively installed with hand tools. Often, 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 over-compacted. Conventional earthwork equipment, such as bobcats, backhoes, augers, excavators and tree spades can be useful for installing 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, which is used to plant cemented floodplain soils; and the water-jet stinger[25 26] 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 Stinger Method

The stinger method makes it easier to plant cuttings in compacted streambank soils and riprap revetments. 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[23 27]. 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. Care is required to ensure that cuttings are footed in moist subsoil and that there is 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.

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, with an internal plant receptacle (**Riparian Restoration and Management Figure 4**). 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). The bottom tips of the probes can be closed to hold the plant within the plant receptacle and opened to release the plant into the ground. Like the Janicki stinger, the expandable stinger also attaches to an excavator bucket. The cutting is placed inside the probe's plant receptacle, 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 (leading to potentially higher survival rates) rather than being pounded into place.
- 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.
- Field crews remain relatively safe on the top of the bank rather than having to climb along the banks in close proximity to heavy equipment operation.

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.

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 (see **Riparian Restoration and Management Figure 5**).

Riparian Restoration and Management Figure 4: Expandable stinger for live stakes and 3” plugs. It has been used to plant 30 to 250 cuttings per hour, depending upon site conditions.

Riparian Restoration and Management Figure 5: Expandable stinger variation capable of planting 3”-diameter rooted-plant plugs into unarmored streambanks at a rate of up to three hundred per hour.

7.1.2 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 only be used 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.

7.1.3 Water Jet Stinger Method

Another method to create a deep, narrow hole for long willow or cottonwood pole cuttings is the water jet method[28,22]. 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.

7.1.4 Construction Sequencing

Construction sequencing for riparian restoration activities must consider vehicular access as well as material placements to ensure efficient progress. For example, consider the re-vegetation of a floodplain surface dominated by weedy plants. A comprehensive sequence might be as follows:

- Clear and grub surface sod and vegetation temporally, stockpile salvage materials as shown on the plans
- Excavate planting holes for bare-root stock in zone A on as shown on the plans.
- Plant bare root stock and salvage materials in zone A and prepare soil surface for hydromulch
- Hydromulch zone A using access road through zone B as shown on plans
- Disc zone B to ensure soil compaction of haul roads meets specifications
- Place erosion control fabrics and broadcast seed mix per specifications in zone B
- Plant stem cuttings using hand crews in zone B as shown on the plans
- Construct temporary irrigation using hand crews

- Erect site access barriers.

It is important that heavy equipment has access to areas where necessary, but compaction caused by access should be minimized. Similarly, once seed or erosion control fabrics are in place, access by heavy equipment should not be permitted. Vehicular traffic on top of fabrics or seed, or through areas densely planted with stem cuttings should be avoided as damage could 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. However, on larger jobs the efficiency and expertise of a contracted work crew is generally more cost effective and easier to manage than a volunteer crew.

Contracts with paid work crews should allow for some “fit-in-field” adjustment. This applies especially to planting efforts so adaptive management can respond to unanticipated field conditions such as unexpected soil types, higher flows 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.

Also 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 90% survival of planted vegetation usually 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 COST ESTIMATION

Revegetation efforts are sometimes given a low priority in aquatic restoration projects because they are perceived to be expensive or natural regeneratation 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 between $0.15 to as high as $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 (e.g., if the stream is incised or the floodplain has been filled or levied. In some cases, revegetation costs are cheaper in the long-term, due to reduced maintenance and replanting costs, if extra money is spent initially to purchase larger plant materials, install browse protection or implement an irrigation plan. Use of heavy equipment to create deep trenches to plant high-density willow clumps is often less expensive than spreading more labor-intensive hand-planted individual cuttings uniformly over a broad area.

Some approximate costs for woody plant materials are as follows: Please note that these represent wholesale material costs only and depend on the quantity ordered.

- 3 feet long willow cuttings - $2;
- 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 containerized shrub - $3 - 8;
- Locally salvaged willow clump - $25; (includes labor and equipment to dig, transport and store on site)
- 1 to 2 foot tall bare-root shrub - $.50 - 1.50; and,
- 1.5-inch caliper ball and burlap tree - $100.

Costs for installation depend on equipment costs, site conditions and the scale of job.
Labor costs vary depending on the project location. **Riparian Restoration and Management Table 6** provides labor time estimates for various kinds of planting work. These times can vary depending on the physical condition and experience of the planting crews[29].

Riparian Restoration and Management Table 6: Estimated labor time for various types of plant material.

Activity	Per Person Labor Required
Dormant posts	10-20 posts/hr
Willow cuttings	45-50 cuttings/hr
Seedling planting	30-120 plants/hr
Ball and burlap shrubs	1-15 plants/hr
Containerized plants	20-100 plants/hr
4 cubic inch plug	120 plants/hr
10 cubic inch plug	90 plants/hr
Seeding	
Broadcast	0.05-0.5 ac/hr
Hydroseeding	0.12-0.37 ac/hr

Approximate installed costs for fencing per linear foot are: $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.

Organic erosion control fabrics used to protect seedlings and reduce surficial erosion typically cost between $2 and $3 dollars a square yard to buy and another $2 to 3 dollars 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 dollars per tree installed. Temporary irrigation systems can run as high as $6,000 per acre for large areas. In some areas this cost can be reduced somewhat if irrigation lines and sprinklers can be rented.

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.
- Nose pump - Livestock pump own water. Can lift water 26 feet vertically, and 126 feet horizontally. $325 (this includes required foot valve and platform) (www.nosepump.com)

9 MONITORING

Plant growth and mortality should be monitored annually, at a minimum, during the growing season when identification of plant species is easiest. During the first year, and in arid areas, monitoring should be more frequent perhaps immediately following germination in the spring and again in late summer to identify and correct any problems early on. The objectives of a monitoring plan should be clearly specified, consistent with project goals, and linked to project maintenance. The monitoring plan should indicate the methods used to evaluate plant establishment and growth relative to design criteria (see Stream Habitat Restoration Guidelines, Chapter 5.3.4, *Design Criteria*). 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 a very inexpensive, simple, and useful technique for monitoring riparian zone recovery [30,31]. However, depending on the monitoring objective, quantitative data may be required. If so, care should be taken to determine the minimum sample size necessary to draw statistically valid conclusions. Following are additional recommendations:

- Monitoring of plantings is sometimes complicated by the fact that installed plants may be obscured by naturally colonizing plants. If this is expected, it may be beneficial for success criteria to be achieved with a combination of installed *and* naturally colonizing vegetation, rather than simply requiring survival of a minimum percentage of installed plants.
- Use of reference sites to compare to the restored sites is encouraged.
- 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.
- Monitoring for the effectiveness of landuse changes such as changes in grazing strategy, complete cattle exclusion, or changes in mowing frequency along an urban stream corridor may consist of seasonal site visits summarized in photo points and a brief

memo.

- All monitoring activities should identify threats to project success.
- Monitoring frequency will depend on specific restoration objectives and performance criteria, and may range from once a year to several times during the first one or two growing seasons. In some cases more intensive annual monitoring events may be supplemented by more frequent and qualitative site visits.
- For specific details on vegetation monitoring, including monitoring methods, monitoring frequency refer to the *Monitoring Considerations* appendix and Elzinga et al.[32].

Determining the success of riparian restoration projects may require monitoring for longer than project budget and management scenarios allow[5]. For example, herbaceous groundcover may recover in a few years or less, while development of a woody canopy can require decades or centuries for full recovery. While decades of project monitoring is desirable, it is often beyond an individual project's scope. Three to five 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 MAINTENANCE

Where establishment of riparian vegetation is critical to long-term streambank stability and habitat restoration, planting is just the beginning. A commitment to maintain the site until the plants get established is critical. Establishment times vary, but three years is considered about average with some commitments out to ten. Young trees and shrubs are very susceptible to drought, competition from other vegetation for moisture, light, space, and nutrition, and browsing/trampling by livestock and wildlife. During the first three years following planting, inspect the area annually (perhaps more in arid areas) to identify problems and implement repairs/modify management strategies, as needed. Be sure that those responsible for on-site maintenance are aware of the commitment and the location of all new plantings. There have been numerous examples of park, golf course, utility company, and other maintenance crews mowing down new plantings because they were unaware of their existence or intension.

Maintenance may include:

- *Irrigation*. Drought is a particular hazard to young plants due to their small tissue mass and root system. Plants that are not rooted in moist soils will need to be watered regularly throughout the dry season until the fall rains. Watering needs depend on site conditions, soil texture and planting depth. Watering heavily and infrequently, as opposed to frequent shallow watering, encourages deep root growth, which increases drought tolerance. In general, plants should be watered for at least the first growing season, and watering should only be stopped when the plants develop root systems capable of reaching a depth where the soils are permanently moist. This normally occurs by the end of the second growing season[4].

- *Browse Protection*. Foliar repellents (such as DeerAway™), bud caps, mesh tubing or stem screens (http://www.for.gov.bc.ca/hfp/forsite/progress/may1997/mammal~1.htm#one) may protect highly palatable species such as dogwood and willow from large mammal browse damage. In cases of heavy ungulate use fencing may be the only option. However, consider that all these methods may be less effective in floodprone areas subject inundation and hydraulic forces of flowing water.

- *Fences*. Livestock fences should be inspected and maintained to prevent livestock access to the planted area. Even small numbers of livestock or short-duration grazing can severely reduce plant survival. Although grazing may not impact non-palatable species, they are subject to other impacts such as trampling[4]. Temporary or permanent fences may also be needed in areas subject to heavy foot and pet traffic such as at parks. Chaney et al.[33] provide additional information on the benefits of fencing, rotational grazing, and livestock access limitations. Keep in mind that fences that are capable of excluding domestic livestock are not normally effective at excluding deer, elk or moose. Exclusion fences for these species must be significantly more robust and taller.
- *Protection from Small Mammal Damage*. Aluminum foil, arbor guards or photodegradable, plastic-tube, plant protectors may be needed to protect plants from rodent girdling, a common problem in open pastures and meadows. Aluminum foil has proved effective provided it is checked and replaced as needed. Plastic-tube plant protectors shield plants from direct sun and wind exposure; they retain moisture, creating a humid microclimate, and they protect plants from mowers. Chicken wire fencing may be needed to protect plants from beaver and muskrat during the plants' critical period of establishment.
- *Plant replacement*. Replacing plants that died may be important, but not if the cause of the stress has not been eliminated or if naturally colonizing plants are meeting monitoring objectives.
- *Weed Suppression*. Weed suppression may be needed, but should focus on controlling or eradicating long-lived, perennial weeds that are likely to degrade the site or violate state/county regulations. If planting was in a pasture or other heavily vegetated site, vegetation surrounding the plant should be periodically removed or mown to maintain the three-foot-diameter open area surrounding each plant. Mowing twice a year during the first three growing seasons is generally recommended – once in the spring and once in midsummer. On sites where reed canary grass grows, a third mowing in the fall right down to the ground is sometimes recommended to reduce the amount of grass that comes back the following spring. Consult your local or state weed control board for more information concerning weed control and removal or see the excellent reference by Tu et al.[20].

Riparian Restoration and Management Table 7: Woody plants recommended for revegetation of riparian corridors

Species		**Indicator Status(1)**	**Max. Height(2) (ft)**	**Elev. Range (3)**	**Soil Moisture (4)**					**Light Req (5)**	**Rooting Character (6)**	Comments
Common Name	**Scientific Name**				A Dry	B	C	D	E Wet			
TREES												
Grand fir	Abies grandis	NOL	100-250	l-h	●	●	●			sn-pt sh	deep taproot; many lateral branches	Best conifer for soil binding roots; prefers deep, well-drained, alluvial soils; seedlings are shade tolerant; drought tolerant
Noble fir	Abies procera	NOL	90-250	m-h	●	●	●			sn		
Douglas maple	Acer glabrum var. douglasii	FACU†	10-25	l-m	●	●	●			sn-pt sh	deep, lateral	Found along canyons, rocky cliffs, forest openings on mountain slopes, moist but well-drained streambanks, floodplains, avalanche tracks; requires well-drained soils
Big-leaf maple	Acer macrophyllum	FACU †	80-100	l	●	●	●			sn-pt sh	deep, wide	Good soil binding properties; grows in a variety of soils but seldom in saturated soil; fast growing; flood tolerant
Red alder	Alnus rubra	FAC †	40-80	l-m		●	●	●		sn	shallow, strong, lateral, spreading, fibrous	Does well on disturbed sites in a variety of soils; fast grower; N fixer; high survival from "pull-ups"; tolerates drought, flooding, or brackish conditions; relatively short-lived (60-70yr); subject to wind throw, broken crowns, ice damage; west of Cascades only
Sitka alder/ Slide alder	Alnus sinuata	FACW †	25	m-h			●	●		sn-pt sh		Moderate flood and deposition tolerance; does well on disturbed sites and alluvial floodplains in rocky or gravelly soil; prefers some shade or north facing aspect
Mountain alder/ Thinleaf alder	Alnus tenuifolia	FACW	30-40	l-h			●	●		sn		Most common alder of the interior; usually found in pure stands; east of Cascades only

Pacific madrone	Arbutus menziesii	NOL	50-90	l	●	●				sn	deep tap root, wide, tenacious	Evergreen; drought and salt spray tolerant; sensitive to air pollution; found along coast on rocky sites or coarse textured soils; slow grower; west of Cascades only
Water birch	Betula occidentalis	FACW	20-50	l-m			●	●		sn-pt sh	shallow to deep, spreading	Moderate flood and deposition tolerance; east of Cascades only
Paper birch	Betula papyrifera	FACU	60-70	l-m	●	●	●			sn-pt sh	deep	Fast growing; prefers sandy loam but tolerates poorly drained soils; tolerates periodic flooding and drought, acid soils; does well on disturbed sites
Pacific dogwood	Cornus nuttallii	NOL	10-65	l	●	●	●			pt sh-sh		Prefers deep well-drained soils high in nitrogen; found in open to fairly dense mixed forests; west of Cascades only
Oregon ash	Fraxinus latifolia	FACW	60-80	l			●	●	●	sn-pt sh		Prefers flat loamy soil; tolerates standing water early in growing season; west of Cascades only
Western crabapple	Malus fusca	FAC+ †	15-40	l		●	●	●		sn	shallow, spreading	Forms dense thickets; does well in a variety of soils and near salt water, sloughs, and estuaries; prefers acid soils; tolerant of prolonged soil saturation; west of Cascades only
Sitka spruce	Picea sitchensis	FAC	100-230	l		●	●	●		sn-sh	shallow-moderate, dense	Tolerates flooding, salt spray, acid soil; found on alluvial floodplains, marine terraces, recent glacial outwash, avalanche tracks, and old logs or mounds in boggy sites; subject to blowdown in areas of high water table; west of Cascades only
Lodgepole pine	Pinus contorta var. latifolia	FAC-	100- 120	m-h	●	●	●	●		sn		Found in saturated to excessively well-drained soils; tolerant of low nutrient soils; highly adaptable

Shore pine	Pinus contorta var. contorta	FAC-	45-60	l-m	●	●	●	●		sn	deep, wide	Highly adaptable; found in dunes and bogs to rocky hilltops and exposed outer shorelines; coastal; tolerates salt and low-nutrient soils
Ponderosa pine	Pinus ponderosa	FACU-	150-200	l-m	●	●				sn		Dry gravelly soils; drought tolerant once established; mainly east of Cascades
*Black cottonwood	Populus balsamifera ssp. trichocarpa	FAC †	100-200	l-m		●	●	●		sn	fibrous, shallow-deep and widespread, extensive	Fast grower; susceptible to root rot, windthrow; tolerates seasonal flooding; grows well in a variety of soils
Quaking aspen	Populus tremuloides	FAC+	30-80	l-h		●	●	●		sn	shallow, extensive, invasive, spreading roots send up shoots	Forms dense groves; moderate drought and salinity tolerance; fast growing; prefers sandy loams
Bitter cherry	Prunus emarginata	FACU	40-60	l-m	●	●	●			sn-pt sh	spreading; root system sprouts new growth	Prefers well-drained slightly alkaline soils; establishes easily on disturbed sites; can form thickets; may be poisonous to livestock
Douglas fir	Pseudotsuga menziesii	NOL	75-300	l-m	●	●	●			sn-pt sh	tap-modified tap; shallow-deep and widespread	Pioneering species; good soil binding roots; fast grower; needs good drainage; does best in deep, moist, sandy loams; poorest in gravelly soils; potential for wind throw in thin or disturbed soils
Oregon white oak	Quercus garryana	NOL	75	l	●	●	●			sn	deep tap root	Typically found on gravelly outwash prairies and floodplains; slow growing
Cascara	Rhamnus purshiana	FAC-	25-35	l		●	●	●		sn-sh	moderately deep tap root	Good soil binding qualities; grows well on disturbed sites; prefers loamy soils, shaded southern aspects and swampy clearings; sensitive to air pollution
*Peachleaf willow	Salix amygdaloides	FACW		l			●	●	●	sn	fibrous	Deposition and flood tolerant; moderate salinity tolerance; found on streambanks in plains and foothills; east of Cascades only

*Pacific willow	Salix lasiandra	FACW+ †	20-40	l-m	● ● ●	sn	fibrous, moderately deep and widespread	Flood and deposition tolerant; grows well on sandy, gravelly, or loamy soils; found on riverbanks, floodplains, lakeshores, wet meadows; often standing in quiet, shallow river backwaters; generally found in pure stands
*Scouler willow	Salix scouleriana	FAC †	10-40	l-m	● ● ●	sn-pt sh	fibrous, moderately deep and widespread	Flood, drought, and deposition tolerant; moderate salinity tolerance; prefers gravelly soil; does not grow in standing water
Pacific yew	Taxus brevifolia	FACU-	15-45	l-h	● ● ●	pt sh-sh	deep	Very slow growing; prefers loamy soils under canopy of large trees; foliage is poisonous to livestock
Western red cedar	Thuja plicata	FAC	150-210	l-m	● ● ●	sn-sh	shallow, widely spreading	Tolerates seasonal flooding and perennially-saturated soils; seedlings require some shade; tends to be wind-firm except in very wet sites; prefers loamy soils
Western hemlock	Tsuga heterophylla	FACU-	120-180	l-m	● ●	sn-sh	shallow-moderate	Does best on deep, moist, well-drained soils; requires high organic content in soil; thrives in dense shade; seedlings are often dried out by full sun; susceptible to wind throw

Species		Indicator Status(1)	Max. Height (2) (ft)	Elev. Range (3)	Soil Moisture (4)	Light Req (5)	Rooting Character (6)	Comments
SHRUBS/ GROUNDCOVER								
Vine maple	Acer circinatum	FACU+ †	15-25	l-m	● ● ●	sn-sh	fibrous, moderately deep, spreading	Needs canopy shade or lots of moisture; excellent soil binding qualities; prefers sandy loam; mostly west of Cascades

Serviceberry	Amelanchier alnifolia	FACU	6-25	l-h	●	●			sn-pt sh	deep, spreading	Edge-loving; very drought tolerant; thicket forming; prefers well-drained, loamy soils but found on dry gravelly and rocky sites; good stabilization value; sensitive to competition around roots; slow to establish
Kinnikinnik	Arctostaphylos uva-ursi	FACU-	1	l-h	●	●			sn	fibrous, shallow, dense, extensive, highly branched	Slow grower; evergreen; likes dry stony soil; tolerates salt spray; prefers slightly acidic soil
Tall Oregon grape	Berberis aquifolium	NOL	3-10	l	●				sn-pt sh	deep	Slow grower; thicket forming; grows in variety of soils; found in drier (often rocky) sites than *B. nervosa*; evergreen
Low Oregon grape	Berberis nervosa	NOL †	2	l-m	●				pt sh-sh		Slow grower; thicket forming; good on slopes; grows in a variety of soils; evergreen; west of Cascades only
Hackberry	Celtis reticulata		30	l					sn		Limited range, mostly in southeast WA; found on edge of streams and adjacent bluffs
*Red-osier dogwood	Cornus stolonifera	FACW †	6-20	l-m		●	●	●	sn-sh	shallow, strong, lateral, fibrous	Excellent soil binding qualities; thicket forming; grows in a variety of soils; takes full sun if has lots of moisture; tolerates seasonal flooding
Hazelnut	Corylus cornuta	NI †	5-20	l	●	●	●		sn-sh	extensive, branching	Grows well in a variety of soils but prefers well-drained soil; intolerant of saturated soil
Black hawthorn	Crataegus douglasii	FAC †	3-20	l	●	●	●		sn-pt sh	shallow to deep, spreading	Excellent soil and streambank stabilizer; moderate deposition tolerance; thicket forming; well adapted to disturbed sites; prefers well-drained soils; resistant to beaver; not favored by deer/elk

Salal	Gaultheria shallon	NOL †	3-15	l-m	●				sn-sh	fibrous, shallow, dense	Slow to establish; grows in a variety of soils but prefers shade and rich soil; tolerates salt spray, low nutrient soils; good soil binding qualities; thicket forming
Ocean spray	Holodiscus discolor	NOL †	6-15	l	●				sn-pt sh	fibrous, moderate depth, spreading	Grows well on dry steep slopes; very drought tolerant; grows well on disturbed sites in a variety of soils including gravelly and rocky soils
Trumpet honeysuckle	Lonicera ciliosa	NOL	vine	l	●				sn-pt sh	shallow to moderate	
*Black twinberry	Lonicera involucrata	FAC †	3-15	l	●	●	●		sn-sh	fibrous, shallow, spreading	Takes full sun if has lots of moisture; tolerant of shallow flooding early in growing season; prefers loamy soils; fast growing; good soil binding characteristics
Mock azalea	Menziesia ferruginea	FACU+	2-7	m	●	●			pt sh-sh		Found in moist conifer woods with acid humus, slopes, and streambanks, edges of coastal sphagnum bogs
Sweetgale	Myrica gale	OBL	2-7	l			●	●	sn		Found in freshwater wetlands, bogs, and lakes, upper fringes of salt marshes and tidal flats; thicket forming
Indian plum	Oemleria cerasiformis	NOL †	5-15	l	●	●			sn-pt sh	fibrous, shallow, spreading	Prefers some shade; grows well in a variety of soils but intolerant of saturated soil: west of Cascades only
Oregon boxwood	Pachystima myrsinites	NOL	1-3	l-m	●	●			sn-sh		Found on shallow, gravelly clay and silt loam; prefers light to deep shade, moist atmosphere; evergreen
Mock orange	Philadelphus lewisii	NOL	3-12	l-h	●	●	●		sn-pt sh	spreading, fibrous	Fast vigorous grower; grows well in loamy to rocky, poor soils
*Pacific ninebark	Physocarpus capitatus	FAC+ †	6-13	l-m	●	●	●		sn-pt sh	fibrous, shallow, lateral	Fast vigorous grower; excellent soil binding qualities; grows well in a well-drained loamy to rocky soils; mostly west of Cascades

*Mallow ninebark	Physocarpus malvaceous	NOL	2-6	1-m	●	sn		Tough, tenacious shrub; prefers sandy to silty clay loam, dry canyon bottoms, rocky slopes; thicket forming; east of Cascades only
Choke cherry	Prunus virginiana	FACU	10-20	l	● ●	sn-pt sh		Moderate salinity and drought tolerance; tolerates slightly saline soil; good soil binding characteristics; forms dense stands
Smooth sumac	Rhus glabra	NOL	3-20	l	●	sn	Rhizomatous	Prefers open habitats; forms loose thicket; east of Cascades only
Golden currant	Ribes aureum	FAC+	6	l	● ● ●	sn-pt sh	spreading	East of Cascades only
Squaw currant	Ribes cereum	FAC	2-4	l	● ● ●	sn-pt sh		East of Cascades only
Mountain gooseberry	Ribes irriguum		6	m	● ● ●			Found along streams in mountains of eastern Washington
Black gooseberry/ Swamp gooseberry	Ribes lacustre	FAC+ †	2-7	l-h	● ● ●	pt sh-sh		Drought tolerant; grows in a variety of soils but prefers loamy soils; often grows on rotting wood and spring seepage sites that become dry in late summer; NOTE: is alternate host for White Pine Blister Rust—may not be an issue if it's naturally abundant in area
Red-flowering currant	Ribes sanguineum	NOL	5-10	l	●	sn-pt sh	fibrous, shallow	Prefers dry loamy soils; found on rocky slopes, disturbed sites, and dry open woods; intolerant of saturated soils
Wood rose/ Baldhip rose	Rosa gymnocarpa	FACU	2-6	l-m	● ●	pt sh		Tough, hardy; extremely drought tolerant; prefers rocky soils; excellent soil binding characteristics
*Nootka Rose	Rosa nutkana	FAC- †	2-10	l	● ● ●	sn-pt sh	fibrous, shallow	Rapid volunteer on damp soil; thicket forming; tolerates salt spray, saturated soils, or inundation for much of the growing season; excellent soil binding characteristics; prefers nitrogen-rich loamy soils

Clustered Rose/ Swamp Rose	Rosa piscocarpa	FACU †	6	l	●	●			sn-pt sh		Tolerates infertile soils; prefers loamy soils; excellent soil binding characteristics; west of Cascades only
Wood's Rose/ Prairie Rose	Rosa woodsii	FACU †	6	l-m	●	●			sn-pt sh		Prefers moist, well-drained clay loam, sandy loam, or sandy soil; thicket forming; east of Cascades only
Thimbleberry	Rubus parviflorus	FACU+ †	2-10	l-h	●	●			sn-pt sh	fibrous, shallow	Found along road edges, clearings, avalanche tracks, and shorelines, or under light forest canopy; drought tolerant; intolerant of saturated soils; good soil binding qualities; thicket forming; prefers sandy loam rich in humus
*Salmonberry	Rubus spectabilis	FAC †	6-15	l-m	●	●	●		pt sh-sh	fibrous, shallow	Well-adapted to eroded or disturbed sites; takes full sun if lots of moisture; spreads rapidly; dense thickets can inhibit native tree establishment; mostly west of Cascades
*Under-green willow	Salix commutata	OBL †	8	m-h			●	●	sn		Edges of rivers, lakes, wetlands, gravelly benches, fresh alluvial and morainal materials, open forests
*Drummond willow	Salix drummondiana	FACW †	12	l-h		●	●	●	sn	shallow to deep	East of Cascades only
*Coyote willow	Salix exigua	OBL †	15	l			●	●	sn	shallow, widespread	Colonizes coarse gravel and bar islands; usually grows partly submerged; thicket forming; east of Cascades only
*Columbia R willow	Salix fluviatilis	OBL †	13	l			●	●	sn		Prefers sand, gravel, or silt; banks of Columbia River only
*Geyer willow	Salix geyeriana	FACW+ †	15	l-h		●	●	●	sn	shallow to deep	Likes inundation, sluggish water, wet meadows; deposition tolerant
*Hooker's willow	Salix hookeriana	FACW - †	20-30	l		●	●	●	sn	fibrous, moderately deep	Naturally found <5mi from coast; salt spray tolerant; sandy, gravelly, or loamy soils
*Arroyo willow	Salix lasiolepis	FACW †	35	l		●	●	●	sn	shallow to deep	Flood and deposition tolerant; prefers coarse textured soils; east of Cascades only

*Heart-leaf willow	Salix rigida	OBL †	12	l-m	● ●	sn		Generally uncommon, except on gravel and sandbars along major rivers
*Sitka willow	Salix sitchensis	FACW	3-26	l-m	● ● ●	sn	fibrous, moderately deep and widespread	Tolerates seasonal flooding; prefers sandy or loamy soils; found in clearings, avalanche tracks, on edges of streams, lakes, wetlands, moist forests
*Blue elderberry	Sambucus caerulea	FAC-	20	l	● ●	sn-pt sh		Good soil binding qualities; grows well in a variety of soils; moderate salinity tolerance; favors moist soils of valley bottoms and sunny open slopes; in arid areas, restricted to streambanks and river bottoms
*Red elderberry	Sambucus racemosa	FACU †	6-20	l-m	● ●	sn-pt sh	fibrous; strong adventitious roots; spreading; moderate	Rapid grower; grows well on disturbed sites in a variety of soils; found on streambanks, swampy thickets, moist clearings, open woods; moderate salinity tolerance
Cascade mountain ash	Sorbus scopulina	NI	20	m-h	●	sn		
Sitka mountain ash	Sorbus sitchensis	NOL	12-20	m-h	● ●	sn		Found on streambanks, forest openings, edges of meadows or rock slides; prefers rich well-drained soils
*Douglas spirea	Spiraea douglasii	FACW †	3-6	l-h	● ● ●	sn	extensive, fibrous, shallow	Forms dense thickets; spreads quickly and aggressively; tolerates seasonal inundation; prefers loamy soils
Creeping snowberry	Symphoricarpos mollis	NOL †	1.5	l-m	●	pt sh	extensive, branching, fibrous	Forms dense thickets
Snowberry	Symphoricarpos albus	FACU †	2-6	l-m	● ●	sn-pt sh	extensive, branching, fibrous, shallow	Forms dense thickets; tolerates high winds, some flooding while dormant; excellent soil binding characteristics; prefers loamy well-drained soils
Oval-leaf huckleberry	Vaccinium ovalifolium	UPL	2-6	l-m	●	pt sh-sh		Prefers loamy acid soils; found in bogs, moist coniferous forests

Evergreen huckleberry	Vaccinium ovatum	NOL	2-15	l-m		●				pt sh-sh	fibrous, shallow	Slow growing; tolerates salt spray; prefers mature shade, slightly acidic rocky or gravelly soils; evergreen; coastal
Wild cranberry	Vaccinium oxycoccos	OBL	1	l-m				●	●	pt sh		Boggy sites; vine-like; evergreen
Red huckleberry	Vaccinium parvifolium	NOL	3-13	l		●				pt sh-sh	moderate	Prefers loamy, acid soils or rotting wood; requires lots of organic matter; west of Cascades only
Highbush cranberry	Viburnum edule	FACW	2-12	l-m			●	●	●	sn-pt sh		Found in moist woods, wetland margins, streambanks, river terraces
Oregon viburnum	Viburnum ellipticum	NOL	10	l		●	●			sn-pt sh		Found in thickets and open woods; west of Cascades only
Wild guelder rose	Viburnum opulus	NOL	10			●	●	●		sn-sh	strong adventitious roots	Found in moist woods

FOOTNOTES

* Indicates plant propagates well from hardwood cuttings planted directly in the field, according to Leigh[21] and Myers[13] .

(1) **Indicator Status** = plant indicator status (UPL, FAC, etc.) From USFWS (Reed 1988, 1993 supplement[34]). A positive (+) sign, when used with indicators, indicates "slightly more frequently found in wetlands" and a negative (-) sign, when used, indicates "slightly less frequently found in wetlands". Species marked (†) indicate trees and shrubs tolerant of severe pruning (or grazing); these either stump sprout readily or sucker from roots.

UPL	Obligate upland: occurring almost exclusively in non-wetland environments.
FACU	Facultative upland: occurring primarily in non-wetland environments, but occasionally found in wetlands.
FAC	Facultative: occurring with approximately equal frequencies in wetlands and non-wetlands.
FACW	Facultative wetland: occurring primarily in wetland environments, but occasionally found in non-wetlands.
OBL	Obligate wetland: occurring almost exclusively in wetland environments.
NI	No indicator: there was insufficient data available to determine an indicator status.
NOL	Not on list: Species does not occur in wetlands anywhere in the United States. Therefore, it is not included in the National List of Plant Species that Occur in Wetlands[34].

(2) **Maximum Height** = the approximate height (feet) to which plants will grow under natural conditions with sufficient time. Mature height or the size at which plants begin to flower and produce seeds is substantially less in many species.

(3) **Elevation Range** = the elevations where the species commonly occurs. l=low, sea level to 2500 feet; m=med, 2500 to 4500 feet; h=high, above 4500 feet. All elevations are variable depending on microclimates.

(4) **Soil Moisture** = Plant associations recommended for various soil moisture levels:

A. Very droughty soils: use UPL and FACU species. These conditions may be expected in porous or well-drained (sandy) soils or high on the bank, especially on south or west facing banks with little shade.

B. Droughty soils: use mostly UPL and FACU species; FAC species may be used occasionally if site conditions are somewhat moist. These soils occur in areas similar to very droughty soil, but where moisture retention is better (e.g., less sandy soils, shade, and north or east facing banks).

C. Moderate soils: use FACU, FAC, and FACW species. Much of Western Washington has these soils. They are loamy soils with some clay, on level areas to steep slopes. They may be shallow soils over hardpan, or areas where seeps are common. Plant selection should consider microclimatic conditions including seeps, slope, aspect, etc. Steeper slopes, for example, will be drier than soils because of water run off.

D. Wet soils: use mostly FAC and FACW species; OBL species can be used in particularly wet areas as long as the soil is not compacted. They retain water rather than allowing it to run off after rain, and are moist to wet for most of all of the year. Because these areas have minimal slope and typically slow-moving streams, erosion is seldom a problem.

E. Very wet soils: use FACW and OBL species. These soils may be found along meandering rivers and streams with low banks. There is typically a high water table that allows the development of organic soils (peats and mucks). They are not well suited to large woody vegetation, as trees tend to blow over. Dense thickets of shrubs and small trees are common. Because these areas have minimal slope and typically slow-moving streams, erosion is seldom a problem.

(5) **Light Requirement**: sn = full sun, pt sh = part shade, sh = full shade

(6) **Rooting Character**: “Fibrous” indicates that plant lacks a central root; root mass is composed of fibrous lateral roots. “Tap” indicates that plant has a stout, central main root. Shallow, moderate, and deep refer to relative rooting depth. Note that depth and character of roots are determined by soil conditions as well as species characteristics.

11 EXAMPLES

Riparian Restoration and Management Figure 6: Contrast in plant communities in areas from which livestock are excluded and areas from which they are not.

Riparian Restoration and Management Figure 7: Natural recovery of vegetation at Asotin Creek 5 years after fencing livestock from the stream, Asotin County, Washington.

Riparian Restoration and Management Figure 8: Revegetation project on Harrison Creek, Skagit County, Washington. Site was dominated by reed canary grass. Strips of ground were disked prior to planting to facilitate maintenance. Tubes were used to protect plants from small mammals.

Riparian Restoration and Management Figure 9: 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.

Riparian Restoration and Management Figure 10: Revegetation project in Palouse County, Washington.

(a) (b)

Riparian Restoration and Management Figure 11: (a) New growth emerging from live cutting; (b) Bare-root Ponderosa pine.

12 GLOSSARY

Scarification – A method of soil preparation that consists of exposing or loosening patches of mineral soil through mechanical action to create favorable conditions for the establishment of seedlings and seed.

Amendment – Soil amendments organic matter, mineral, or other substances added to the soil to improve conditions for plant growth.

Solarization – Soil solarization, also referred to as solar heating, is a non-chemical method used to kill soil borne pathogens and weed seeds using mulch or transparent polyethylene tarps during the hot season. Used mostly as a pre-planting soil treatment. See Katan et al. 1987[35] for additional information.

Channel migration zone – The area within which a stream channel has or may migrate laterally under its current geomorphic regime. Commonly defined by historic meander limits or meander belt width[36]

Mass wasting - a general term for a variety of processes by which large masses of rock or earth material are moved down slope by gravity.[1]

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FISH PASSAGE RESTORATION

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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NUTRIENT SUPPLEMENTATION

The following protocols for distributing carcasses, analogs, or fertilizer for salmonid restoration are in DRAFT form. When finalized, the process to be established will ensure that approved projects have all necessary governmental approvals. If you have questions or would like to propose a project, contact Hal Michael at WDFW at (360) 902-2659 or by email at michahhm@dfw.wa.gov. Alternatively, contact the Science Division of WDFW's Fish Program at (360) 902- 2800.

> *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 can be attributed to a combination of factors including harvest and hatchery issues, hydroelectric operations, habitat degradation and loss, alterations to stream flow, altered basin hydrology, and reduced stream productivity. Restoration of salmon populations to levels capable of sustaining fully functional ecosystems and consumptive fisheries will require addressing all these issues; nutrient restoration addresses only a part of the overall problem.

There are currently four options being considered to increase the level of nutrients in freshwater ecosystems in order to restore ecosystem productivity to "historic levels". These are the application of fertilizers, the application of carcass analogs (processed fish cakes), the distribution of salmonid carcasses from fish hatcheries, and the allowance of increased levels of natural spawning by anadromous fish. These protocols and guidelines deal with nutrient recovery utilizing the first three methods; provision for increased spawner escapements will be dealt with in other forums.

The application of fertilizer to increase wild fish production has been conducted in the Pacific Northwest for years. Currently, there are two methodologies in use. One involves the introduction of liquid fertilizer into the water, either through intermittent dosages or through low-level drip. The second involves the placement of solid fertilizer pellets that dissolve at a predetermined rate, releasing nutrients over a period of months. Both methods have been shown to cause substantial increases in fish growth, survival, condition factors, and the like. Water quality monitoring associated with the application of these fertilizers has shown that they are rapidly taken up into the food chain and are generally not detectable in the water column outside of the treatment area/reach.

The use of carcass analogs is an emerging technology. The concept is that fish carcasses and other fish processing waste material is converted into a solid cake. The cake would be treated to kill associated fish pathogens. The advantage of the analog is that they are lighter in weight per unit of nutrient (when compared to carcasses) and they would present a much lower risk of pathogen transfer. The technology is currently in development and testing.

The predominant method currently used to increase nutrients in freshwater and terrestrial ecosystems has been through the distribution of carcasses of salmonids that have returned to hatcheries.

In order to determine whether or not a system is in a state of nutrient deprivation/starvation, the natural spawning escapement level of a total of 1.9 kg/m² of surface area discussed in Wipfli et al. (2003). In order to mimic species-specific spawner densities, levels developed from information contained in Bilby et al. (2001) can be used. These levels are 0.15 kg/m² for coho and steelhead, 0.39 kg/m² for chinook, and 0.78 kg/m² for sockeye, pink, and chum. These numbers will be modified as research continues. Escapements below these levels will be assumed not to meet the minimal nutrient needs of the ecosystem. Other direct measures, such as smolt becoming older and/or smaller, analysis of benthic sediments, analysis of sequestration of marine derived nutrients in trees, etc. will also meet the assumption of lack of nutrients. For the application of fertilizer to streams the target concentration over the course of application will be 3-5 ppb of phosphorus based on Ashley and Slaney (1997) and Ashley and Stockner (2003). The application of fertilizer will require preliminary sampling of the waterbody to determine if or how much material needs to be added in order to avoid situations where phosphorus or nitrogen are excessive. Further, for the foreseeable future, the application of fertilizer will be done as part of a comprehensive study in order to avoid water quality problems.

GOAL OF NUTRIENT RESTORATION ACTIVITIES:

> 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 zone of spawning streams. Ultimately, the goal is the functional restoration of ecosystems supported by naturally spawning salmonids. Restoration of this functionality will require the restoration of the terrestrial and aquatic plant and animal communities in addition to simple anadromous fish restoration. It will also require the restoration of hydrologic cycles, restoration of the relationship between rainfall and streamflow, and restoration of aquatic habitat. Finally, restoration occurs when the nutrients are delivered to the ecosystem by naturally spawning fish and not through artificial methods.

OBJECTIVE # 1:

> Enrich the nutrient supply to all aspects of an aquatic ecosystem (primary producers, scavengers, browsers, predators), enabling their population increases to be used for the trophic benefit of all interdependent species. This will result in increases in individual size, condition factor, and survival of juvenile salmonids living in the streams.

OBJECTIVE # 2:

> Increase productivity in riparian zones and associated upland areas that will benefit the animals and plants that depend upon them.

OBJECTIVE # 3

> Provide analogs or carcasses for direct consumption by juvenile fish and aquatic macroinvertebrates.

OBJECTIVE # 4

Provide alternatives to the use of anadromous salmonid carcasses where carcasses are not available.

OBJECTIVE # 5

Where appropriate, conduct water quality monitoring to document the uptake of nutrients while maintaining water quality for non fish-producing purposes. This monitoring should be structured to document not only the cultural oligotrophication of watersheds but demonstrate the uptake of the nutrients and the ecosystem benefits therefrom. Monitoring will be structured, where possible, to result in peer reviewed publication in appropriate scientific journals.

OBJECTIVE # 6

Increase the production of salmonid smolt and adults so that returning adult spawners can transport nutrients to the ecosystem.

PREMISES:

Actions taken to restore a stream's productivity through restoration of nutrients shall not be viewed as supplanting or supplementing natural spawning by wild salmonids. The ultimate goal is to provide the nutrients necessary to drive the ecosystem only through natural spawning by anadromous fish.

Streams identified for nutrient enhancement with carcasses must be within a designated Fish Health Management Zone (FHMZ), or smaller, that contains the source hatchery facilities.

No nutrients will be distributed in stream reaches formally identified as being impaired because of excess nutrients without the express approval of the Department of Ecology. The Department of Ecology will provide WDFW with a current list of impaired water body segments and, if appropriate, the specific timing (within the year) of that impairment.

All projects that exceed the identified biomass densities or those that introduce fertilizer will be part of a formalized research program designed to produce peer-reviewed publication. At the minimum the project water quality will be monitored as follows: One sample immediately upstream of the uppermost input point to serve as a control, one sample at the downstream end of the calculated treatment zone and one sample half a kilometer downstream from the point where calculations of nutrient spiraling (accounting for flow) suggest 100% consumption of the nutrient (Thomas et al. 2003). Samples will be collected monthly during the period of nutrient introduction and will continue for two months after the calculated date of pellet disintegration, after last application of liquid fertilizer, or after final degradation of carcasses or analogs. Measurements will be for parameters identified in the specific Memorandum of Agreement (MOA) developed for the project.

All projects will be covered by formal approval of the Department of Fish and Wildlife (WDFW) and Department of Ecology (DOE) through individual project MOAs. The MOA will accompany transport and depositing of materials.

All carcasses distributed under these protocols shall be from salmonids killed at WDFW or WDFW supported Coop hatcheries or from fish collected during a WDFW authorized wild brood stock capture project. Carcasses that are the result of mortality during holding at a hatchery, eggs which are "picked" or otherwise determined to be non-viable following placement into incubation environment, and mortality of juveniles during rearing are covered by the National Pollution Discharge Elimination System (NPDES) permits and their disposal will follow the procedures described in the permit.

Once approved, the requested number of carcasses will be added to next year's hatchery planning processes. Since the number of fish returning to freshwater are controlled by many factors, some of which (ocean conditions) are outside of WDFW control, there can be no guarantee that a fixed number of fish will be available for distribution.

CRITERIA FOR TREATMENT STREAM IDENTIFICATION:

1) Treatment reaches shall be within the current anadromous zone of a watershed or within areas historically accessible to anadromous fish with exceptions based on specific research study needs.

2) Streams that have historic data sets and/or ongoing assessment projects that can be complemented by nutrient restoration will be given high priority in project planning. Conversely, streams with ongoing ecosystem assessment studies that would be adversely affected by nutrient enhancement will be avoided.

3) Streams or stream reaches where treatment ends less than two km upstream from municipal water supplies will be considered only with the expressed written concurrence of the water purveyor. Similarly, private domestic water diversions recognized by DOE will receive the same 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) Treatment streams should have access points to the treatment reaches, (bridges, wet crossings, culvert crossings, etc.) to accommodate nutrient deposition, distribution, and monitoring.

6) Spawner index streams and smolt evaluation streams will not be selected for nutrient restoration unless potential impacts are resolved with the research or evaluation agency or organization.

7) Written landowner approval for access to deposit materials will be obtained.

8) Carcasses will be marked with an easily identified external mark if it is necessary to avoid having deposited carcasses being mistaken for naturally spawning fish.

CRITERIA FOR ADULT CARCASS DEPOSITION:

1) Temporal and spatial distribution should reflect historic anadromous spawn timing and abundance for a particular stream, for each species. For purposes of 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 be used as a substitute for coho, and vice versa, depending upon availability. Further, testing for pathogens, availability of access due to snow, etc. shall be considered when setting up distribution schedules.

2.) The maximum number of carcasses distributed within a stream segment will be 1.9 kg/m^2

based on Wipfli et al. (2003). In streams where estimates of the natural spawning escapement are routinely made, carcass numbers will be reduced by the recent 5-year moving average for natural escapement to the treatment reach. For determining total carcass deposition maximums, the area historically available to each species will be used to calculate the loading rates. This results in a separate calculation for each species/timing segment. Spawn timing will be factored into distribution schedules.

3) Carcasses will be used within designated watersheds or FHMZ as identified by WDFW Fish Health Specialists.

4) Carcasses will be used from stocks that have been screened for pathogens as prescribed in the Co-managers Disease Control Policy.

5) If necessary to avoid duplicate counting, interference with spawner enumeration, or other studies, carcasses used for nutrient enhancement will receive a distinctive external mark or tag. As noted in (1), species may be substituted in order to avoid the potential for enumerating a distributed carcass as natural escapement.

6) If necessary to avoid confusion with specific genetic sampling studies, carcasses will have an identifiable external mark or non-target species will be utilized.

7) All use of carcasses for nutrient restoration will follow the specific plan submitted by the applicant and approved in the formal project review process.

8) A copy of the annual project authorization will accompany transport and deposition of carcasses.

9) Deposition of carcasses should be avoided at flow levels (e.g. high flows/freshets) that would compromise the carcass placement objectives.

10) Artificial deposition of salmonid carcasses must not create a direct human health hazard.

11) Frozen carcasses can be used to approximate historic run (mortality) timing and to improve distribution to inaccessible stream reaches.

12) Distribution of carcasses should include shoreline and shallow water reaches of the stream.

13) Final Project approval or denial will occur at the WDFW Regional Fish Program Manager level after appropriate internal review. The Regional Fish Program Manager will ensure that Co-managers, the Department of Ecology, and other affected fish management entities have been consulted during project approval. Distribution of final approval/disapproval will be by the WDFW Science Division.

14). When there are concerns about within-stream fish pathogen transmission or concerns about contribution to an existing degraded water quality condition, carcasses may be applied to the terrestrial riparian zone (outside ordinary high water mark (OHW)) as long as they are not within 20 meters of OHW. This is done to meet the nutrient needs of terrestrial resources known to utilize carcasses.

15). Carcasses from fish treated with antibiotics or other chemicals such as anesthetics can be distributed if the fish met the labeled withdrawal period listed on the product label.

CRITERIA FOR CARCASS ANALOG DEPOSITION:

1) Temporal and spatial distribution should reflect historic anadromous spawn timing and abundance for a particular stream, for all species. For purposes of this program, the amount of analogs to be distributed will be converted to carcass biomass by correcting for the moisture/nutrient content of the analog. The actual distribution goal will be calculated as biomass and then converted to analogs.

2.) The maximum number of analogs distributed 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/square meter of stream surface area. Summer low flow area will be substituted as a conservative density. In streams where estimates of the 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 maximums, the area historically available to anadromous species will be used to calculate the loading rates. Spawn timing will need to be factored into distribution schedules.

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) Deposition of analogs should be avoided at flow levels (e.g. high flows/freshets) that would compromise the analog placement objectives.

7) Deposition of analogs must not create a direct human health hazard.

8) Final Project approval or denial will occur at the WDFW Regional Fish Program Manager level after appropriate internal review. The Regional Fish Program Manager will ensure that Co-managers, the Department of Ecology, and other affected fish management entities have been consulted during project approval. Distribution of final approval/disapproval will be by the WDFW Science Division.

CRITERIA FOR FERTILIZER DEPOSITION:

1) Application of fertilizer 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 targets only the dissolved nutrient fraction contained in a salmonid carcass. Consequently, extreme care must be taken to control application levels to achieve enhancement without degrading water quality. Applications should be timed to promote maximum uptake by the phytoplankton community.

2) The maximum amount of fertilizer to be deposited will be based on the recommendations of Ashley and Slaney (1997) and Ashley and Stockner (2003) which is to achieve an instantaneous Soluble Reactive Phosphorus level over the 120-day treatment of 3-5 micrograms per liter at average streamflow during application/release. Treatment reach will be defined based on the

Ashley/Slaney or Ashley/Stockner calculations or other methodologies as information is developed.

3) Determination of the need to apply fertilizer will be based on specific water quality sampling undertaken at least one year prior to the intended time of treatment. For lakes, sediment core studies showing historic phosphorus deposition and/or zooplankton communities will be used as justification for programs and for determining natural levels of nutrient input to the system.

4) The fertilizer formulation for use in streams must be Food or Pharmaceutical Grade. Liquid fertilizers, to be used only in lakes, shall be of agricultural grade and must be certified for use on food crops to be used. If a water right certificate has been issued for domestic water use from that water body, fertilizers must be Food or Pharmaceutical Grade. Chemical evaluation of fertilizer formulations must include screening for metals.

5) Use of fertilizer for nutrient restoration 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) Transport and deposition of fertilizers will be accompanied by the appropriate approvals.

7) Placement of fertilizer should avoid flow levels that would compromise the placement objectives.

8) Each fertilizer application project will include a water quality-monitoring component. At the minimum, the proponents will be required to collect Soluble Reactive Phosphorus, Total Dissolved Phosphorus, Nitrate, Nitrite, and Ammonia samples from 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 from one month before fertilizer deposition to 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 number -30, 0, 30, 60, 90, 120, 150, and 180. The minimum detection level will be 1 part per billion. Sampling protocols will be designed to meet this detection standard.

9) Final Project approval or denial will occur at the WDFW Regional Fish Program Manager level after appropriate internal review. The Regional Fish Program Manager will ensure that Co-managers, the Department of Ecology, and other affected fish management entities have been consulted during project approval. Distribution of final approval/disapproval will be by the WDFW Science Division.

CRITERIA FOR TERRESTRIAL DEPOSITION OF CARCASSES

Deposition of carcasses or analogs in terrestrial areas within twenty (20) m of flowing water will be treated as if they were placed in the stream and will comply with the conditions listed above with regard to Fish Health Management Zones. It is desirable that, under normal deposition plans, some of the carcasses or analogs be applied terrestrially or in shallow water.

CRITERIA FOR ALL PROJECTS:

1) Approval is continuous as long as all operational requirements of a specific project are met.

2) Proponent must annually report to WDFW per the MOA. The report will indicate source of materials (carcasses, analogs, 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 will be reported to the WDFW Science Division and will serve as the application for renewal for the subsequent year's program. In order to be automatically approved for the next year, the report must be received by June 30 following deposition. WDFW will ensure that interested agencies receive data summaries and results of monitoring. WDFW will annually issue an MOA, 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 applied.

3) These criteria apply only to projects reviewed by the WDFW procedure. For carcass distribution projects, these protocols apply only WDFW operated facilities or to WDFW associated Coops. 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. In order to have approval by September 1 it will be necessary to apply by July 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, growth, and diversity, predator and scavenger use, plant (aquatic or terrestrial) growth, etc.

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) Completed application forms are forwarded 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:

A) The completed application will be reviewed by the WDFW Aquaculture Coordinator who will approve/deny use of carcasses.

B) WDFW Fish Health Manager will forward a copy of the application to the Northwest Indian Fisheries Commission for Co-Manager review. Following review by the Fish Health Manager the application will be forwarded to the appropriate Hatchery Complex Manager for review and approval. The application will then be returned to the Science Division.

C) Applications that are recommended, as Denied will be returned to the applicant with explanation. If changes in the application are recommended, the Science Division will contact the applicant to address the necessary modifications.

3) All completed applications (fertilizer, analog, and carcass) 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 for, landowners controlling access to application sites, and the Department of Ecology Regional Office.

4.) Following regional review the Regional Fish Program Manager will approve or deny the application.

5.) The approved application and review forms will be returned to the Science Division for distribution. An MOA will be developed for each project based on the approved application and will be append to the WDFW approval.

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BEAVER RE-INTRODUCTION

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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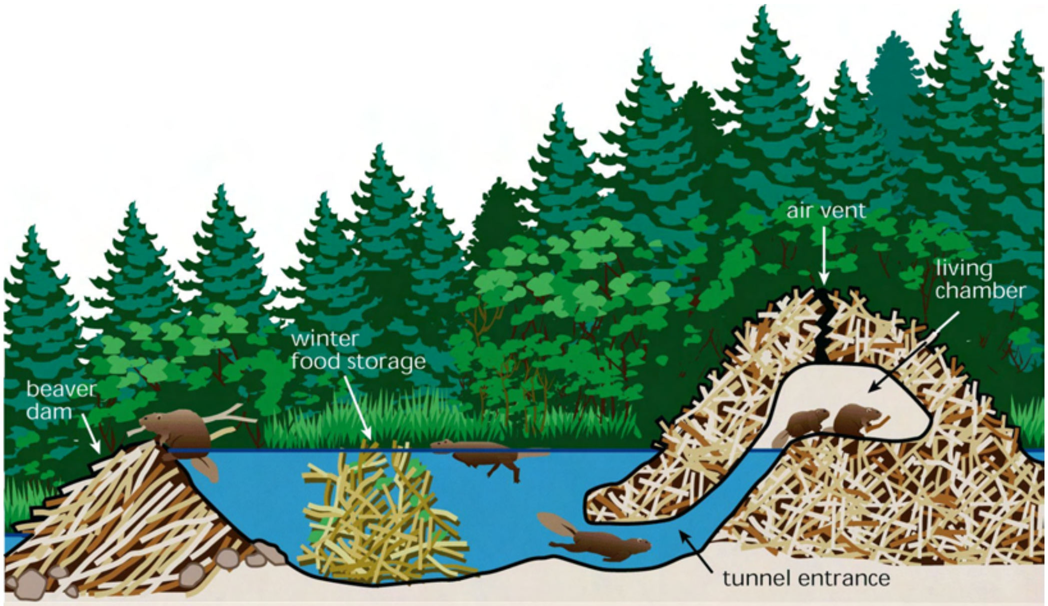

Fig. 8.21 -- A beaver lodge.
In Stream Corridor Restoration: Principles, Processes, and Practices, 10/98.
Interagency Stream Restoration Working Group (FISRWG)(15 Federal agencies of the US).

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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SALMONID SPAWNING GRAVEL CLEANING AND PLACEMENT

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.

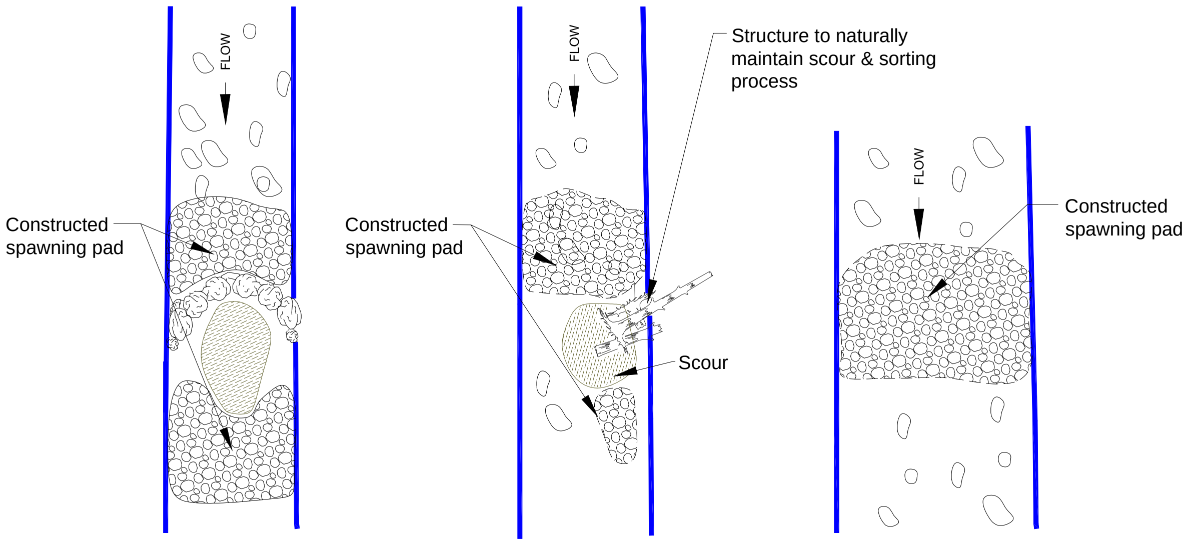
Fine sediments that settle out in spawning habitats can also cause decreased spawning success by filling the interstitial spaces between gravel partials. The presence of excessive fine sediments (<0.841 mm) within redds has been shown to reduce egg to fry survival due to a reduction of inter-gravel water 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%. [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

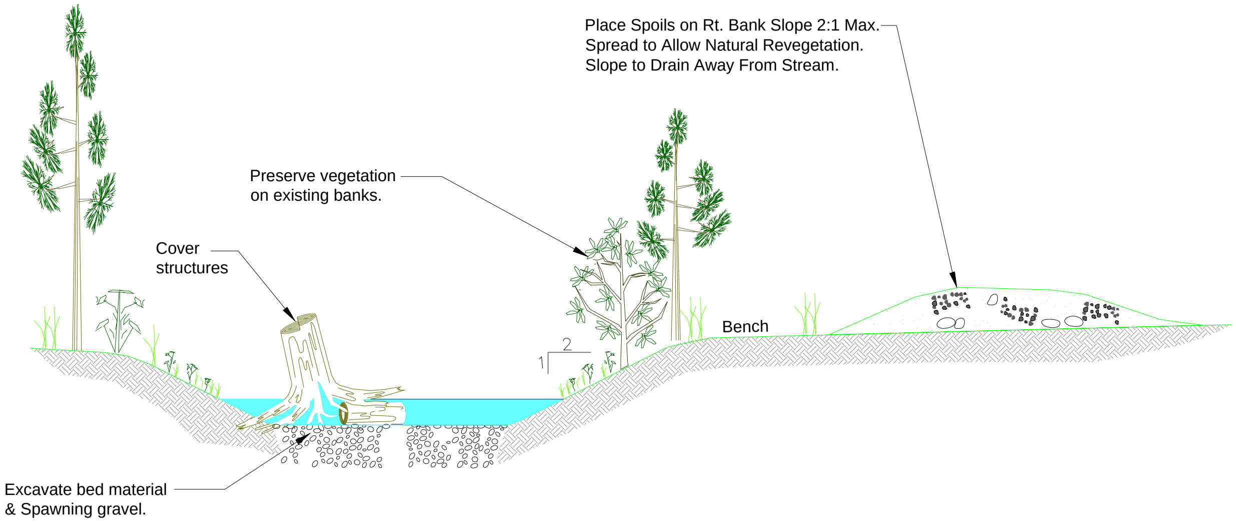
Potential rehabilitation sites must be assessed and projects carefully designed to ensure favorable results. Situations that should be avoided include channels that are laterally or vertically unstable, and streams that carry large volumes of fine sediment that can bury spawning gravels. Ideally, any 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.

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

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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.

13 – 50 mm	38	43	51
51 – 100 mm	21	23	12
101 – 150 mm	12	3	2

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 (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 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.

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

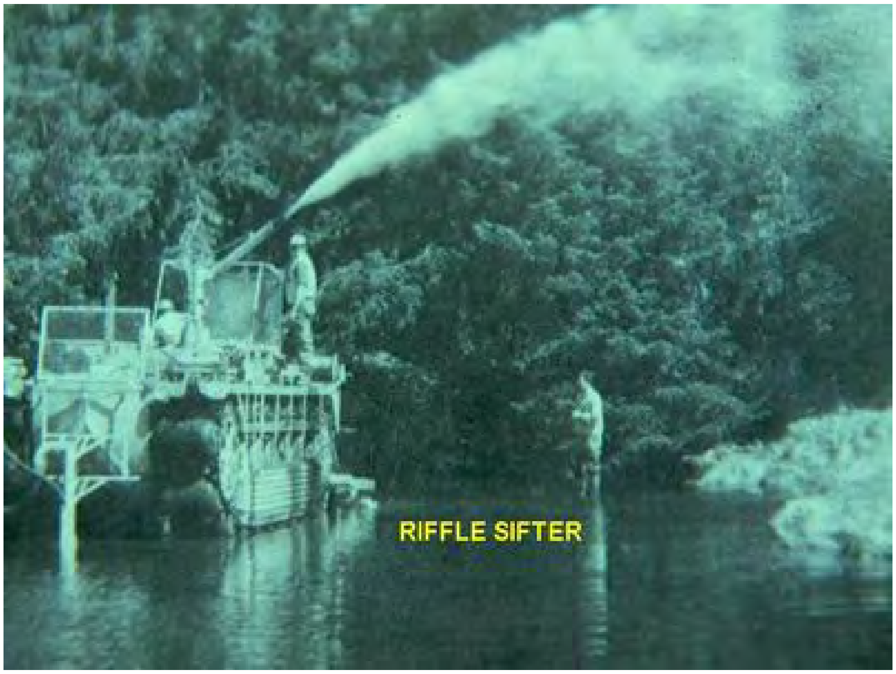
In 1987, WDFW constructed and improved access to a tributary of the Suiattle River, North of the town of Darrington, WA. The site, know as "Suiattle Slough" was a spring fed channel which beavers had blocked off from the main river channel. In addition to providing access to several thousand square meters 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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GENERAL DESIGN AND SELECTION CONSIDERATIONS FOR INSTREAM STRUCTURES

This chapter is a draft version and the Aquatic Habitat Guideline program will be working to finalize it in the future

The term "structure" (in the context of these restoration guidelines) refers to any intentionally placed object in the stream or floodplain. Structures that come in contact with water obstruct streamflow and force it to run over, around, and/or under the structure. This redirection, concentration, or expansion of flow influences the form, structure, hydraulics, and consequently, the function of the stream. As a result, instream structures are prone to having unintended consequences; caution must be exercised when using this approach.

Placement of instream structures is commonly done as a means of improving instream habitat for fish. These structures are typically intended to serve as analogs to otherwise naturally-occurring features. Certain benefits associated with instream structures (such as cover, shelter from fast moving current, or creation of velocity gradients) are available to fish and wildlife immediately following their installation. However, other benefits (such as scour, deposition, or sorting of bed material) require one or more high flow events before they are realized. Instream structure installation can be successful. However, there is a tendency when using this approach to focus on the symptoms of habitat degradation rather than the cause[1], to act without full understanding of the needs of affected fish and wildlife communities[2], and to provide benefits for a specific target fish species, sometimes at the expense of other fish and wildlife[3]. As a result, benefits may be temporary without maintenance and repeat application, they may be limited in scope, or they may never be achieved if the treatment does not address the factors that limit ecosystem productivity and recovery. In addition, incorrectly designed or constructed structures are prone to failure and causing further ecosystem degradation (Beschta et al.[4], as cited by Roper et al.).

In a review of stream restoration techniques, Roni et al.[5] found that projects that involved installation of common instream structures had a moderate to high variability of success at meeting project goals and a low to high probability of success, depending upon the species studied and project design. Instream structures are most effective at restoring or rehabilitating ecosystems when they address the principal cause of ecosystem degradation or when they are used to provide immediate improvement of habitat condition in conjunction with other techniques that address the root cause of the problem but have a long delay before benefits will be realized. They can also be used to enhance habitat when the materials and processes necessary for the natural occurrence of desirable habitat features and conditions are absent and cannot be restored given current constraints.

Considering the risk of project failure and unintended consequences, structure installation and other instream restoration, rehabilitation, or enhancement work should never be conducted without adequate site, reach, and watershed assessment to determine the nature and extent of problems in the watershed, determine the nature and extent of the cause(s) of those problems, and to establish realistic restoration goals, objectives, and priorities (see Stream Habitat Restoration Guidelines Chapters 3, *Stream Habitat Assessment*, and Chapter 4, *Developing a Restoration Strategy)*.

Structures encompass a broad range of objects, consisting of differing materials, functions, longevity, and scale. In the interest of brevity, the structural techniques included in these guidelines are limited to those that are most commonly applied to habitat restoration, rehabilitation, enhancement, and creation projects and that have the potential to provide sustainable benefits to fish and wildlife when used appropriately. These structures include:

- Large wood and log jams
- Boulder clusters
- Porous weirs
- Drop structures

Considering the spectrum of possible structures that are not included in these guidelines, the purpose of this introduction is to provide general guidance on factors to consider when adding ANY structure to a stream.

1 PHYSICAL FUNCTION OF STRUCTURES

All structures placed in a channel have the potential to affect channel hydraulics, sediment scour and deposition patterns, and wood and sediment transport. The degree to which these effects achieve the desired results or place nearby habitat, infrastructure, property, and public safety at risk depends on a number of important variables that affect the way in which a structure functions in the stream. The following parameters should be considered in structure design.

- Channel constriction caused by the structure
- Location of the Structure Within the Channel Cross-section and Its Height Relative to the Depth of Flow
- Structure spacing
- Structure configuration and position in the channel
- Sediment supply and substrate composition
- Channel confinement
- Hydrology
- Time

The effects of these variables vary along a continuum, ranging from slight changes in the channel or floodplain, to huge, catastrophic channel aggradation, incision, or avulsion. Where a given project should be on this continuum depends on the project goals, which must be clearly identified from the outset. There are always potential unintended consequences of any structure placement. The designer should be aware of these consequences and realize that forces in streams act in ways that are beyond our control.

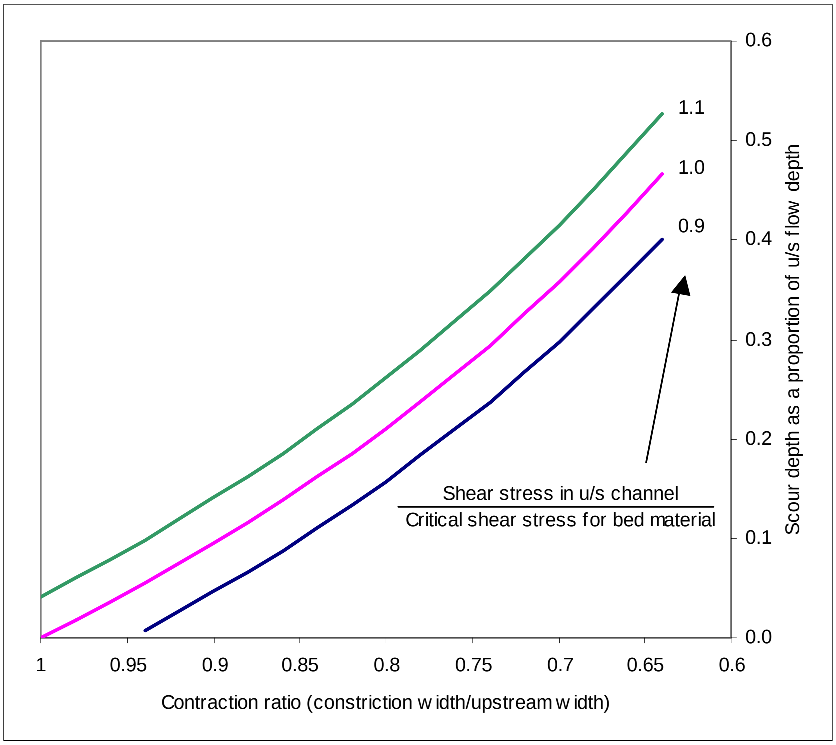
1.1 Channel constriction

Channel constriction is a fundamental parameter describing the scale of the structure relative to the channel. A given structure's effect on a channel is determined in part by how much of the cross-section it occupies. A structure that hugs the bank and blocks a very small percentage of flow in a gravel bed stream will have little effect on channel morphology in the short term. Placed so that it occupies one half or more of the bankfull channel cross-section, the structure has the potential to fundamentally change the channel during the first storm.

In channels with erodible beds and banks the response to significant channel constriction is scour in the vicinity of the structure, deposition of sorted bed material where the flow expands downstream of the constriction, and deposition of bed material upstream in backwatered sections of the channel. Scour results in an increase in cross-sectional area, relieving some of the constriction and decreasing the velocity of flow. The important point to make here is that, no matter how large the structure is or how much of the cross-sectional area it occupies, the deformable boundaries of the channel will adjust to accommodate it. The designer's purpose is to specify how much channel to affect.

The degree of scour created by a given constriction is a function of the bed material size and the available hydraulic stresses to move that substrate[6 7]. Even a minor constriction can cause scour in a sand-bed stream. But it takes a more significant constriction to cause scour in a cobble- or boulder-armored streambed. In an unpublished study, WDFW found that in three small streams (<8 feet) with slopes of 1.3 to 2.6 % and gravel beds, approximately 50% of the bankfull channel cross-section must be blocked by a structure to produce pools and sort gravel in a straight reach of channel. In larger streams [size of bed material???, slope???], Mike McHenry (Lower Elwah tribe, personal communication) has built many structures that occupy 25% of the channel width and significantly influenced morphology. Drury [8] installed structures on a larger river (average bankfull width 413 ft) [slope???, bed material???] that protruded out from the bank 7% of the channel width and produced 10 feet of scour. These structures were placed in the thalweg, a consideration covered below. Refer to the discussion of sediment supply and substrate composition, below, for further discussion.

The simplest approach to constriction scour functionally associates the depth of scour with the degree of constriction and ratio of upstream shear stress to the critical shear stress needed to scour the bed material. **Considerations for Instream Structures Figure 1** gives an example of the performance of this relationship. As the constriction ratio (width in the constriction divided by the width upstream) decreases, scour increases. As the shear stress ratio increases, so does the scour. The mathematical analysis of constriction scour shown here can be found in Raudkivi. This chart is for illustration purposes only and should not be used for design.



Considerations for Instream Structures Figure 1: Scour depth as a function of constriction, depth of flow, and shear stress. This figure was developed from Equation 9.15 on page 245 of A. J. Raudkivi, *Loose Boundary Hydraulics*

For information on how constriction relates to scour near groins (rock bank protection structures, an analog for habitat structures) see Klingeman et al.[9], Richardson and Davis[10] and Gill.

Constrictions also cause backwater effects upstream from the constriction. In the backwatered area, velocity is lowered and sediment tends to accumulate, a familiar phenomenon above undersized bridges and culverts. The upstream extent of backwater depends upon the scale of the constriction and the slope of the channel. Backwater effects extend much further on low-gradient streams than on high gradient streams. Effects will be localized for relatively small channel constrictions. But if the structure causes a significant reduction in channel cross-sectional area or a series of structures collectively increase the hydraulic roughness of the channel, backwater effects may be far reaching. Effects of large-scale backwatering can include increased flood levels and frequency of floodplain inundation, an adjustment of the elevation of streamside vegetation as lower-growing plants are drowned out, potential change in riparian species composition and distribution in response to changing inundation patterns and water table elevations, and reduced reach transport of sediment. Other effects associated with reduced sediment transport include channel aggradation and associated channel widening, bank erosion, increased channel meandering, decreased channel depth, and increased potential for avulsion where the main channel moves to the other side of the structure or to an entirely different location (refer to the *Fluvial Geomorphology* appendix for a discussion on channel avulsion).

Which, if any, backwatering effects are acceptable depends on the setting and the objectives of the project. For instance, encouraging large-scale sediment deposition may be desirable in an incised channel whose bed was scoured down to bedrock as a result of splash-damming or stream-cleaning activities so that it now lacks the structure necessary to retain bed material that is transported through the system. Installing a series of large wood complexes in such a setting can promote bed material retention, floodplain reconnection, and habitat diversity. On the other hand, implementing a similar project in close proximity to homes, businesses, or agricultural fields may be unacceptable. The risk to property, infrastructure, public safety, and the environment must be assessed for every project

Backwater effects associated with a constriction can be assessed using hydraulic analysis. General references include any book on open channel flow, such as Jobson and Froehlich[11] or Chanson[12]. Specific references for the blocking effects of wood in a stream include Young[13], who measured the backwater effect by placing increasing quantities of wood in a flume, and Gippel et al.[14], who developed a momentum equation specifically for wood loading in streams. Backwater effects of bridge constrictions have been thoroughly explored. See Matthai[15] for hydraulic effects in rivers. For smaller channels, Fiuzat and Skogerboe[16] developed constriction ratings. Computer modeling is widely used, employing such programs as HEC-RAS, available free from the USACE, to determine backwater effects in channels.

1.2 Location of the Structure Within the Channel Cross-section and Its Height Relative to the Depth of Flow

The proportion of flow blocked by the channel varies with the depth of flow. Low profile structures can redirect and block a relatively large percentage of base flow, but constrict a decreasing proportion of flow once the structure is overtopped. The effect of that structure on flow characteristics (resistance, velocity, shear, turbulence) will likewise change as the depth of flow increases over the submerged structure. In contrast, the constriction formed by a relatively high boulder cluster or log structure that breaks the surface during high flows could increase, decrease, or remain the same with increasing depth of flow, depending on the shape of the structure and the channel in cross-section. Breaking the surface in combination with significant constriction increases the likelihood of supercritical flow and associated hydraulic jump, producing high turbulence and scour. [Free surface resistance is one of the three components of flow resistance[17], which results in energy loss through turbulence and scour. Hubbard and Thorne[18] thoroughly examined the effects of boulders that break the surface and the associated hydraulic jump and drag, an effect that can easily be transferred to other structures that break the surface.]

In addition to having the potential to cause turbulence and scour, structures that protrude above the water surface increase flow resistance and are very effective at catching floating debris, carcasses and other material as they comb the water surface. Material that racks up on the structure increases the size of the constriction and the degree of backwater or hydraulic drop caused by the structure. Structures that protrude above the water surface are also less buoyant since a portion remains above the water surface.

Hubbard and Thorne discuss the relative submergence of boulders in a mountain stream. Gippel et al. comment on the effect of the relative depth of wood in the water column.

*Discuss effect and function of structures that are located in low flow channel vs. those above low flow but within bankfull channel vs. those suspended above channel vs. those outside the channel in the floodplain.

1.3 Spacing

The relative spacing of structures 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[19] 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. 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.

Similar spacing effects are shown in the study of groins (large roughness elements that project into the channel from the bank and extend above the high-flow water surface elevation[20]) that could be applied to any habitat structure that blocks flow. Groins are spaced to maximize bank protection with a minimum number of structures. This could be reinterpreted in the habitat context as maximizing hydraulic effect (roughness and channel diversity). Lagasse et al.[21] show that the expansion angle (the angle of the line that marks the expansion of flow off the tip of a structure that constricts the channel) is a function of the structure length as a percentage of channel width and of structure permeability. Impermeable structures have an expansion angle of about 17° for most lengths [range??—later it says the angle increases with length]. This means that such structures should be spaced roughly 3 times their effective length (perpendicular to the bank) in order to maximize their hydraulic effect. The expansion angle increases with permeability and length, meaning that closer spacing is necessary to achieve similar results. Lower profile barbs, which are submerged during high flows, are typically spaced 4 to 5 times their effective length[22].

The natural distribution of wood in small streams is somewhat random, having more to do with delivery than transport[23], whereas in larger streams wood is more associated with regular stream features[24]. This can be seen as a scale effect; as the size of the material diminishes with respect to the channel, structure spacing is determined by flow. In larger streams, structures should be spaced in conjunction with natural wood deposition sites to maximize their stability and mimic the effects of naturally deposited wood.

*Discuss combination effects of one structure on another (constriction, redirecting flow).—this relates to fact that one structure can focus/direct thalweg into the next structure

1.4 Structure configuration and position in the channel

*Discuss how orientation of structure relative to flow effects flow redirection and scour/deposition patterns (e.g., straight flat structure vs. a sloping structure; one that points upstream vs. downstream vs. perpendicular vs. parallel to flow)
*Located in thalweg vs. channel margin
*Located in pool vs. riffle (deep vs. shallow flow)

1.5 Sediment supply and substrate composition

*Will have a profound effect on structure performance (primarily scour and deposition).
*Aggrading vs. incising vs. equilibrium channel.
*Qualitative relationship between current shear stress and critical shear stress.

1.6 Channel confinement

*Discuss increased hydraulic forces and risk associated with placing structures in a channel with broad flood plain vs. one that is moderately entrenched vs. one that is severely confined.

1.7 Hydrology

*Free flowing streams vs. backwater due to beavers, vegetation, undersized bridges, etc
*Runoff vs. groundwater streams
*Urban flow regime vs. natural landscape.

1.8 Time

*****Time is extremely important when altering a stream.
*Are delayed effects (e.g., avulsion leads to u/s incision, then sediment pulse, passing of pulse, back to equilibrium conditions, may take many years).
*Maturation, number of restructuring flows may be necessary before effects of structure are fully realized (see Madej 2001[25]).
*Design life is caught up in the concept of disturbance. Structures installation can create disturbance. When they fail structures will also create disturbance. Where possible, disturbance should be considered a part of restoration design[26].

2 APPLICATION

The following table highlights the primary function of structures covered in this manual as they relate to restoration, enhancement or creation of stream habitat. Structures often provide numerous functions – only the primary function for typical applications is listed in this table. Most of the structure types listed herein can transcend their categorical listing and provide added habitat value beyond their primary function. This can be accomplished through site-specific and structure-specific design. Combinations of structures can be used to meet several different objectives at the same time.

Considerations for Instream Structures Table 1: Primary functions of instream structures in habitat applications.

Application	**Large Wood & Log Jams**	**Boulder clusters**	**Porous Weirs**	**Drop Structures**
Create bed and bank scour	X	X	X	X
Sort sediment	X	X	X	X
Create backwater	X	X	X	X
Stabilize or raise streambed	X		X	X
Alter stream grade	X		X	X
Provide cover, resting and high flow refuge	X	X	X	
Armor streambanks	X			
Improve wildlife habitat	X	X		
Redirect flow	X	X	X	X
Trap material	X	X		
Provide fish passage	X			X

Determination of when the application of structures to restoration efforts is appropriate will necessarily be dependent upon specific restoration objectives, site and watershed conditions, and an identified biological or morphological need.

3 DESIGN OF STRUCTURES

Design of structures in fluvial environments can involve considerable site-specific analysis, and as such it is impractical to establish common design routines that can be universally applied. While there are established analytical tools for estimating such design components as maximum scour depth and minimum size of material, and for conducting a hydraulic analysis, the specific tools applied for each of these design components will vary with site and channel conditions, risk, as well as the relative complexity of the project.

3.1 Common Design Criteria for Instream Structures

Design criteria are specific, *measurable* benchmarks developed to meet and clarify project objectives. They provide numeric allowable limits of project performance and tolerance. Common design criteria for instream structures are discussed below. Further discussion on developing and using design criteria is provided in Stream Habitat Restoration Guidelines Chapter 5, *Designing and Implementing Stream Habitat Restoration Techniques*.

Physical or Biological Response.
The first set of criteria for an instream project relate to the desired channel or biological response. For instance, if the intent of the project is to increase salmonid spawning utilization, then the criteria should relate to fish usage and structure design must create appropriate depositional patterns. If the intent is to create a forced pool-riffle morphology in a plane-bed channel, design criteria should specify a target pool/riffle ratio and minimum residual pool depth. While criteria are intended to be measurable, some projects may have criteria that are more qualitative. A qualitative design criterion might be to increase flow to a side channel to increase off channel habitat. A more complicated project associated with dam mitigation will require a specific flow in the side channel, e.g., 10 cfs during 1500 cfs main channel flow. Design criteria are further discussed in Stream Habitat Restoration Guidelines Chapter 5, *Designing and Implementing Stream Habitat Restoration Techniques*.

Design Discharge.
Design discharges are relevant to many aspects of structure design, including structure stability and desired habitat effects. The design discharge up to which a structure is expected to remain relatively stable will vary with the type of structure, the objectives of its installation, and the risk associated with its structural failure. For instance, drop structures installed to provide fish passage through an upstream culvert may need to withstand a 50- or 100-year flow without failure. A much lower design discharge could be applied to boulder clusters intended to increase habitat diversity and provide holding habitat for fish. But specific discharges may only be relevant when hydraulic analysis is required. Less stringent criteria may be appropriate in certain situations, such as the often-used bankfull flow (*e.g.* “roughly one quarter of the bankfull flow will be diverted into the side channel”).

Habitat created by structures may be critical at specific times of year or ranges of discharge. Therefore, it may be appropriate to establish design discharges that relate to specific fish and wildlife benefits, in addition to those that dictate structural failure. For instance, the limiting factor for fish may be cover during summer low flow or shelter during high flow events. Under these circumstances structures will need to be designed to function during this critical time, at a minimum, in order to optimize their effects. Timing and discharge requirements may be specific to the stream and target species and age class (e.g., fish passage requirements for adult chum salmon will differ from that for juvenile coho salmon).

Structures whose habitat value is realized after and during high flow events capable of redistributing sediment and wood should be designed to be effective at the dominant discharge. The *Hydrology* appendix provides discussion and guidance on how to determine dominant discharge.

Design Life.

The desired design life for a structure will vary with the application. Some structures may be temporary features intended to fill a function lost at this time in the watershed. In contrast, mitigation projects must last as long as the impacts for which it is intended to mitigate. Although a desirable goal of a project is to last long enough to realize the full maturation of its restoration benefits, including any delayed effects, the design life of an instream structure is virtually impossible to predict or account for. The longevity of a structure is influenced by some features that can be controlled (the structure design and the materials used to construct it) and others that are generally beyond our control (peak flows and channel or watershed disturbance). The design discharge for stability has an equal probability of being exceeded in every year, and therefore, the structure may fail at any time.

Deformability.

Structures can be designed and constructed to be relatively non-deformable, meaning that they persist as constructed indefinitely. 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 the design flow, or as a result of channel incision or other changing watershed conditions. Deformation differs from design life and ultimate failure – deformation implies that the function of a structure may evolve or diminish over time through gradual mobility of materials rather than catastrophic and sudden failure.

Deformation of structures typically involves the gradual undermining of individual structural components (e.g., rocks or logs), or entrainment of a percentage of them during extreme flows. The downstream edge of a structure is most likely to deform, as scour below the structure may create holes into which part of the structure falls. In this manner, 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, rigid structures (e.g., anchored log, plank, concrete, or sheet pile weirs) cannot adjust to changing flows, stream profile, cross-section, or planform.

Structures designed to deform over time should be comprised of natural materials; unnatural materials, such as rebar, wire rope, and concrete blocks should be avoided. Deformability may be achieved by sizing the material to withstand relatively low design flows, or by minimizing the amount of structure keyed into the channel bed or banks to prevent undermining and end runs, respectively. Designers should note that there is a high degree of uncertainty in the final form of a deformable structure once it deforms.

3.2 Design Factors to Consider

Some form of assessment of fish and wildlife communities, stream geomorphology, watershed processes, and channel and watershed history is necessary to evaluate the system conditions and the appropriateness of a site-specific structure project. This assessment will aid in estimating the project's likely effects on adjacent stream reaches and the system as a whole, as well as on nearby property and infrastructure. Without some level of understanding of the stream ecosystem and the factors that influence its condition, a structure project is not likely to fulfill its intended purpose and may have unintended consequences.

The amount of data collection and assessment required will be dictated by the project scope, availability of existing watershed assessment information, and by allowable risk and uncertainty. While it may seem prudent to collect an abundance of data, make sure that it is collected for a predefined purpose. This is especially the case for monitoring where data should be associated with specific goals. Assessment completed prior to adding a structure to a stream should be of a sufficient level so as to reveal the scale and cause of the problem in order to ensure the problem is correctly and fully addressed. At a minimum, the scale of assessment should be equal to or greater than the anticipated scale of the structures' effects. Refer to Stream Habitat Restoration Guidelines Chapter 3, *Stream Habitat Assessment*, for a detailed discussion of assessment. The following are minimum recommended assessment and analysis requirements for installing instream structures.

- *What is the objective of structure placement?* The type, configuration, and number of structures will vary with the objective.
- *Are structures the best alternative to meet those objectives?* Will structure placement treat only the symptom of the perceived problem or deficiency, or will it address its root cause? Are there other realistic alternatives that can provide a more long-term, far-reaching, and self-sustaining solution?
- *Have other complementary treatments been implemented that are necessary to maximize the effectiveness and longevity of benefits provided by instream structure placement?* For instance, if natural structures were dislocated, washed out, or otherwise prevented from functioning as a result of modifications to the channel, hydrologic regime or sediment supply, structure placement will be most effective when used in conjunction with other measures that restore the channel, hydrologic regime and sediment supply. If the project involves placing wood in the stream, have riparian restoration and management techniques been implemented to ensure a long-term source of wood is available to the stream that will replace the added wood as it decays or washes downstream?

- *Document baseline conditions of the project site.* Baseline conditions should be documented for the purpose of monitoring, liability in the event that there is damage or loss of property, to provide information needed in design, and to determine if conditions are appropriate for the structure under consideration. Analysis and documentation of baseline conditions typically includes the following.
    - A plan view sketch or, when necessary, a contour map. Use this to determine the structure's orientation to flow, its location in relation to the channel thalweg, and structure spacing.
    - General characteristics of bed material. What is the dominant substrate?
    - A channel profile can be used to determine channel gradient, structure spacing, resulting water surface and slope, head developed over the structure and other important details.
    - Cross-section survey at the structure site and a minimum of one channel-width upstream and downstream. Cross-sections should include the flood prone region, high water marks, top of bank, Ordinary High Water line, toe of bank, and at least three points within the active channel, including the thalweg. These cross-sections are easy to survey and provide the basis for determining important parameters such as structure constriction and height, and channel width and confinement. The depth of flow and, thus, shear stress on the bed and banks of the channel during high flow events increase with the degree of channel confinement. This increases the potential for boulder, wood, or other material transport and for bed and bank scour.
    - Condition of the banks. Are they relatively stable or actively eroding?
    - General assessment of the lateral and vertical stability of the channel and the overall stability of the watershed. Is the channel aggrading or incising in the vicinity of the site? If the channel is actively incising, has the cause of channel incision been identified and addressed? If not, the channel may continue to incise downstream and undermine or create a fish passage barrier at the lowermost structure.
    - Does the channel carry a relatively high bed or debris load? High gradient, high bedload channels can wear away structures placed in the stream (especially wood). Bed material and wood may become trapped on or upstream of the structure, potentially increasing its backwater effects and redirecting flow. Limiting the potential backwater effects of a structure may be desirable where wood accumulations could compromise the project or adjacent infrastructure.
    - Additional baseline data may be required for any monitoring planned at the site. The scope and nature of such an assessment depend upon monitoring objectives. Note that photo documentation of site, upstream, and downstream conditions is often valuable. Provide a brief written description of each photo.
- *Evaluate structure stability.* What is the necessary design life or design discharge of the structure? What kind and size of material will be necessary to meet those design criteria?

- *Material selection*. Structures are typically designed and constructed using either rock or large wood but may also be constructed using synthetic materials, such as concrete, sawn timber or steel. The selection of materials should be based primarily on its ability to meet restoration objectives and design criteria, which may include blending with natural material in the stream, project life, and deformability.
- *Evaluate access and materials availability.* Access to the site and availability of materials may influence structure design and construction as well as remediation or mitigation requirements. What access routes and staging areas are available? Will they limit the type of equipment, and therefore, the type and volume of material, that can be utilized? What impacts are likely to occur as a result of ingress and egress of equipment and materials? Will the cost or availability of materials limit the design? Refer to the *Construction Considerations* appendix for further discussion of access roads and implications to design, feasibility, and disturbance reclamation and mitigation.
- *Document the location and nature of instream and nearby infrastructure and utilities that may benefit or be harmed by the proposed structure.* This is best done in conjunction with developing good plan, profile and cross-section drawings of the site and reach. The presence of infrastructure will likely place limitations upon flow redirection, structure location and configuration, and the degree of allowable backwater.
- *Biological assessment*. Biological assessment of existing conditions within the project reach and associated riparian wildlife habitats is essential to develop appropriate design criteria and project solutions and to document baseline habitat use conditions. Biological assessment may include availability and distribution of spawning, rearing, high flow refuge, cover, and pool habitat as well as wetlands, riparian areas and associated uplands. Particular attention should be paid to priority habitats and species (http://wdfw.wa.gov/hab/phspage.htm) so that the project does not contribute to the loss of valuable wildlife habitat. Further information about and guidance on the value and application of biological assessment is provided in Stream Habitat Restoration Guidelines Chapter 3, *Stream Habitat Assessment*. The content and level of detail of a biological assessment will be dictated by the objectives of the project and the potential risks it poses to fish and wildlife. For example, a full spanning structure is legally required to provide fish passage over or through it and so will require a thorough assessment of species present. Additional information, such as an assessment of populations upstream and downstream of the project site and at a reference or control site may be necessary as a baseline assessment for subsequent monitoring of project success and impacts. The local state Area Habitat Biologist, Fish Biologist, and Wildlife Biologist should be consulted for additional information on local aquatic fauna
- *Will the placement adversely affect recreational navigation*? What measures can be taken to minimize public safety risks?
- *What are the potential impacts to upstream, downstream, and adjacent habitat, fish and wildlife, infrastructure (including utilities), and public safety during and following construction if the project succeeds, or if it fails structurally*? What is

the probability of those impacts occurring? What factors influence that risk (e.g., degree of channel confinement, slope, bedload, high flow events, material selection, structure configuration)? What can be done to minimize the risk? Is the risk acceptable?

- *Budget.* Cost is often a limiting factor in design and must be balanced with the level of acceptable risk. Lesser budgets may not allow for detailed design. In addition, cost may influence the number or size of the structures, the size or type of materials or equipment used to construct or place them, or the extent and scope of the project.

In relatively small, low energy streams where there is minimal risk to infrastructure, habitat, and public safety, elements of the design may be based on observing natural analogs at reference sites, rather conventional hydraulic or civil engineering analysis. For instance, the necessary size of material, structure configuration, and the anticipated depth of scour can be estimated by observing stable structures located in similar channel reaches operating under similar conditions. However, high risk projects, high cost projects, and projects conducted on larger streams (greater than 20’ wide), on steeper or more confined channels, and in close proximity to infrastructure may have additional data collection and assessment requirements. These could include, but are not limited to:

- *Hydrologic analysis*. Hydrologic analysis may be necessary to generate discharge values used in design and to evaluate potential impacts to the channel or nearby property. Common design discharges applied to design of structures include:
  - Low fish passage -flow
  - High fish passage flow
  - Dominant discharge
  - Maximum design discharge where structural integrity will be maintained. The design discharge will vary with the objectives of the project and risk associated with structural failure.
  - Flood discharge - 100-year discharge for determining impacts on regulatory flood flows

  A discussion of hydrologic statistics and their derivation is available in the *Hydrology* appendix.
- *Scour analysis*. Most structures create some degree of scour. The integrity of many structures depends, to some extent, on their depth of installation relative to the depth of scour. Critical flow conditions can occur at the crest of the structure with supercritical flow possibly occurring along the face of the structure at certain flows. These conditions create a hydraulic jump downstream of the structure that can cause bed or bank scour. The *Hydraulics* appendix defines varying types of scour under various site conditions, and how to estimate depth of scour. Data required for scour analysis depends on the type of scour evaluated. While scour can be evaluated empirically in some instances, analysis usually requires a minimum of three cross-sections (one at each structure plus upstream and downstream of the structure), a channel profile survey (extending upstream and downstream of the project for a distance of at least 200-ft above and below the first and last structure or 10 bankfull widths), and an evaluation of the bed substrate distribution. Substrate size should be estimated by sieve analysis, Wolman pebble count, (both of which are detailed in the

Sediment Transport appendix) or some other acceptable method. At a minimum, one representative substrate sample should be taken at each structure location. Significant changes in substrate composition along the project reach should be noted.

- *Sediment transport*. Sediment transport analysis may be necessary where large-scale backwatering effects are likely or where the project is intended to trap sediment or otherwise affect sediment transport (alter channel width, depth, or slope). Such effects are more likely to occur when a series of structures are installed. Local, individual structures will most likely affect scour and sorting without impacting general sediment transport characteristics through a reach. Sediment transport is a function of channel hydraulics (slope and depth in particular), sediment size, and volume of sediment supply. The evaluation of sediment transport is detailed in the *Sediment Transport* appendix.
- *Hydraulic analysis*. Hydraulic parameters for design include flow depth, velocity and bed shear. These parameters should be estimated for a range of flows for existing and post-project conditions. Common design discharges applied to design of structures are discussed above in *Hydrologic analysis*. These parameters will be used to size rock, wood, and other materials, and demonstrate fish passage conditions are met. Hydraulic design in a natural environment, using natural materials, necessarily involves a significant degree of uncertainty. Equations and methods presented in the *Hydraulics* appendix are useful in the analysis and design of instream structures. These tools should be employed with an understanding of the variability in natural stream systems and sound professional judgment.
- *Backwater analysis*. This effort will help identify potential flooding locations, both pre- and post-project. In some cases frequent floods or excessive flood elevations have to be avoided. In others, one of the main objectives will be to restore floodplain function and connectivity with the channel. A backwater analysis can help determine if the design will achieve that goal at the design discharge.

3.3 Expertise Required for Design

Certain analyses and design processes will require specialized expertise. 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 typically only available to professionals with specialized training in engineering. The degree of expertise required to design and install instream structures will also be determined by the risk imparted to property, infrastructure, public safety and the environment due to both the presence and failure of the structure. For example, if a project has the potential to cause significant backwater that could compromise an upstream road via accelerated bank erosion and increased flooding, practitioners whose experience enables them to select and apply appropriate analytical methods to quantify and minimize the risk should conduct its design. Similarly, if failure of a drop structure has the potential to compromise the integrity of a high-pressure sewer line and cause significant damage to the ecosystem and public drinking water, that structure may be required to withstand all hydraulic forces up to a 100-year discharge. To ensure such integrity, its design should be conducted by someone experienced with modeling the forces associated with all flows up to the 100-year discharge and analyzing scour. They should also be familiar with the physical qualities of materials being used and their ability to withstand calculated forces.

On the other hand, less expertise is required to undertake small projects in areas where little is at risk if the structure fails to meet project objectives or if it fails structurally. Such designs could be effectively conducted using an analog approach (whereby a practitioner replicates features and structures found in nature[27]) by individuals familiar with stream processes, fish habitat requirements, and an appreciation for the unpredictability of the natural environment.

4 PERMITTING

Installation of structures necessarily involves in-channel work, streambed and bank 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 a Section 404 Permit). A Clearing and Grading Permit, Washington Department of Natural Resources Use Authorization, and an Endangered Species Act Section 7 or 10 Consultation may also be required. Refer to the *Typical Permits Required for Work In and Around Water* appendix for more information regarding each of these permits and checklists, and other permits that may apply.

5 MONITORING

When designing instream structures, long-term monitoring and maintenance may be a pending issue. Monitoring conducted at the site depends on project objectives and the risks it imparts on property, public safety, infrastructure, fish passage, and the environment. Potential questions include: Did the structure stay in place? Does the structure provide unobstructed fish passage? Is infrastructure, property, public safety, or fish and wildlife compromised or at risk as a result of the structure? Is maintenance required? How has the habitat changed since the addition of the structure? Does the structure provide favorable fish and wildlife habitat (for what species, season, and age class)? Did the treatment affect overall fish and wildlife production in the system? Did the treatment prevent further erosion of the bank (if applicable)? The level and frequency of monitoring required will vary with monitoring objectives and project risk. Low risk projects may simply warrant annual site visits and a documentation of qualitative observations regarding patterns of scour and deposition, bank erosion, fish use, and structure stability. On the other hand, projects that pose a relatively high risk to infrastructure, property, public safety, or the environment may require frequent quantitative physical and biological surveys to be conducted. Such surveys may include taking photos, pre- and post-construction snorkeling of the site and a reference reach to document fish use, and detailed surveys of structure locations, channel cross-sections, and channel profiles to document changes over time. Annual monitoring would be required to insure unobstructed fish passage where it may be compromised by the presence of the structure. Refer to the *Monitoring Considerations* appendix for guidance on developing and implementing a monitoring plan.

6 MAINTENANCE AND MONITORING

Maintenance requirements for instream structures will be revealed through regular monitoring. It varies with the type of project. In general, maintenance will only be necessary if the structures do not meet project objectives or if unintended and unacceptable consequences have occurred. Maintenance or repair should be completed only after careful evaluation to determine the cause of project failure to avoid repeating the same mistake. Maintenance may include replacement, adjustment, or removal of the entire structure of elements of the structure, clearing of accumulated debris, or installation of additional structures. The legal requirement to provide fish passage necessitates that any necessary repairs to restore fish passage be identified and promptly addressed.

7 GLOSSARY

Structure - any object in a channel that protrudes from the bed or bank and creates an obstruction to flow within the channel

Stage – the elevation of the water surface in a channel relative to some arbitrary benchmark

Dominant discharge - the flow that produces the greatest morphologic effect over an extended period of time

Flow vectors – a quantity consisting of both magnitude and direction, which in the case of stream flow typically denotes velocity and direction in the horizontal plane

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BOULDER CLUSTERS

1 DESCRIPTION OF TECHNIQUE

This technique describes the strategic placement of large immobile boulders (>1 cubic yard) and boulder clusters within homogenous sections of streams to increase or restore structural complexity and hydraulic diversity. Plane bed stream reaches may occur naturally or as a result of both direct and indirect human activities that simplify a channel. Direct human activities may include modifications of the channel (e.g. levee construction, bank hardening, channel straightening, dredging, wood removal). Indirect human activities alter watershed processes by reducing the source of roughness elements (e.g., trees) for delivery to the stream or, on a larger scale, contribute to an increase in peak flows that often leads to channel incision and scouring out of roughness elements from the reach (e.g. long-time deforestation, urbanization). The loss of roughness elements and simplification of the channel results in a loss of habitat diversity and complexity, that has a pronounced effect on the abundance, composition, and distribution of aquatic biota inhabiting that area. Structural and hydraulic diversity is important to a broad variety of organisms including aquatic insects, fish, amphibians, mammals, and birds. Much of the impetus behind the use of this technique, however, centers on providing holding and rearing habitat for fish, principally salmonids[1], and on sorting bed material to improve fish spawning habitat.

Boulder placement has been used successfully throughout North America to enhance fish habitat. Though this discussion is limited to placement of individual boulders and clusters of boulders, boulders may also be used as a component of larger structures to concentrate scour (see *Porous Weirs*), provide grade control (see *Drop Structures*), provide bank protection (see *Barb, Groin, Riprap*, and *Rock Toe* techniques in the Integrated Streambank Protection Guidelines[2]), and to provide ballast for logs (see *Placement and Anchoring of Large Wood* appendix).

This technique provides some immediate benefits (e.g., cover, refuge) and works in conjunction with stream flow to create and maintain additional habitat. It has short- or long-term effectiveness, depending on the stability of the channel and site conditions.

2 PHYSICAL AND BIOLOGICAL EFFECTS

Placement of individual boulders and boulder clusters within the stream channel creates a diversity of water depth, substrate, and velocity, thereby increasing habitat diversity of an otherwise plane bed stream. Increased diversity is evident immediately after boulder placement and improves over time as substrate is scoured and sorted during high flow events. Diverse habitats can support a greater diversity of species and age classes than homogeneous habitats; of course use of these habitats depends on the species present in the system. Boulders provide cover in the form of interstitial spaces between the boulders, relatively deep water, air bubbles, and turbulence[3] and they create water velocity gradients, where slow water velocities occur in close proximity to faster ones. As cited by Ward[4], the presence of water velocity gradients is desirable for many fish species, including both juvenile and adult salmonids, because it allows them to maintain a position near the faster, food-delivering current without expending much energy. The enhanced structural complexity associated with boulders also allows for increased fish densities within these energetically favorable environments. In the absence of sufficient refuges from higher velocity, the energetic costs to fish occupying such habitat increase dramatically. Moreover, such velocity-homogeneous habitats tend to be food poor. Both of these factors translate to fish that are in poorer physical condition and have diminished survival.

In addition to benefiting fish, the microhabitat created by boulders provides localized refuge or reproductive habitat for a variety of other aquatic organisms. For example, the downstream face of a boulder, which experiences lower velocities, is often preferably selected as an attachment site for caddis flies, mayflies, and stoneflies, dominant invertebrates in many stream systems.

Boulders confine and direct flow, typically creating bed and/or bank scour in the immediate vicinity of the stones and depositing sorted bed material downstream[5]. These scour pockets provide cover and forage habitat for fish during low flows. Whether or not scour occurs depends heavily on sediment transport dynamics. Scour will occur only where the shear stress induced on the bed is sufficient to scour out the bed material. For this reason, scour pools may not develop in backwatered channel reaches, channels comprised of relatively large bed material (e.g., cobbles), and in low energy sites such as certain off-channel or side-channel habitats. The benefits of boulder clusters will also be diminished in channels that carry relatively high levels of fines that tend to fill the interstitial spaces. Where such conditions occur, upslope rehabilitation techniques may be required before, or used in conjunction with, boulder cluster placement to reduce sediment delivery rates and insure sediment conveyance is maintained near the boulders. Habitat benefits will be limited to cover in backwatered areas.

Depending on the pattern, spacing, and location of boulders and the degree to which they confine flow, boulders may have a backwater effect on the upstream reach of the channel. Backwater can cause upstream deposition, a localized increase in floodwater stage, and can increase the likelihood of bank erosion and channel avulsion in the area of deposition. This backwater effect may be caused by the boulders themselves or by the boulders in combination with any sediment and wood that becomes racked up against them. Backwater is most likely to occur when boulders are placed at or near the riffle crest. When placed in the lower section of riffles, boulder clusters act to stabilize the riffle crest and transfer scouring forces to the downstream pool. The potential for unanticipated scour, deposition, flooding, and streambank erosion must be considered.

The longevity of benefits provided by boulder placement depends on sediment transport dynamics that, in turn, depend on the hydrologic and sediment regimes of the stream. Benefits provided by boulder placement will be short-term if the boulders become mobile during frequent storm events. But even if the boulders remain in place, their effects may be short-lived if they are placed in deposition zones where they become buried in sediment or in readily scoured material, such as fine-grained or unstable beds. When placed in readily scoured material, boulders will tend to sink into their own scour holes. The lateral stability of the stream reach also plays a factor in project longevity. In dynamic channels, placed boulders may be abandoned as the channel shifts and migrates, or they may end up in unintended locations. In either case, the durability of benefits will depend on the rate of change within the channel.

The placement of boulders may result in disturbance in the form of increased turbidity and rearranging of bed material during construction activity. Construction impacts, and ways to reduce them, are discussed in the *Construction Considerations* appendix. Consideration should be given to the potential habitat impacts to source areas for boulders, access to and from the source area, and to and from the installation site. Access and staging areas may experience short-term impacts and may require reclamation or mitigation. Disturbance will vary with the ease of access, equipment chosen for construction, and the skill of equipment operators.

3 APPLICATION

This technique can be used to restore habitat diversity to plane bed streams from which boulders have been removed. (Boulders may have been removed historically to facilitate navigation and wood transport.) It can also be used as an enhancement technique to increase habitat diversity in new channels, naturally plane bed stream reaches, and altered plane bed channels that were historically dominated by wood. Due to the dynamic nature of wood movement in streams, in-stream boulder placement may be a preferred alternative to wood when a static condition is desired (movement of channel roughness elements is not acceptable), wood of adequate size is not available, and when the source of adequately sized wood to the stream will take decades to recover. Boulder clusters should only be applied where a biologic or geomorphic need has been identified.

When identifying potential boulder placement sites, consideration must be given to what locations will provide the most biological benefit. The intent of this technique is to provide cover and favorable holding and rearing habitat for fish while providing a mechanism for substrate scour and sorting. However, sites that are attractive from a biological standpoint may not necessarily be attractive from a hydraulic standpoint (excess scour, degraded bank stability) or may pose an unacceptable level of risk. Thus, site selection will require consideration of both biological and hydraulic conditions.

Boulder placement projects are usually intended to provide habitat benefits on a small (relative to channel size) localized scale. They are most effective in wide, shallow streams with gravel or cobble beds[6]. They are not recommended in fine-grained streambeds as bed scour in the vicinity of boulders may undermine them and cause them to fall or sink into their scour holes . Boulder placements in bedrock channels may not be able to resist shear forces that would propel them downstream. Flosi et al.[7] state that boulders and boulder clusters should be “located in straight, stable, moderately to well-confined, low gradient riffles (0.5 to 1 percent slope) for spawning gravel enhancement and in higher gradient riffles (1 to 4 percent slope) to improve rearing habitat and provide cover”. Slopes that exceed 4 percent typically exhibit step-pool channel morphology. Most streams that have a low sediment supply would already have incised into stable boulder step pools or bedrock channels. These channels easily transport incoming sediment downstream. Channels greater than 4 percent that are entrenched or incised into glacial, alluvial or colluvial depositional material provide much more sediment to the channel. These step pool channels are much more unstable and can be associated with debris torrent tracts or active glacial environments that are common in the Northwest. Therefore, channels greater than 4 percent slope start to become inappropriate for boulder placements because they are either already boulder step pool channels with no additional need for boulders or unstable entrenched channels with active bank erosion. Boulder placements would tend to increase bank instability in these environments. Boulder placements in bedrock channels scoured by splash dam activity or large wood removal is an example of a potential project in this gray area between appropriate and inappropriate work gradients. Work in gradients exceeding 4 percent requires a more thorough geomorphic and hydraulic analysis.

Avoid placing boulders in depositional areas, such as aggrading channels or braided channels, as they may be buried in sediment and become ineffective or abandoned during a channel shift. Caution should be exercised in incised or incising channels. In addition to boulder stability concerns, boulder placements in unstable incising beds may create conditions that accelerate lateral erosion. Incised channels that have lower gradients (less than 4 percent) often become laterally dynamic because hydraulic forces are typically confined within an entrenched channel rather than being distributed over the floodplain. This increases hydraulic shear on bank material that can accelerate bank erosion. Boulders may exacerbate this process. Consequently, boulder placement in incised channels requires a greater degree of geomorphic and hydraulic scrutiny to determine consequences and risk needed to form a plan of action.

In watersheds that have become unstable from development, forest management, or other land use activities, boulder clusters, as with any in-stream restoration work, are best used in conjunction with watershed restoration techniques that address the cause of watershed instability. Improving road drainage and stormwater management, revegetating streambanks and unstable slopes, or removing unnecessary and degrading roads to improve natural drainage patterns and limit the increase in peak flow hydrology are examples of upland restoration activities that would facilitate successful channel restoration and boulder applications.

Additional boulder application considerations are provided in Methods and Design.

4 RISK AND UNCERTAINTY

Boulder placements are relatively low risk treatments in streams provided they block a relatively small proportion of the bankfull flow area and thereby limit their hydraulic influence on the channel. However, where boulders, or the bed material and wood that racks up on them, significantly confine a channel or collectively increase the roughness of the reach by a significant amount, the upstream channel may become backwatered, causing deposition (in streams that carry high sediment loads), localized flooding, and bank scour. There is also an increased risk of channel avulsion. Even where the encroachment of boulders on bankfull channel area is low, boulders redirect flow and may cause adjacent or downstream banks to erode.

In some stream channels boulder treatments have a greater degree of uncertainty and risk. The following are examples of situations that point towards a greater degree of complexity, risk or uncertainty.

- *High gradient, confined, or bedrock channels.* Boulder stability will be more difficult to achieve.
- *Channels with high natural sediment loads.* Boulders increase channel roughness. This

could potentially result in sediment deposition and instability near the boulders. This is more likely in lower gradient alluvial streams because sediment transport thresholds are easier to achieve. Non-alluvial steeper channels and incised streams tend to transport incoming sediment much more easily and deposition isn't as likely to occur.

- *Watersheds with changing hydrologic or sediment regimes.* These are deceptive environments because existing channel dimensions and substrate are undergoing change. Assuming existing conditions are stable and designing under that premise will result in failure if elevated sediment and hydrology increase due to present or future development. This is common in urban and suburban growth watersheds.
- *Incised channels.* These channels have been previously disturbed. Understanding what caused the disturbance and recovery processes that are underway are important before adding boulders to the channel. Another factor to consider in incised channels is that boulders can accelerate lateral bank erosion. Whether this is desirable depends on factors such as infrastructure near the site, existing watershed stability, future habitat goals and riparian complexity goals. In previously incised but now vertically stable streams, lateral erosion provides more space to develop channel and riparian complexity. In this sense boulders can provide the same hydraulic and geomorphic influences as large wood material.

These examples underscore the need to understand stream sediment loads, watershed stability, bed and bank mobility, and long-term habitat goals before designing boulder habitat.

4.1 Risk to habitat

Boulder placements typically pose a low risk to existing habitat. Potential impacts would include temporary loss of habitat value associated with rearranging gravels through scour or burial of habitat through deposition. However, in these instances, habitat lost will probably be offset by habitat or habitat value gained, and therefore risks are only short-term and should not persist beyond the first high flow event. Risk to habitat increases if boulders create upstream backwater that causes large-scale deposition, potentially leading to chronic dredging of the channel or to channel migration or avulsion.

4.2 Risk to infrastructure and property

When boulders are located relatively low in the channel profile and don't direct flow into banks, boulders pose minimal risk to infrastructure and property. However, there is the risk of excessive bed or bank scour, catching of debris, and upstream deposition causing a localized increase in flood stage or lateral channel migration that places nearby infrastructure at risk.

4.3 Risk to public safety

Risk to the safety of boaters associated with physical obstructions in the stream and resultant channel hydraulics is a concern. When possible, consult with the local boating community to educate, inform and collaborate.

4.4 Uncertainty of technique

Though there is a relatively low risk of boulders being transported far downstream, there is a fairly high degree of uncertainty in boulder placement design and performance. Boulder placement design ideally should consider sediment budgets and local hydraulic interaction between complex boulder shapes and flow vectors that vary with discharge. But both of these evaluations can be complex and uncertain, and typically require a level of effort that is unjustified in light of the low risks associated with typical applications. Even if boulders perform hydraulically as anticipated, the anticipated biologic benefits may not be realized or they may be shorter-lived than expected.

5 METHODS AND DESIGN

5.1 Data and Assessment Requirements

Although boulder placement has been successful in habitat creation, the risk of inadvertently causing problems should not be ignored. Consider the factors outlined below when planning and designing boulder placement projects. If needed, consult with a fisheries biologist, hydrologist and/or geomorphologist to help answer questions and provide guidance. While the primary intent of introducing boulders may be to create habitat, one must carefully consider the geomorphic, hydraulic, and biologic ramifications associated with the introduction of large roughness elements.

The amount of data collection and assessment required will be dictated by the project scope, availability of existing information, and by the degree of acceptable risk in implementation. The *General Design and Selection Considerations for In-Stream Structures* includes a discussion of the minimum data and analyses typically required for in-stream structure placement. Those and additional requirements relevant to boulders are listed below.

- *What are the objectives of boulder placement?* Are boulder clusters the best alternative to meet those objectives?
- *Conduct a biological assessment.* What species are present in the area and what are the limiting factors affecting their growth and survival? Document existing habitat features and use. This assessment is important to determine whether the treatment has a chance of relieving those limiting conditions and yielding the desired biological effects.
- *Document baseline conditions of the channel and bed material.* Are they appropriate for the use of Boulder Clusters (refer to Section 3, *Application*)? Such an analysis may include:
    - Evaluation of existing flow patterns. How will boulder placement change them?
    - Dominant substrate
    - Channel gradient. The shear stress on the bed and banks of the channel increase with channel gradient. This increases the potential for boulder transport and bed and bank scour. Steeper streams are more powerful and can do more work per unit discharge.
    - Cross-section survey(s)
    - Condition of the banks. Are they relatively stable or actively eroding?
    - Degree of channel entrenchment. The depth of flow and, thus, shear stress on the bed and banks of the channel during high flow events increase with the degree of entrenchment. This increases the potential for boulder transport and bed and bank scour because velocity and depth have increased along with the ability to move larger and greater sediment volumes.
    - General assessment of the lateral and vertical stability of the channel and the

  overall stability of the watershed. Is the channel aggrading or incising in the vicinity of the site? Is the watershed unstable and at risk for increased debris flow activity?
  - Additional baseline data may be required for any monitoring planned at the site. The scope and nature of such an assessment depend upon monitoring objectives. It may include, but is not limited to, documentation of fish presence and abundance at treated and control sites, fish use of the area, spawning gravel quality, pre-construction bed topography survey, as built survey, or a qualitative description of habitat and habitat complexity, among other things.
- *Conduct a scour assessment to determine the minimum design depth of boulders, estimate likely pool habitat development, and identify any threat to infrastructure.* In low risk projects, observing the depth of scour associated with other in-stream structures may be sufficient to estimate the likely depth of scour associated with boulder placement. In higher risk projects, a scour analysis may be necessary.
- *Evaluate boulder mobility*. What is the necessary design life or design flow of the structure? What kind and size of material will be necessary to meet those design criteria? In low risk projects, determining the size of boulders currently maintained in stream reaches with similar characteristics (e.g., width, depth, slope, flow, degree of confinement) may be sufficient. In higher risk projects, incipient motion and scour analyses will likely be necessary as part of design.
- *Evaluate access and materials availability*. These impact the type of equipment used, the construction schedule, and the cost of the project. What impacts are likely to occur as a result of ingress and egress of equipment and materials? Will in-stream and riparian site conditions permit construction? Will the cost or availability of materials limit the design?
- *Document the location and nature of in-stream and nearby infrastructure that may benefit or be harmed by the proposed structure.* This is best done in conjunction with developing good plan, profile and cross-section drawings of the site and reach. The presence of infrastructure will likely place limitations upon flow redirection and the degree of allowable backwater.
- *Will the project adversely affect recreational navigation*? What measures can be taken to minimize public safety risks?
- *What are the potential impacts to upstream, downstream, and adjacent habitat, fish and wildlife, infrastructure, and public safety*? What is the probability of those impacts occurring? What factors influence that risk (e.g., degree of channel confinement, slope, bedload, high flow events, material selection)? What can be done to minimize the risk?
- *Develop a plan view sketch or contour map, as necessary, to illustrate current and proposed conditions and boulder placement.*

Projects with a greater degree of complexity, risk or uncertainty (refer to Section 4, *Risk and Uncertainty*) should have project site hydrology, scour analysis, hydraulic analysis and sediment transport characteristics completed before boulder project designs are implemented. Such projects may require a reach-scale assessment. A site scale assessment should be sufficient for design and monitoring of isolated boulder or boulder cluster placements in low risk stable channels as such placements typically do not have reach-scale impacts.

Adjacent reaches with natural analogs can provide very useful design information, including:

- Minimum boulder size
- Spacing between boulders in a cluster
- Spacing between boulders and banks, or effective location within the channel
- Boulder density
- Boulder pattern and orientation
- Anticipated effects, including scour and deposition zones and depths

5.2 Boulder Placement

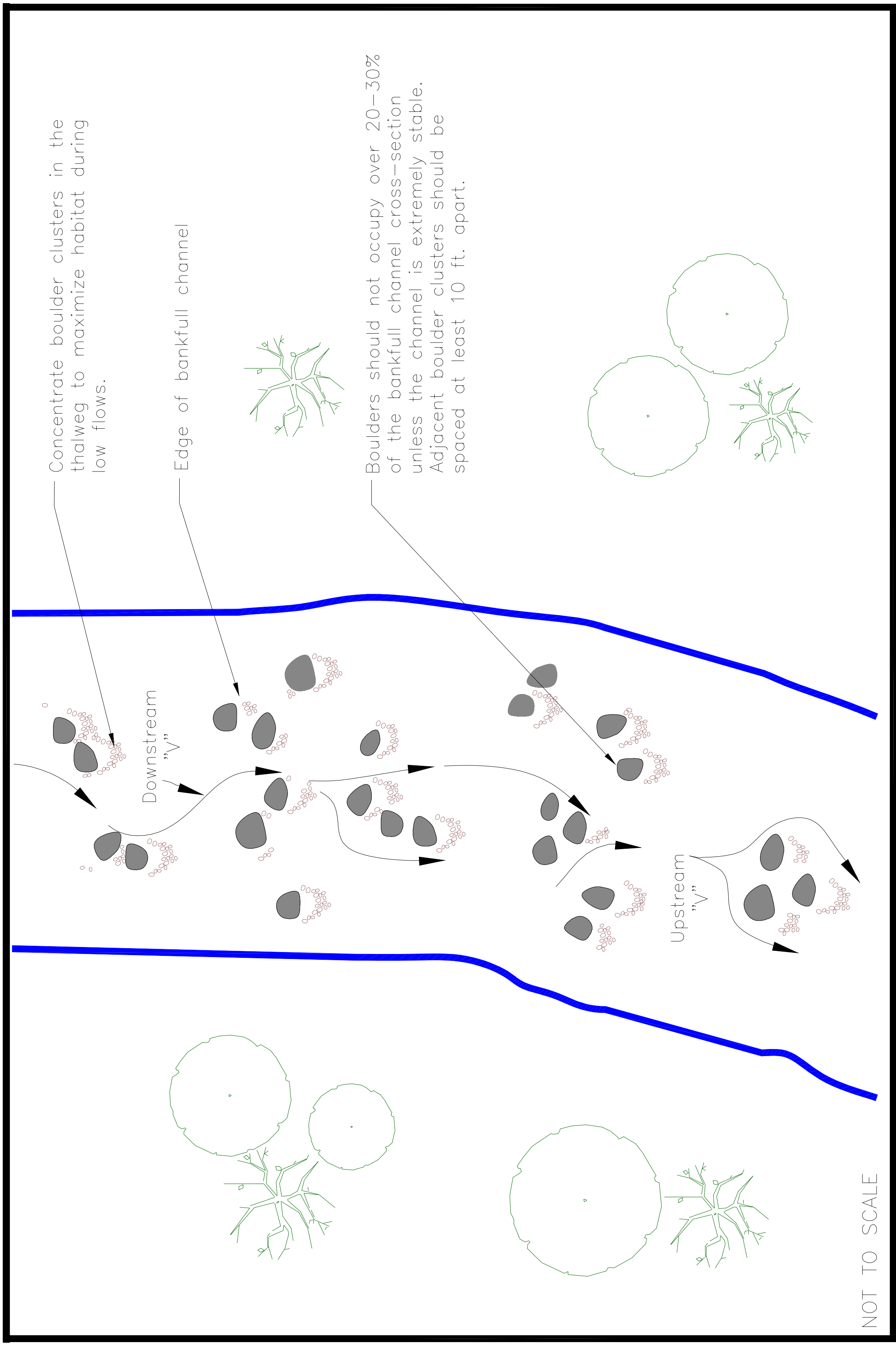
Generally, boulders should be placed in random patterns that replicate natural stream conditions and do not substantially modify overall stream hydraulics. By keeping the hydraulic influence of boulders to a low or moderate level, the designer can create local scour while minimizing the risk of unintended consequences such as excessive bed or bank scour, debris collection, upstream deposition and backwater, higher water surface elevations, and increased risk of channel avulsion. To limit their hydraulic influence, boulders should not be allowed to block a significant portion of the channel cross-section and should be kept relatively low in the channel profile. As cited by Johnson and Stypula, the Oregon State Highway Division[8] suggests that boulder placements not block more than one-third of the bankfull channel area at any cross-section. Johnson and Orsborn[9] suggest limiting bankfull area blockage to 20 to 30 percent. The Federal Highway Administration[10] recommends that a maximum of one fifth of the low flow capacity should be reduced if the gradient of the stream channel is less than three percent. It is recommended that boulders be completely submerged during bankfull discharge.

Boulders can trap and retain wood on the upstream side of the boulders. This can create excellent rearing habitat around the boulder. During high flow events, accumulated wood will float over the top of the boulder and downstream as stage rises, provided the boulders are completely submerged. If overtopping flows occur on a relatively frequent basis (e.g., bankfull flow), it will prevent a large buildup of wood and reduce flood and bank erosion risk. However, if boulders extend to or above the bankfull elevation, wood may not be dislodged and instead may accumulate, thereby increasing the hydraulic and backwatering impacts of the structures which may or may not be desirable. In high-risk situations, the potential scour and backwater effects and potential interaction of wood can be quantified with the use of hydraulic models. A design elevation for the boulders can then be determined so as to limit undesirable consequences. Calculation of scour and backwater are detailed in the *Hydraulics* appendix.

Boulder location is also a factor in the likely occurrence of upstream deposition and channel avulsion. Ward states that boulder clusters placed at or near the riffle crest are more likely to cause aggradation and diversion than those placed further downstream. Boulders placed in the bottom half of riffle habitats will tend to be more stable, less likely to fill in with bedload, and less likely to create large scour holes. Boulders placed near the thalweg of the stream, typically within the middle two quarters of the channel width, will maximize the availability of boulder-created fish habitat during low flow.

Boulders are most frequently installed as a clustered arrangement of several individual boulders due to the increased habitat benefits they provide over single boulders . Groups of boulders create a greater range of velocity and depth conditions and more abundant living space than a single boulder can; there are many void spaces in between boulders that provide velocity refuge and cover that don't exist with a single boulder. Rock clusters also provide a greater opportunity to catch and trap wood material if that is desired.

Clusters typically consist of three to seven boulders that are spaced 6 inches to 3 feet apart, the distance increasing with the size of the stream (see to **Boulder Cluster Figure 1**). Clusters should be located 10 to 12 feet apart[4 9] to allow passage of bed material and floating wood and limit the reduction in streamflow capacity. Bearing this in mind, boulder clusters should be arranged to compliment each other and work together to direct flow into areas where scour is desired (particularly at bankfull discharge) and away from those where it is not (e.g., an eroding bank supporting critical infrastructure). Boulder clusters should guide flow into and through natural channel meander bends. For example, boulders could be placed to accelerate flow into a natural bend to deepen the scour pool during bankfull stage. The next set of boulders downstream should then complement the upstream locations by being far enough downstream to prevent a backwater that would reduce the upstream scour objectives and be in line with the natural stream thalweg coming out of the upstream bend. Where flow redirection is the primary project objective of boulder placement, porous weirs may offer a complementary or alternate technique to boulder clusters. Further details on their application and design are provided in the technique titled *Porous Weirs*.



Concentrate boulder clusters in the thalweg to maximize habitat during low flows.

Edge of bankfull channel

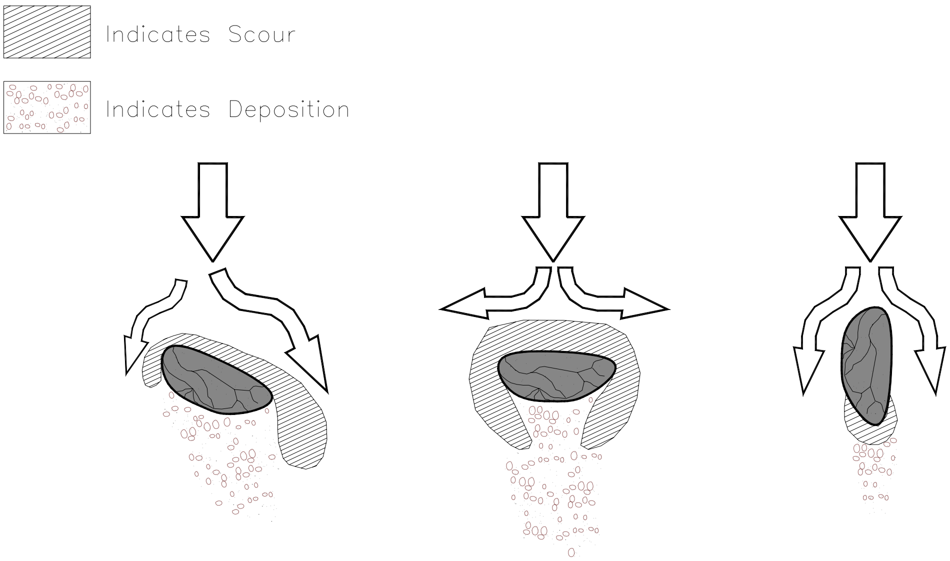
Boulders should not occupy over 20–30% of the bankfull channel cross-section unless the channel is extremely stable. Adjacent boulder clusters should be spaced at least 10 ft. apart.

STREAM HABITAT
RESTORATION GUIDELINES
http://www.wa.gov/wdfw/hab/ahg/shrgdoc.htm

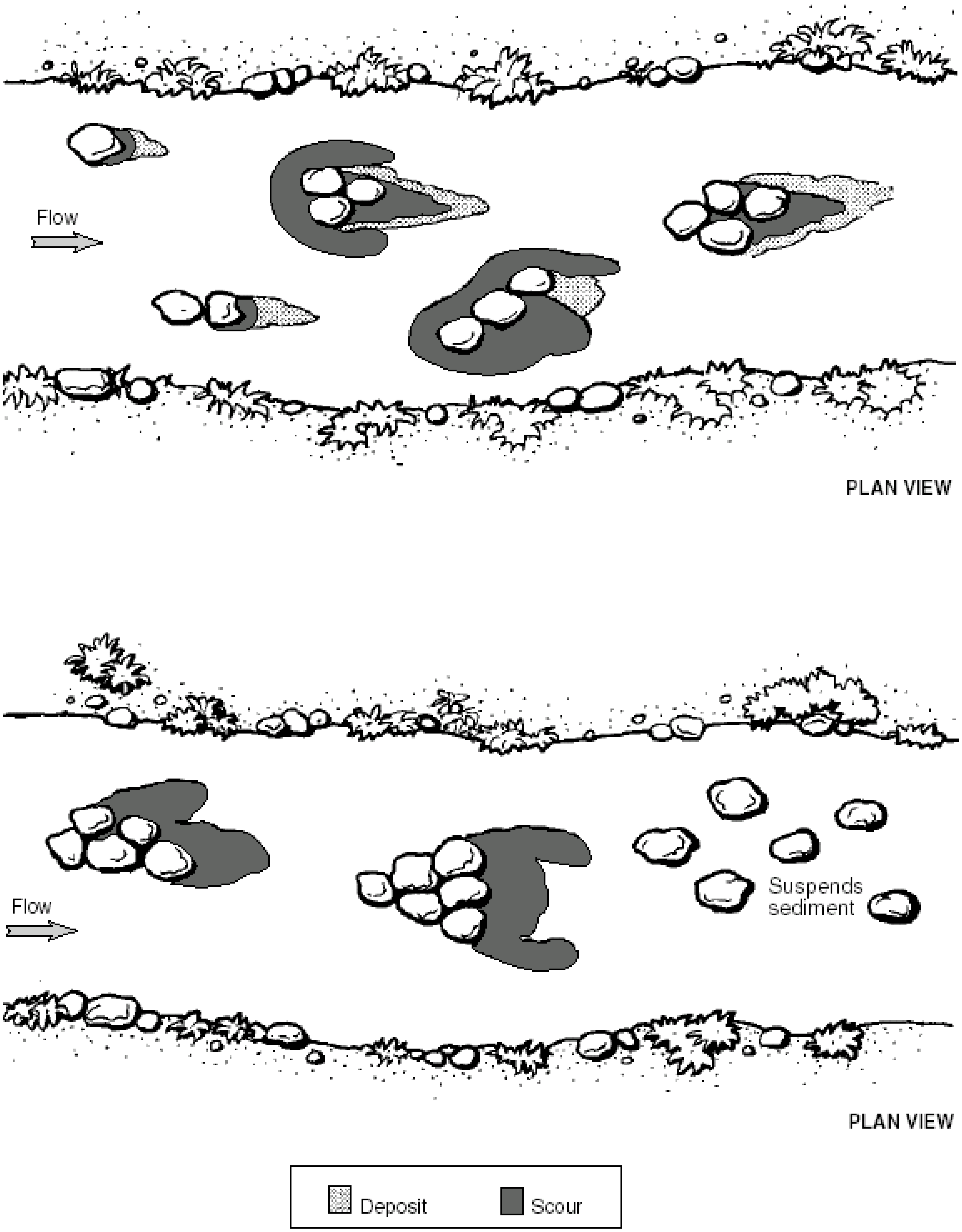
BOULDER CLUSTERS
CONCEPTUAL DESIGN

FIGURE 1

Boulders divide and redirect streamflow around them. The pattern of scour and deposition around boulders is related to the hydraulic action of the site during bankfull discharge. It is a function of the shape of the rock and its orientation relative to that of flow (see **Boulder Clusters Figures 2 and 3**). Rocks and rock clusters with a blunt upstream face placed perpendicular to flow cause an abrupt redirection of flow and create horseshoe-shaped scour around them, the deepest scour occurring at their upstream face. Rocks placed in this orientation are more likely to undermine and tip into their scour holes and to direct flow into nearby banks. They are also prone to being rotated by flow and point flow in a new direction. As a result, Johnson and Stypula recommend that, when using elongated rocks, they be installed with the long axis parallel or at a slight angle to flow, as they will be more stable.



Boulder Cluster Figure 2: Flow redirection as a result of boulder placement.



Boulder Cluster Figure 3: Typical patterns of scour and deposition associated with boulder clusters. Reprinted with permission from Johnson and Stypula (1993).

As scour pools develop in the vicinity of boulders, boulders will likely sink or tip into them unless they are embedded into the streambed to the maximum depth of scour during construction. Rock may be embedded by either digging a receiving hole or by wiggling or pushing the rock into the bed with an excavator. Being embedded should increase the rock's resistance to shear stress. Where movement or rotation of boulders following placement will be unacceptable, embedding the rocks so that their lower edge is at or below the anticipated depth of scour is highly recommended and will lower the risk of unintended consequences caused by rock rotation or by the rock sinking further or not as far as expected. Rocks that sink deeper than expected may become completely buried or protrude very shallowly into flow and provide less habitat benefits than desired. Rocks that remain higher than expected will have a bigger impact on channel hydraulics and debris collection than planned. As cited by Johnson and Orsborn, Cullen[11] found that the depth and extent of scour in the vicinity of boulders increases little with increasing flow once the boulders are completely submerged (once submerged, boulders obstruct a decreasing percentage of the total flow area as flow continues to rise). All else being equal, lower amounts of scour will be generated as the height of rock protrusion into bankfull flow declines.

Designers are encouraged to visit and review earlier boulder projects and natural analogs to familiarize themselves with habitat characteristics resulting from various placement strategies, particularly within the stream in question. Ideally, the size and shape of the boulders, their arrangement and their orientation, should all be based on the watershed hydrology and the hydraulic conditions at the candidate reach. In reaches lacking any natural analogs, detailed scour evaluation should be conducted as part of design. For further discussion of scour and the computation of scour, refer to the *Hydraulics* appendix. If possible, in high-risk situations it may be prudent to proceed stepwise in placement giving each placement time to have its effect before going so far as to cause undesirable results.

5.3 Boulder Materials

Generally, minimum boulder size is of greater concern than maximum boulder size. Boulders that are too small will wash away, or simply fall into scour holes and become buried or ineffective. Boulders should be sized to be immobile at the design flow, and large enough that they will not fall into scour holes and become buried. Considering the cost of completing habitat projects, it is recommended that boulders be sized withstand the shear stress or tractive force generated during the 50-year flow at a minimum, and ideally for the 100-year flow. Lower design flows are acceptable, but there is little reason for such rock forms to be deformable and, therefore, little harm in erring on side of conservative design flows to minimize risks and ensure long-term value. Also, the cost of larger boulders may be inconsequential when looking at total project costs. Any debris caught on boulders magnifies the total shear stress imposed on the boulders substantially during large floods. If these torques and additional forces are not estimated directly and accounted for, the 100-year design flow provides some degree of protection against these additional forces during lesser (20 to 50 year) storm events. The risk of boulder movement increases with channel gradient, water depth, degree of channel confinement, and the likelihood of wood impacting or collecting against them. Material sizing guidance given in the *Drop Structure* technique also applies to boulder clusters. Calculated rock sizes should be verified against the size of boulders that are naturally maintained in the stream.

In general, the designer should strive to use natural materials as much as possible, and to use materials appropriate to the location and stream type. Rock used in porous weirs should be sound, dense, and free from cracks, seams and other defects that would tend to increase its deterioration from weathering, freezing and thawing, or other natural causes. Angular and irregular shaped boulders (e.g., quarried rock) typically provide greater hydraulic complexity and cover than rounded boulders. Angular rock is also less likely to roll[12] and, therefore, offers greater resistance to shear. Most rock-sizing equations and methods are based on angular, durable rock. 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. While angular rock may offer some advantages for stability and habitat, the use of angular boulders can have significant aesthetic impact, particularly in systems that are dominated by rounded rock.

6 PERMITTING

As boulder placement involves in-channel work 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). An Endangered Species Act Section 7 or 10 Consultation or a Washington Department of Natural Resources Use Authorization may also be required. Refer to the *Typical Permits Required for Work in and Around Water* appendix for more information regarding each of these permits and checklists, and other permits that may apply.

7 CONSTRUCTION CONSIDERATIONS

Compared to other in-channel construction, the installation of boulder clusters will have low to moderate impacts on the stream with regards to increased turbidity and rearranging of bed and bank material. The greatest in-stream impacts are associated with digging receiving holes for the boulders within the channel. General construction considerations relevant to all in-channel work, and ways to reduce them, are detailed in the *Construction Considerations* appendix. Principle construction issues relevant to boulder placements include locating, transporting and installing boulders. Permit restrictions may require that additional factors be considered.

Installation of boulder clusters requires careful placement of rock. Rock should never be dumped into the stream. A hydraulic excavator with a bucket and thumb attachment that can comfortably move the boulders for a project is a good choice. Front-end wheeled loaders and track loaders can move boulders but have a limited ability to accurately place them. Clam shell buckets or grapple loader attachments on track machines have a greater degree of refinement or ability to place material exactly where needed but they are limited in their digging ability and strength. Therefore, in most projects an excavator with a thumb is the best all around ground based machine for boulder placement, provided that there are many available access points to the site and the excavator can easily move up and down the stream channel. A long arm excavator (60 feet reach) may be needed to reach over vegetation and put the rock out in the stream channel. However, long reach excavators are limited in their weight lifting capabilities and should only be considered for smaller boulders (less than 2 foot diameter) on smaller streams. Helicopters have been used to place boulders in remote sites that can’t be accessed by heavy equipment. Boulder weight will determine the type of helicopter needed to move the boulders.

Note that motorized wheel barrows, rock bars, winches, and other hand tools may be required where heavy equipment access is limited and to fine-tune boulder placement.

It is possible to work in water if precautions are taken. In many cases boulder placements are very unobtrusive and only require an excavator to walk the boulder to the location and place it. This type of project will produce very little sediment and can be very feasible when implemented during appropriate in-water work windows. It is recommended that fish be removed and excluded from the work area and that hydraulic fluid in heavy equipment be replaced with biodegradable fluid (e.g., vegetable oil) when working in or near moving water.

Except under special circumstances, construction equipment used for placement will not be permitted to operate in flowing water due to the potential impacts to in-stream habitat and biota. The project site will need to be dewatered or else equipment will be restricted to the bank where riparian vegetation will be trampled or removed. Depending on the condition of the riparian zone, the later may or may not be acceptable. Dewatering (discussed in the *Construction Considerations* appendix) facilitates installation, prevents siltation of the stream during construction, and minimizes trampling of habitat and aquatic life.

In addition to in-stream habitat, consideration should be given to the potential riparian habitat impacts to access and staging areas for construction. These areas will probably experience short-term impacts and will require reclamation and revegetation. The number and location of access points must be selected to minimize damage to the existing riparian vegetation. At project completion, disturbed areas, including staging and access areas, will need to be graded smooth, seeded, and planted to repair damage and restore the riparian zone.

Construction should be conducted during a period where impacts to critical life stages of fish and wildlife are avoided. Low-flow conditions are ideal for the placement of boulders and may be essential in situations where dewatering is required. Allowable in-stream 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.

Boulder placement techniques can be conducted either as time and materials contracts or as unit cost contracts (per boulder placed). Unit cost contracts may be most appropriate when using experienced contractors and when placements have been thoroughly planned. Time and materials contracts are more appropriate when considerable uncertainty exists with regards to access and when fit-in-field placement is anticipated.

8 COST ESTIMATION

The costs associated with boulder placement depend on the availability of boulders, proximity of the material source to the site, available access to the site, and the type of equipment used. Access to the stream may be limited to certain locations. As a result, boulders are often delivered to access points and stockpiled. The cost to deliver boulders to the stockpile locations is estimated to be between $35 and $300 per boulder (based on a 3-ft diameter rock).

A hydraulic excavator (with operator) will cost $100 to $150 per hour. With this type of equipment, a laborer ($35 per hour) and a construction supervisor / site engineer ($65 per hour) would be required. The total hourly cost would therefore be about $200 to $250 per hour. Assuming access conditions do not limit progress rates, an average of four boulders could be placed per hour. The average cost for placing each boulder is therefore estimated to be about $50 to $65.

A small helicopter (with pilot) will cost about $1,200 per hour. With this type of equipment, two laborers (one at the stockpile and one at the placement location) and a site engineer would be required. The total hourly cost is therefore estimated to be about $1,335. It is estimated that an average of 10 boulders could be placed per hour. With this method, the average cost for placing each boulder is therefore estimated to be about $135.

The total cost for delivering a boulder to the stockpile and placing it in the river is therefore estimated to range from $85 to $400, depending on whether a hydraulic excavator or a helicopter is used. In some portions of the river, it might be feasible to operate the hydraulic excavator while other portions of the river might require the use of a helicopter.

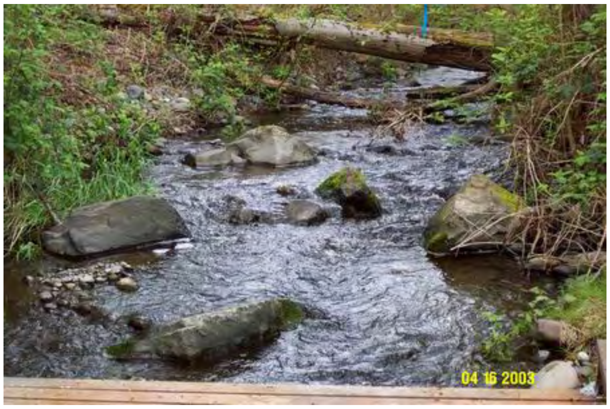
9 MONITORING

Monitoring methods employed depend on your objectives. Potential questions include: Did the boulders stay in place? Is maintenance required? Did the treatment affect overall fish production in the system? How has the habitat changed since the addition of the boulders? Does the structure provide favorable fish habitat (what fish, season, and age class)? The level and frequency of monitoring required will vary with monitoring objectives and project risk. Low risk projects may simply warrant annual site visits and a documentation of qualitative observations regarding scour, deposition, fish use, and boulder stability. On the other hand, projects that pose a relatively high risk to infrastructure, property, or habitat may require frequent quantitative physical and biological surveys to be conducted. Such surveys may include photos and detailed pre- and post-construction surveys of boulder locations and bed and bank topography to document changes over time, pre- and post-construction snorkeling of the site and a reference reach to document fish use. Refer to the *Monitoring Considerations* appendix for guidance on developing and implementing a monitoring plan.

10 MAINTENANCE

Regular monitoring of the site after high flow events will identify any maintenance requirements. Maintenance of a boulder placement project should not be required except in a few situations where the project is no longer meeting its objectives or unintended consequences have occurred and are unacceptable. Maintenance, when needed, may include re-positioning or removal of individual boulders, removal of wood that has racked up against the boulders, or armoring of eroding banks. However, keep in mind that repositioning of boulders is only recommended after careful evaluation to determine what went wrong to avoid repeating the mistake.

11 EXAMPLES



Boulder Clusters Figure 4: Constructed boulder clusters in Hylebos Creek, King County, Washington

Boulder Clusters Figure 5: Constructed boulder clusters in Lynch Creek, King County, Washington

Boulder Clusters Figure 6: Constructed boulder cluster in Touchet River, Columbia County, Washington

Boulder Clusters Figure 7: Constructed boulder cluster in Hamilton Springs, Skamania County, Washington. Note the presence of chum salmon in the photo on the left.

(a) **(b)**

Boulder Clusters Figure 8: Constructed boulder cluster during **(a)** low and **(b)** high flows in the Washougal River, Clark County, Washington. Photo provided courtesy of the Lower Columbia Salmon Enhancement Group.

Boulder Clusters Figure 9: Constructed boulder clusters in the Tucannon River, Columbia County, Washington.

Boulder Clusters Figure 10: Constructed boulder clusters in unknown stream.

Boulder Clusters Figure 11: Constructed boulder clusters in Murderers Creek.

12 GLOSSARY

Plane bed – a streambed characterized by a planar, formless surface
Shear stress – The force exerted on the bed and banks of the channel by moving water. Shear stress is a function of the slope of the water surface and the hydraulic radius of the channel (cross-sectional area divided by the cross–sectional length of the wetted channel). In very wide shallow channels, the hydraulic radius approximates the depth of flow.

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LARGE WOOD AND LOG JAMS

1 DESCRIPTION

The *Large Wood and Log Jams* technique refers to adding and trapping wood in stream channels and floodplains to compensate for a deficiency of wood and wood-related habitat. The general emphasis is on large wood (LW), commonly called large woody debris (LWD) and typically defined as logs with a diameter of at least 10cm along 2m of their length, or rootwads < 2m long with a minimum bole diameter of 20cm.[1, 2] Large wood includes whole trees with rootwad and limbs attached, pieces of trees with or without rootwads and limbs, and cut logs. 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. The influence of wood in the stream system produces physical and biological benefits to stream morphology and aquatic organisms.

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. Excess wood removal for the benefit of fish passage also occurred prior to widespread understanding of LW benefits. In these instances, large wood and log jam placement may accelerate the natural recovery of streams, while riparian forests recover. Large wood may also be used to promote stability in incising channels while providing additional habitat value. The placement of large wood should be viewed as an interim solution - a short-term improvement providing habitat as natural rates of woody debris recruitment are restored through riparian forest regeneration. (see *Riparian Restoration and Management* technique).

Three approaches to establishing log structures are presented:

1. *Placed large wood, LW complexes, and constructed log jams* (similar to LW complexes though comprised of 10 or more pieces of large wood[1]). This approach is the deliberate placement of wood in streams and floodplains to form discrete structures at specific locations. Placed LW and logjams create habitat directly, but also use natural processes that scour and deposit bed and bank material to create and maintain new stream habitat. There are some immediate habitat benefits, but others may take years to develop.
2. *Large wood replenishment.* This approach is the introduction of LW to a stream with the intent of re-establishing natural LW loading volumes and distributions. The objective is reaching LW volume targets, such as those developed in the Timber, Fish and Wildlife (TFW) process or in more localized analyses. LW is delivered without mechanical anchoring, allowing high flow events to arrange it in natural formations and frequently distributing it downstream. Replenishment may involve the delivery of various piece sizes, depending on the needs of the system. Results may be immediate, or take years to develop, and are typically part of a long-term strategy of system level restoration.

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. 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. The goal is to reduce LW mobility in the stream and create complex logjams in geomorphically appropriate locations. However, the lateral, longitudinal, and vertical extent of the logjams that form is difficult to predict.

In addition to the above techniques, large wood 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 ISPG[34], respectively. LW can also be incorporated in most other techniques as a supplemental feature to enhance habitat.

2 PHYSICAL AND BIOLOGICAL EFFECTS

Large wood influences the physical form of the channel, channel processes, addition and retention of organic matter and biological community composition[3]. LW in streams serves many functions, which can be summarized as follows[4]:

- Absorbing the force of high flows and reducing bank erosion
- Creating pool habitat for fish by concentrating flows and creating scour around structures
- Recruiting additional wood and gravel via stream bank scour
- Maintaining connectivity between the channel and floodplain by increasing flooding frequency, which transports nutrients and additional wood into the stream, and sequesters fine sediments in floodplain vegetation
- Retaining and sorting spawning gravel
- Providing cover and food for salmon and other aquatic, terrestrial, and avian species.
- Providing pathways for wildlife to cross, enter, or more easily access the channel for selected uses.
- Retaining organics (wood, detritus, carcasses) that provides nutrients to aquatic organisms.

2.1 Physical Effects

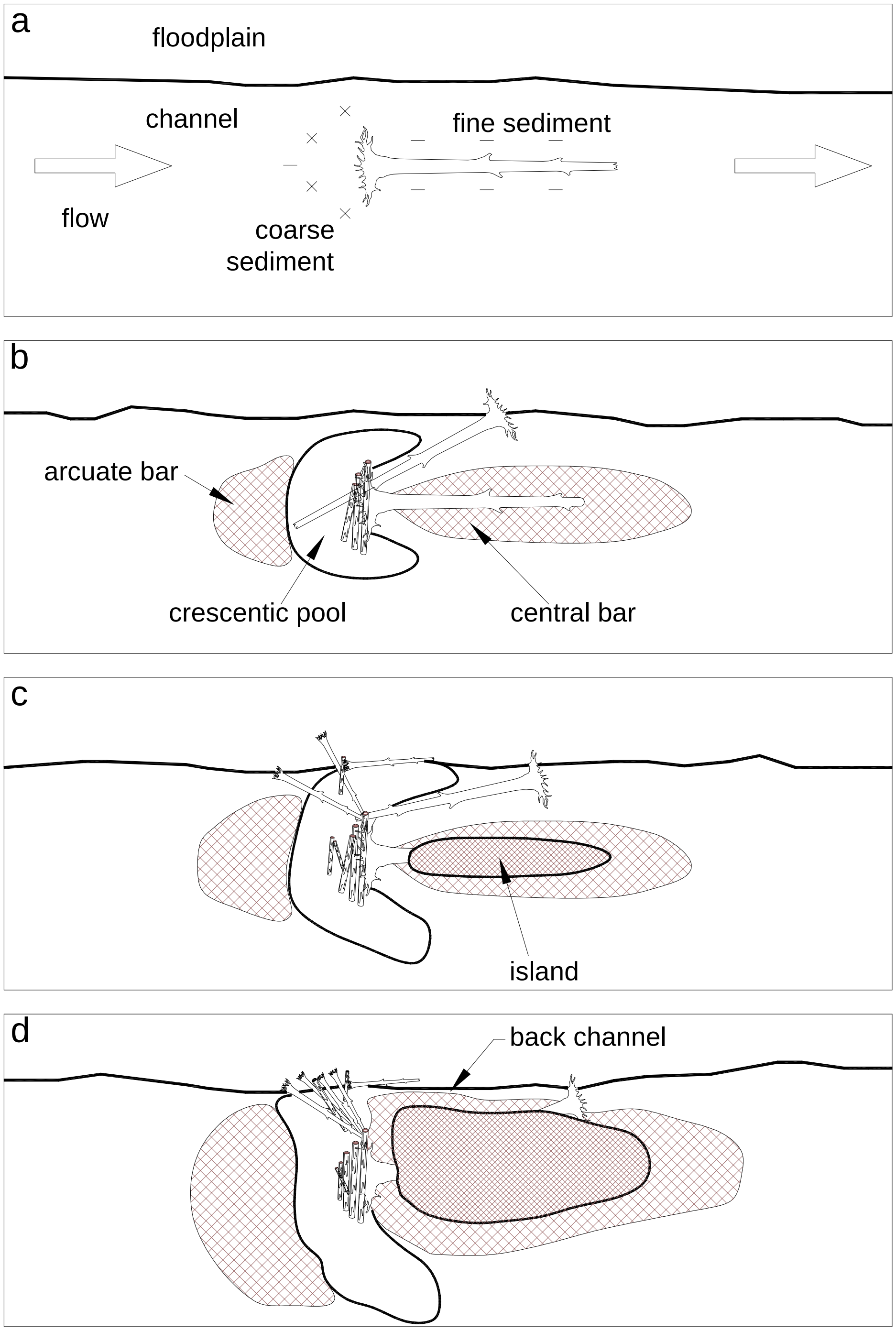
Large wood has a dominant influence on stream habitat and channel formation across the spectrum of time and space.[5] On a large scale, channel-spanning logjams can influence the routing of water, sediment, and wood as well as the processes of channel formation, floodplain formation, floodplain hydrology[6] and nutrient supply and storage. At the site scale, wood is essential in creating and maintaining pool habitat, sorting and storing sediment and organic material, and providing refuge from predators, competitors and high flows. 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 the structural stability and retention.[7, 8] For example, whereas small woody debris pieces may be unstable and transport easily, whole trees can be large enough to bridge the stream or the entire floodplain, or to be completely immobile on the streambed. In larger streams and rivers, large whole trees can accumulate smaller wood that would have normally been transported downstream. Over time, the complexity and size of a single original tree can grow to a lateral or channel-spanning logjam that backwaters an entire stream reach. As channel size and flood flows increase, the size of LW required for stability (key pieces) must also increase.

The effect of LW varies by stream type. In smaller headwater channels, in-channel wood traps substrate and can form steps within step-pool channels[9]. Generally scour pools are limited in these steep streams due to the large, bed-armoring rock. In large streams, large wood creates scour pools, controls floodplain construction and side channel development. [10, 11, 12, 13] Collins and Montgomery (2002)[5] 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 was highly dependent on scour around LW and pool frequency was 2-4 channel widths per pool in areas with high wood loading. This is less than the 5-7 channel widths per pool indicated by Leopold et al. (1964)[14] for unobstructed alluvial channels.

Multiple logjams can affect reach-scale channel characteristics. A series of logjams can increase the roughness coefficient of a reach, thereby reducing average velocity and increasing water surface elevation. They may reduce velocity sufficiently to increase sediment deposition and increase the frequency of overbank flooding. Increased deposition and roughness improves hyporheic flow, and related benefits of temperature regulation, invertebrate habitat and nutrient processing.[15]

Logjams in alluvial environments produce scour at the margin of the jam, which, depending on the degree of channel constriction, may result in scour at the opposite bank or point bar. Occasionally a side channel forms on the backside of the jam, against the bank (see **Large Wood and Log Jams Figure 1**). This is usually a result of the jam causing an obstruction to flows above the bankfull elevation. At sites where the banks are prone to erosion (poor riparian vegetation density, fine grained non-cohesive soils) there is an increased risk of erosion behind a logjam, leaving it isolated in mid-channel. Additional logjams upstream or other bank protection measures may be needed at these sites.



Large Wood and Log Jams Figure 1. 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 (1996).

Sediment retention associated with logjams provides valuable habitat and maintains sediment transport equilibrium in steeper stream channels. Research has shown that wood retains sediment and removal of wood can increase reach bed scour and lead to channel instability.[16]

2.2 Biological Effects

The structural and hydraulic diversity created by logjams provides habitat for a multitude of fish species at nearly every stage of life. Spawning habitat may be created at the scour hole tailout. The scour hole provides depth for cover. The LW provides hiding cover and respite from high flow velocities. Immediately following the development of logjams, there may be temporary, short-term impacts on spawning. Existing spawning areas may shift or scour while deposition may cover others. These short-term adjustments are normal in natural systems. The long-term habitat benefits of logjams far out-weigh these short-term impacts.

Placement of LW in streams often creates pools that may influence the distribution and abundance of juvenile salmonids[17, 18]. The presence and abundance of large wood are correlated with growth, abundance and survival of juvenile salmonids[18, 19]. Carlson et al. (1990)[20] found that pool volume was inversely related to stream gradient with a direct relation to the amount of large wood. Fausch and Northcote (1992)[19] indicate that size of wood is important for habitat creation. Hicks et al. (1991)[21] conclude that lack of LW available for recruitment from the riparian zone also leads to reduction in the quality of fish habitat.

LW provides visual and physical refuge cover within the stream. Salmonids, other fish, and stream-associated amphibians and invertebrates require cover habitat throughout their life cycle. These organisms need secure refuges and foraging areas while expending as little energy as possible. In alluvial channels, and to lesser extent non-alluvial channels, placement of LW in streams alters local hydraulics, scouring the channel bed or bank. This creates pools that provide cover in the form of water depth that protects against overhead predators. Air bubble entrainment by turbulence at the head of a pool is another form of overhead cover. The accumulation of wood under water provides physical refuge from both predators and competitors. Greater complexity in a logjam results in visual and physical isolation for more fish (see **Large Wood and Log Jams Figure 2**).

Cover habitat provided by wood changes with the rise and fall of a stream. Trees or wood above low flow water become important during flood flows. In confined channels with no backwater areas or floodplain, channel margins become 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 in non-alluvial channels. Even single trees that fall in to the channel can provide cover during high flow. In alluvial channels, floodplain wood plays an important role in providing high flow cover habitat during flood events. During floods of extended duration, floodplain surfaces, side channels and backwater sloughs are used by juvenile salmonids. Wood in these areas creates hydraulic roughness that provides low velocity refuge (see **Large Wood and Log Jams Figure 3**).

Large Wood and Log Jams Figure 2. Visual and physical isolation provided by a rootwad for juvenile coho salmon. (photo from NF Stillaguamish River, Snohomish County, Washington, Source: Roger Peters, USFWS).

Large Wood and Log Jams Figure 3. LW placed on the floodplain will provide low velocity refuge during high flows. (Finney Creek, Skagit County, Washington).

The decay of organic detritus adds nutrients to the stream, and LW accumulates smaller twigs and leaves that decay rapidly and supports the aquatic invertebrate food web. Logjams also trap and retain carcasses that add nutrients such as carbon, nitrogen and phosphorous to the stream system.[22] Logjams sometimes stimulate beaver activity, which contribute nutrients in the form of cut trees and branches and feces.

Large wood plays an important role in stabilizing spawning gravels used by many species of salmonids. LW and other in-channel obstructions help dissipate peak flow energy, and stabilize spawning beds. Simplified and straightened channels become high-energy 'bowling alleys' during peak flows, where a substantial portion of the streambed is mobilized. Highly mobile gravel can significantly reduce egg incubation success and decrease fecundity. In-channel obstructions will reduce this scour to pockets in and around the LW, logjams and other structures. This pocket scour is benign relative to the broadcast scour of simplified channels.

Wood within riparian floodplains can also provide substantial habitat values to terrestrial wildlife. Smaller logs provide escape cover and shelter for small mammals, amphibians and reptiles. Increased log volume may increase densities of certain amphibians and small mammals.[23] Larger diameter logs, especially hollow logs, provide denning, resting, and litter rearing sites for larger vertebrates such as marten, bobcat and black bears. High densities of large logs and upturned stumps provide security cover for lynx kittens [24]. Jackstrawed logs provide prime foraging habitat for mink, marten and cougar [25].

Most in-channel wood, whether naturally recruited or placed, will be transported downstream sooner or later. Slow decomposition and episodic fragmentation from peak flows will reduce wood to the size where it can be mobilized. However, this wood still 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. LW 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.[26] Wood accumulations on ocean beaches provide habitat value to shoreline wildlife and aquatic species. LW is habitat for inter-tidal species (barnacles, isopods, mussels, and 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 (annelid worms, bivalve mollusks, crabs, selected marine fishes).

3 APPLICATION OF TECHNIQUE

LW can be used for many of the same applications where other structures are appropriate. However, because wood is a natural structural and habitat component of most stream systems, the application of wood can add considerable value to structures. Refer to the *General Design and Selection Considerations for All In-stream Structures* technique for a general discussion of the application of structures in streams.

Addition of LW and logjams is appropriate where:

1. A biological or geomorphic need for in-stream wood and wood-related habitat has been identified, and/or
2. Existing riparian trees are too small to provide natural LW recruitment.

Historically, in-channel LW placement in the Pacific Northwest has been used indiscriminately to mitigate for fish-habitat damage[27]. In more recent years, advocates of LW placement have developed standards for site selection, LW size and placement to assure LW survival and effectiveness (e.g., ODF and ODFW (1995)[28], and WFPB (1997)[29]). The massive flood of February 1996 was a key test for these techniques, and many success stories were reported [30, 31, 32].

LW that is added to a stream purely for its habitat value (not for channel stabilization) should not be placed in degrading streams unless the cause of degradation is addressed[33]. LW addition, as with any in-stream restoration work, is not recommended in unstable watersheds subject to debris flows[10]. Where unstable watersheds exist, restoration work should focus primarily on watershed restoration and hill slope stabilization.

Any wood placement approaches that are not coupled with riparian forest restoration should be considered short-term solutions. Collins and Montgomery (2002)[5] suggest that restoration that focuses solely on in-stream wood placement without restoring the long-term supply of wood to a stream has an effective life of 1 to 10 years. They encourage river restoration including riparian reforestation to provide sustainable LW in the form of key pieces and logjams. This philosophy includes acceptance of bank erosion and avulsion to supply LW to the river, as well as employing constructed logjams as a short-term function.
Forest restoration, and in particular, riparian forest restoration, is discussed further in *Riparian Restoration and Management* technique.

Finding good locations to establish wood habitat requires an understanding of the physical characteristic of the channel and the size of material (diameter and length) necessary for stability. Areas with lower stream energy at high flows often provide good locations to place wood cover habitat. For instance, wood will be more likely to deposit in unconfined and lower gradient reaches than steep or narrow reaches. Typically, breaks in slope and width become natural zones that collect wood being transported to the site from higher energy steeper stream reaches. The downstream end of sharp bends or constrictions located near bedrock, landslides and debris torrents are areas that can also retain large wood. LW has the most significant impact on moderate-slope (1-3%) alluvial channels classified morphologically as pool-riffle or plane-bed. Marston (1982)[25] showed that the V-notch topography of 1st and 2nd order channels can prevent the formation of logjam steps, and thus 3rd order streams had the highest concentration of steps/log dams.

Logjams can also be used to protect eroding banks. For further details on the use of logjams for protection of streambanks, refer to the Integrated Streambank Protection Guidelines (ISPG)[34].

3.1 Placed Large Wood, Large Wood Complexes and Constructed Log Jams

Constructed logjams and 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. They can be applied to any site 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; constraints which limit pre-project research; lack of state-of-the-art knowledge in the applicability of structures to field conditions; or the tendency to install the same structure on all stream types with a one-size-fits-all approach[35].

Generally, constructed log jams work well in alluvial channels having less than a 2% slope[36]. 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 logjams in non-alluvial channels with up to 4% slopes is appropriate. However, channel-spanning logjams in confined non-alluvial channels may create fish passage barriers, particularly if they collect additional wood. The step pool morphology, greater stream power, and steeper valley walls in channels with slopes greater than 4% tend to prevent the natural formation of log jams (although they can occur).

Side channels provide stable rearing and spawning habitat in many streams. Stable side channels can be a critical safety factor for fish populations in streams that experience frequent, large magnitude flows that destroy redds in the main channel. Jams can be assembled at the inlet of pre-existing or constructed side channels to regulate the amount of flood flow entering the side channel (see **Large Wood and Log Jams Figure 4**). This can slow or delay imminent channel avulsion while allowing riparian vegetation to mature. Logjams are also applicable downstream of backwater sloughs or side channels. They increase backwater elevation in the side channel thus providing high flow rearing habitat.

Large Wood and Log Jams Figure 4. A naturally formed logjam at the head of a side channel on Ahtanum Creek allows low flow in the side channel while limiting high flow impacts. (Ahtanum Creek, Yakima County, Washington.)

Incised alluvial channels can benefit from logjams as well. In incised channels the channel capacity increases so discharge that previously accessed the floodplain now stays in the channel and begins to laterally erode the vertical stream banks. Where additional sediments are not detrimental, logjams can facilitate this lateral migration process and eventually develop a new floodplain at a lower elevation. Remnants of the abandoned floodplain will be perched above the new floodplain as terraces. The logjams may also stabilize some of the mobile sediments in the channel.

When adding log jams to aggrading stream segments, the potential for avulsions should be considered. Low density of large wood and mature riparian vegetation on the floodplain decreases resistance to erosion during flooding. In stream segments with poorly developed riparian zones, a repetitive avulsion cycle retards the maturity of riparian vegetation and large trees, thereby reducing the health and productivity of the stream. Where the riparian area is healthy, avulsions can be a benefit as they add substrate, additional wood and nutrients to the stream.

3.2 Large Wood Replenishment

Large wood replenishment can be applied directly to the channel or to adjacent floodplains, side channels or banks where it can be readily recruited and/or redistributed by flow. Since detailed wood placement is not necessary, an advantage of wood replenishment over other LW techniques lies in its lower cost and less restrictive access requirements. It is not appropriate in small, shallow channels with limited ability to transport wood[37]. Though 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. LW replenishment in steep mountainous regions prone to debris torrents may add to channel impacts and should be avoided or considered with caution.

Wood can be a naturally occurring feature anywhere in a stream system where trees are present in the adjacent riparian zone or upstream watershed. However, there is greater risk associated with adding mobile wood to certain stream types. As the velocity and depth of flow increases, so do the buoyant and drag forces acting to transport the wood. And as the width and depth of the stream increases, the likelihood of wood getting wedged between banks, or held up on bank and channel obstructions decreases. Consequently, the risk of wood transport (though not necessarily project failure) increases with channel gradient, channel depth, and channel width. Risks are inevitable when designing log jams for large rivers. As the formation of wood structures and habitat is flow dependent, use of a wood replenishment technique is only appropriate where immediate results are not necessary or expected and where the ultimate distribution of wood has limited risk. 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 collected or otherwise rendered harmless before reaching heavily developed areas. At a minimum, LW replenishment should be applied at a reach scale.

3.3 Trapping Wood

Trapping wood refers to approaches that rely on key pieces of immobile wood, wood pilings, or other structures to trap, or rack, mobile wood and form LW complexes and log jams. LW-trapping structures should be built at hydraulically appropriate locations, similar to LW complexes and logjams (see section 3.1 *Placed Large Wood, Large Wood Complexes and Constructed Log Jams*). Since 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.

4 RISK AND UNCERTAINTY

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 or intent of the structure fails or is not realized. However, as with any structure, placed wood may disrupt existing habitat. Scour and deposition that occurs in the vicinity of wood structures may disrupt or bury existing spawning beds and alter the size, extent, and location of pools. Large-scale log jams may cause an avulsion that results in the abandonment of existing habitat and the creation of new. Lastly, changes in stream habitat from the addition of wood may be more favorable to one species than another, potentially causing a redistribution of species. However, in each of these examples it can be argued that the same impacts can result from natural accumulations of wood and that such impacts are necessary to create new habitat and maintain stream habitat diversity.

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. 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 large woody debris recruitment.

Riparian zones are important for both fish and wildlife. Knutson and Naef (1997)[38] stated, "Approximately 85% of Washington's terrestrial vertebrate species use riparian habitat for essential life activities and the density of wildlife in riparian areas is comparatively high." Birds use mature trees extensively for breeding, and removal of trees during breeding and nesting season should be avoided. In forests west of the Cascade crest in Washington, 150 terrestrial wildlife species are known to use dead and down woody materials[39], which furnish cover and serve as sites for feeding, reproducing, and resting. A strategy to minimize negative wildlife and ecosystem impacts should be developed, especially when very large wood is called for in the project or protected species (including northern spotted owls, bald eagles, or marbled murrelets) may be affected.

Some riparian buffers (those less than 75’ wide) are too narrow to risk harvesting trees or are still recovering from recent timber harvest or land clearing. However, many forestlands have dense stands of mature (age 40+) riparian trees, and other objectives may be more important. Included may be stand age diversity, species diversity, canopy layering, protecting beaver ponds, preserving deciduous stands, fire management and protecting snags. Thinning can help address some of these objectives. Using nearby riparian or upland trees for in-channel placement can reduce impacts associated with vehicle access and hauling of off-site trees. The following recommendations should be considered:

1) Do not use snags or downed wood for in-channel placement.
2) Do not cut trees rooted in the bank of the stream.
3) Never cut trees that shade the stream if water temperature or shade exceeds state water quality standards. Apply forest practices rules for shade if possible.
4) Avoid significant impacts to long-term large wood recruitment. Light thinning will not have much impact on long-term impact to large wood recruitment. Harvesting clusters of riparian trees or narrowing the buffer width will impact recruitment.
5) In mixed age stands, avoid felling the largest trees for large wood recruitment.
6) Pay attention to regulations that may be more restrictive than above guidelines (i.e., forest practices).

4.2 Risk to Infrastructure and Property

The hydraulic effects of LW and logjams that create habitat (creating local scour, re-directing flow, increasing floodplain connectivity, initiating avulsions) are undesirable in some locations. These actions may cause property loss through erosion, threaten the structural integrity of nearby infrastructure and increase the risk of flooding. Mobile wood may block culverts, become lodged on bridge piers leading to scour at the pier or cause other structural damage. Blocked culverts can sometimes trigger debris torrents, which 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 these risks. Similarly, LW replenishment or trapping wood 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 logjams to alert the public.

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 become 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

Wood structures present significantly greater design challenges than structures composed of rock or other materials - wood is buoyant, irregularly shaped and may collect additional material floating downstream. Consequently, some uncertainty exists in the performance of wood structures, from the perspective of the structural integrity of the structure itself and from the perspective of its intended function in the stream. While tremendous advances have been made in recent years in the design of wood structures, few structures have yet proven the test of time structurally or in terms of intended function. While the uncertainty in structural integrity can be greatly reduced through greater detail in design analysis, the uncertainty in performance may not. Specific habitat benefits resulting from wood structures may prove difficult to predict or achieve as intended. While a wood structure may provide grade control and generate scour as predicted, the effectiveness in providing desired habitat value is not certain. The best chance for creating the desired habitat is by placing LW in locations and orientations that have been shown to provide habitat. As both wood supplementation and wood trapping rely on the redistribution of wood during high flow events, the lag time before effects are realized, the longevity of effects, and the final results are variable and difficult to predict. Although trapping wood provides a greater certainty than wood supplementation 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

5.1 Application of Engineering to Design

The term “engineered” is widely applied in stream restoration, but is not often carefully defined and often loosely applied to any constructed or fabricated wood structure. In this document, the use of the term “engineered” refers primarily to the integrity and performance of the structure. Refer to the technique *General Design and Selections*

Considerations for All In-stream Structures for a comprehensive list of structure design criteria, and Chapter 5.3 *Design of Techniques* for further general discussion of design criteria. Engineered structures include the following characteristics of design[40]:

1. Designs are based on clearly defined criteria that define project objectives and include:
   - Functional performance as it relates to habitat objectives
   - Design life of the structure
   - Design discharge for structural stability, compensation for varying forces
   - Allowable construction impact and mitigation
2. Design includes evaluation and assessment of the following risks:
   - Public safety
   - Flooding
   - Nearby infrastructure
   - Geomorphic impact and response, including bank erosion and avulsion
   - Structure failure
3. Design of structures is integrated with site conditions
   - Geomorphic processes at the site are considered
   - Structures are designed to affect geomorphic processes according to clearly defined criteria
   - Hydraulic modeling of design conditions
4. Detailed design plans and specifications
5. Detailed as-built plans
6. Design responsibility by qualified, licensed engineer

Two relatively common uses of the term engineering as it relates to wood are “Engineered Log Jams”[41] and “Engineered Large Woody Debris”. Engineered log jams is a term applied to log jams which have been designed according to standard engineering principles discussed above, though is often more loosely used. Engineered large woody debris (ELWD™) is a commercial product which consists of smaller interlocking pieces (see **Large Wood and Log Jams Figure 5**) intended to simulate a single large log[4], and is discussed in section 5.3 *Factors that Influence the Stability of Wood in Streams*.

Not all wood structure applications necessarily require engineering to be effective, and engineering alone does not meet all of the requirements of a successful project. A design team should include expertise in aquatic ecology, fluvial geomorphology, and riparian and/or upland plant ecology. A structure may be constructed without engineering and meet project objectives of stability and function. However, engineered structures create a distinct connection between the design of the structure and its structural and functional performance.

Large Wood and Log Jams Figure 5.
ELWD^{TM} is a commercial form of a constructed LW piece.

5.2 Data and Assessment Requirements

Specific discussion of data and assessment requirements as they relate to wood structures is provided below. Generally, the amount of data assessment required is proportional to risk. Wood placements in small remote streams may require little data collection and assessment, while large-scale placements or projects in proximity to infrastructure will require more. An initial discussion of data requirements is in *Introduction to Structures.* Items specific to LW and logjams are described here in more detail.

5.2.1 Basic Information and Data Needs

Once general goals, objectives and restoration sites have been identified, the next step is to collect information on the site's characteristics. At a minimum, a design should include:

- *Documentation of baseline conditions.* Monitoring of wood structure projects is best facilitated by documentation of pre-construction conditions, as well as the location and orientation of each log placed, and in the case of logjams the locations and orientation of key pieces at a minimum. 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 (refer to Introduction to Structures).
- *Project site hydrology.* Understanding the flow characteristics of a stream is essential for designing quality stable habitat. Hydrology data can be quantitative and/or qualitative. The amount of data required depends on the energy of the stream, the risk level of the project and the experience of the designer. Evaluating hydrology based on site conditions may be adequate at low risk or low energy sites. Is there a significant floodplain? Is the channel incised or actively aggrading? What existing LW indicates past flood levels? Does vegetation indicate stable flow patterns? Higher risk projects will require more quantitative data (See 5.2.3). 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, it is not recommended to place wood in a channel that cannot withstand a 20-year return interval flood. Designs should either be improved to ensure stability, or it should be accepted that the reach chosen for the habitat has too much stream power and is a natural transport reach for LW. In some projects (IFIM studies, FERC re-licensing) specific flows for specific species or life stages may need analysis. In most other cases structures should be designed to provide habitat through a wide range of flows; developing scour, low flow cover and pools, and high flow refuge. Streams should be observed during both low and high flow.

- *Access availability* (detailed in *Introduction of Structures*).
- *Wood material available to use in a project.* It is best to either have the wood collected before designs begin or be certain of the volume, size and quality of wood available for delivery to a project. Key piece sizes are critical and should be specified and identified prior to construction. Racked wood can be specified more generally. Designing a project without knowing what wood is available is difficult and less efficient.
- *Biological assessment.* This is an evaluation of habitat conditions for various fish species and age classes at the site or reach. A good habitat restoration project will address the stream processes that create that habitat. If only certain habitat types are lacking, specific wood placements may provide that habitat.
- *Wood mobility.* In low risk, low cost projects, the size of stable and mobile material can be estimated by observing existing unanchored debris elsewhere in the channel and in reference reaches that have been exposed to flood water. Standard charts for key-piece wood size may also be helpful.[28, 29]
- *Infrastructure.* In urban areas, buried pipelines, phone lines, waterlines and sewer lines are commonly found near streams. It is important to find these early to make sure conflicts between design requirements and the existence of buried lines do not conflict. Culverts, bridges and buildings near a project should be identified to insure they are considered in the design process (as detailed in *Introduction of Structures*).
- *Analog site data.* Natural wood-related habitats existing near a work site provide an invaluable study opportunity. The size of the wood, orientation, location, bankfull indicators, geologic conditions, cross-sectional and longitudinal characteristics, substrate, riparian vegetation and bank conditions can all be surveyed and used to help in the design phase. These sites are referred to as analog sites. Other projects that have functioned well over time are also valuable study sites and could be used like natural analog sites.

5.2.2 Advanced Data Needs for More Complex Projects

The following additional data may be required for projects with a moderate to high risk, cost, or degree of complexity. Such situations may include projects in urban streams, or confined, high gradient, or large channels upstream of or in close proximity to critical habitat, and projects that involve construction of large structures (e.g., a log jam) or a number of structures.

- *Representative cross-section and profile data at project sites and any analog sites.* This information is needed for more detailed hydraulic analysis. It will aid in characterizing stream types and the typical habitat features found there. It will also allow better identification of comparable analog sites. Harrelson et.al. (1994)[42] developed a guide that shows field techniques and basic survey methods to collect quality field data that can be used to develop project designs. *Floodplain conditions* above and below the project site are important for identifying areas where project work could potentially result in more water on the floodplain or in side channel areas. As previously discussed, disturbed alluvial valley bottoms tend to have a predominance of younger riparian trees with little age diversity. This creates a condition where floodplain roughness is diminished and the potential for channel avulsion or bank erosion is greater. Projects that increase floodplain connectivity in areas that have poor wood loading, cleared floodplain or young riparian stands should be evaluated for avulsion potential. Cross-section and hydraulic analysis can help determine the risk of avulsion during floods.

- *Air photo analysis of current and historical conditions*. Review of the air photo record provides a good opportunity to compare channel changes in alluvial channels with flood records. Wood deposits and geomorphic change provide valuable information about potential response to floods. Air photo analysis also helps identify abandoned or active channels and side channels that may be incorporated in restoration activities.
- *Data needed for monitoring* (see *Monitoring Considerations* appendix).
- *Hydraulic analysis* (as detailed in *Introduction of Structures*).
- *Scour analysis* (as detailed in *Introduction of Structures*).
- *Backwater analysis.* This effort will help identify potential flooding locations, both pre- and post-project. In some cases, frequent floods or excessive flood elevations have to be avoided. In others, one of the main objectives will be to restore floodplain function and connectivity with the channel. A backwater analysis can help determine if sufficient LW is being added to achieve that goal at the design discharge.
- *Wood mobility*. High-risk projects will require completing hydraulic models to calculate water elevations and wood mobility during floods. This information will be related to proximity of infrastructure or unstable slopes to evaluate the risk of the project. Refer to the *Placement and Anchoring of Large Wood* appendix for further information.

The level of assistance needed from professionals working in this field varies greatly with the project and experience of the project manager. Many projects are straightforward and are in low risk environments. Others may be in very disturbed areas or in highly volatile stream environments with substantial risk to downstream or adjacent infrastructure. Practitioners that are unsure of the aspects of design and implementation should consult with others that are more experienced.

5.3 Factors that Influence the Stability of Wood in Streams

Many factors influence the stability of both natural and artificially placed LW in stream channels. The longevity of wood and wood-related habitat is a function of the wood's stability, which in turn is a function of its buoyancy, the friction of the wood against the stream bed and banks, flow depth and velocity, the material strength of the wood, wood decay resistance, and the deformability of the bed[43]. A structure 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)[44]. These forces are discussed in the *Placement and Anchoring of Large Wood* appendix.

Important factors influencing structural stability include natural accumulation patterns and location in the channel. Even where artificial anchoring techniques are used, incorporating characteristics of naturally stable wood in the design 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. Example locations are at the downstream end of a meander bend, the head of a side channel, the apex of a bar, in backwatered reaches, pools, or relatively low energy sites. Refer to section 5.4 *Natural Distribution of Wood in Streams* for further discussion.

Initiation of logjams in non-alluvial channels is similar to the process that starts bar apex jams or meander jams in alluvial channels. Large boulders, bedrock constrictions, and large immobile trees can form the foundation of a logjam in larger non-alluvial channels by collecting wood as it floats downstream. Large trees can form key pieces when they fall across smaller non-alluvial channels, though they typically enter the channel when the fall breaks the tree into several pieces.

The size of wood relative to bankfull width also influences its stability. The size of stable wood generally increases with the size, depth, and gradient of the stream, and thus wood that is as long or longer than the bankfull width of the stream is more likely to become wedged between banks or channel obstructions than shorter wood. Using short, undersized material often requires artificial anchoring or ballasting to compensate for lack of mass and length. Often it is appropriate to use a key piece of wood that serves as an anchoring device for the structure. Key pieces are defined as those pieces of LW that are large enough to be at least temporarily immobile and serve as a foundation for other pieces of a structure or log jam. The ideal key piece is a tree complete with rootwad and limbs intact. The minimum size of wood necessary to qualify as a key piece varies with the size of the channel. Schuett-Hames et al (1999)[1] provided the following key piece criteria.

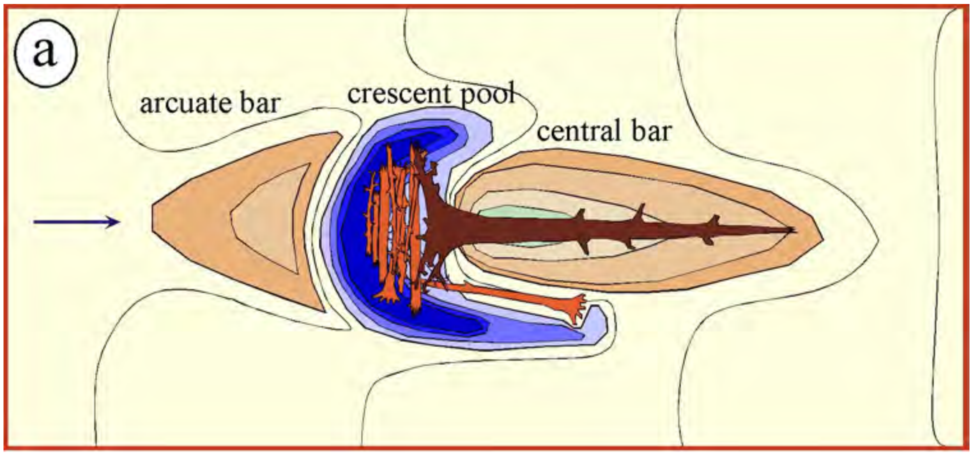
Min Log Diameter (m)	**Bankfull Width 0 to 5m**	**Bankfull Width 5 to 10m**	**Bankfull Width 10 to 15m**	**Bankfull Width 15 to 20m**
	Minimum Length (m)			
0.50	6	13	31	---
0.55	5	11	26	---
0.60	4	9	22	32
0.65	3	8	19	28
0.70	3	7	19	24
0.75	3	6	14	21
Min Volume (m^3)	1.0	2.5	6.0	9.0

Table 1. Fox (2001)[45] determined that these key piece minimum volumes were appropriate for eastern Washington streams. He 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; 10.75 m^3 for channel greater than 50m wide. LW in channels larger than 30 m should have an attached rootwad to qualify as a key piece. These values are the 25th percentile points of his data. He suggests optimum values of LW and key piece volumes would be represented by the 75th percentile quantities, which are at least more than double the 25th percentile quantities.

Key pieces can be naturally stable or may be stabilized by artificial means. By observing and mimicking the characteristics of stable wood in streams, the designer can reduce the risk of wood being transported out of the target stream reach during small to moderate flow events. However, when wood of sufficient size to be naturally anchored is unavailable, impractical, or cannot be hauled to the site, or when design process cannot develop a factor of safety sufficient to accommodate risk, additional anchoring may be necessary. In large river systems, single pieces of sufficient size to be naturally anchored may not exist[36].

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[43]. In a study of streams draining unmanaged forested basins in Washington, Fox (2001)[45] found that in channels with bankfull widths over 30m, 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 (see **Large Wood and Log Jams Figure 6**).

Wedging a log between stable features within or adjacent to the stream can increase its stability by preventing its movement in one of more directions. Stable features may include standing trees (see **Large Wood and Log Jams Figure 7**), old-growth stumps, boulders, bedrock, or log pilings (vertical or angled untreated logs driven deep into the bed or bank of a stream; these are further discussed in the *Placement and Anchoring of Large Wood* appendix). Three-dimensional complexity can also influence logjam structural stability. A log may be pinned between other logs, effectively sheltering each other from the full force of erosive flow. When multiple logs are “jackstrawed” together to form a knit 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 (1984)[46] found that anchoring one end or the face of a log in the bed or bank greatly reduced the probability of movement.



Large Wood and Log Jams Figure 6. Deposition in the hydraulic “shadow” of an instream tree, burying the bole of the tree. (courtesy Tim Abbe)

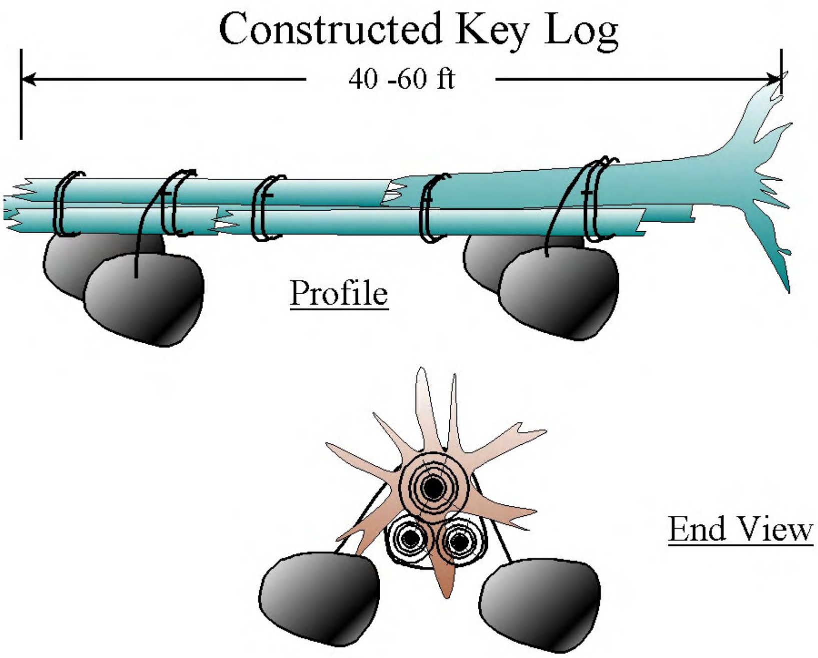
Large Wood and Log Jams Figure 7. LW complex on the Little Hoko River anchored by wedging LW between trees on the bank.
(Little Hoko River, Clallam County, Washington)

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 was less frequently subject to flows capable of its transport. Similarly, ensuring that some of its weight is above the design discharge elevation may increase the stability of wood placed in the channel[43]. This will increase the weight of the wood complex, resisting the buoyant and drag forces acting against it. Keep in mind that wood placed high on the floodplain will provide habitat less frequently than wood in the active channel.

Differences in the durability between coniferous and hardwood species can be quite dramatic when not fully submerged. Lacking tannins that slow decay, deciduous wood decays much more rapidly and may lose structural integrity within a decade, depending on its size and the degree of wetting and drying that occurs. However, Bilby et al. (1999)[47] 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; 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 and may not be continuously submerged. However, deciduous species could be used to make up a portion (e.g., up to50%) of non-key piece members in an effort to reduce costs and provide diverse nutrient sources.

Depending on the application, it is desirable to use trees with intact branches and rootwads to provide additional complexity, particularly when using a single wood piece. The more complex the wood configuration, the more living space, refuge and stability it provides. Maintaining limbs, however, may be impossible or impractical if wood must be transported by truck. Typically, maintaining limbs is only possible for wood materials salvaged on site or those transported by helicopter. 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. Soil and rocks may need to be washed off rootwads if they are transported on public roads.

In situations where large logs are impossible to deliver to a site due to their size, weight, or access limitations, large 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 (see **Large Wood and Log Jams Figure 8**). One commercial product, ELWD^{TM,} is an organic, constructed alternative to large woody debris. These structures can be filled with rock to increase their weight, which reduces construction problems associated with buoyancy of large logs. The application of ELWD^{TM} is most appropriate in small streams (less than 200 cfs average maximum flow)[4]. This study comparing ELWD^{TM} to natural large wood found no significant differences in hydraulic performance and biological effects and benefits. However, as they are comprised of smaller material than an equivalent sized whole log, they are likely to decay faster. At this date, there is no long-term monitoring data available to evaluate the longevity of this type of LW.



Large Wood and Log Jams Figure 8. 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)

5.4 Natural Distribution of Wood in Streams

As described in section 2.1 *Physical Effects*, 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 1 or 2 pieces[45]. But as the size of the stream increases, so does the proportion of wood that is associated with jams[33]. Wood distribution in large streams (>5th order streams) is characterized by infrequent jams comprised of a number of large and small pieces of wood [11].

In a study on the Queets River watershed located on the Olympic Peninsula, Abbe[43] describes nine types of stable naturally occurring wood debris accumulations, organized into three main categories. These categories include wood that has not moved since entering the channel except for possible rotation (in-situ wood debris), wood that has moved downstream as a result of fluvial processes (transport jams), or a combination of the two (typically comprised of stable in-situ key members with smaller material racked against and on top of it).

In-situ Accumulations

Bank Input Deposits. These consist of trees that are fully or partially located within the channel where they first fell in. Though only a portion is located within the bankfull channel, the channel bed supports most of the tree weight. Bank input deposits form a partial obstruction to flow and their effects on channel morphology tend to be localized (e.g., pool and bar formation), unless additional wood and sediment is trapped or otherwise added.

Log Steps. These consist of 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. Oblique steps, those oriented at an angle to flow, tend to occur in low order, steep, semi-confined channels. As the gradient declines, logs perpendicular to flow become more frequent. Log steps are uncommon in low gradient streams (slope <2%).

Combination Accumulations. These are comprised of stable in-situ wood that trap large quantities of transported debris.

Valley Jams. Valley jams are 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. Key members experience little movement once in the channel. Additional wood collects on these key members, eventually forming a full-spanning jam that causes bank erosion, further wood recruitment, channel widening and upstream sediment accumulation. The sedimentation causes decreased channel depth and slope, increased floodplain inundation, and possibly formation of multiple channels or a channel avulsion. Valley jams occur in confined and unconfined channels, in small headwater streams to rivers 50m wide, and are generally limited to stream gradients of 2 to 20%. These jams can expand across the width of the valley floor. Valley jams that form in confined channels are more likely to suffer catastrophic failure than those in unconfined channels.

Flow Deflection Jams. Flow deflection jams are partially spanning jams consisting of one or more key members and large quantities of racked debris. Key members are locally recruited, typically entering the channel perpendicular to flow but eventually rotating the crown downstream. These were documented in all portions of the Queets drainage with the exception of steep headwater streams. Flow deflection jams deflect flow nearly perpendicular to the channel axis, causing large pools to develop along the upstream edge of the jam, with bar development downstream.

Transport Jams. These are the dominant type of woody debris accumulations in the main stem channel of large alluvial rivers.

Debris Flow Jams. Debris flow jams result from the deposition of wood following debris flows initiated by shallow landslides. The orientation and composition of wood within the jam tends to be chaotic. Debris flow jams tend to be full spanning and retain large amounts of sediment upstream. As the valley gradient decreases, pieces of the debris flow may break off and be left as smaller jams along the fringe of the flow path. Debris flow jams can also deposit where they enter a larger order stream.

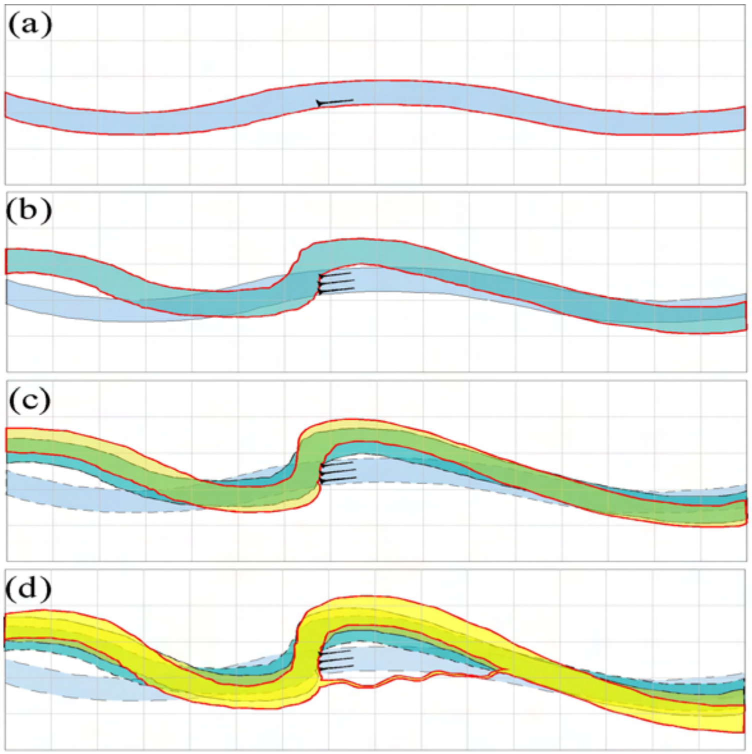
Flood-peak jams. These jams are often mobile during large floods or dam-break events. They may temporarily obstruct the channel and cause a significant backwater, followed by re-mobilization of the accumulation. They frequently deposit in the floodplain against standing trees or shrubs.

Bankfull Bench Jams. Bankfull bench jams are partially spanning jams that form along the margins of headwater channels with gradients ranging from 6 to 20%. They consist of one or more key pieces of wood (oriented at an angle to flow) that become wedged into bedrock outcrops, boulders or other obstructions along the channel margin. Bankfull bench jams create hydraulically sheltered areas that encourage sediment and debris deposition.

Bar Apex Jams. These are relatively stable jams that are initiated when a large key piece of wood deposits in the thalweg, on a mid-channel bar or a point bar during a flood event. The key piece is always oriented parallel to flow with the rootwad upstream. As other wood material becomes racked against and along the flanks of the key piece, flow accelerates around the face of the jam, scouring an upstream pool and forming a downstream bar (see **Large Wood and Log Jams Figure 9**). Such jams are termed bar apex jams because they are located at the apex of a bar that develops in the slow velocity water behind the jam. In larger alluvial systems, this natural bar-forming process plays a critical role in developing stable forested communities on the bar behind the debris jam as the stream laterally migrates across valley floors. Bar-apex jams are one of the most common types of debris accumulations in large pool-riffle channels. Using wood found on site or imported, bar apex jams can be emulated by strategically placing large key pieces and then using other wood to form racking members and ballast on top for stability during flood flows.

MeanderJams. These jams normally form on the outside bank at the downstream end of meander bends, primarily in large, low gradient alluvial channels. They are typically initiated by the deposition of two or more key members oriented as in bar apex jams. Wood that is floating downstream is racked against the rootwad(s), diverting flow toward the opposite bank. The racked wood and key pieces act to stabilize the stream bank and limit further lateral migration. The flow re-direction of these deposits can compress the radius of curvature far greater than what one would expect in unobstructed meanders[48] (see **Large Wood and Log Jams Figure 10**). This naturally creates more complex habitat, deeper pools and a longer flow path than would be expected without in-stream wood. It may also trigger a channel avulsion through the floodplain adjacent to the jam. Stability of meander jams depends on the resistance provided by the key pieces, sediment accumulation around the key pieces, the quantity of racked debris and the stability of the adjacent bank.

Large Wood and Log Jams Figure 9. Formation of arcuate scour pool at the head of a bar apex jam, and downstream deposition (courtesy Tim Abbe).



Large Wood and Log Jams Figure 10. Potential flow re-direction caused by a meander jam (courtesy Tim Abbe).

Wood accumulations comprised of relatively small material (not key piece) may deposit along channel banks, on floodplains and on bar tops during flood events. However, these collections are relatively unstable and become mobile at discharges approaching bankfull.

5.5 Target Wood Loading

Target wood loading refers to the density of large woody debris needed to accomplish project goals and objectives. Project managers need to determine how closely the target wood loading will approximate natural densities of wood or *natural wood loading*. In some cases the limitation of resources (funds, available LW) may lead to lower LW densities over longer reaches than high densities in a small reach. The question of natural wood loading within watersheds is difficult to determine simply due to the lack of empirical historic data available from watersheds that have been disturbed by humans. The use of undisturbed watersheds as natural analogs has great potential, though it can be argued that there are not enough undisturbed watersheds regionally to provide an accurate template. The few places that have not been disturbed include parts of Alaska, National Parks or high elevation wilderness areas. Montgomery et al. (1995)[49] found that in unmanaged streams LW frequency was 0.4 pieces per meter of channel length. However in 73% of the managed streams the large wood loading was less than 0.2 pieces per meter of channel length. What can be determined from these areas must be applied with caution to areas with no reference sites.

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. Anecdotal accounts should be considered critically since many watersheds were severely impacted at or before the turn of the century. Collins, Montgomery and Hass (2002)[6] have studied a protected reach of the Nisqually River, a tributary of Puget Sound that appears to be functioning close to historical conditions. The Nisqually reach had a minimum of 1400 LW pieces/km. They surmise that managed rivers in the Puget Sound Lowlands have 1-2 orders of magnitude less LW than the historic condition. Nisqually River wood is found mostly in logjams, which create the majority (61%) of the pools in the reach and which initiate the anastomosed 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 logjams.

The Center for Streamside Studies (University of Washington) has developed guidelines to estimate the volume of LW and key pieces necessary to emulate natural loading in streams. They state that basin size is the most consistent predictor of wood volumes and quantities[2]. They have stratified streams by bankfull width and by region (western Washington, alpine, and Douglas Fir/Ponderosa Pine regions) and developed target quantities and volumes of LW and quantities of key pieces per length of stream[2, 45].

5.6 Placed Logs and LW Complexes

The following are additional 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 objective. Placement of wood to trap other wood in order to form logjams is discussed in section 6.2 *Trapping Mobile Wood*.

5.6.1 Size of Complex

Multi-log structures generally provide better habitat than single logs, particularly if there are no rootwads or branches attached to the logs (see **Large Wood and Log Jams Figure 11**). They are more likely to be hydraulically active through a broad range of flows. The diversity of microhabitat features (velocity, depth, substrate, cover) and the depth and volume of pool habitat created by wood typically increases with the number of pieces forming a complex 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 the sum 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 of species. Single log structures should have a rootwad and/or branches left attached.

Large Wood and Log Jams Figure 11.
Comparison of habitat complexity developed by (a) single bare logs and (b) a LW complex. (Crooked River, Idaho County, Idaho).

5.6.2 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 large wood 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 segment, wood should be placed along the outside of meander bends. 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 (1989)[3] 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, the appropriate habitat will be provided for the various species and life stages adapted to that stream type.

Logs placed for in-channel cover are most effective where hydraulics favor resting such as in pools, glides and side channels, or other low energy environments (see **Large Wood and Log Jams Figure 12**). Many fish and some stream-associated amphibian larvae prefer to feed in and around glides and pools where they expend minimum energy feeding. 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.

Large Wood and Log Jams Figure 12. LW provides cover habitat by being placed in or directly over instream habitat features (pools, glides, side channels) in Finney Creek, Skagit County, Washington.

5.6.3 Placement and Orientation

Creating habitat with LW depends upon a number of factors that the designer can control (the channel constriction created, the height, number and spacing of logs and log complexes, the position of wood within the channel and its orientation to flow) as well as those that they cannot (sediment supply and substrate composition, the degree of channel confinement, stream hydrology, and time). In actively migrating channels there is a good chance that during the life of the structure the main channel will abandon it. An orphaned structure may be viewed by some as project failure. However, the structure will still be there when the river returns. In the interim the structure can provide refuge and roughness during floods. One approach to actively migrating channels is to analyze several potential channel paths through the reach and place structures at appropriate locations along several of those paths. This approach will require more structures than typically used, and only part of them will be in the active channel simultaneously. Consequently an education outreach is important to understand the value of LW complexes built in dry channels or in the floodplain.

Distributing individual logs and log complexes among both low flow, near bank and floodplain habitats more closely mimics the characteristics of unmanaged channels, and therefore will likely achieve the best results during restoration or enhancement projects.[45] As an example, in-channel wood is important for summer cover and winter refuge habitat, while wood on the channel margins is critical for juvenile rearing and roughness. Wood in the floodplain and near bank areas is important for high water refuge. In a study of many log structures, Roper et al. (1998) [50] found that structures connected to a bank had more durability.

In addition to the considerations described in the *General Design And Selection Considerations for Instream Structures* techniques, the designer is encouraged to consider the characteristics of naturally occurring wood in streams. Robison and Beschta (1990)[51] studied large woody debris 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 (1989)[3] 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 include:

- *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 often create step pools. Since 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 (see **Large Wood and Log Jams 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[33]. The outside of bends and the head of natural gravel bars tend to be relatively stable locations for wood placement.

Large Wood and Log Jams Figure 13.
Significant intrusion of LW into Finney Creek (Skagit County, Washington) has developed a deep pool and habitat diversity.

- *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 (logjams, LW complexes, wood trapping structures). 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[33]. As with medium-sized streams, locations at the outside of bends and the head of natural gravel bars tend to be relatively stable.

Many channel restoration projects have relied on very geometric structures placed with cookie-cutter regularity in the channel. While log weirs, K-dams, vortex weirs, Hewitt ramps, single and double V deflectors, digger logs and J-hook vanes (to name a few) can all be useful techniques, few natural systems are a monochrome of a single habitat structure. Diversity is the “spice” of stream life.

With the exception of providing cover in slow water, most structures are intended to change channel hydraulics to impact sediment deposition and scour patterns. Scour is elicited by increasing water velocity, either through channel constriction laterally or with a vertical drop (plunging flow). LW structures can be designed to do either, or both functions simultaneously.

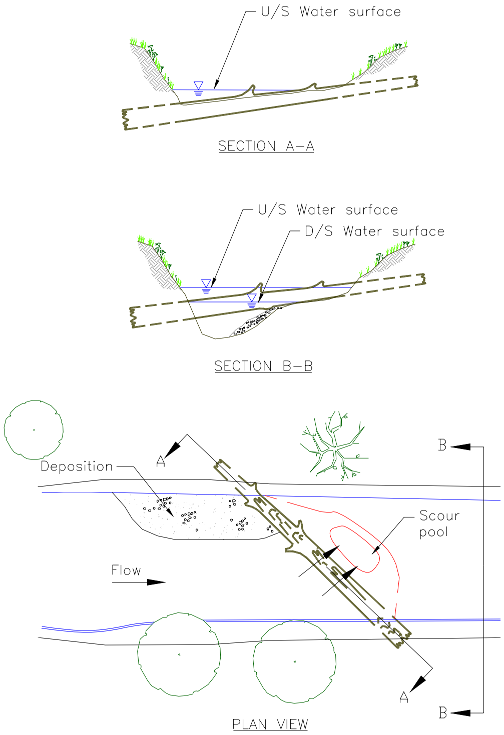
Log sills, or weirs, can be found at many orientations to the flow in natural channels and that approach should be encouraged in small-and-medium-sized stream restorations. Natural sills do not often have a level crest. A sloping-crest sill can both constrict the flow laterally and create plunging flow (see **Large Wood and Log Jams Figure 14**). An angled sill with the crest sloped down at the upstream end will tend to develop a long, narrow scour pool, and may undercut the adjacent bank if the sill spans the entire channel. This may be desired in small channels with large stable trees to reinforce the bank. A sediment bar will form upstream on the opposite side of the channel. Increasing the slope of the crest will result in a deeper and narrower scour zone. Burying the end of the sill partway across the channel, rather than in the far bank, will reduce the channel constriction and likewise the undercutting of the far bank. Though no single model will predict all scour scenarios, the general rule is that the greater the reduction of channel cross-section, the greater the downstream scour and upstream deposition.

Angled sills with the low point downstream tend to focus flows back toward the center of the channel, reducing scour of the near bank (see **Large Wood and Log Jams Figure 15**). This effect can be overpowered if the crest slope is too great, or when flow velocity is too high to be deflected. Rosgen (1996)[35] recommends a crest slope of 3-7% for J-hook vanes, which may be a good starting point for log sills.

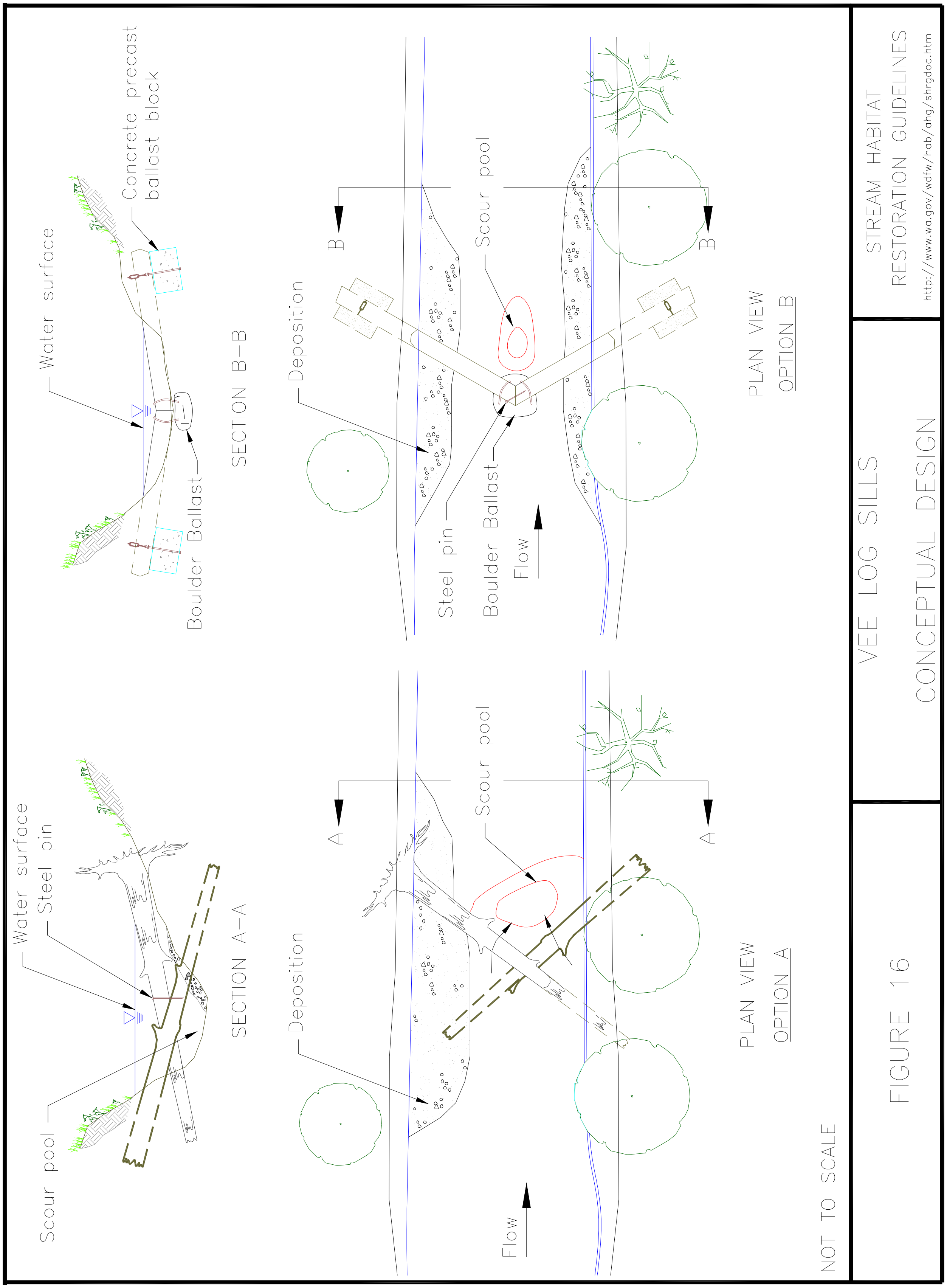
Horizontal-crest log sills develop scour through plunging flow, with the depth of scour dependent on the height of drop and substrate size. Although the horizontal crest aids in log longevity by keeping it continuously submerged, no thalweg develops in the upstream deposition zone. Adding single or double angled logs anchored on the stream bank and resting on the sill (as in a K-dam) adds diversity to a horizontal sill, concentrates low flows for greater depth upstream, and increases the depth of the scour pool.

V-shaped sills (in plan view) can be built by burying the ends of two crossing logs somewhere in the center half of the streambed (see **Large Wood and Log Jams Figure 16**). The crests should slope down to the point of the V. Another method is to saw-cut the logs and pin them together at the point of the V. This point is usually anchored to a buried boulder.

Large Wood and Log Jams Figure 14. A log sill with a sloping crest is a typical natural channel feature (Finney Creek, Skagit County, Washington).



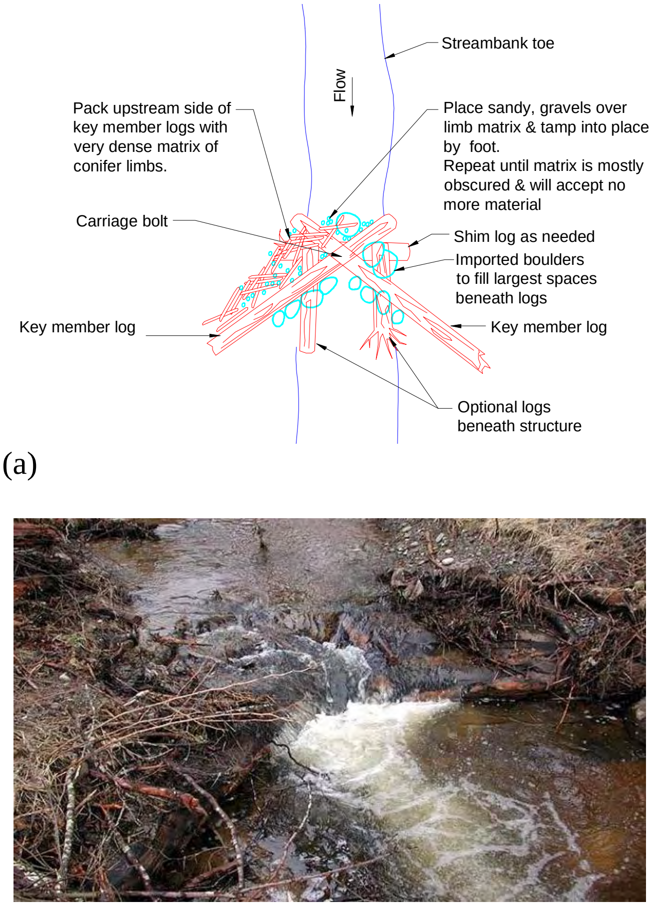
Large Wood and Log Jams Figure 15. Concept drawing of an angled, sloped-crest log sill.



STREAM HABITAT RESTORATION GUIDELINES
http://www.wa.gov/wdfw/hab/ahg/shrgdoc.htm

VEE LOG SILLS
CONCEPTUAL DESIGN

FIGURE 16



(a)

(b)

Large Wood and Log Jams Figure 17. A V-shaped log sill created with two crossed logs: (a) concept sketch showing small wood on upstream side of log to retain streambed sediment; (b) photo of crossed log structure (unidentified creek near Pysht River, Clallam County, Washington).

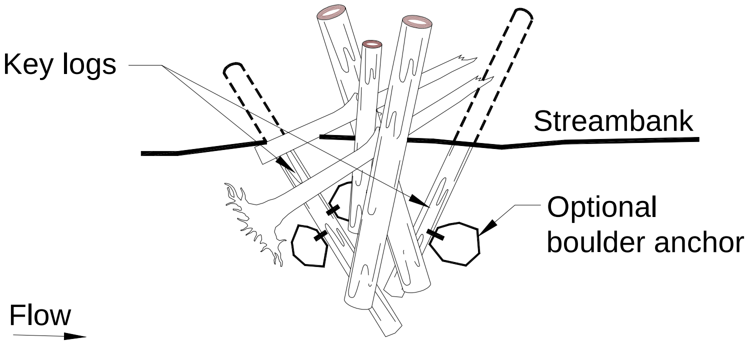
In low gradient or spring-fed channels (low energy systems) both individual logs and LW complexes are used to improve habitat. The low energy or limited vertical drop (hydraulic head) available means that greater constrictions are necessary to create scour. Often 50% or more of the cross-section needs to be blocked to initiate significant scour. Where head is limited, lateral constrictions and digger logs are appropriate. Digger logs are similar to log sills, except the log does not rest on the streambed and flows forced under the log(s) creates the scour pool. They also provide overhead cover for fish. Lateral constrictions in spring channels have been successfully used to increase velocity for fine sediment removal and increase depth for spawning trout and salmon. LW complexes are generally preferred to single logs because of their multiple habitat benefits.

One of the most basic structures is comprised of 3-4 pieces and making a triangular shape at one bank (see **Large Wood and Log Jams Figure 18**). At least one piece is on the downstream side supporting much of the hydraulic force as a compression member. It can be anchored to trees on the bank or buried in the bank, buttressed by undisturbed soil (see *Placement and Anchoring of*

Large Wood appendix). The number of pieces in a LW complex is not rigidly defined, though eventually they become more logjam than LW complex. A longer, continuous, multi-layered LW complex called a chaotic crib has been used for bank protection purposes, but it also provides significant habitat values. It is described in the ISPG document[34].

LW complexes usually create scour and deposition by constricting flow laterally. Channel widths are typically reduced by 20-30% in small and medium streams, but constrictions of 50% or more may be appropriate in low energy systems. The channel width constriction can be increased if the structure is low profile, or reduced if a LW complex is tall relative to design flood elevations.

LW complexes in mid-channel are more difficult to anchor and more likely to evolve into a logjam. They should be considered a high risk LW complex. In large streams LW complexes would not be a significant channel constriction, but would provide relatively small roughness elements that create local scour and cover.



(a)

(b)

Large Wood and Log Jams Figure 18.
Typical triangular LW complex: (a) concept drawing of LW complex on a streambank; (b) triangular LW complex on Finney Creek, Skagit County, Washington.

5.7 Constructed Log Jams

Constructed logjams (typically defined as being comprised of 10 or more pieces of large wood) are an extreme example of a LW complex. But because of their size, complexity, and, thus, the risk associated with their construction, a separate discussion is warranted to supplement that provided in section 5.6 *Placed Logs and LW Complexes*.

5.7.1 Site Selection

The occurrence of log jams in nature is varied and is discussed in section 5.4 *Natural Distribution of Wood in Streams*.

5.7.2 Orientation, Anchoring and Jam Design

Log jam designs typically consist of two basic elements: one or more key anchoring pieces that consist of a large immobile log or rootwad, usually placed parallel to the channel with the rootwad facing upstream; and racked members of smaller wood placed against the root wad(s), perpendicular to the stream. Logjams can take many alternative forms based on the natural distribution of wood as described in section 5.4 *Natural Distribution of Wood in Streams*. A logjam can be designed with a single key piece or with multiple parallel key pieces. Key pieces should ideally be large enough to self-anchor, meaning that their weight and size is sufficient to counter forces acting to mobilize them. 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. If sufficient wood is not available, key pieces can be ballasted by attaching large boulders. Multiple key pieces facilitate stable designs with minimal or no anchoring. They present opportunity to “weave” stacked and racked members between the key pieces and each other. The number of pieces racked against the root wad(s) depends upon the need for immediate scour and deposition, and the likelihood of recruiting additional LW.

The shape of engineered logjams depends upon channel hydraulics, desired results and cost. In many cases, wood collects upstream against the bank. Different methods of anchoring the jam may allow different shapes and alignments. The collection of additional wood on a logjam during floods will potentially change its shape and dimensions.

The size of materials used in the engineered logjam will depend upon the method of anchoring. Force balance evaluations (detailed in the *Placement and Anchoring of Large Wood* appendix) can determine the size of key pieces that can be installed without artificial anchoring. **Table 2 and 3** may also be employed as a guide. If wood of sufficient size is not available, artificial anchoring may be necessary. It is also important to take into consideration the anticipated rate of wood decomposition, wood density and the length of project life. Racked pieces do not usually function as structural members of engineered logjams, so they can be any size. When additional accumulation is anticipated, doubling or tripling the factor of safety for the structure in the design is recommended to account for additional drag or buoyancy forces.

Table 2. Key piece criteria based on mean segment bankfull width and volume [1].

6 KEY PIECE CRITERIA	
Mean Segment Bankfull Width (m)	Minimum Volume (m^3)
0 to <5	1.0
≤ 5 to < 10	2.5
≤10 to < 15	6.0
≤ 15 to < 20	9.0
≤20	9.0

Table 3. Detail of key piece volume matrix based on *Watershed Analysis Fish Habitat Module*, Table F-5 [1].

Min Dia. (m)	**BFW 0 to 5**	**BFW 5 to 10**	**BFW 10 to 15**	**BFW 15 to 20**
	Min 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

Hydraulic conditions around a jam often result in sediment deposition on the downstream side. This deposition buries much of the bole of the key piece(s) and will increase the effective weight and, hence, the stability of the logjam. Using excavated sediments during construction to bury the key pieces can accelerate the process of deposition.

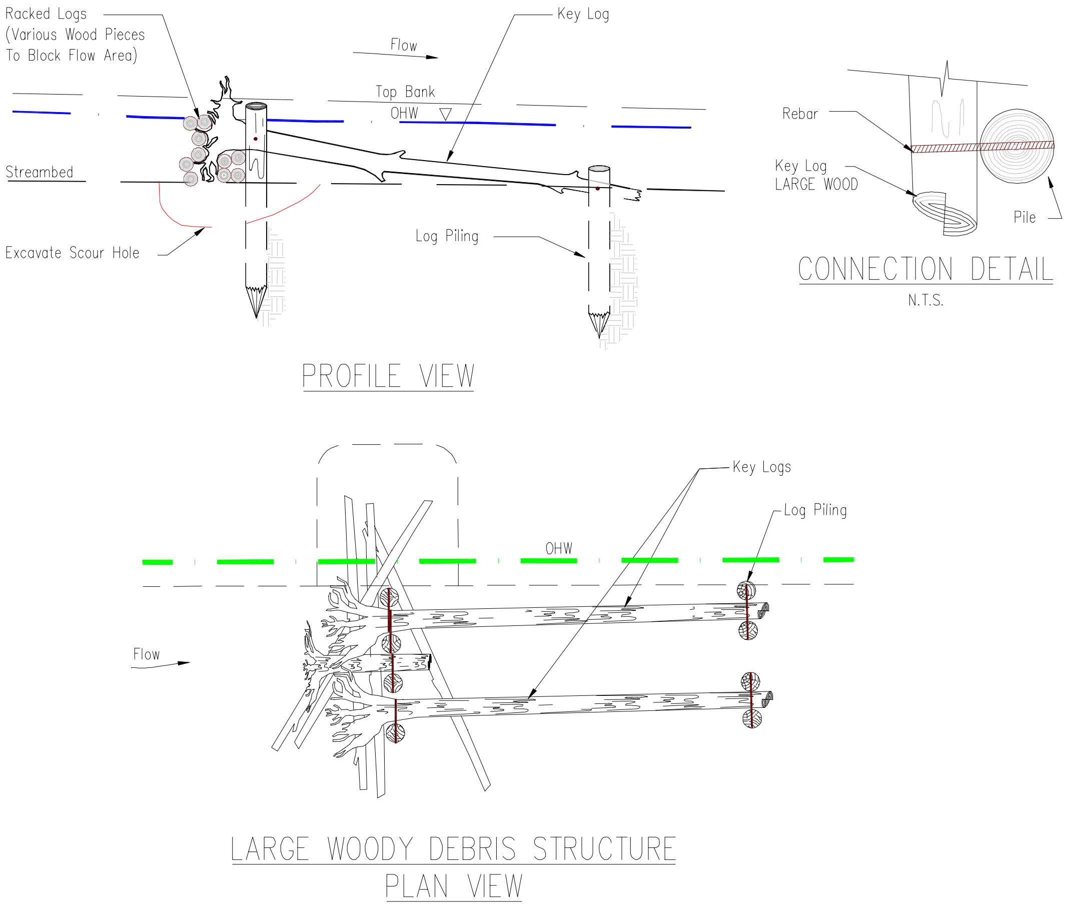
Stabilizing a logjam may require excavation of the streambed or bank to provide a trench for the key piece(s). The depth of excavation depends on channel hydraulics, substrate characteristics, bank material, channel dimensions, existing vegetation and the size of wood. Once a key piece is placed in a trench, the trench is covered with excavated sediment to provide additional ballast and frictional resistance to drag forces. The soil replaced in the trench is relatively loose and subject to scour. It should be compacted and protected (see *ISPG* for protection techniques)[34]. The potential for scour around a logjam against non-cohesive fine-grained banks may make additional local bank protection necessary.

Unanchored, engineered logjams must be dense, with racked 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 ballast well. Although building logjams in non-alluvial channels is preferable using trees with root wads, it has been successful using logs that lack roots by amassing and orienting the logs to function like a natural logjam.

Logjams in alluvial channels can also be anchored with pilings (see **Large Wood and Log Jams Figure 19**). In small-grained substrate, a row of log pilings can be driven vertically into the streambed using the excavator bucket. In larger substrate, pile-driving equipment may be required, as well as steel tips on the logs. The logs need to be long enough to extend below estimated scour depths and resist all associated forces during maximum scour events. A second row of pilings should be driven into the streambed at least 20 feet downstream, and brace logs (effectively key pieces) should be anchored between them (see **Large Wood and Log Jams Figure 20**. LW is then racked against the upstream side of the brace logs and the first row of pilings, just as they are for unanchored engineered logjams. The braces are needed because there is a limit to the size and, consequently, the strength of log piles that can be driven with an excavator. The braces distribute the shearing force of the racked logs between the two rows of pilings. The upstream row of piles is in the area of scour around the face of the logjam. The downstream row is positioned in the deposition zone, safe from the undermining effects of scour.

Another approach is to partially bury logs into the bank so that they still extend into the channel, perpendicular to the direction of flow. Logs are then racked against the upstream side of the partially buried log. Some sites may require riprap or other protection for the backfill soil in the trench.

Large Wood and Log Jams Figure 19. A logjam anchored by driven log pilings on the Little Hoko River, Clallam County, Washington.



Large Wood and Log Jams Figure 20. Piling-anchored logjam concept.

6.1 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. Evenly distributed wood throughout a reach is preferable, as inputting all wood at a single location is likely to result in unwanted large jams. The delivery of entire trees with rootwads and limbs is emphasized.

Generally, key piece wood additions should be large enough to develop a logjam without significant movement downstream. When the goal is to allow wood movement downstream, size mobility calculations are not critical. The minimum size of wood necessary to qualify, as a key piece is further discussed in section 5.3 *Factors that Influence the Stability of Wood in Streams*.

Man-made impoundments such as reservoirs and collections on bridge piers make good source locations for supplemental wood. Other sources include selective thinning of stream corridor forest stand outside of a functional stream buffer zone.

6.2 Trapping Mobile Wood

The design of wood-trapping structures follows the same formula as LW complexes or engineered log jams, except that racked logs are provided naturally through mobile wood transport. To catch mobile wood more efficiently, structural designs and locations must be modified to maximize contact and minimize passage of smaller mobile pieces. Capture and stabilization of the structure is more likely when it is oriented perpendicular or angled upstream to the flow direction, catching wood floating downstream in the pocket formed by the tree and the streambank. Consider the likelihood that a resultant debris jam will create a flow constriction with the attendant impacts as discussed in Introduction to Structures. Site selection should also consider the recreational use of the stream because of potential hazards to recreational users.

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 could include single key pieces, log pilings, or logs anchored in a trench in the bank. One method that has been used effectively in the USFS Mt. Baker/Snoqualmie District is to tether LW complexes, allowing for limited vertical and lateral movement. The complex is tied together to act as a unit and several anchor points are used. The structure can float during floods and be at the surface where floating wood can be intercepted. A floating structure allows flow to pass below it, reducing the total force on the structure and the anchoring system. However, the tethers will be subject to different dynamic forces than a rigid structure (bouncing, change in angle of forces), so it is not recommended to reduce the capacity of the anchoring system.

7 PERMITTING

In-channel work including streambed and bank excavation and the placement of fill within the channel requires permits and checklists. These 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). An Endangered Species Act Section 7 or 10 Consultation may also be required. Refer to *Typical Permit Requirements for Work In and Around Water* appendix for more information regarding each of these permits and checklists.

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.

A wetland assessment prior to designs will establish the extent and type of jurisdictional wetlands within a project area. Some wetland types such as forested wetlands are rare and require a greater degree of protection than other more common wetland types. Working with the Washington Department of Ecology and the Army Corps of Engineers early in the design process to identify wetlands constraints can reduce design changes and permitting delays later.

8 CONSTRUCTION CONSIDERATIONS

Details of construction, such as access, haul roads, material sources and disposal, utilities, dewatering or earthwork should be considered in the design phase of any project. Completing designs independent of construction considerations risks resource damage during construction, underestimating construction costs and creating hazardous working conditions.

8.1 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 anchoring or while the other machine places additional logs or ballast. 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 Considerations* 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[43] 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 logjam. 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

Large Wood and Log Jams Figure 21.
A large boulder (4-ft + dia) placed on a matrix of small, racked logs
provides ballast for a logjam on the Tucannon River, Columbia County, Washington..

8.2 Equipment

Equipment needed to move wood can include self-loading log trucks, excavators, end dumps, skidders and dump trucks. LW 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 can 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 it has been steam cleaned of 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. LW 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.

8.3 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 there is a road immediately adjacent to a stream, 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.

9 COST ESTIMATION

9.1 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. In forestlands, live trees near the stream may be the most cost effective source. However, regulations and forest management practices often discourage taking trees from riparian buffers. 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.

Some basic understanding of log value/worth is needed to approach timber or mill owners. 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, there is approximately five thousand board feet on a loaded log truck. This can vary depending on the weight of the wood.

9.2 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 than shuttling it with an excavator. This process will invariably remove most limbs and often parts of the root wad. Skidders cost approximately $70/hour and can move several trees at once with a set of choker cables. The haul distance from a stockpile site to the work site would 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 have 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.

Helicopter use is a significant cost issue. Helicopter flight distance equals money, so the faster the turn around time the more cost effective a helicopter becomes. Depending on size, helicopters range from $900 to $8200 per hour for a 234 Chinook capable of lifting old growth-sized material up to 26,000 pounds.

9.3 Unit Costs For Structures

Once delivered, the placement cost of individual log units is typically about $100 per log or tree. A small to moderate-sized log jam could take up to a half a day to build and cost approximately $600 to install using a medium-sized excavator. Total costs for logjams may range from approximately $1,000 to over $50,000 for large jams on large rivers.

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. LW 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% of a total project cost in remote areas. In small streams or areas with little anchoring or good access it can be less than 5%.

LW replenishment is the least expensive aspect of LW placement projects. 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.

9.4 Contracting

LW 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 habitat expert be provided to ensure habitat and stability requirements are met.

See the *Construction Considerations* appendix for additional details such as construction timing issues, sequencing, access and reclamation of disturbed areas.

10 MONITORING

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 monitored. Designs should specify procedures for pre- and post-construction studies so resulting physical and biological changes can be evaluated[52]. Further discussion of the relation of design criteria to monitoring is provided in the *Monitoring Considerations* appendix. In some cases, independent monitoring is provided by the funding agency (e.g., SRFB), reducing the need for project proponents to conduct it.

Monitoring is expensive, and biological monitoring can be as expensive as the project itself. In the case of experimental methods and controversial projects, every project should be monitored. For standardized methods, a subset should be sufficient.

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[53]. Habitat-monitoring protocols will likely require a schedule that is more comprehensive than that required for the integrity of the structure.

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 intense monitoring to insure stability. New anchoring techniques or designs that emulate natural function not discussed in this guide should also be closely monitored for stability and effectiveness. Successful new and/or better designs should be shared to allow more widespread application.

11 MAINTENANCE

Maintenance of large wood projects should not be required except in a few situations where the wood is no longer meeting project 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 an obvious hazard.

Public outreach may help avoid some maintenance costs. Local landowners may view LW projects as a source of firewood. Rafters have also been known to cut up logjams or LW complexes. Notifying and educating local residents, governments and recreation businesses 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.

12 EXAMPLES

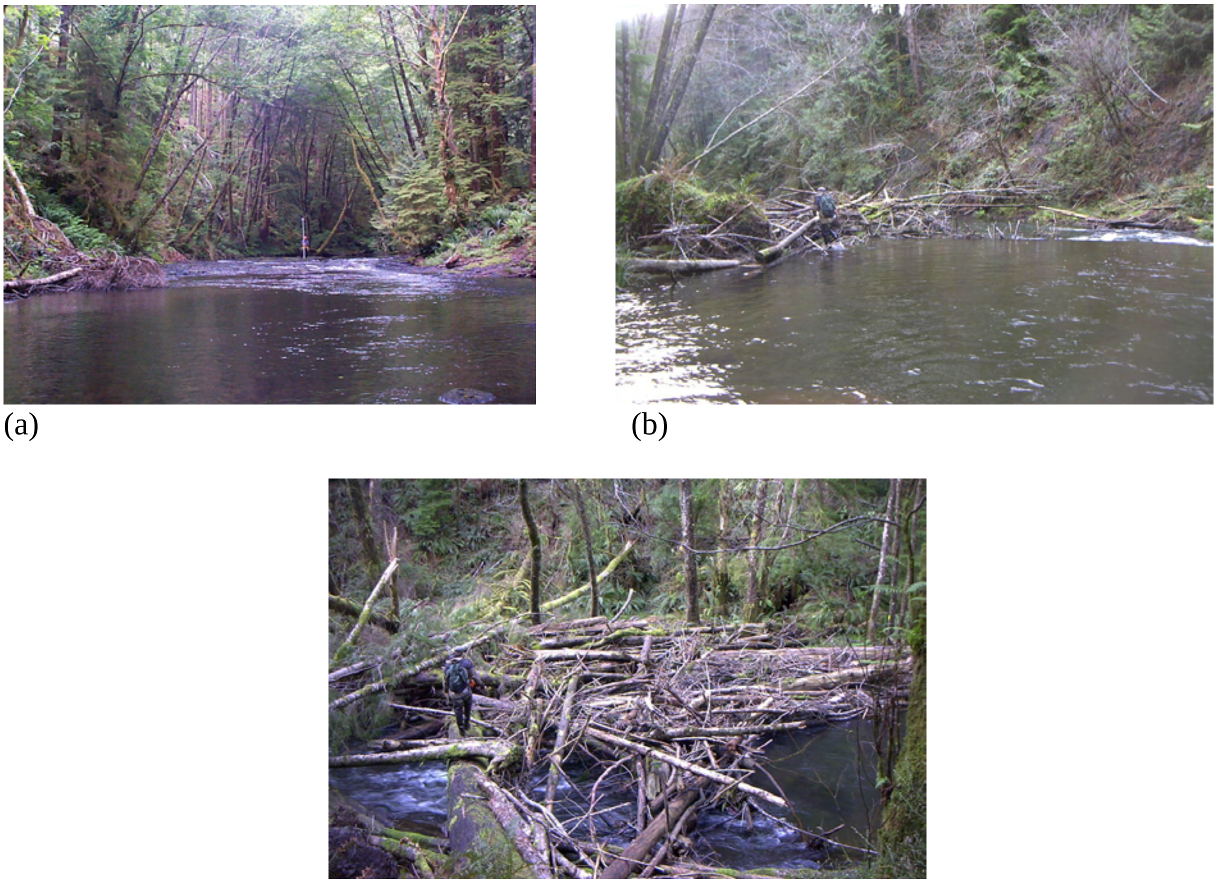
Constructed Log Jam--- West Fork of the Hood River (Mike Brunfelt, Interfluve)

A channel-spanning logjam was constructed at the upstream end of an alluvial fan that was historically subject to debris torrents. The site in Hood River County was a natural area of deposition within the Pacific Silver Fir vegetation zone. The size of historical LW was up 5 feet in diameter. Over time the initial logjam accumulated more wood from upstream sources. This caused the channel to aggrade to a depth of 4 feet near the logjam, 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 historic side channels are now re-watered during low flow. Off channel beaver activity has increased. The logjam was constructed in 1991 and has sustained numerous over bank flows and one 25-year return interval flood.

LW Replenishment--- Palix River (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, 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 chum 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. Since the most powerful flows tend to occur when chum redds were incubating in these beds, this population was impacted. Chum salmon spawner recruit analysis shows that over the 27 years of record an average of one of three chum generations failed to reproduce brood year replacement number. Since 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.



(a) (b)

(c)

Large Wood and Log Jams Figure 22. 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)

Upper Finney Creek Logjams (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: 1) impacts to fisheries and aquatic habitat values of Finney Creek downstream of the site 2) impact to water quality (Finney is on 303d listing). The project addressed these impacts with strategically placed logjams 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 logjams. Channel deepening and narrowing has been measured. Riparian area adjacent to this reach lack large diameter trees for LW recruitment due to past timber harvest and channel cleanout. The logjams 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.


(a)


(b)


(c)

Large Wood and Log Jams Figure 23. 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)

Klahowya Creek (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. Since 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 large wood 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 (1990)[54] in two similarly sized low order old growth streams in Alaska.

Large Wood and Log Jams Figure 24. 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 Logjams (Bruce Heiner, WDFW)

A small stretch of the Tucannon River in Columbia County, owned by WDFW, had significant erosion during the 1996 flood, resulting 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 logjams were constructed along a designed new channel meander. The concept was that during high flows each logjam would keep the main flow trained in the new channel until it met the next logjam. Flood flows could still spread into the flood terrace created by the 1996 flood, but with less volume or energy than before. The logjams 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 has far outstripped any planted vegetation. The last high flow season is 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.

(a)

(b)

(c)


(d) (e)

Large Wood and Log Jams Figure 25. 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.

13 GLOSSARY

Aggradation - The geologic process by which streambeds are raised in elevation and floodplains are formed. It is the opposite of degradation. See also "channel scour and fill."

Alluvial stream - Self-formed channels composed of silts, clays, sands and gravel. Alluvial streams are characterized by the ability to alter their boundaries and their patterns in response to changes in discharge and sediment supply.

Alluvium - A general term for all deposits resulting directly or indirectly from the sediment transport of streams, thus including the sediments laid down in streambeds, floodplains, lakes, fans and estuaries.

Anastomosed channel – A very stable multiple-thread channel system in broad, low gradient floodplains of cohesive soils. Stability is significantly influenced by riparian vegetation.

Avulsion – A significant and abrupt change in channel alignment resulting in a new channel across the floodplain.

Bankfull discharge - The discharge corresponding to the stage at which flow begins to spill onto the active floodplain.

Bar - (a) Accumulation of sand, gravel or other alluvial material found in the channel, along the banks, or at the mouth of a stream where a decrease in velocity induces deposition. (b) An alluvial deposit or erosion feature composed of sand, gravel or other materials, which obstructs flow. A description of bar types follows:

Diagonal - Elongated bodies with long axes oriented obliquely to the flow. They are roughly triangular in cross-section and often terminate in riffles.

Longitudinal- Elongated bodies parallel to the local flow, of different shape, but typically with convex surfaces. Common to gravelly braided streams.

Point Bar - Bar found on the inside of meander bends. They are typically attached to the stream bank and terminate in pools.

Transverse Bar - Typically solitary lobate features that extend over much of the active stream width but may also occur in sequence down a given reach of river. They are produced in areas of local flow divergence and are always associated with local deposition. Flow is distributed radially over the bar. Common to sandy braided streams.

Baseflow – see “*Flow*.”

Bedload - Sediment moving on or near the streambed and frequently in contact with it. See also "suspended load."

Bed Roughness - A measure of the irregularity of the streambed as it contributes to flow resistance. Commonly measured in terms of Darcy-Weisbach roughness coefficient.

Biomass - The weight of the standing crop of a specified organism or group of organisms present in a specified space at any one time. Usually expressed as weight per unit area.

Braided Channel - A stream characterized by flow within several channels, which successively meet and re-divide. Braiding may be an adjustment to a sediment load too large to be carried by a single channel. Braided channels often occur in deltas of rivers or in the outflow from a glacier.

Buffer Zone - An area situated between two zones, which have conflicting interests. As applied to streams, a narrow strip of natural vegetation along streambanks to reduce the possibility of adverse impacts from land use on water quality.

Canopy - The overhead branches and leaves of streamside vegetation.

Canopy Cover - The vegetation that projects over the stream. Can arbitrarily be divided into two levels: *Crown cover* is more than 1 meter above the water surface. *Overhead cover* for fish is less than 1 foot above the water surface.

Carrying Capacity (biological) - The maximum average number of a given organism that a stream or section of stream can maintain under a given set of conditions and over a specified period. Carrying capacity may vary from season to season or from year to year.

Cascade - Habitat type characterized by swift current, exposed rocks and boulders, high gradient and considerable turbulence and surface agitation, and consisting of a stepped series of drops. See "water types".

Channel - A natural or artificial waterway of perceptible extent that periodically or continuously contains moving water. It has a definite bed and banks, which serve to confine the water.

Channel Habitat Types -

- *Pools* - Water of considerable depth for the size of stream. Pools generally have slowly flowing water and a smooth surface, but they may often have a swift, turbulent area where the water enters them.
- *Flats* - Water with slight to moderate current and with an unbroken surface, but with less depth than pools.
- *Pocket Water* - Similar to "runs", however, the flow is blocked by numerous partial obstructions, usually boulders, and is fairly turbulent.
- *Riffles* -Shallow water with rapid current and with flow broken by gravel or rubble.
- *Runs* - Moderate to rapid current flowing in a deeper, narrower channel than a riffle. Flow less turbulent than in a rapid or cascade.
- *Rapids* - Those parts of large streams and rivers that are relatively swift and shallow with a bed of boulders. Analogous to riffles of a smaller stream.
- *Cascades* - A reach of stream in which steep gradient and a bed of large rocks combine to produce a very irregular rapid flow, often with white water. A cascade may be somewhat deeper and narrower than a "rapids".

Channel Scour and Fill - Words used to define erosion and sedimentation during relatively short periods of time, whereas *degradation* and *aggradation* apply to similar processes that occur over a longer period of time. Scour and fill applies to events measured in minutes, hours, days, perhaps even seasons, whereas aggradation and degradation apply to persistent trends over a period of years or decades.

Channel Stability - A relative measure of the resistance of a stream to erosion. Stable streams do not change markedly in appearance from year to year. An assessment of stability helps determine how well a stream will adjust to and recover from changes in flow or sediment transport.

Channel Width - The horizontal distance along a transect line from bank to bank at the high water marks, measured at right angles to the direction of flow. Multiple channel widths are summed to represent total channel width.

Cover - An area of shelter in a stream that provides aquatic organisms with protection from predators and/or a place to rest and conserve energy.

Cross-Sectional Area - The area of a stream or waterway, usually taken perpendicular to the stream centerline.

Cubic Foot per Second (cfs) - A unit of stream discharge. It represents one cubic foot of water moving past a given point in one second. Expressed another way, it is the rate of discharge of a stream whose channel is 1 square foot in cross-sectional area and whose average velocity is 1 foot per second.

Debris Jam - Debris jam. Accumulation of logs and other organic debris. Can be large accumulations of debris partially or completely blocking the stream channel, creating obstructions to flow.

Debris Loading - The quantity of debris located within a specific reach of stream channel, due to natural processes or human activities.

Degradation - The geologic process by which streambeds are lower in elevation and floodplains are removed. It is the opposite of aggradation. See "aggradation".

Deposition - The settlement or accumulation of material out of the water column and onto the streambed or floodplain. Occurs when the energy of flowing water is unable to transport sediment load.

Depth - The vertical distance from the water surface to the streambed.

Detritus - Organic debris from decomposing plants and animals.

Discharge - Rate of flow expressed in volume per unit of time, for instance, in cubic feet per second or liters per second. Discharge is the product of the mean velocity and the cross-sectional area of flow. See "mean annual discharge".

Drainage Area or Drainage Basin - That area so enclosed by a topographic divide that surface runoff from precipitation drains into a stream above the point specified. (The term "watershed" is commonly misapplied to the drainage area.) A drainage area can be contained within a single watershed or include a number of watersheds.

Ecosystem - An ecological system or unit that includes living organisms and nonliving substances, which interact to produce an exchange or cycling of materials.

Enhancement - An improvement of conditions that provide for the betterment over existing conditions of the aquatic, terrestrial and recreational resources.

Environment - Apart from the dictionary definition: Surrounding; surrounding objects, region, or circumstances. The word represents an animal's environment in four major components: (1) weather, (2) food, (3) other animals and pathogens, (4) a place in which to live. (See "habitat"). This term cannot, in its strict sense be applied to the latter category. Some environmental items may fall into more than one of these components (some of the "food" may be "other animals", for instance), but this breakdown serves well as a basis for ecological study and discussion. One can generally think of the environment of any animal in terms of these four components and the interactions between them. Since parts of an animal's environment are animals of his own kind, and since the density of the population must be regarded as part of the environment, the confusion in speaking of a population being a part of its own environment can be avoided by speaking always of the environment in regard to the *individual*.

Fill - See "channel scour and fill".

Fine Sediment - Silt and sand-sized materials.

Fish Habitat - The aquatic environment and the immediately surrounding terrestrial environment that, combined, afford the necessary biological and physical support systems required by fish species during various life history stages.

Flood - Discharge overflowing the banks of a stream.

Floodplain - A strip of relatively smooth land bordering a stream, which is typically overflowed during periods of high water. Though the floodplain is generally composed of finer material near the surface than at the base, this gradation in particle size is by no means universal. Floodplains are generally formed by the progressive channel migration and deposition from overbank flows.

Flow - (a) The movement of a stream of water and/or other mobile substances from place to place. (b) The movement of water, and the moving water itself. (c) The volume of water passing a given point per unit of time. Syn: Discharge.

Baseflow - The portion of the stream discharge that is derived from natural storage i.e., groundwater outflow and the draining of large lakes and swamps or other source outside the net rainfall that creates surface runoff; discharge sustained in a stream channel, not a result of direct runoff and without the effects of regulation, diversion, or other works of man. Also called sustaining, normal, ordinary or groundwater flow.

Instantaneous flow -That discharge measured at any instant in time.

Interstitial flow - See intragravel flow.

Intragravel flow - That portion of the surface water that infiltrates the streambed and moves through the substrate pores.

Low flow - The lowest discharge recorded over a specified period of time. Also called minimum flow.

Mean flow - The average discharge at a given stream location, usually expressed in cubic feet per second, computed for the period of record by dividing the total volume of flow by the number of days, months or years in the specified period.

Minimum flow - (a) the lowest discharge recorded over a specified period of time (preferred definition). (b) Negotiated lowest flow in a regulated stream that will sustain an aquatic population at agreed upon levels. This flow may vary seasonally. (This recently developed definition is in conflict with the older definition (a) and to avoid confusion should not be used. A suggested alternative is to apply this definition to the term *least flow*).

Peak flow - The highest discharge recorded over a specified period of time. Often thought of in terms of spring snowmelt, summer, fall or winter rainy season flow. Also called maximum flow.

Subsurface flow - That portion (part or all) of the water that infiltrates the streambed and moves horizontally through and below it. It may or may not return to the stream channel at some point downstream.

Fluvial - Pertaining to streams or produced by stream action.

Gradient - (a) The general slope, or rate of change in vertical elevation per unit of horizontal distance, of the water surface of a flowing stream. (b) The rate of change of any characteristic per unit of length. See "stream bed gradient"

Gravel - Stones larger than sand, but smaller than rubble. See table "Substrate Particle."

Geomorphology – The study of the classification, description, nature, origin and development of landforms and their relationships to underlying structures, and the history of geologic changes as recorded by these surface features.

Habitat - Loosely used now, but the strict concept was that a certain habitat (an area with rather uniform physiography, vegetation or other animal-influencing quality) has a certain community of animals. However, the word "habitat" probably brings into mind a view of an animal's environment, the central aspect of which would be "a place in which to live" (see "environment"), but which would include a few other things around the fringes. The fringe aspects might be food, competitors for the food, and some of the animal's predators (not fishermen). In keeping with variability of meaning, "habitat" is used in various ways.

Hiding Cover - Used to mean places where animals can hide from predators.

Hydraulics - Refers to water, or other liquids, in motion and their action.

Hydrograph - A curve showing discharge over time.

Hydrologic - Refers to water in all its stages, and its properties, distribution and circulation through the hydrologic cycle.

Incised – Cut down into or entrenched.

Infiltration - That part of precipitation that soaks into the ground. See also "runoff" and "recharge".

Instream Cover - Areas of shelter in a stream channel that provide aquatic organisms protection from predators or competitors and/or a place in which to rest and conserve energy due to a reduction in the force of the current.

Invert - Refers to the bottom, inside surface of a pipe, log, or other object. Occasionally used to refer to the bottom or base elevation of a structure.

Key piece – A LW piece in a logjam that has sufficient mass to provide structural stability to the logjam. In natural logjams the key piece(s) typically initiate jam formation.

Large Wood - Any large piece of relatively stable woody material having a least diameter greater than 10 cm and a length greater than 1 m that intrudes into the stream channel. Syn: LWD, large woody debris, log. Specific types of large organic debris include:

- *Affixed logs* - Single logs or groups of logs that are firmly embedded, lodged or rooted in a stream channel.
  - *Bole* - Term referring to the stem or trunk of the tree.
  - *Large bole* - 10 meters or more in length; often embedded, remain in the stream for extended periods.
  - *Small bole* - Less than 10 meters, usually sections of bole, seldom stable, usually move downstream on high flows.
  - *Rootwad*- The root-mass of the tree. Syn: rootmass.
  - *Snag* - (a) A standing dead tree. (b) Sometimes a submerged fallen tree in large streams. The top of the tree is exposed or only slightly submerged.

Large Wood Complex – A single LW structure composed of 3 – 10 inter-connected pieces.

Lateral Migration – Movement of channel perpendicular to the direction of flow.

Longitudinal Profile - A graph of the vertical fall of the streambed or water surface measured along the course of the stream.

Meander - A reach of stream with a ratio of channel length/valley length greater than 1.5. By definition, any value exceeding unity can be taken as evidence of meandering, but 1.5 has been widely accepted by convention.

Morphology – The study of form and structure.

Organic Matter - Any part of a substance which once had life. Organic matter, then, consists of any animal or vegetable waste or by-product.

Overhead Cover - Material (organic or inorganic) that provides protection to fish or other aquatic animals from above; generally includes material overhanging the stream less than a particular distance above the water surface. Values of less than 0.5 meter and less than 1 foot have been used.

Overland Flow - See "runoff".

Peak Flow - The maximum instantaneous rate of flow during a flood.

Phreatophytes - Plants growing on or near the stream bank with their roots in the ground water and decreasing streamflow by transpiration during their growing season.

Planform – The configuration of a river system viewed from above.

Point Bar - A deposit of sand, gravel or other material on the inside of a stream bend, which causes some obstruction to the flow.

Pool - (a) A portion of the stream with reduced current velocity, often with water deeper than the adjacent areas, and which is frequently usable by fish for resting and cover. (b) A small body of standing water, e.g., in a marsh or on the flood plain.

Pool Tailout - The downstream end of a pool where the bed surface gradually rises and the water depth decreases. The tailout of a pool may vary in length. This feature usually occurs immediately upstream of a riffle.

Reach - (a) Any specified length of stream. (b) A relatively homogeneous section of a stream having a repetitious sequence of physical characteristics and habitat types. (c) A regime of hydraulic units whose overall profile is different from another reach.

Critical Reach - A segment of the stream that is required for the development and/or survival of a particular aquatic organism or to a particular life stage of an aquatic organism.

Representative Reach - A length of stream that represents a large section of the stream with respect to hydraulic variables (area, depth, discharge and slope) and biological constituents.

Specific Reach - A length of channel uniform with respect to selected habitat characteristics or elements (discharge, depth, area, slope, population or hydraulic units), fish species composition, water quality, and type and condition of bank cover.

Recurrence interval - interchangeably used with "return period"; a statistic based on frequency analysis derived from annual or partial duration peak flow series that describes the average interval (in years) between events equaling or exceeding a given magnitude.

Redd - An area of streambed dug out by a female trout or salmon before spawning and in which she buries her eggs after spawning.

Return period - see "recurrence interval".

Riffle - A shallow, rapid section of stream where the water surface is broken into waves by obstructions that are wholly or partly submerged.

Riparian - Relating to or living on or near the bank of a watercourse.

Riparian Area - The area between a stream or other body of water and the adjacent upland identified by soil characteristics and distinctive vegetation. It includes wetlands and those portions of floodplains and valley bottoms that support riparian vegetation.

Riparian Vegetation - Vegetative growth along the banks of a stream.

Roughness Element - Large obstacles in a channel that deflect flow and affect a local increase in shear stress that causes scour and deposition.

Runoff - Water from precipitation flowing above or below ground to surface water without entering the groundwater table.

Surface Runoff or Overland Flow - Runoff water flowing over the land surface.

Subsurface Runoff - Runoff water flowing beneath the land surface.

Salmonid - Refers to a member of the fish family classed as Salmonidae, including the salmons, trouts, chars, whitefishes and grayling.

Scour - The localized removal of material from the streambed by flowing water. This is the opposite of fill.

Scour and Fill - See "channel scour and fill".

Sediment - Any mineral or organic matter from those particles measured in microns to those measured in meters.

Sediment Discharge - Rate of flow of sediment contained in a stream, expressed as volume or weight per unit time. Sediment discharge includes" suspended load discharge" and "bed load discharge". Suspended load discharge is the product of streamflow discharge and concentration of suspended sediment.

Sediment Transport - The rate of sediment movement through a given reach of stream.

Shear Stress Force- The shear stress or tractive force results from the tangential pull of flowing water on the streambed and banks, and is expressed in pounds per square foot or n/m^2. The energy expended on the wetted boundary of the stream increases proportionally with the energy slope and water depth.

Side Channel - Lateral channel with an axis of flow roughly parallel to the mainstem and which is fed by water from the mainstem; a braid of river with flow appreciably lower than the main channel. Side channel habitat may exist either in well-defined secondary (overflow) channels, or in poorly defined watercourses flowing through partially submerged gravel bars and islands along the margins of the mainstem.

Silt - In common usage, silt designates sediments finer than sand. Technically, however, silt is a specific grain size, finer than sand but coarser than clay.

Sinuosity - The ratio of channel length to direct down valley distance.

Species - The smallest unit of plant or animal classification commonly used. Members of a species share certain characteristics, which differ from those of other species, and they tend not to interbreed with other species.

Stage - (Also known as water level or gage height). Elevation of water surface above any chosen reference plane.

Stream - A natural watercourse containing flowing water, at least part of the year, supporting a community of plants and animals within the stream channel and the riparian vegetation zone. Streams in natural channels may be classified as follows:

a) Relation to time:

Ephemeral - One that flows briefly only in direct response to precipitation in the immediate locality and whose channel is at all times above the water table.

Intermittent or seasonal - One in contact with the ground-water table that flows only at certain times of the year as when the ground-water table is high and/or when it receives water from springs or from some surface source such as melting snow in mountainous areas. It ceases to flow above the streambed when losses from evaporation or seepage exceed the available stream flow.

Perennial - One that flows continuously throughout the year. Syn: Permanent stream.

b) Relation to space:

Continuous - One that does not have interruptions in space.

Interrupted - One that contains alternating reaches that are perennial, intermittent, or ephemeral.

c) Relation to ground-water -

Insulated - A stream or reach of stream that neither contributes to nor receives water from the zone of saturation. It is separated from the zones of saturation by an impermeable bed.

Gaining - A stream or reach of stream that receives water from the zone of saturation.

Losing - A stream or reach of stream that contributes water to the zone of saturation.

Perched - Either a losing stream or an insulated stream that is separated from the underlying ground-water by a zone or aeration.

d) Other -

Incised - A stream that has, through degradation, cut its channel into the bed of the valley.

Streambank - The portion of the channel cross-section that restricts lateral movement of water at normal water levels. The bank often has a gradient steeper than 45 degrees and exhibits a distinct break in slope from the stream bottom. An obvious change in substrate may be a reliable delineation of the bank.

Lower bank - The periodically submerged portion of the channel cross-section from the normal high water line to the water's edge during the summer low flow period.

Upper bank - That portion of the topographic cross-section from the break in the general slope of the surrounding land to the normal high water line.

Streambed - The substrate plane, bounded by the streambanks, over which the water column moves. Also called stream bottom.

Streambed Gradient - The vertical distance a stream falls per unit of distance it flows horizontally. Commonly expressed as feet of fall per mile or meters of fall per kilometer.

Stream Bottom - See "streambed".

Stream Power - The rate of doing work, or a measure of the potential energy available for moving rock, sediment particles or other debris in the stream channel, as determined by the product of discharge, water surface slope and the specific weight of water, divided by the bottom width. Also equal to the product of shear stress and mean velocity.

Structure - (a) Any object, usually large, in the stream channel that affects water and sediment movement. (b) The diversity of physical habitat within a stream. (c) When applied to a biological community, the organization of taxa into various functional or trophic groups.

Table 3. *Substrate Particle -Size*

	Size Range	
Name of particle	*Millimeters*	*Inches*
Large boulder	>1,024	40-160
Small boulder	256-1024	10-40

Large cobble (rubble)	128-256	5-10
Small cobble (rubble)	64-128	2.5-5
Gravel	2-64	0.08-2.5
Sand	0.062-2	
Silt	0.004-0.062	
Clay	<0.004	

Succession – The progressive change in plant or forest communities over time. Primary succession begins on a bare surface not previously occupied.

Suspended Load - That part of the sediment load whose immersed weight is carried by the fluid. See also "bed load".

Thalweg - The path of maximum depth in a river or stream. This path commonly follows a meandering pattern, back and forth across the channel.

Tributary - Any channel or inlet that conveys water into a stream.

Undercut Bank - A bank that has had its base or toe cut away by water or has been man-made and overhangs part of the stream.

Water Level - See "stage".

Water Quality - A general term denoting a category of properties that water has. Commonly used in reference to chemical characteristics and temperature of the water. It can logically be the title of an organization which deals with these aspects of water and can even serve as a general heading in a paper, but the term is often misused; for example, "Dog Creek lacks water quality" is an obscure way to say that it gets too hot in summer for trout. "Water quality" is a vague term and should be used sparingly. Where one means "water temperature" or "chemical content" or "pollution", one should say so.

Watershed - A convex surface such as a mountain or hill which sheds water from one high point or ridge into several streams which may form its boundary. "Watershed" is commonly confused with "drainage basin": a concave surface collecting precipitation into one stream.

Woody Debris – See “large wood”.

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DROP STRUCTURES

1 DESCRIPTION OF TECHNIQUE

Drop structures (also known as grade controls, sills, or weirs) are low-elevation structures that span the entire width of the channel, creating an abrupt drop in channel bed and water surface elevation in a downstream direction. Drop structures have been used extensively in Washington State to stabilize channel grades, improve fish passage, and to reduce erosion. Generally speaking, in fish bearing waters, vertical drops must not exceed 1 foot [WAC 220-110-070]; lesser drops are often required to accommodate certain species and age classes of fish.

Drop Structures are designed to spill and direct flow such that there is a distinct drop in water surface elevation at normal low flows. The purpose of drop structures may include but is not limited to:

- redistribute or dissipate energy;
- stabilize the channel bed;
- restore a step pool morphology to an altered channel
- limit channel incision;
- limit bank erosion by directing flow away from an eroding bank;
- modify the channel bed profile and form by promoting collection, sorting and deposition of sediment;
- create structural and hydraulic diversity in uniform channels;
- improve fish passage over natural and artificial barriers by backwatering the upstream reach;
- scour the channel bed, creating holding pools for fish and other aquatic life;
- provide backwater (depth) in groundwater fed side channels; or
- raise the bed of an incised stream to reconnect it with its floodplain.

Drop structures may resemble porous weirs in appearance. But while drop structures direct water over the structure and are applied primarily to modify the profile of a channel, porous weirs allow water to flow through the structure and are applied primarily to redirect or concentrate flow. Like porous weirs, their longevity is limited by their structural integrity and the lateral and vertical stability of the channel. Drop structures can be constructed to be either deformable or non-deformable. They are commonly constructed with natural materials (rock or logs), but timber planks, sheet pile, concrete, and other rigid artificial materials have also been used.

2 PHYSICAL AND BIOLOGICAL EFFECTS

Drop structures alter the velocity, flow hydraulics, and sediment transport characteristics upstream and immediately downstream of the structure. The common characteristic of all forms of drop structures is that they create a distinct drop in the channel bed and in the low-flow water surface profile, producing backwater effects upstream and a plunge pool immediately below the structure.

Drop structures create low velocity backwater conditions upstream by raising the effective bed elevation, thereby reducing channel slope. Backwatering commonly induces sediment deposition and increases the water surface elevation upstream of the structure at low to moderate flows. Typically, at high flows, no backwatering effect of the structure is evident provided the structure lies low in the channel profile and does not significantly reduce the channel cross-section. Deposition upstream of a drop structure is particularly common in moderate to high bedload channels. Sediment deposition upstream of the structure is not as likely for low bedload or incising channels due to limited sediment availability. The upstream extent of backwater depends upon the scale of the structure and the slope of the channel. Backwater effects extend much further on low-gradient streams than on high gradient streams. As drop structures typically lie low in the channel profile, backwater effects associated with them are generally localized. However, if the structure causes a significant reduction in channel cross-sectional area or a series of structures collectively increase the hydraulic roughness of the channel, backwater effects may be more far reaching. Effects of large-scale backwatering can include increased flood levels and frequency of floodplain inundation, an adjustment of the elevation of streamside vegetation as lower-growing plants are drowned out, potential change in riparian species composition and distribution in response to changing inundation patterns and water table elevations, and reduced reach transport of sediment. Other effects associated with reduced sediment transport include channel aggradation and associated channel widening, bank erosion, increased channel meandering, and decreased channel depth.

As flow passes over a drop structure, it is directed perpendicular to the structure’s alignment. It is also funneled towards any low spots that occur on the structure. Thus, drop structures may redirect, concentrate, or disperse flow depending on their shape in both plan view and cross-section. This, in turn, may alter the patterns of scour and deposition in the downstream channel. Depending upon its shape, drop structures may also affect the channel cross section. Drop structures that are flat and straight across the channel tend to create a channel cross-section that is flat and uniform. The pool created in this case is at the base of the structure and spans the entire channel. Drop structures that have a “V” cross-section geometry create a thalweg in the pool and generate more diversity. The pool is longer but narrower and may not span the channel.

An important benefit of drop structures is the habitat they can provide. Drop structures may increase habitat complexity by breaking up a long glide or riffle into a series of step/pools. They create surface turbulence and bubbles that provide hiding cover, and a diversity of plunge pools, eddies, velocity chutes, and interstitial hiding areas that can benefit a host of fish and other aquatic organisms. They also catch debris, provide aeration, and collect and sort gravel in the tailout of associated scour pools. The scour pool formed by plunging flow over the structure provides energy dissipation and holding habitat for fish[1]. However, drop structures also pose a risk of becoming barriers to fish passage. This is most likely to occur if the downstream channel incises over time, if it or an adjacent structure fails such that the drop becomes too high. Or if the plunge pool is obstructed or of inadequate depth, if the depth of flow over the weir is too shallow, or if the head differential during fish passage flows is higher than predicted. For this reason, periodic monitoring is essential. However, keep in mind that even properly functioning drop structures create a distinct drop in water elevation that may pose a barrier or impede the upstream or downstream passage of non-target fish and wildlife species.

The impact of drop structures on channel grade and flow redirection is immediate. However, scour and the resulting redistribution of sediment may not occur until the first high flow events following construction. The physical and biological benefits and impacts drop structures provide may extend upstream and downstream of their application, particularly along low gradient streams.

3 BIOLOGICAL CONSIDERATIONS

3.1 Mitigation Requirements for the Technique

Placement of drop structures in the channel will fix the bed profile and prompt adjustments in the thalweg alignment and pattern of sediment scour and deposition. Existing fish spawning areas and pools may be impacted by these changes unless the structure is specifically designed to maintain them. In addition, the opportunity for future development of near-bank pool habitat may be lost. These near-bank pools provide some of the best types of rearing habitat, especially when they contain wood and cover from the overhanging bank. Loss of near-bank pool habitat may be mitigated by the scour pool that will develop on the downstream side of the structure and by adding wood to the affected or nearby reach. Refer to Section 6.2.9, *Incorporating Large Wood into Drop Structure Design*.

In addition to direct habitat loss, natural channel evolution, including dynamic erosion and deposition processes such as channel migration, will be reduced. This represents a lost opportunity for future development of habitat complexity resulting from periodic inputs of gravel and wood and side channel development. Placing large wood in the channel or floodplain can mitigate some negative impacts to habitat as discussed above. The drop structure itself may also provide mitigation, at least in part, if it restores fish access to historically available upstream habitat.

Refer to the Integrated Streambank Protection Guidelines[2], Chapter 4, *Considerations for a Solution* and Matrix 3 in Chapter 5, *Identify and Select Solutions* for additional guidance concerning mitigation requirements when used as a bank protection technique.

3.2 Mitigation Benefits Provided by the Technique

Drop structures can increase the habitat diversity of otherwise homogenous reaches. They can create and maintain pools that provide holding and rearing habitat for fish, improve fish passage, and sort and capture sediment to improve fish spawning habitat. These and other habitat benefits provided by drop structures are further described in Section 2, *Physical and Biological Effects*. Refer to Matrix 3 in Chapter 5 of the Integrated Streambank Protection Guidelines[2], for more detail on the mitigation benefits of this technique.

4 APPLICATION

Drop structures can be applied as a stand-alone technique, or in concert with other techniques. They can be applied at a site or reach scale. Though they can be applied individually, many project objectives require that multiple drop structures be installed in series, throughout a stream reach. For example, when replacing an undersized culvert that has a high outlet drop, it may be necessary to install several drop structures to incrementally step up the channel grade to provide fish passage through the new culvert.

Despite the potential benefits of drop structure placement (e.g., target fish passage, habitat complexity, floodplain reconnection), drop structures are an "unnatural anomaly in the fluvial system"[3] and may have serious negative impacts on the stream ecosystem. For instance, drop structures prevent the channel from moving laterally or adjusting vertically to maintain itself, to respond to changing watershed conditions, and to create and maintain new habitats and habitat diversity. Drop structures may exclude passage of non-target fish and wildlife species; and they may become barriers to target fish passage if the downstream channel incises or a downstream structure fails. Therefore, drop structures should only be applied where necessary, and only where they will be monitored regularly to ensure they do not become barriers to fish passage. Assurances should be in place for future access in case maintenance is needed. Drop structures should be discouraged solely for the purpose of habitat enhancement such as scour pool development or sorting of sediments. Other structural techniques (e.g., porous weirs, large wood and log jams, or boulder clusters, all of which are discussed in this document) or non-structural techniques (e.g., channel modification or removal or modification of infrastructure) may meet the same objectives with less detrimental impact to the ecosystem.

Siting of structures is a critical component of the design process. Drop structures should be located in straight channel sections and at the entrance and exits of channel bends; they should not be installed in the bends themselves. One reason for this is that flow is directed along the outside bank as it enters and moves through a channel bend. If a structure is located on the bend, it is difficult to redirect the flow if that is the objective. Flow will naturally tend to stay along the outside bank, making it very susceptible to an end run as the plunge pool forms downstream. The other reason why channel bends should be avoided is that the pattern of sediment scour and deposition created by the drop structure does not coincide with natural patterns of scour and deposition near a meander bend. Pools naturally form along the outside of meander bends and create a pool tailout comprised of sorted sediment deposits downstream. In channels that carry a sediment load, sediment is expected to deposit upstream of a drop structure and a pool to form immediately downstream.

Channel Width: Drop structures have been installed in channels up to 400 feet wide. Their use in systems above that threshold may be limited depending on project goals and objectives and the influence of other factors limiting their success. Application of drop structures on large rivers may encounter practical design and construction limitations imposed by the size of available rock or wood, equipment, and impacts that cannot be effectively mitigated. The scale of the structure should be roughly proportional to the size and slope of the channel.

Channel Gradient: The applicable channel gradient varies with the type of drop structure and the energy of the stream. The Washington Department of Fish and Wildlife (WDFW)[4] recommends a maximum finished gradient of 5 percent for straight log weirs placed in series in streams with typical rainfall-dominated hydrology. In small, spring-fed streams that don't experience extreme high flows, higher gradients may be possible (up to 7 percent). The recommended maximum final gradient of boulder weirs and other configurations of log weirs is 3 percent. California Department of Fish and Game[5] recommends limiting the use of log weirs to gradients of 1.5 to 4 percent in moderately entrenched channels. In steeper channels, the relatively close spacing of drop structures necessary to meet the maximum allowable vertical drop criteria for fish passage may cause the scour pool of one structure to collide with the next structure downstream and potentially undermine it or prevent it from sealing. (Drop structures that contain spaces between individual structural elements, such as double log or boulder weirs, rely upon upstream deposition of material to form an effective seal.) Interception of the scour pool with the next downstream structure also prevents total dissipation of energy between structures and, instead, transfers the energy downstream where it will likely scour the channel bed or banks. Therefore, the maximum recommended finished gradient for a series of solid (non-porous) drop structures, such as concrete or sheet pile weirs, is also 5 percent. As a result, it is difficult to steepen a rainfall-dominated channel with a natural slope greater than about 3 percent.

Drop structures are generally inappropriate in low-gradient (less than 1%) reaches where a step-pool morphology is uncommon in nature. Low gradient channels are typically characterized by plane-bed, pool-riffle or dune-ripple morphology. An exception to this is the incorporation of drop structures in constructed groundwater-fed side channels that are often at a level grade and the drop structures are used to maintain an optimal water depth for rearing and spawning.

Channel Stability: Drop structures are inappropriate in aggrading reaches. Aggrading reaches will deposit sediment above, around and over the drop structure burying it, thereby counteracting their intended function. Structures that create large backwater effects should be used with caution in flood-prone developed areas and streams that carry high bedload due to the potential for causing upstream aggradation and increased flooding. Caution should also be exercised when installing drop structures in laterally dynamic channels where there is the potential for an avulsion that could bypass the structure.

When applying drop structures to raise the bed of an incised channel, care is needed to ensure downstream incision is not exacerbated. The sediment-storage capacity of a drop structure can be enough to exacerbate downstream incision. This is especially true if the cause of channel incision is due to a decrease in sediment supply. Users of this technique should note that drop structures typically address only the symptoms of channel incision, not the cause. Drop structures may not be appropriate in actively incising reaches unless the root cause of vertical instability is also addressed. Refer to Chapter 4.5.5, Restoring an Incised/Incising Stream for further discussion on potential causes and treatments for channel incision.

Channel Bed: Drop structures are best applied to channels with gravel or cobble beds[6]. Securing drop structures into bedrock channels presents a challenge, but log weir drop structures have been successfully bolted to bedrock using rock bolts. Sand, silt, and other fine-grained material are easily erodible and can compromise the structural integrity of the structure if subject to high flow events. However, this becomes less of a concern in groundwater streams with stable flows and in small, low-gradient (<0.12%[6]) streams provided the banks are well vegetated. Boulder weirs are inappropriate in sand or other fine-grained bed streams.

Bank Protection: When using drop structures to protect streambanks, it is important to determine whether drop structures are the appropriate solution for the particular mechanism of failure and causes of bank erosion in question (see Integrated Streambank Protection Guidelines[2], Chapter 2, *Site Assessment*, Chapter 3, *Reach Assessment*, and Chapter 5, *Identify and Select Solutions* for guidance).

Drop structures are not useful in emergency streambank protection. They completely span the stream channel and usually require construction from within the channel, which may not be possible during an emergency. However, on smaller channels that are actively degrading or headcutting, rock may be placed as a grade-control measure during emergency conditions to arrest formation or progression of a nickpoint.

Other Siting Considerations: Drop structures may not be appropriate if navigation or recreation is a concern as they can create hazardous hydraulic conditions that trap objects. Drop structures should be located at least 20 feet downstream of the outlet of a culvert[4] to prevent scour at the culvert outlet from undermining the structure and to limit the amount of debris trapped within the culvert as a result of the drop structure. Drop structures should be located at least 35 feet (50 feet where possible) from the inlet of the culvert[4]. When placed in closer proximity to its upstream end, turbulence created by the drop tends to scour out the inlet of the culvert and occasionally its entire bed. The proximity of drop structures to other in-stream structures, such as bridge piers, should be similarly limited.

Use caution when locating drop structures in streams that carry a high debris load as debris may become trapped on the structure and increase the degree of backwatering caused by the structure or redirect flow[7].

5 RISK AND UNCERTAINTY

5.1 Risk to Habitat

Drop 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 damaged. Relative to other habitat-enhancement options, traditional drop structures tend to provide uniform habitat features with little diversity if placed in a series. However, drop structures can be installed to provide complex and variable flow and scour conditions, which may benefit habitat in the long term.

Drop structures can create a barrier to upstream migration of non-target species or age classes of fish and other aquatic organisms. Where drop structures enable fish species to gain access to areas they don't currently inhabit, they could significantly alter predator, prey, and competition relationships among resident fish species upstream. These effects should be given careful consideration.

Installation of drop structures typically requires significant channel disturbance, which must be minimized with sediment control and dewatering. As such, there will be short-term negative impacts to the stream environment and its inhabitants in the form of either increased turbidity, temporary loss of habitat as flow is diverted around a construction site, and loss or disturbance of vegetative, invertebrate, and vertebrate life forms within the disturbed channel reach. In addition, access and staging areas will probably experience short-term impacts and will require temporary erosion and sediment control and best management practices to minimize impacts, followed by reclamation and restoration measures. Refer to the Section 8, *Construction Considerations* and the *Construction Considerations* appendix for further discussion of construction impacts and ways to reduce them. Consideration should also be given to the potential habitat impacts to source areas for boulders, logs, and other materials.

Potential impacts to habitat are further discussed in the Section 2, *Physical and Biological Effects*.

5.2 Risk to Infrastructure and Property

Improperly designed and/or poorly constructed drop structures endanger habitat and public safety. The risk to infrastructure is typically low, but is dependent upon the configuration of the drop structure and its influence on channel scour and flow hydraulics. Drop structures have the potential to greatly increase channel scour within the channel bed and along channel banks. For example, drop structures should not be placed immediately upstream of bridge piers, as the downstream scour may undermine the piers. Similarly, structures placed across the channel may redirect the channel thalweg toward a channel bank, thereby increasing risk to streamside infrastructure.

Drop structures that create significant upstream backwater can place upstream property and structures at increased risk of flooding and erosion. Drop 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.

5.3 Risk to Public Safety

Risk to public safety is generally lower on smaller streams. Drop structures discussed here typically provide a small increase in elevation and generally do not create hydraulic conditions dangerous to the public. There is some risk of debris becoming lodged on the structure and creating a public safety hazard. On the other hand, larger channel spanning structures can create hazardous hydraulic conditions that trap objects and prevent flushing downstream. Kayakers, canoeist, inner tubers, swimmers and boaters should use caution when navigating through these structures. It is best to scope out your route ahead of time, since these low-head dam situations often create a hydraulic jump that may trap a boat or person[8].

5.4 Uncertainty of Technique

Drop structures can be designed and constructed with a high degree of certainty for structural integrity and longevity. Log controls built in accordance with Washington Department of Fish and Wildlife standard details as early as 1984 are still in good condition today (2003). If properly constructed and maintained, it is reasonable to expect that drop structures will serve the intended function for many years. Certain functions of drops structures are immediate and virtually guaranteed provided they are properly designed and installed (e.g., grade control, water level control, flow redirection). However, scour and deposition patterns resulting from drop structures may prove difficult to predict or achieve as intended, depending upon the substrate, sediment transport characteristics, and the accuracy of hydrologic and hydraulic estimates.

6 METHODS AND DESIGN

As part of the design process, site, reach, and watershed assessment should be performed, as necessary. The extent of assessment will depend on the objectives of the project, and the factors the project is intended to address. For example, installation of a single or short series of drop structures to provide upstream passage in proximity to a culvert may not warrant a watershed assessment. Conversely, a drop structure project intended to trap sediment or otherwise affect sediment transport may require a comprehensive assessment of sediment supply and transport, which generally involves watershed scale assessment. Refer to Chapter 3, *Stream Habitat Assessment* for further discussion. Because drop structures create backwater conditions that may impact channel processes upstream and downstream of the structure, a reach assessment will likely be necessary to evaluate potential influences on structure performance and impacts resulting from the structure itself.

Additional information on structures that alter the channel profile is available in the Washington Department of Fish and Wildlife's Design of Road Culverts for Fish Passage[4] (http://wdfw.wa.gov/hab/engineer/cm/).

6.1 Data and Assessment Requirements

The following are minimum assessment requirements for drop structures. Many of these are further discussed in *General Design and Selection Considerations for In-Stream Structures*.

- *What is the objective of drop structure placement?* The elevation, configuration, and number of drop structures will vary with the objective. Are drop structures the best alternative to meet those objectives?
- *Document baseline conditions of the channel and bed material.* Are they appropriate for the use of a Drop Structure (refer to Section 4, *Application*)? Develop plan, profile, and cross-section drawings of the site and reach, as appropriate. An analysis of baseline conditions may include:
    - General characteristics of bed material. What is the dominant substrate?
    - Channel width.
    - Channel gradient.
    - Cross-section survey(s)
    - Condition of the banks. Are they relatively stable or actively eroding?
    - Degree of channel entrenchment. The depth of flow and, thus, shear stress on the bed and banks of the channel during high flow events increase with the degree of entrenchment. This increases the potential for boulder transport and bed and bank scour because velocity and depth have increased along with the ability to move larger and greater sediment volumes.
    - General assessment of the lateral and vertical stability of the channel and the overall stability of the watershed. Is the channel aggrading or incising in the vicinity of the site? If the channel is actively incising, has the cause of channel incision been identified and addressed? If not, the channel may continue to incise downstream and undermine or create a fish passage barrier at the lowermost drop structure.
    - Does the channel carry a relatively high bed or debris load? High gradient, high bedload channels can wear away log weirs at a relatively rapid rate. Limiting the potential backwater effects of a drop structure may be desirable in channels with high debris loads where wood accumulations could compromise the project or adjacent infrastructure.
    - Additional baseline data may be required for any monitoring planned at the site. The scope and nature of such an assessment depend upon monitoring objectives. It may include, but is not limited to, documentation of fish presence and abundance upstream of the structure, the extent and nature of eroding banks, or the frequency, extent, and depth of over bank flows.
- *Evaluate structure stability.* What is the necessary design life or design flow of the structure? What kind and size of material will be necessary to meet that design criteria?
- *Evaluate access and materials availability.* What access routes and staging areas are available? Will they limit the type of equipment, and therefore, the type of material, that can be utilized? What impacts are likely to occur as a result of ingress and egress of equipment and materials? Will in-stream and riparian site conditions permit construction? Will the cost or availability of materials limit the design?
- *Document the location and nature of in-stream and nearby infrastructure that may benefit or be harmed by the proposed structure.* This is best done in

conjunction with developing good plan, profile and cross-section drawings of the site and reach. The presence of infrastructure will likely place limitations upon flow redirection, drop structure elevation, and the degree of allowable backwater.

- *Conduct a biological assessment*. What species of fish and wildlife require passage over the drop structures (refer to *Fish Passage Table 1* in the *Fish Passage Restoration* technique for a list of migratory fish species native to Washington State)? What is the maximum allowable hydraulic drop over the structure to accommodate these species? What is the current distribution of habitat, including spawning, rearing, high flow refuge, cover, and pool habitat, within, upstream, and downstream of the site that may be impacted by the structure? The local WDFW Area Habitat Biologist should be consulted for additional information on local aquatic fauna. Contact the WDFW Habitat program at (360) 902-2534 to find a WDFW Habitat Biologist in your project area. Further information regarding biological assessments is provided in Chapter 3, *Stream Habitat Assessment*.
- *Will the placement adversely affect recreational navigation*? What measures can be taken to minimize public safety risks?
- *What are the potential impacts to upstream, downstream, and adjacent habitat, fish and wildlife, infrastructure, and public safety during and following construction if the project succeeds or if it fails structurally*? What is the probability of those impacts occurring? What factors influence that risk (e.g., degree of channel confinement, slope, bedload, high flow events, material selection, structure configuration)? What can be done to minimize the risk? Are the costs acceptable?

In relatively small, low energy streams where there is minimal risk to infrastructure, habitat, and public safety, elements of the design may be based on reference site conditions. For instance, the necessary size of material, structure configuration, and the anticipated depth of scour can be estimated by observing stable structures located in similar channel reaches operating under similar conditions. However, high risk projects, high cost projects, and projects conducted on larger streams (greater than 20’ wide) and steeper or more confined channels may have additional data collection and assessment requirements. These could include, but are not limited to:

- *Hydrologic analysis*. Hydrologic analysis may be necessary to generate discharge values used in design and to evaluate potential impacts to the channel or property. Common design discharges applied to drop structures include:
    - Low fish passage -flow
    - High fish passage flow
    - Ordinary High Water flow
    - Structural integrity and maximum design discharge. Specific design flow recommendations are provided in Section 6.2, *Design*.
    - Flood discharge - 100-year discharge for determining impacts on regulatory flood flows

  It is recommended that non-deformable drop structures be designed to be stable for all flows up to and including the 50-year flow event. In locations where infrastructure may be at risk, a higher design discharge (e.g., 100-year flow recurrence interval) may be required. Further discussion of hydrologic statistics and their derivation is available in the *Hydrology* appendix.

- *Scour analysis*. The integrity of drop structures depends, to some extent, on the depth of installation relative to the depth of scour. Critical flow conditions can occur at the crest of the structure with supercritical flow possibly occurring along the face of the structure at some flows. These conditions create a hydraulic jump downstream of the drop structure that can create scour and bank erosion. The *Hydraulic* appendix defines varying types of scour under various site conditions, and how to estimate depth of scour. Data required for scour analysis depends on the type of scour evaluated. While scour can be evaluated empirically in some instances, analysis usually requires a minimum of three cross-sections (one at each structure plus upstream and downstream of the structure), a channel profile survey (extending upstream and downstream of the project for a distance of at least 200-ft above and below the last structure or 10 bank full channel widths), and an evaluation of the bed substrate distribution. At a minimum, one representative substrate sample should be taken at each structure location. Significant changes in substrate composition along the project reach should be noted.
- *Sediment transport*. Sediment transport analysis may be necessary where large-scale backwatering effects are likely or where the project is intended to trap sediment or otherwise affect sediment transport (alter channel width, depth, or slope). Such effects are more likely to occur when a series of drop structures are installed. Local, individual structures will most likely affect scour and sorting without impacting general sediment transport characteristics through a reach. The evaluation of sediment transport is detailed in the *Sediment Transport* appendix.
- *Hydraulic analysis*. Channel hydraulics must be analyzed for fish passage at low flows and for stability at flood flows. Hydraulic parameters for design include flow depth, velocity and bed shear. These parameters should be estimated for a range of flows for existing and post-project conditions. These parameters will be used to size rock, wood, and other materials, and demonstrate fish passage conditions are met. An analysis of the hydraulic effects of backwatering is also recommended and can be accomplished using computer programs such as HEC-RAS. Hydraulic design in a natural environment, using natural materials, necessarily involves a significant degree of uncertainty. Equations and methods presented in the *Hydraulic* appendix are useful in the analysis and design of in-stream structures. These tools should be employed with an understanding of the variability in natural stream systems and sound professional judgment.

The above parameters are further discussed in *General Design and Selection Considerations for In-Stream Structures.*

6.2 Design

Dozens of various drop structure designs have been applied to stream channels; many have proven successful in multiple applications, while others have prematurely failed or never achieved the desired results. The most common instances of premature failure include:

- Structure undermining from scour or channel incision
- Water flowing around the structure, making an "end run"
- Water flowing subsurface through the structure rather than over it, preventing fish passage
- Materials comprising the structure becoming mobile or breaking, and
- Fish passage over the structure being inhibited by inadequate depth of flow over the weir, or an excessively shallow or obstructed plunge pool

The following text provides guidance to increase the success of any drop structure design.

6.2.1 Preventing Structure Undermining

A common and intended characteristic of all drop structures is that a scour pool develops downstream of the structure in response to plunging flow. The volume of the pool increases with increasing drop height or channel slope (which is directly related to shear stress), and with decreasing substrate size (e.g., from boulder to cobble, or from to gravel to sand). 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, concrete blocks) exposed and suspended over the channel bed.

Several techniques can be employed individually or collectively to prevent the structure from becoming undermined. One technique is to ensure that the depth of the structure meets or exceeds the anticipated depth of scour. For example, WDFW's standard log weir design uses two logs, placed one on top of the other (at approximately a 15 degree angle from the vertical), to prevent scour from compromising the integrity of the structure. Scour by flows over a drop can be estimated using jet or sill scour equations[9] [10]. The *Hydraulics* appendix presents equations for estimating scour depths for flow pouring over both vertical and sloping drop structures. Additional scour may occur if the structure forms a constriction to flow. Scour conditions at constrictions can be estimated using abutment or contraction scour methods, also detailed in the *Hydraulics* appendix. A series of flow conditions, representing the full range of design flows, should be considered in the scour analysis to determine worst-case scour conditions (there is not necessarily a linear relationship between scour and discharge). Depth of scour can also be estimated from field conditions by measuring the depth of scour associated with similar drops under similar site conditions. However, the reader should consider such measurements to indicate a minimum depth of scour. Scour measurement taken during high flow events will be higher than those taken during low flow. As a rule of thumb, expect the depth of scour to be 2-1/2 to 3 times the height of the drop in gravel or cobble bed streams. The depth of scour will be greater in sand bed streams.

Woven geotextile fabric is typically installed on the upstream face of wood drop structures to help "seal" them and minimize subsurface flow. Properly installed, this fabric also provides a factor of safety against structure undermining by preventing upstream bed material from eroding out from underneath the structure should it become undermined. The capacity of the material to provide this service is limited by its strength and durability.

Another method to minimize the risk of undermining the drop structure is to line the plunge pool with immobile material to limit the extent of its formation. This method was employed in the Goldsborough Dam Removal project on Goldsborough Creek in Mason County. At that site, the plunge pool downstream of each weir was lined with a 12" layer of riprap below a design scour depth of 6 feet. Lining the plunge pools is less desirable than other methods to prevent structure undermining due to the risk of forcing the plunge pool to extend horizontally into the banks or longitudinally into the next downstream structure in order to achieve the pool volume necessary to fully dissipate the energy over the drop. Any excess energy due to inadequate pool volume will be transferred downstream where it may scour the channel bed or banks.

In addition to energy dissipation, adequate plunge pool depth is necessary to enable fish to leap over a drop. Stuart[11] (as cited by Powers and Orsborn[12]) suggests that the minimum plunge pool depth should be 1.25 times height of the drop to provide the best standing wave for leaping salmonids. Aaserude[13] (also cited by Powers and Orsborn[12]) reported that optimal leaping conditions for coho and chum salmon in a test fishway at Johns Creek Fish Hatchery near Shelton, Washington occurred when the plunge pool depth exceeded the depth of penetration of the falling water. And the depth of the plunge pool was equal to or greater than the length of the fish trying to pass. It is recommended that a pool at least two feet deep by six feet long be excavated immediately downstream of each drop structure during construction in preparation for the plunge pool that will develop[4]. Otherwise, there is an increased risk that fish passage will be impeded prior to plunge pool formation and that initial high flows will stream over the structure such that energy is not fully dissipated and the downstream channel erodes.

There is a risk that if a lower drop structure of a series fails, those above it will be undermined and fail in a chain reaction. To limit the extent of any chain reaction, it's recommended that, if a number of drop structures are placed in a series, deeper structures should be placed at intervals (for instance, every fifth structure)[4]. These deeper structures should be designed as independent dams, assuming the downstream controls do not maintain a backwater.

Although typically placed above the existing grade of the channel, drop structures can be constructed at or below grade to account for and limit future changes to the channel profile that could create a barrier to fish passage over the weir or ultimately undermine the weir and cause it to fail. Subsurface drop structures are especially useful in newly constructed channels and at the lower end of a series of drop structures. Energy is often not fully dissipated over a drop structure series during peak floods[4]. The downstream channel is, therefore scoured and lowered in the vicinity of the logs.

6.2.2 Preventing structure end run

End runs, or flanking of a structure, are most likely to occur when the structure or the next upstream structure directs flow towards the bank, when the downstream plunge pool extends laterally to the banks and erodes the bank toe, or when overbank flow spilling into the channel scours the bank creating a headcut around the structure. The risk of an end run can be minimized by configuring the weir such that water is directed towards the center of the channel rather than toward the banks during all flows and by keying the structure into the banks. The extent to which the structure is keyed into the banks will depend upon bank characteristics and the stability of the channel. The key should extend from the bank line into the bank at a slope of 1.5H:1V or flatter. The minimum recommended length for a rock drop structure bank key is four times the D_{100} diameter of the header rocks[14] or six feet[6]. The minimum recommended length for a log drop structure bank key is five feet. In laterally dynamic channels that have a high probability of frequent or impending channel shifts, it may be appropriate to install structures to the full width of the floodplain. The above recommended bank key lengths are measured perpendicular to the bank line, even if the key itself is at an angle. Materials keyed into the bank should be of the same dimensions as those used within the wetted channel.

Armor is often placed on the banks near the structure (generally 3 feet upstream and far enough downstream to reach the beginning of the pool tailout). An exception may be when the weir is configured to concentrate and direct flow into the center of the channel at all flows. Though riprap is most commonly used, other materials can be utilized such as logs, coir, or root wads. Armor placed downstream of the structure should extend to the anticipated depth of scour. Otherwise, it will simply fall into the scour pool as it develops alongside it. Alternatively, bank armoring can be placed along the bank as launchable material (see the Integrated Streambank Protection Guideline's[2] *Riprap* technique for more information on launchable rock. When using riprap, care should be taken to fill the voids in the riprap as much as possible to minimize interstitial flow and piping of bank material.

It is important to minimize bank disturbance and vegetation removal during construction. Revegetating the bank at both keys is necessary for added structural strength cover, shade and habitat needs.

6.2.3 Minimizing Subsurface Flow

It is critical in small streams to minimize the occurrence of subsurface flow where the potential exists for a substantial portion, if not the entire amount, of low flow to go subsurface through the structure and thus prevent fish passage. Subsurface flow may occur through any porous elements of the structure (e.g., between the logs of a double log weir, between the boulders of a boulder weir, or through the riprap armoring the banks adjacent to the weir). Sealing of the voids in the structure is most often achieved by installing a well-graded mix of sediment (including at least 10 to 15 percent fines) upstream of the structure and within the voids of any rock (e.g., boulders, riprap) utilized in the design. Woven geotextile fabric is typically placed between the structure and the added sediment mix to prevent piping of material. This fabric should extend from the top of the drop structure, down its upstream face to a depth at least two feet below the streambed, and upstream at least five feet. The sides of the fabric along the banks should be at least as high as the top of the weir and should extend into the key trenches to completely seal the structure. Installing the fabric in this manner minimizes the risk of fabric exposure which often occurs as a result of installing the fabric too close to the bed surface such that it becomes subject to abrasion, tearing, and photodecomposition.

Geotextile fabric used in drop structure construction should have a tensile strength of at least 600 lbs and a burst strength of at least 1,200 lbs[4]. It is sometimes underlain by wire fencing for reinforcement, as necessary. Geotextile fabric has the advantages of longevity, availability, and flexibility for ease of construction. It is easier to install than impermeable material, which tends to billow in the stream current during installation and is extremely vulnerable to punctures. Impermeable liners may, however, be necessary at sites with a limited source of sediment (e.g., downstream of pond or reservoir, or within a groundwater-fed channel). Consult the liner manufacturer for installation recommendations.

Once sealed, the drop structure should remain sealed provided that the sealant material is not transported downstream (e.g., in a low energy groundwater-fed side channel not subject to storm flows). If it is, the seal will be maintained only if hydraulic conditions allow a fresh supply of bed material transported from upstream during high flow events to accumulate and protect the upstream face of the structure.   For the latter to occur, the stream must carry an adequate supply of sediment, including fines, to replenish the lost material. Any upstream structures (including other drop structures, wood, or boulders) must be located sufficiently far enough upstream such that their associated scour pools do not extend to the drop structure in question.

Note that subsurface flow may occur at newly constructed drop structures, but they should seal after the first high flow events.

6.2.4 Material Selection

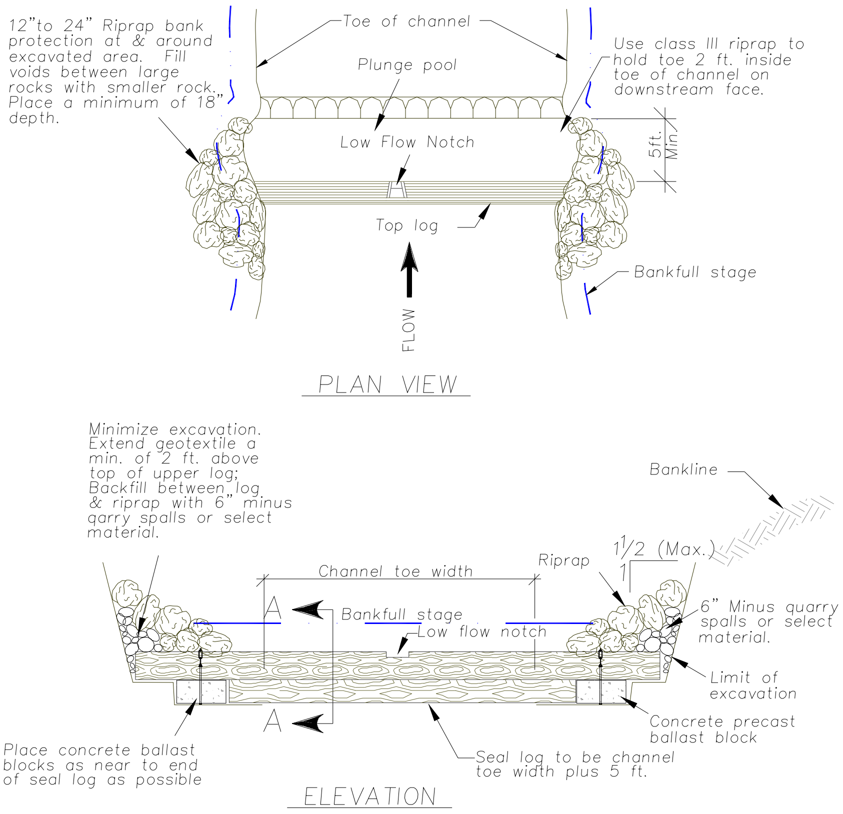
Drop structures are typically constructed using rock, wood planks or logs, although sheet pile, concrete, and other artificial material may also be used. The selection of material should be based, in part, on the required durability and deformability to meet design criteria. Drop structures installed to provide fish passage over or through a man-made obstruction must persist, or be replaced, so as to provide fish passage as long as the obstruction exists. In other settings, drop structures may only be required to provide temporary stability and hydraulic effects and so may deform over time. Another potential design criterion is aesthetics. Drop structures constructed in a stream dominated by large wood should be comprised primarily of wood, while those in a boulder dominated stream should be comprised of rock in order to blend with their surroundings. Similarly, the species of wood, and type of rock, should be selected to replicate the naturally occurring materials. Limitations on equipment, access, cost, and available materials will also influence material selection.

Drop Structure Table 1: General comparison of drop structure types.

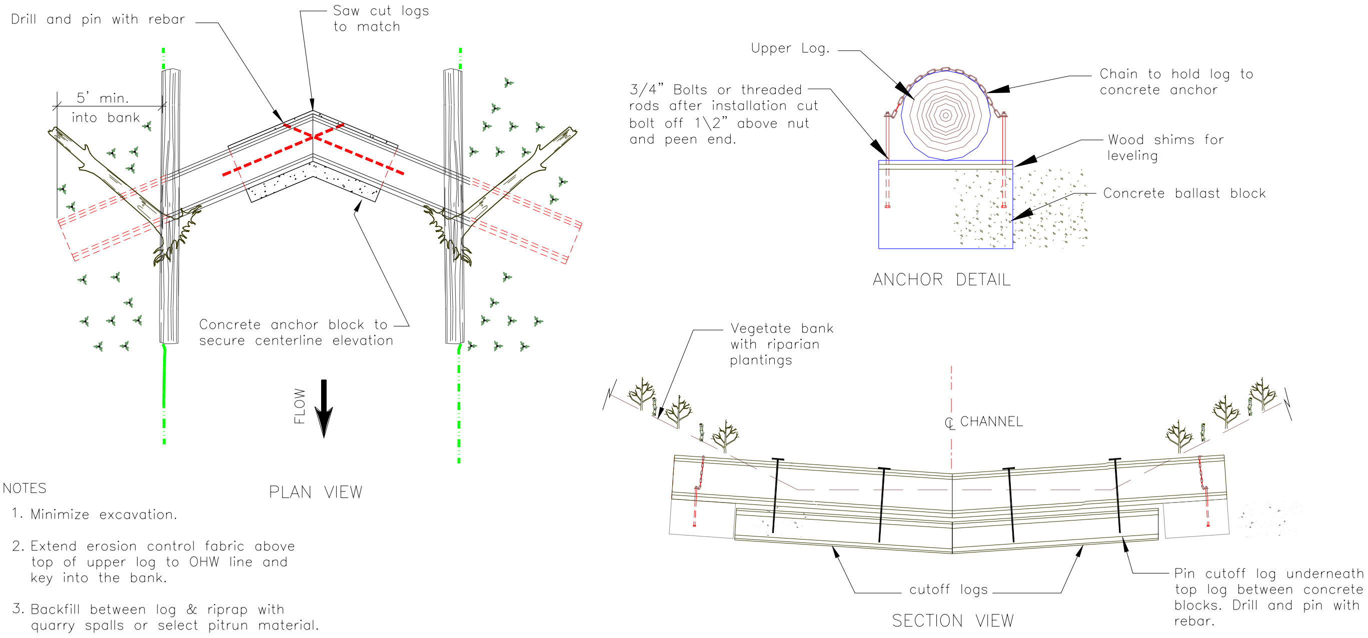
Type of Drop Structure	Advantages	Disadvantages
Log Weirs	Low cost; durable	Limited to ~30' max channel toe width; Max recommended final grade is 5% for straight weirs and 3% for up-stream pointing arch or chevron weirs; Wood will decompose over time if exposed to drying and wetting; Wood must be securely anchored to counteract its buoyancy
Boulder Weirs	Deformable; Due to uneven nature of boulders, provides greater diversity of water depths and velocities over the weir; May be installed in relatively wide channels	Greater uncertainty of long-term durability; Difficult to maintain a specific water surface elevation; Inappropriate in sandy and other fine-grained streams; 9" max recommended drop
Plank Weirs	May be installed by hand; Well-suited to streams with sandy beds; Low cost	Less durability; Limited to small or groundwater-fed streams with regular flow
Concrete or Sheet Pile Weirs	Self-ballasting; Impermeable Deep cutoff wall	Aesthetics; Large equipment required to place heavy, pre-cast concrete units and drive sheet pile

Wood

Wooden drop structures may be comprised of entire logs or wooden planks. Log weirs can be built into the streambed to span the entire channel width. They are a low-cost and durable means of fish passage for streams with natural gradients of less than about three percent and channel toe widths of less than about 30 feet. Adequately sized material for wider streams may be relatively difficult to find, costly, and have higher environmental impacts on the source area. A variety of designs have been employed, including single logs, multiple logs, straight weirs, angled weirs, V-weirs, and K-dams. Design of simple, straight, double-log weirs is detailed in the Design of Road Culverts for Fish Passage[4] and illustrated in **Drop Structure Figure 1**. Refer to **Drop Structure Figure 2** for an example of a chevron weir design.



Drop Structure Figure 1



NOTES

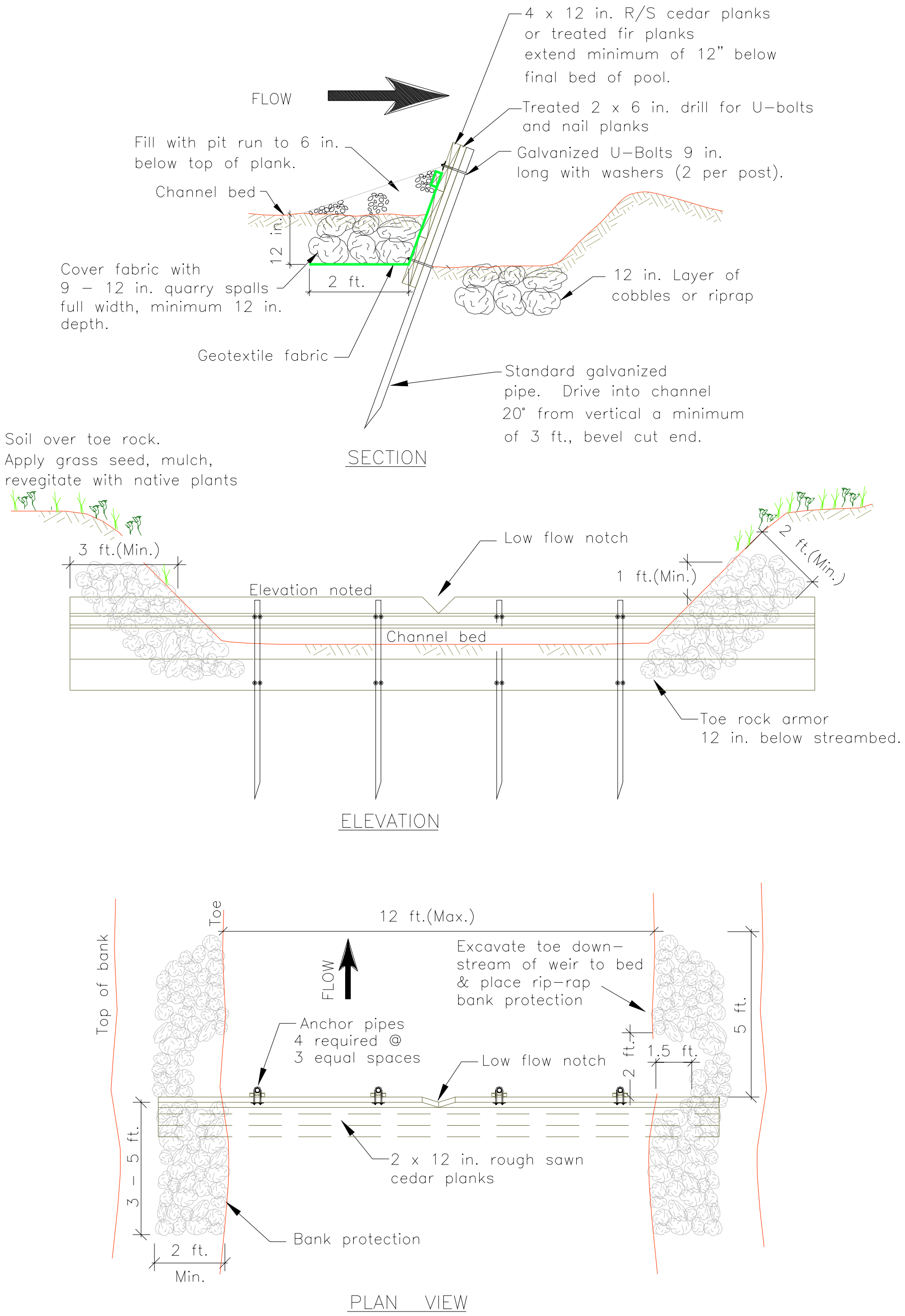
1. Minimize excavation.
2. Extend erosion control fabric above top of upper log to OHW line and key into the bank.
3. Backfill between log & riprap with quarry spalls or select pitrun material.

Drop Structure Figure 2

Disadvantages of log weirs include their eventual decomposition and the common requirement for anchoring logs with rock, concrete blocks, or other ballast to counteract their buoyancy (refer to the *Anchoring and Placement of Large Wood* appendix). Slow-decaying species such as cedar, fir, and pine are recommended to maximize the design life of the drop structure. Use of deciduous species such as alder or maple is discouraged, as their decomposition rates are relatively high. However, if the log remains submerged year round, their life expectancy is greatly increased[15].

Although log weirs are by far the most common form of wooden drop structure, wooden plank weirs have their application. Being thinner than entire logs, they are less strong and subject to decay that is more rapid. As a result, plank weirs are typically used in very small streams or ground water channels where stream energy, debris load, and sediment load are low. Plank weirs are especially useful for providing upstream juvenile salmonid passage in small streams and creating a backwater for placing and retaining spawning gravel. They are well suited for streams with sandy beds.

A benefit of plank weirs is that they can be constructed entirely by hand, thereby reducing construction impacts to the riparian zone and access areas. Plank weirs are comprised of rough-cut, milled timbers. Untreated fir timbers are used in perennial streams where the wood will always be submerged. Cedar is used in intermittent streams. Straight plank weirs have an application limited to channel toe widths of about 10 feet. (The maximum standard timber length available is 16 feet; each end is embedded three feet into the bank.) Plank weirs have been constructed in wider channels using zigzag and spider-weir designs to shorten the span lengths of individual members. Design of Road Culverts for Fish Passage[4] provides further details on plank weir design. A typical plank weir design is illustrated in **Drop Structure Figure 3**.



Drop Structure Figure 3: Conceptual plank weir design.

Rock:

The size, shape, and placement of rocks that comprise a drop structure are chief factors governing its longevity. Individual rocks must remain relatively immobile up to the selected design flow, with the knowledge 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[16]. Additional force may be exerted on the rock by wood, debris, or ice.

Riprap sizing methods are based on a blanket of stone, placed roughly parallel to flow, and rely on interlocking for a degree of 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[17]. The NRCS 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 may be more applicable to drop structure design than riprap sizing equations as they do not rely on inter-stone contact. Two such equations, developed independently by Isbash[18] and Costa[19], 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:

$$V_{min} = 0.86 \{2\, g\, [(SG_s - SG_w)/SG_w]\}^{.5}\, D^{.5} \qquad \text{[Isbash, 1936 [18]]}$$

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:

$$\mathbf{D_{min} = V^2/\{1.479\, g\, [(SG_s - SG_w)/SG_w]\}} \qquad \text{[Equ. 1]}$$

Costa studied nine steep bedrock channels in the Colorado Front Range to test the accuracy of velocity and depth estimates for historic 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.

$$V_{avg} = 9.571\, D^{.487} \qquad \text{[Costa, 1983 [19]]}$$

where:
V_{avg} = average velocity (ft/s)
D = diameter of the stone (ft)

Rearranging to solve for D:

$$\mathbf{D_{min} = (V_{avg}/9.571)^{2.05}} \qquad \text{[Equ. 2]}$$

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 in-stream structure subject to direct flow. As a factor of safety, it is recommended that D_{50} of the structure be at least 2 times D_{min}. D_{100} of the structure should be approximately 1.5 times D_{50}.

Drop Structures Table 2 includes rock specifications developed by Allan and Lowe[6] for in-stream structures. They suggest that rock from the next lowest velocity column may be applied to bank armor and keys as they do not lie within the channel. However, because the bank keys may become exposed at some time, this document recommends that the key be comprised of the same size of material as that used within the channel. For comparison, minimum stone diameters calculated using Equations 1 and 2 are also provided.

Drop Structures Table 2: Specifications for rock for in-stream structures. (Modified from Allan and Lowe[6])

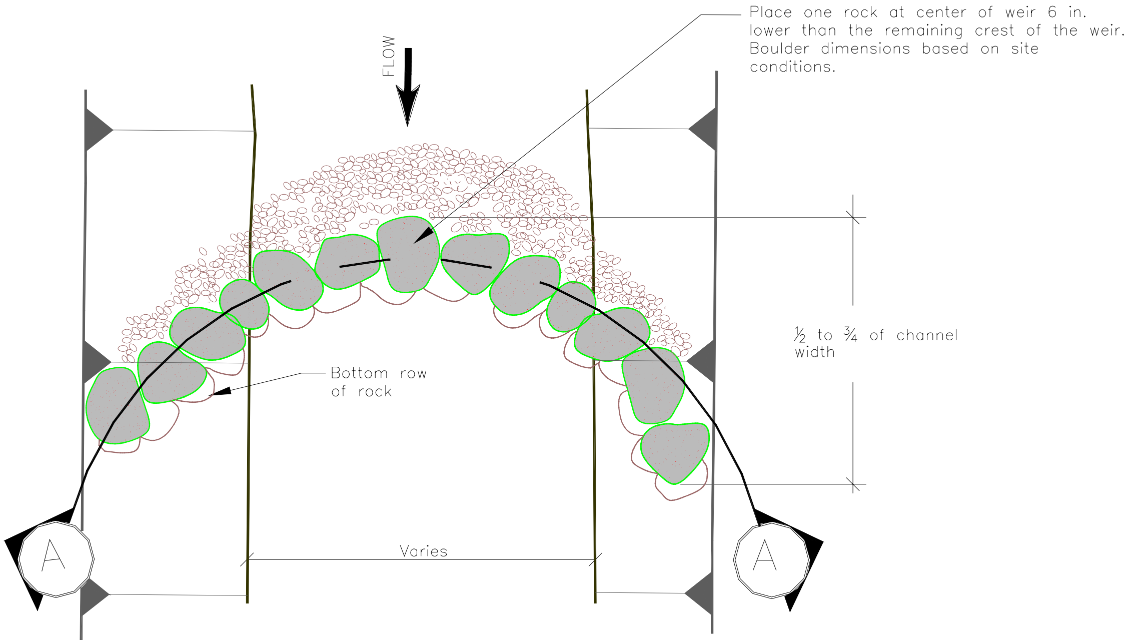
	Design Velocity			
Nominal Rock Diameter	<7.5 ft /s	<9.8 ft /s	<12.5 ft /s	<15.4 ft/s
D_{max}	2.6 ft (1540 lb)	3.9 ft (5290 lb)	5.9 ft (17600 lb)	8.8 ft (59500 lb)
D80	2.0 ft (660 lb)	3.0 ft (2200 lb)	4.9 ft (10400 lb)	7.2 ft (33100 lb)
D50	1.6 ft (440 lb)	2.6 ft (1540 lb)	3.9 ft (5290 lb)	5.9 ft (17600 lb)
D20	1.0 ft (90 lb)	1.6 ft 440 lb)	2.6 ft (1540 lb)	3.9 ft (5290 lb)
Isbash[18] (Equ. 1)[a]				
D_{min}	0.7 ft	1.1 ft	1.8 ft	2.7 ft
Costa[19] (Equ. 2)				
D_{min}	0.6 ft	1.1 ft	1.8 ft	2.7 ft

[a] Specific gravity of stone assumed equal to 2.85.

Rock sizes should be verified by engineering judgment and comparison to field conditions as hydraulic models can be limited in their ability to accurately predict rapidly varied hydraulic conditions that occur at the crest and along the profile of the drop structure. The minimum required rock size for drop structures should be at least as large as naturally occurring rocks in the channel under similar conditions; twice the D_{100} is recommended[4]. As a rule of thumb, drop structures in small, lower-gradient streams should use a minimum two-foot mean-dimension rock. Larger, higher-gradient streams require rock as large as four to six feet.

Rock should be sound, durable, dense, and free from cracks, seams and other defects that would tend to increase its deterioration from weathering, freezing and thawing, or other natural causes. Angular rock is 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. Its greatest dimension should be no greater than three times the least dimension[20]. 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.

Boulder weirs are typically placed in an upstream-pointing configuration to maximize their stability, although other configurations can be used. Careful attention must be paid to ensure that rocks are stable and gaps between rocks are reduced to a minimum. Place rock at a stable angle of repose so that it will remain in place once the plunge pool forms. Care must be taken to ensure that rock placed near the plunge pool does not obstruct plunging flow over the weir or block fish passage. Further guidance on boulder weir design is provided in the Design of Road Culverts for Fish Passage[4] and illustrated in **Drop Structure Figure 4**.



Drop Structure Figure 4: Conceptual boulder weir design.

6.2.5 Ensuring unobstructed fish passage

Even if fish passage is not the primary goal, in fish bearing waters it is a requirement that any human-made obstruction across or in a stream must freely pass fish [RCW77.55.060]. For fish passage to be achieved, the hydraulic drop over the structure must not exceed maximum criteria for fishways given in WAC220-110-070 and summarized below in **Drop Structure Table 2.**

Drop Structure Table 2: Maximum allowable hydraulic drop in fishways [WAC220-110-070]

Adult Trout >6” (150 mm)	Adult Pink, Chum Salmon	Adult Chinook, Coho, Sockeye Salmon, Steelhead
0.8 ft	0.8 ft	1.0 ft

If upstream passage of juvenile salmonids is critical, the drop is dependent on structure type and flow profile but should be a maximum of 0.7 feet. Other fish and wildlife species may require lesser drops. Note that, due to the deformability and mixed success of boulder weirs, it’s recommended that their use be limited to a maximum drop of 9 inches (0.75 feet). Improvements in design and construction of this technique may eventually expand their recommended application.

Hydraulic drop is the difference in elevation between the water surface upstream and downstream of the structure. Typically, the maximum hydraulic drop is equal to the elevation drop between the tops of two successive weirs, provided the conditions at each weir are the same. However, conditions may differ significantly if the degree of backwater upstream of the uppermost weir is higher than that for the lower weir, causing a greater drop to form over the structure. The maximum allowable hydraulic drop in Table 2 must be satisfied at all flows between the low and high fish-passage design flow. The low fish passage design flow is the two-year, seven-day, low-flow discharge or 95-percent exceedance flow during the migration months for the species of concern. The high fish passage design flow is the flow that is not exceeded for more than 10 percent of the time during the months of fish migration. The two-year peak flow may be used as the high fish passage flow when stream-discharge data is unavailable.

To maximize the depth of flow over the structure during low summer flow, and thus improve fish passage, flow should be concentrated through a low point on the structure. This may be accomplished by cutting a notch in the log or plank or having the structure slope to one low spot, usually in the middle third of the channel. The notch should be cut during low flow after the structure is installed to ensure that it isn’t so big that the rest of the log is dewatered. If it becomes dewatered, the likelihood is it will decay more quickly. Notches should be sloped down in the direction of flow so that fish don’t have to struggle across a long flat weir crest.

The nappe of flow plunging over the structure and the plunge pool should both be kept free of rock and debris to facilitate fish passage.

6.2.6 Structure Configuration

A drop structure’s configuration in plan form and cross-section influences its hydraulic effect on the stream and the shape of the channel bed. Drop structures can be built in a number of different configurations. The effects of typical configurations are described and illustrated below. Desired habitat modifications and other project objectives dictate the type of structure selected.

Channel-spanning structures that are straight, level, and placed perpendicular to flow evenly spread water and energy out across the stream and encourage a relatively flat cross-section upstream. They have limited backwater effect once bed material fills in to the top of the weir. The plunge pool created at the base of the structure tends to be wide and shallow and spans the entire channel. Such weirs generate a minimum degree of bedform complexity. They can also contribute to bank erosion by directing energy towards channel margins rather than concentrating it in the center of the channel. As a result, such structures are not recommended where bank protection or habitat enhancement within the altered reach is one of the primary objectives. They are more applicable where a short series of drop structures are intended to provide fish passage over or through a man-made obstruction to gain access to habitat upstream. Level weirs should include a low-flow notch to facilitate fish passage (see Section 6.2.5, *Ensuring Unobstructed Fish Passage* for guidance).

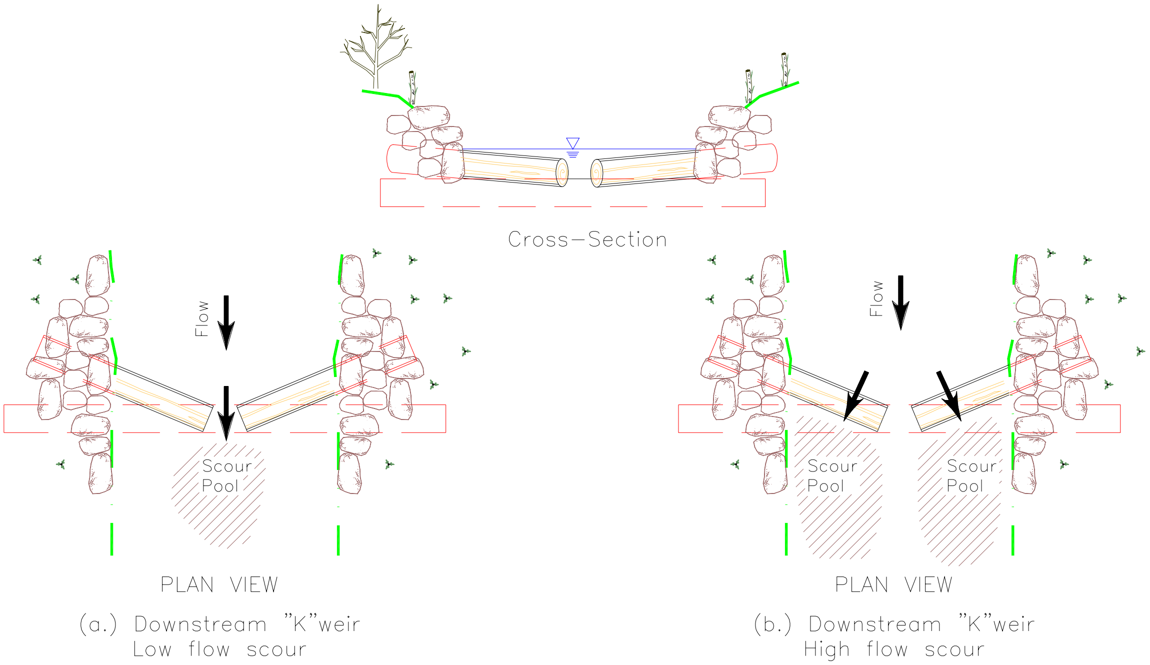
Flow over a drop structure moves roughly perpendicular to its alignment in planform and is funneled towards any low spots that occur on the structure. Thus, drop structures may redirect, concentrate, or disperse flow depending on their shape. Straight weirs oriented diagonally to flow can be used to redirect flow towards or away from channel features. Typically installed such that the upstream end is lower than the downstream end (California Fish and Game recommends a drop in elevation of 6 inches for every 10 feet of weir length[21]), diagonal weirs, also known as sloped log weirs, are effective at collecting sediment along the bank at the higher end of the log.

Arch or chevron ("V" shaped) weirs in plan view concentrate flow through their apex when pointing upstream, and direct flow to the outside of the channel when pointing downstream. Chevron drop structures are hydraulically very similar to barbs (see the Integrated Streambank Protection Guidelines[2], Chapter 6); they are basically two barbs that extend from opposite banks toward one another and connect at the center of the channel. Upstream-pointing structures create longer and deeper, but narrower plunge pools than straight weirs and avoid potential impacts to adjacent streambanks. They have the strength inherent in an arch design[6]; the thrust of streamflow and bedload is transferred through the weir into the banks making them more stable than straight or downstream-pointing weirs. Downstream-pointing weirs are more effective at dissipating energy as they spread scour over a wider area, creating shallower pools. They are frequently used to collect gravel to create spawning habitat[21]. Their application, however, is limited to areas with good bank stability.

The recommended angle of the apex of upstream and downstream-pointing weirs ranges from 90° [22] to 120° [7]. As the angle of the apex decreases (the point gets sharper), the scale of effects resulting from flow redirection increases such that more and more flow is directed to the center of the channel at upstream-pointing weirs, deepening the pool and increasing the risk of undermining, and more and more flow is directed into the banks at downstream-pointing weirs.

Arch and chevron drop structures can be symmetrical or asymmetrical, depending upon the thalweg alignment as it approaches the structure and the desired thalweg alignment immediately downstream. Typically, the apex is located within the center third of the channel. A meandering thalweg can provide additional channel complexity and should be taken into account in positioning the apex. WDFW recommends that upstream-pointing weirs be limited to a final grade of 3 percent whereas straight weirs can be placed at a final grade of 5 percent. Chevron weirs concentrate flow energy toward the center of the channel at the thalweg. Straight weirs spread the energy across the channel and are therefore more efficient at energy dissipation, which allows them to be placed in steeper streams.

Drop structures can be designed and constructed to appear relatively random in configuration to promote maximum hydraulic complexity and natural appearance, similar to natural step-pool structures. Natural step pools and drops within the same or similar streams provide excellent analogs for arrangement and orientation of drop structures. However, the proximity to infrastructure may place limitations on the orientation of redirected flow or the degree of allowable backwatering. Flow should not be directed into structure footings or bridge pilings as it may undermine the structure. When designing drop structures, consider how water will interact with the structure at various flows. A structure that funnels flow to the center of the channel during low flow events may direct water to the banks during high flow events (see **Drop Structure Figure 5**). This will need to be accounted for in the design.

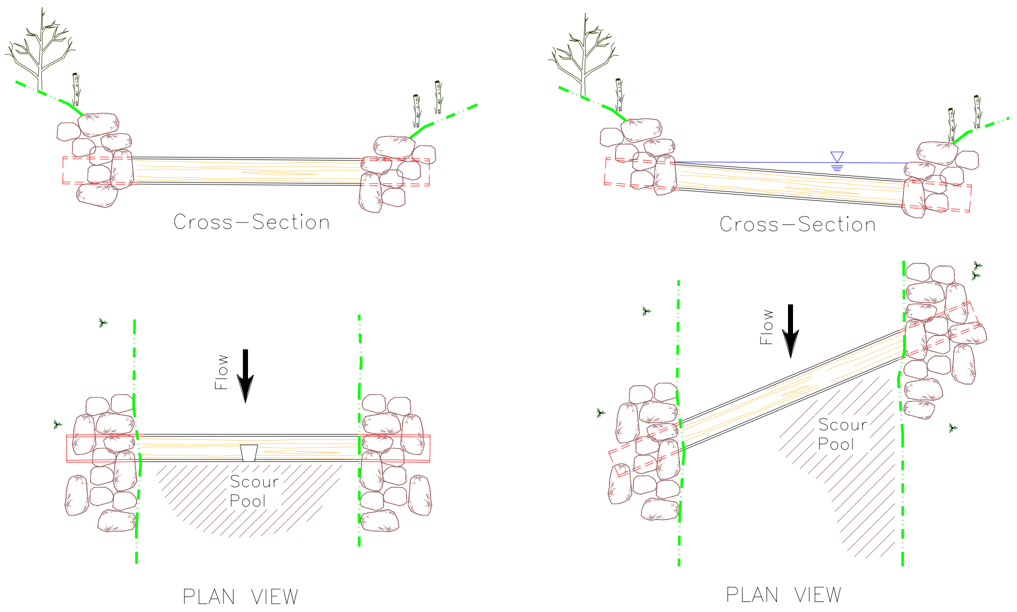


Drop Structure Figure 5: "K"-weir with side logs resting on top of main log during (a) low flow, and (b) high flow events where flow overtops the side logs.

Drop structures that are sloped down from the banks will maintain a concentrated low flow channel thalweg and have increased backwater effects over a level weir. Generally, the horizontal-to-vertical ratio for this slope should not exceed 5H:1V. At the bank line, the top of the structure should not exceed the elevation of the ordinary high water mark.

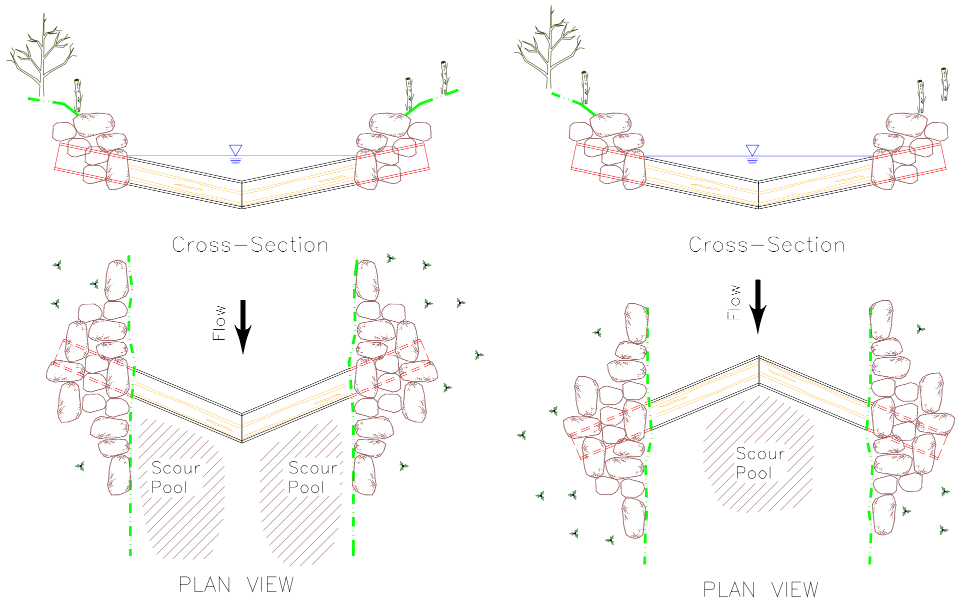
The lowest point in the structure should coincide with the elevation of the desired thalweg. The bigger the difference between the low and high elevation on the weir, the greater the backwater effect and the higher likelihood that wood or other objects will become trapped on the structure. For example, K weirs in the configuration illustrated above create significantly higher backwater than a level weir. Potential backwater effects include deeper water, gravel accumulation, and increased risk of upstream flooding, aggradation, and bank erosion, among others (see Section 2, *Physical and Biological Effects* for further information). These effects may be positive or negative depending on their magnitude, extent, and on site conditions and limitations. Significant backwater will likely need to be avoided where it may put nearby infrastructure or developed property at risk of flooding. A typical rule of thumb provided by Fripp et al.[7] is that backwater effects of a structure will be negligible at water depths over five times its height. Therefore, provided the height of the structure remains less than twenty percent of the height of the bank, no noticeable increase in out of bank flow should occur. However, patterns of sediment scour and deposition may still be affected. Possible affects of backwater should be considered on a case-by-case basis.

It is recommended that the configuration of structures placed in series be similar in order to produce uniform hydraulics during high flows[4]. The water depth over a weir varies with its configuration. Where structures with differing configuration are used, there is a greater risk of creating hydraulic drops that exceed fish passage criteria.



(a.) Straight, level log weir

(b.) Diagonal log weir



(c.) Downstream V–log weir

(d.) Upstream V–log weir

Drop Structure Figure 6: Typical Patterns of Scour Associated with Common Drop Structure Configurations.

6.2.7 Structure Elevation

The desired upstream water stage, allowable head differential between drop structures, and desired hydraulic effects will help dictate the height of the drop structure. The presence of infrastructure may also dictate the desired elevation of the structure, such as if the bed needs to be raised or maintained to cover an upstream pipeline.

Although typically placed above the existing grade of the channel, drop structures can be constructed at or below grade to limit future changes to the channel profile. This is especially useful in newly constructed channels and at the lower end of a series of drop structures.

6.2.8 Structure Spacing.

Drop-structure spacing is based primarily on project objectives, channel gradient, maximum allowable hydraulic drop, and plunge pool characteristics at the design flow, although access limitations may also be a factor. Generally, steeper channels will require more frequent structure placement. Consider a natural step-pool system, where each step backwaters the channel upstream such that each upstream step spills water into a backwatered pool. Step-pool channels are most common on slopes between 4 and 8 percent[23]. Steps are commonly spaced between 2 and 4 channel widths[24]. However, experience has found that man-made drop structures installed at gradients higher than 5% for straight weirs and 3% for upstream-pointing weirs and boulder weirs are subject to higher rates of failure and unintended project impacts (see Section 4, *Application* and Section 6.2.6, *Structure Configuration*). These limiting slope criteria can be used to determine the minimum recommended spacing between weirs for a given hydraulic drop.

$$\text{Min spacing} = \text{Max hydraulic drop/ Max final channel gradient}$$

Slope criteria may be revised, as drop structure design is refined over time. Where constructing a long series of structures over an entire reach, the designer may want to consider breaking them up into smaller groups with resting areas in between.

6.2.9 Incorporating large wood into drop structure design

Large wood can be incorporated into the drop structure for added habitat benefit, additional roughness, and flow realignment. When adding wood near drop structures, consideration must be given to the scour, deposition, and flow patterns that are likely to develop. Care should be taken to ensure that flow is not directed to bypass or flank the next downstream structure and that the scour pool does not undermine adjacent drop structures or prevent them from sealing. Consideration should also be given to the fact that wood can create a constriction and additional backwater that may or may not be desirable. Wood may also recruit additional wood and other material moving downstream which can exacerbate constriction and backwater effects, impede fish passage over the weirs, and can cause unexpected shifts in flow direction or scour and deposition patterns. For this reason, wood is most often placed in or along the fringe of the plunge pool created by the drop structure where it can provide critical in-stream cover, in the adjacent floodplain to provide floodplain refuge, or in the upstream or downstream channel away from the drop structures (the later two options pose the least risk of compromising the structure). Structures low in profile that don’t constrict a significant percentage of the channel will be less likely to trap material and create backwater. Refer to the *Anchoring and Placement of Large Wood* appendix and the *Large Wood and Log Jams* technique for further guidance on wood placement.

6.2.10 Deformable Drop Structures

When the situation allows (e.g., when a drop structure is installed purely to create channel complexity, provide temporary bed stability, or slow channel regrade), drop structures may be designed to deform over time through undermining, end scour, or entrainment of structural components. Deformation generally occurs during high flow events that exceed the design flow, or because of channel incision or other changing watershed conditions. Deformation differs from design life and ultimate failure – deformation implies that the function of a structure may evolve or diminish 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, rigid structures (log, plank, concrete, or sheet pile weirs) cannot adjust to changing flows, stream profile, cross-section, or planform. For these reasons, rigid drop structures are not generally recommended in habitat enhancement projects except for the purpose of providing fish passage through man-made structures and other situations where long-term monitoring and maintenance can be guaranteed.

Rock lends itself best as a building material in deformable drop structures. However, any natural material may be used. Unnatural materials, such as rebar, wire rope, and concrete blocks should be avoided. Deformability may be achieved by sizing the rock to withstand relatively low design flows, or by minimizing the amount of structure keyed into the channel bed or banks to prevent undermining and end runs, respectively. Designers should note that there is a high degree of uncertainty in the final form of a deformable drop structure once it deforms. Deformable drop structures placed in series may create fish passage barriers due to uneven deterioration of weirs over time.

7 PERMITTING

The installation of drop structures involves in-channel work, streambed and bank 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 a Section 404 Permit). A Clearing and Grading Permit and an Endangered Species Act Section 7 or 10 Consultation may also be required. Refer to the *Typical Permits Required for Work in and Around Water* appendix for more information regarding each of these permits and checklists, and other permits that may apply.

8 CONSTRUCTION CONSIDERATIONS

As with all in-channel construction, the installation of drop structures will result in considerable in-stream disturbance in the form of increased turbidity and rearranging of bed and bank material. Construction impacts, and ways to reduce them, are discussed in the *Construction Considerations* appendix. In addition to in-stream habitat, consideration should be given to the potential riparian habitat impacts to access and staging areas for construction. Access and staging areas will probably experience short-term impacts and will require reclamation and revegetation.

Principle construction considerations that apply to drop structures include:

- Fish exclusion/removal
- Isolating the work site/dewatering. To facilitate construction and meet regulatory restrictions the work area will need to be isolated from stream flow during construction. This is most commonly achieved with a diversion dike or flow bypass[7]. A diversion dike can be used to neck down the stream width to allow work on one streambank at a time. Cofferdams can be used to bypass flow around the entire construction site using pumps or a bypass pipe or channel. It is important to note that constructing a by-pass channel may involve substantial disturbance to the riparian corridor. Measures should be in place to accommodate storm flows during construction.
- Dirty construction water handling
- Temporary Erosion and Sediment Control (TESC) for the banks
- Permit timing, anticipated allowable construction dates
- Access – proximity to site, disturbance of existing vegetation. Because series of drop structures are often constructed in sequence, generally starting from the upstream end and working downstream, access considerations are particularly important to minimize the need to access the channel at multiple points.
- Material size, volume, and availability.
- Restoration of disturbed areas, including staging and access areas, but especially banks affected by installation of structural keys or securing of log materials

Use of experienced contractors with a proven record of accomplishment for constructing in-stream projects with minimal impacts to the environment can facilitate installation. Drop structures will benefit greatly from significant experienced construction oversight and some degree of flexibility in contracting. Construction conducted without careful oversight and done with rigid contracting specifications will likely result in uniform structures that do not maximize the potential added value resulting from creative and variable placement of rock and wood components.

8.1 Equipment Required

Equipment require to install drop structures will depend on the following variables:

- Access limitations
- Size of materials used in construction
- Size of channel

Tracked excavators are typically the most appropriate type of equipment to perform the majority of the instream work, including excavation and installation. However, plank structures can be 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 a stockpile to the project site.

8.2 Timing Considerations

Drop structures should be constructed during low-flow conditions to minimize instream disturbance. It is typically necessary to work within the stream channel to construct drop structures, which means it may be necessary to dewater the channel. Instream 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 can also be found in the *Construction Considerations* appendix.

8.3 Cost Estimation

The total material and construction costs for drop structure installation ranges from approximately $1,500 to $3,000 per structure, assuming a channel width of 10 to 30 feet. This range excludes the cost of design and permitting. Installation cost will be determined primarily by the size of the channel, cost of materials, proximity of the construction site to the source of materials, equipment and operator rates, access limitations, and the need for dewatering. Rock materials typically range in cost from $25 to $80 per cubic yard. Typical costs for installed rock range from $50 to $100 per cubic yard depending on source and equipment access difficulty. Dewatering, if required, will greatly increase the cost of the treatment. Additionally, access for large equipment may require that either a temporary access road be constructed, or that specialized equipment such as a spider hoe and tracked dump trucks be used to cross riparian areas for channel access and materials delivery. Refer to the Integrated Streambank Protection Guidelines'[2] *Cost of Techniques* appendix for further discussion of material and construction costs.

Cost of logs for log control structures are becoming increasingly more expensive and reflect the current value of saw logs. This figure fluctuates and is often market driven as well as geographically driven. In 2003, a 40-foot long fir log that was 18”-24” in diameter and sound with no apparent rot cost just over $200 each. An extra fee was charged for delivering the logs to the site at a cost of $200 per load.

Complex drop structure designs and projects on small streams that will likely cause significant disturbance to the channel (e.g., a long series of drop structures) may be best contracted as time and materials contracts as they will require considerable detail work. Drop structures on larger streams (greater than 20 feet wide) may be contracted as lump sum contracts if sufficient detail is provided in construction plans and specifications. The amount of detail provided in plans and specifications should be considered when selecting a contract format, and vice-versa.

9 MONITORING

Drop structures may be installed for a number of different reasons and the risks to habitat and infrastructure associated with drop structure placement will vary between sites. Therefore, monitoring requirements to evaluate the effectiveness and impacts of drop structure placement will vary from project to project. At a minimum, monitoring should include annual evaluations of drop structure integrity and their ability to provide unobstructed fish passage to determine if maintenance is required. Conduct an as-built survey to document the location, elevation, and configuration of each structure. An inspection should be conducted early in the project life after a significant flood event, and in later years following flows greater than a 5- to 10-year flood event. The inspection should look for evidence of settling, movement, undercutting, flanking, and subsurface flow. Small movement of individual stones is acceptable but significant movement is probably indicative of a failure in design and may necessitate repair or replacement. Note if there is any exposed fabric. This may cause a break in seal and eventually lead to undermining of the structure. Is there undo wear on the structure resulting from high bed and debris load? Is there any debris accumulation that may require clearing? Should there be frequent inspection to ensure it does not become a problem? Is infrastructure, public safety, or habitat compromised or at risk because of the structure? Is there any evidence of any downstream channel incision that may require installation of additional drop structures to continue to meet fish passage criteria and to prevent undercutting of the weir? A general, qualitative description of the drop structure should also be recorded and may include such observations as its general effect on channel flow characteristics and a visual description of the drop structure. Photos and descriptions of observations made safely during low flow and flood events are particularly useful. Where wood and debris recruitment is likely to occur on or adjacent to drop structures such that fish passage may be impeded, multiple surveys should be conducted during critical periods of fish passage.

Long-term monitoring of other parameters (such as the impacts a drop structure has on the channel, bank stability, the abundance and favorability of habitat for fish and other aquatic species, fish production, infrastructure, and water levels) will probably require both pre-project and post-project surveys. The level and frequency of monitoring required will vary with monitoring objectives and project risk. Channel changes occurring following installation can be documented by reviewing annual cross-sections that were surveyed prior to installation and after construction. Patterns of sediment deposition or scour should be noted. The impact of drop structures on flood levels may require regular recording of water levels during the high flow season. Habitat and fish usage monitoring protocols will likely require more rigorous and comprehensive monitoring plans than those required to evaluate the integrity of the structure as many must be tailored to fish life cycles. For a comprehensive review of salmon 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*[25].

10 MAINTENANCE

Operation and maintenance of drop structures should be minimal. However, logs rot and become worn down from bed and debris loads, hydrology changes, and we live in a constantly changing environment, so designing with the expectation of some need for future maintenance is a good idea. The legal requirement to provide fish passage necessitates that any necessary repairs identified through regular monitoring be addressed. Such maintenance may involve clearing of accumulated debris, installation of additional drop structures, or replacement of geotextile fabric, logs, boulders, riprap, ballast, or other structural elements.

11 EXAMPLES

Drop structures of various size, materials, and configurations can be found throughout the state, especially in the vicinity of culverts. Photos of typical applications are provided below.


(a) K-weir. Longfellow Creek.


(b) ”V” shaped boulder weir.


(c) Boulder weir. Cedar River.


(d) Plank Zig-zag weir. Lear Springs.

(e) Log weir grade controls. Hylebos Cr.


(f) Example of poorly installed and failing log weir.

(g) Log weirs. Aldon Creek.

(h) Log weirs. Aldon Creek.

(i) Plank weirs. Mosley Springs.

12 GLOSSARY

Critical flow – The flow condition with the minimum specific energy (depth plus velocity head) and occurs at, or slightly upstream, of the crest of a weir or steepening in profile.
Launchable – refers to rock that is installed with the intent of falling into place when undermined by scour
Subcritical (tranquil) flow – One of two alternate depths with the same energy representing low velocity and deeper depth.
Supercritical (rapid) flow – One of two alternate depths with the same energy representing high velocity and shallow depth.
Thalweg – The longitudinal line of deepest water along a stream.
Weir – A small dam that causes water to back up behind it and flow over or through it.

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POROUS WEIRS

1 DESCRIPTION

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. They can be utilized to 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 natural sorting of sediment at the pool tailout[1] [2]. Porous weirs may also be designed to provide grade control in addition to other applications. 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 that retain sediment and direct water over them. 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, while porous weirs are used primarily for flow redirection and to increase channel complexity through scour and sorting of sediment.

Three popular variations of porous weirs developed by Rosgen[3] include cross-vane, W-weirs, and J-hook vane structures. They are defined primarily by their shape in plan view (refer to **Porous Weir Figures 1, 2, and 3**). Cross-vanes are full spanning boulder structures arranged in a “V”- or “U”-shape that points upstream; W-weirs are two cross-vanes side by side to span a wider channel; J-hooks are similar in shape and function to cross-vanes but do not fully span the channel. J-hooks typically consist of a double row of boulders or other natural materials angled upstream with a “hook” at the end that focuses flow through a pocket. Scour occurs in the pocket of the “hook” and, to some extent, along the downstream edge of the entire structure. J-hook structures are primarily used to protect streambanks by redirecting the flow away from the bank and toward the center of the channel.

2 PHYSICAL AND BIOLOGICAL EFFECTS

Porous weirs direct and constrict flow within the channel. When water flows through or over a porous weir, it turns to an angle perpendicular to the structure’s downstream face The typical upstream pointing “U”, “J”, or “V” pattern of a porous weir concentrates flow into the center of the arch, away from the stream bank. As a result, the shear stress and stream power near the banks are reduced, encouraging sedimentation and reduced erosion along streambanks. Those in the middle of the-channel are increased, encouraging development of a deeper, narrower channel thalweg and a lower channel width to depth ratio[2] [3]. A scour pool typically develops immediately downstream of the structure, providing energy dissipation. The effects of porous weirs on the direction and definition of the downstream channel thalweg typically extend for 100 to 200 feet. Although redirection of flow will occur immediately following porous weir construction, scour and the resulting redistribution of sediment may not occur until the first high flow events.

Constriction of flow created by the porous weir results in two hydraulic conditions: 1) backwater upstream of the structure, and 2) accelerated flow through the structure.
Backwater that occurs upstream of the porous weir will reduce velocity and increase depth at a variety of flows. As porous weirs typically lie low in the channel profile and angle down toward the center of the channel, backwater effects associated with them are generally localized and occur only in the near-bank region, typically resulting in increased sedimentation along streambanks. However, if the structure (either alone or in combination with debris that it traps) causes a significant reduction in channel cross-sectional area or a series of porous weirs collectively increase the hydraulic roughness of the channel, backwater effects may be more far reaching. Effects of large-scale backwatering can include increased flood levels and frequency of floodplain inundation, an adjustment of the elevation of streamside vegetation as lower-growing plants are drowned out, potential change in riparian species composition and distribution in response to changing inundation patterns and water table elevations, and reduced reach transport of sediment. Other effects associated with reduced sediment transport include channel aggradation and associated channel widening, bank erosion, increased channel meandering, and decreased channel depth. Ultimately, water quality may also be impacted by increased turbidity and temperature.

Accelerated flow through porous weirs typically creates scour between and around boulders and velocity gradients through the resultant scour pool. The velocity gradients that occur at the pool tailout and along the channel thalweg naturally sort sediments to improve aeration and further diversify stream habitat.

The seasonal occurrence of scour and deposition maintains pool depth and provides cleaning, sorting, and retention of gravels. Many aquatic species native to the Pacific Northwest rely upon this seasonal disturbance of bed materials to produce optimal habitat conditions. For example, various salmonids depend on the scour-inducing sorting that creates gravel beds of the appropriate size and location for spawning; tailed frogs depend on the cleaning aspect of scour for suitable oviposition sites among the interstices of selected coarse rocky substrates. Another key aspect of the habitat value of scouring on the streambed is regular renewal of surfaces suitable for primary producers to adhere to (especially diatoms and other algal groups). This process is critically important in illuminated streambeds of higher velocity streams where grazers (e.g., caddis flies, catostomid fishes, tailed frog larvae) depend on the algal production on rock surfaces or thin algal film (“aufwuchs”).

Porous weirs produce a variety of water depth, velocity, and sediment conditions in a relatively predictable pattern. The value of this habitat varies seasonally among species. The structure provides interstitial hiding areas, particularly near the bank (those incorporating large wood will offer additional cover). Surface turbulence creates hiding cover. Gravels deposited downstream of the structure may be utilized by spawning fish and other aquatic species. Scour pools offer good holding and feeding stations for many fish during low to moderate flows. However, turbulence may prevent the structure from being very useful for refuge during high flow events.

As with all in-channel construction, the placement of boulders will result in considerable disturbance in the form of increased turbidity and rearranging of bed material. Access and staging areas will probably experience short-term impacts and will require reclamation or mitigation. Construction impacts, and ways to reduce them, are discussed in the *Construction Considerations* appendix. Consideration should also be given to the potential habitat impacts to source areas for boulders, access to and from the source area, and to and from the installation site.

3 BIOLOGICAL CONSIDERATIONS

3.1 Mitigation Requirements for the Technique

Placement of porous weirs in the channel will alter the thalweg alignment. Existing fish spawning areas and pools may be impacted by new scour patterns that result from the redirected thalweg. In addition, the opportunity for future development of near-bank pool habitat may be lost. These near-bank pools provide some of the best types of fish rearing habitat, especially those with wood in them and cover from the overhanging bank. Furthermore, the control that porous weirs have on channel alignment, especially when applied in series on a reach scale, reduces the opportunity for natural channel migration that can introduce sediment and wood to a stream and create new and diverse habitat. Porous weirs, however, allow flow and sediment to pass through the structure, which may result in establishment of new spawning areas and scour pools, possibly avoiding the need for mitigation. Adding wood to the affected or nearby reach or floodplain may further increase the habitat value of the project (see Section 6.6, *Incorporating Large Wood into Porous Weir Structures).*

Refer to the Integrated Streambank Protection Guidelines[4], Chapter 4, *Considerations for a Solution* and the matrices in Chapter 5, *Identify and Select Solutions* for additional guidance concerning mitigation requirements.

3.2 Mitigation Benefits Provided by the Technique

Porous weirs can increase the habitat diversity of otherwise homogenous reaches. They can create and maintain pools that provide holding and rearing habitat for fish, deepen the thalweg to improve fish passage, and sort sediment at the pool tailout and along the channel thalweg to improve habitat for spawning fish and other aquatic organisms. These and other habitat benefits provided by porous weirs are further described in Section 2, *Physical and Biological Effects*.

4 APPLICATION

Porous weirs are effective tools for enhancing habitat variability, stabilizing banks, controlling channel alignment, and altering or maintaining the width to depth ratio of both new and existing stream channels. They may be applied individually at a site scale or in series to affect the pool/riffle sequence of the channel at a reach scale. However, due to concerns regarding the lost opportunity for future channel migration and habitat development when applying this technique on a reach scale, series of porous weirs are only recommended where the channel alignment is permanently confined due to close proximity of infrastructure or in channelized streams where there is no opportunity to restore a natural meander pattern and wood (or other structural element) recruitment to provide habitat diversity.

Porous weirs are most effective in gravel and cobble-bed streams with slopes less than three percent. At higher slopes, step pools created by drop structures may be more appropriate than porous weirs (refer to the *Drop Structures* technique). The relatively large depth of scour associated with porous weirs placed in sand, silt, and other fine-grained material leaves them prone to being undermined or simply sinking into the substrate. Porous weirs are only applicable in free flowing reaches. They are not applicable in backwatered reaches and pools as they will be ineffective at redirecting flow or creating scour. They may be used in surface-water dominated or groundwater dominated streams. However, effects may be limited to redirection of flow if flows are inadequate to redistribute sediment.

Porous weirs should be placed so that their scour pools occur in areas where pools would naturally form. They are typically located in straight channel reaches (near the downstream end of a riffle) and at the entrance of channel bends. If placed at the head of a riffle, the riffle will be scoured out. Avoid placing porous weirs directly in a channel meander bend. One reason for this is that flow is directed along the outside bank as it enters and moves through a channel bend. If a structure is located on the bend, it is difficult to redirect the flow if that is the objective. Flow will naturally tend to stay along the outside bank, making the structure very susceptible to being flanked. The other reason to avoid channel meander bends is that the pattern of sediment scour and deposition created by the structure on a bend will not coincide with natural patterns of scour and deposition. Pools naturally form along the outside of meander bends and create a pool tailout comprised of sorted sediment deposits downstream. Porous weirs create pools downstream and may retain sediment upstream. When used to redirect flow away from an eroding bank, porous weirs should be located upstream from, or directly adjacent to, the eroding bank.

Because porous weirs are essentially immobile objects within the stream channel, they are typically constructed using medium to large boulders; the size of boulders employed should be roughly proportional to the size and slope of the channel. As a result, application of porous weirs on large rivers may encounter practical design and construction limitations imposed by the size of available material, equipment, and impacts that cannot be effectively mitigated. Access limitations may place additional constraints on where porous weir construction is feasible. W-shaped weirs are recommended over “V”- or “U”-shaped weirs in channels over 100 feet wide. A minimum channel width of 40 feet is desirable to facilitate construction of “W”-shaped weirs[5].

Porous weirs are not recommended in aggrading channel reaches unless the aggradation results from an unnaturally large channel width-to-depth ratio (an over-wide stream) caused, for instance, by the removal of riparian vegetation or the presence of a stream crossing (for cattle, vehicles, etc). A porous weir can restore the natural width to depth ratio of the over-widened channel and, thus, its sediment transport capacity. In such situations, porous weirs are best used in combination with riparian restoration and management. If aggradation is caused by something other than an over-widened stream, the effects of porous weir placement are likely to be short-term. Sediment that accretes along depositional reaches will tend to fill scour holes and the channel thalweg and will ultimately bury the porous weir. Consider also that porous weirs inherently create backwater effects that may exacerbate aggradation.

Caution should be exercised when installing drop structures in laterally dynamic channels where there is the potential for an avulsion that could bypass the structure. It should also be exercised in streams that carry a high debris load as debris may become trapped on the structure and increase the degree of backwatering caused by the structure or redirect flow[6].

Porous weirs should be located at least 20 feet downstream of the outlet of a culvert[7] to prevent scour at the culvert outlet from undermining the structure and to limit the amount of debris trapped within the culvert as a result of the structure. Porous weirs should be located at least 35 feet (50 feet where possible) from the inlet of the culvert to prevent the bed of the culvert from being scoured out. Based on a series of flume studies, Johnson et al. recommend that the apex of a cross vane be placed upstream from a bridge abutment 1.5 to 2 times the bankfull channel width to direct flow through the bridge span and away from bridge abutments. They further recommend that the downstream end of a W-weir be positioned 0.3 times the bankfull channel width upstream of a bridge pier to protect the pier.

4.1 Habitat Restoration and Enhancement

Porous weirs should only be applied for habitat restoration and enhancement purposes where a biologic need has been identified. They can be used to restore habitat diversity and improve fish passage to plane bed streams from which boulders have been removed, or to restore the natural width to depth ratio of a stream that has been over-widened (by livestock access or vegetation removal, for example). Porous weirs may also be used as an enhancement technique to increase habitat diversity and improve fish passage in new channels, naturally plane bed channels, and altered plane bed channels that were historically dominated by wood. However, if creating scour pools and increasing habitat diversity are the sole objectives for porous weir construction, boulder clusters or large wood and log jams should be considered as alternative or supplemental techniques. Boulder clusters and wood are less likely to permanently influence the alignment and cross-section of the channel and so reduce concerns regarding the lost opportunity for future channel migration and habitat development.

4.2 Grade Control

Full-spanning structures that incorporate a solid continuous row of footer rocks below those that protrude above the streambed will control the grade of the stream. The bed elevation will be established at the elevation of the lowest point in the row of footer rocks. J-hook vanes do not fully span the channel and, therefore, are inappropriate where grade control is an objective. Although porous weirs can be used to raise the channel bed, drop structures are more appropriate where significant changes to the channel profile are necessary. Users of this technique should note that porous weirs and drop structures typically address only the symptoms of channel incision, not the cause. They may not be appropriate in actively incising reaches unless the root cause of vertical instability is also addressed. Refer to Chapter 4.5.5, *Restoring Incised Channels* in the Stream Habitat Restoration Guidelines for further discussion on potential causes and treatments for channel incision.

4.3 Streambank Protection

Porous weirs protect streambanks through flow realignment and energy dissipation as a result of local scour and increased channel roughness (when used in series). When being used for these purposes, the advantage of using porous weirs to direct channel flow, as opposed to other river training techniques (riprap, groins, barbs, walls) is that they can be designed to provide benefits to fish and other aquatic species as well. These benefits were previously discussed in Section 2, *Physical and Biological Effects*. Note that while porous weirs do a reasonable job of providing bed roughness, other techniques, such as boulder clusters or large wood placement could be used as a complement or an alternative to porous weirs where increased channel roughness is desired.

When using porous weirs to protect an eroding bank, it is important to determine whether porous weirs are the appropriate solution for the particular mechanism of failure and causes of bank erosion in question (see Integrated Streambank Protection Guidelines, Chapter 2, *Site Assessment*, Chapter 3, *Reach Assessment*, and the selection matrices in Chapter 5, *Identify and Select Solutions* for guidance). Porous weirs are appropriate for sites where the mechanism of failure is toe erosion. Porous weirs can be used alone or, more typically, in conjunction with other bank protection treatments. They can add to the integrity of downstream bank protection practices by realigning the low-flow channel.

Porous weirs are not good candidates for emergency streambank protection. They completely span the stream channel and usually require instream construction, which may not be possible during an emergency situation.

5 RISK AND UNCERTAINTY

The effects of porous weirs on habitat, streambanks, and the channel are fairly predictable as long as the relative locations and elevations of the channel and boulders remain constant. However, the possibility of unwanted effects and impacts, such as increased backwater or redirection of flow into banks supporting critical infrastructure must be considered. In addition, because weirs are typically designed as relatively rigid features, their long-term impacts are unpredictable and uncertain in dynamic systems where the channel alignment or profile is likely to change.

5.1 Risk to Habitat

Porous weirs will cause the bed and thalweg to shift. Existing spawning areas may be impacted by scour patterns that result from the redirected thalweg. Existing pools along the old thalweg alignment may be lost or minimized. This loss in pool habitat may be compensated by new pool habitat created through scour induced by the weir. However, pool habitat associated with weirs will have different velocity characteristics (turbulent, jet and/or plunging flow) than that formed along a bend (helical flow).

Depending upon the channel size, bedload movement and particle size, it may take time for the channel to adjust to this structure. During the adjustment period, spawning areas may scour or accrete and any eggs or alevins in the bed could be damaged.

Porous weirs that cause significant backwater or rise in the channel bed may create a barrier to fish passage. Fish passage barriers may also occur as a result of upstream migration of channel incision. For this reason, porous weirs typically lie low in the channel profile and do not raise the bed of the stream. If the spacing between header rocks is maintained and the head differential across the structure is minimized, fish passage should not be a problem.

5.2 Risk to Infrastructure and Property

The risk to infrastructure situated on the streambanks is relatively low. Properly designed porous weirs focus stream energy towards the center of the channel and away from the banks. However, improperly aligned weirs and weirs that trap large wood can erode nearby banks. In addition, large wood incorporated into porous weirs can become mobile posing a threat to downstream structures. Porous weirs should not be implemented at or immediately upstream of piers, culverts, or other in-channel structures, as resulting scour may undermine structure footings.

Risks to infrastructure and property and the risk of structural failure of the weir itself are often amplified in the urban environment, where channels are typically constricted or incised and culverts and bridges are relatively numerous. Hydraulic forces also tend to be more concentrated in constrained or incised urban channels than in natural streams. Porous weirs in urban streams should be designed with these factors in mind.

5.3 Risk to Public Safety

Risk to public safety is generally low. Porous weirs are typically low profile structures that provide only a small increase in elevation and generally do not create hydraulic conditions dangerous to the public. Porous weirs have been used in some instances to enhance recreational boating opportunities.

5.4 Uncertainty of Technique

Most of the design criteria are based primarily on gravel-bed streams. The Natural Resources Conservation Service (NRCS) design guidance was developed from project examples in OR, WA, and ID[8]. Design processes will be refined as more research is done for Washington stream systems, including habitat needs. The greatest degree of uncertainty lies in the depth of analysis conducted in the design process. The risk of structural failure increases with the size, slope, and degree of confinement of the channel.

6 METHODS AND DESIGN

6.1 Data and Assessment Requirements

Many considerations and analyses that are relevant to the design of porous weirs are the same as those for most or all structures within stream channels. The following are minimum assessment requirements. Many of these are further discussed in *General Design and Selection Considerations for In-Stream Structures*.

- *What is the objective of porous weir placement?* The elevation, configuration, and number of structures will vary with the objective. Are porous weirs the best alternative to meet those objectives?
- *Document baseline conditions of the channel and bed material.* Are they appropriate for the use of a porous weir (refer to Section 4, *Application*)? Develop plan, profile, and cross-section drawings of the site and reach, as appropriate. An analysis of baseline conditions may include:
    - General characteristics of bed material. What is the dominant substrate?
    - Channel width.
    - Channel gradient.
    - Cross-section survey(s)

  - Condition of the banks. Are they relatively stable or actively eroding?
  - Degree of channel entrenchment. The depth of flow and, thus, shear stress on the bed and banks of the channel during high flow events increase with the degree of entrenchment. This increases the potential for boulder transport and bed and bank scour because velocity and depth have increased along with the ability to move larger and greater sediment volumes.
  - General assessment of the lateral and vertical stability of the channel and the overall stability of the watershed. Is the channel aggrading or incising in the vicinity of the site? If the channel is actively incising, has the cause of channel incision been identified and addressed? If not, the channel may continue to incise downstream and undermine the lowermost structure.
  - Does the channel carry a relatively high bed or debris load? Limiting the potential backwater effects of a porous weir may be desirable in channels with high debris loads where wood accumulations could compromise the project or adjacent infrastructure.
  - Additional baseline data may be required for any monitoring planned at the site. The scope and nature of such an assessment depend upon monitoring objectives. It may include, but is not limited to, documentation of fish presence and abundance upstream of the structure, the extent and nature of eroding banks, the pool: riffle ratio of the channel reach, or the frequency, extent, and depth of over bank flows.
- *Evaluate structure stability.* What is the necessary design life or design flow of the structure? What size of material will be necessary to meet those design criteria?
- *Evaluate access and materials availability.* What access routes and staging areas are available? Will they limit the type of equipment, and therefore, the type of material, that can be utilized? What impacts are likely to occur as a result of ingress and egress of equipment and materials? Will in-stream and riparian site conditions permit construction? Will the cost or availability of materials limit the design?
- *Document the location and nature of in-stream and nearby infrastructure that may benefit or be harmed by the proposed structure.* This is best done in conjunction with developing good plan, profile and cross-section drawings of the site and reach. The presence of infrastructure will likely place limitations upon flow redirection, structure elevation, and the degree of allowable backwater.
- *Conduct a biological assessment.* What species of fish and wildlife require passage over and through the structure (refer to *Fish Passage Table 1* in the *Fish Passage Restoration* technique for a list of migratory fish species native to Washington State)? What is the maximum allowable hydraulic drop over the structure to accommodate these species? What is the minimum spacing between rocks within the structure necessary to accommodate these species? What is the current distribution of habitat, including spawning, rearing, high flow refuge, cover, and pool habitat, within, upstream, and downstream of the site that may be impacted by the structure? The local WDFW Area Habitat Biologist should be consulted for additional information on local aquatic fauna. Contact the WDFW Habitat program at (360) 902-2534 to find a WDFW Habitat Biologist in your project area. Further information regarding biological assessments is provided in Chapter 3, *Stream Habitat Assessment,* of the Stream Habitat Restoration Guidelines.

- *Will the placement adversely affect recreational navigation*? What measures can be taken to minimize public safety risks?
- *What are the potential impacts to upstream, downstream, and adjacent habitat, fish and wildlife, infrastructure, and public safety during and following construction if the project succeeds or if it fails structurally*? What is the probability of those impacts occurring? What factors influence that risk (e.g., degree of channel confinement, slope, bedload, high flow events, material selection, structure configuration)? What can be done to minimize the risk? Are the costs acceptable?

The most common unintended impacts of porous weirs are bank erosion, backwatering, and upstream sedimentation in excess of project goals. Bank erosion can result from flanking of structures, inadequate protection of banks near structures, inadequate keying of structures into streambanks, upstream sedimentation, and misdirection of stream flow. All of these factors can be controlled and/or avoided, for the most part, by careful planning and analysis. Backwatering and associated upstream sedimentation can be predicted by employing hydraulic analyses, and therefore minimized or avoided. Because porous weirs create backwater conditions that may impact channel processes upstream and downstream of the structure, a reach assessment will likely be necessary to evaluate potential influences on structure performance and impacts resulting from the structure itself.

In relatively small, low energy streams where there is minimal risk to infrastructure, habitat, and public safety, elements of the design may be based on reference site conditions. For instance, the necessary size of material, structure configuration, and the anticipated depth of scour can be estimated by observing stable structures located in similar channel reaches operating under similar conditions. However, high risk projects, high cost projects, and projects conducted on larger streams (greater than 20’ wide) and steeper or more confined channels may have additional data collection and assessment requirements. These could include, but are not limited to, selection of design discharges, analysis of backwatering effects, sediment transport, and calculation of scour. These aspects of design are discussed in detail in the *General Design Considerations for In-Stream Structures*. Where design considerations are specific to porous weirs, they are presented below.

The primary function of porous weirs is to direct or concentrate flow. As such, hydraulic modeling of design conditions will be essential to project design. Hydraulic modeling will quantify the extent and magnitude of increased water levels upstream (backwatering), changes in flow velocities, and bed shear stresses. These hydraulic parameters will be required for sizing boulders, determining boulder spacing and configuration, and quantifying impacts to sediment transport. The secondary function of porous weirs is to induce scour. It is for most practical purposes inseparable from the primary function, and deserves equal evaluation and consideration in design. Predicting scour depth at varying flows will quantify flow conditions that would be expected to fill or deepen the scour pools as well as equilibrium depths. These characteristics will provide insight to the anticipated benefit of porous weirs to habitat as well as the stability of the structure. The footer rocks of porous weirs must extend to or below the estimated depth of scour in order to prevent the structure from being undermined. Hydraulic modeling and methods used to conduct various hydraulic analyses are described in the *Hydraulics* appendix.

Sediment transport characteristics, such as deposition and erosion rates, govern structure effectiveness in terms of scour pool development and maintenance, depositional bar formation, and substrate size and sorting. Sediment transport analysis may be necessary where large-scale backwatering effects are likely or where the project is intended to trap sediment or otherwise affect sediment transport (alter channel width, depth, or slope). Such effects are more likely to occur when a series of structures are installed. Local, individual structures will most likely affect scour and sorting without impacting general sediment transport characteristics through a reach. The evaluation of sediment transport is detailed in the *Sediment Transport* appendix.

6.2 Structure Spacing

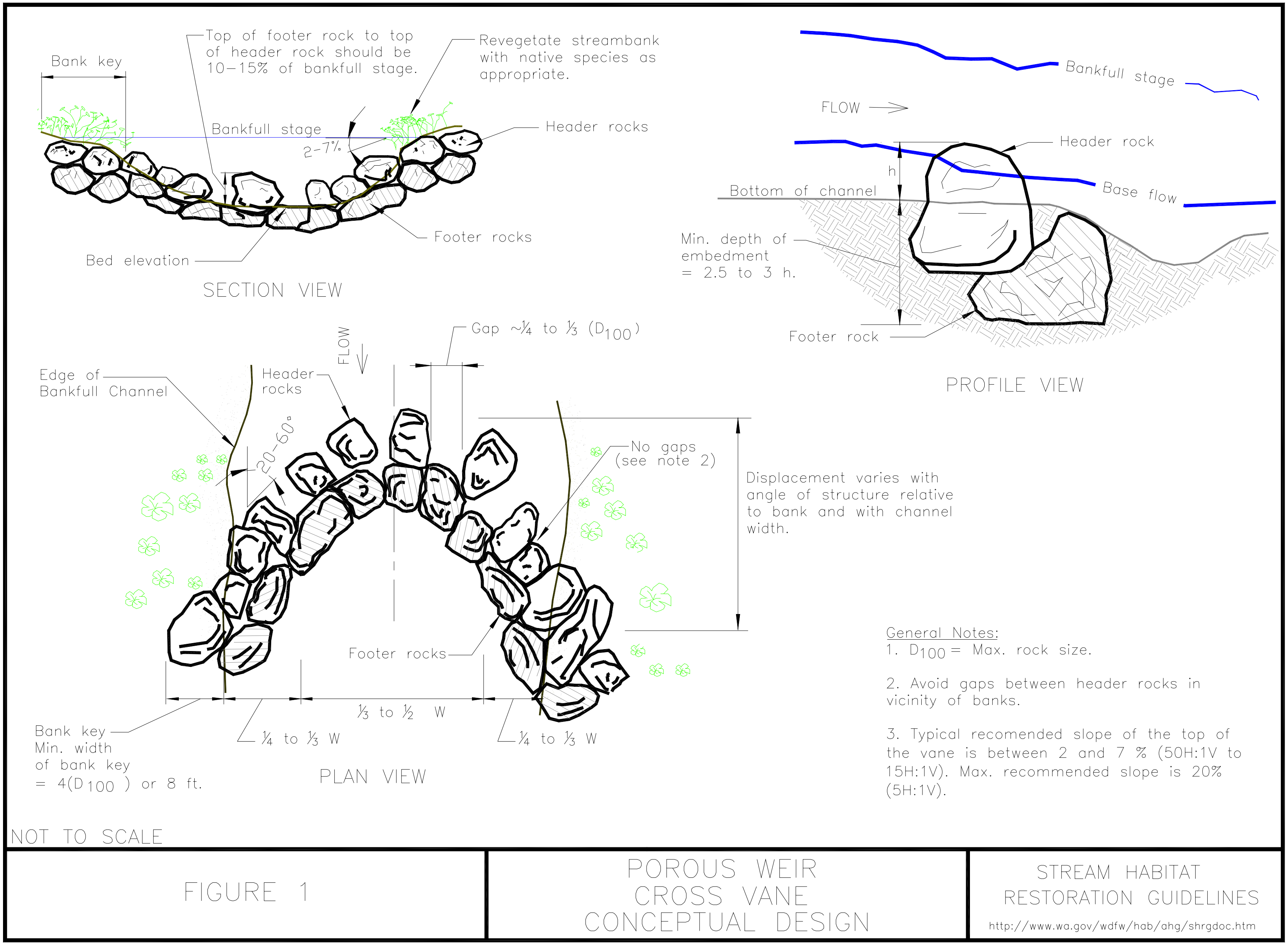
Geomorphic characteristics such as pool frequency and location (e.g. from an analog stream reach) lend information on appropriate spacing, frequency, and locations of porous weirs. In order to be effective in the short and long term, porous weirs should work in concert with these natural bedform characteristics. Typical alluvial channels with slopes between 1 and 3 percent generally have pool spacing between 3 and 10 channel widths and average about six channel widths[9], although closer spacing has been observed in wood-dominated channels[10]. At slopes steeper than about three percent, step-pools created by drop structures may be more appropriate. Refer to the *Drop Structures* technique for guidance on drop structure design and application. Additional guidance on typical spacing of natural pool-riffle sequences for various stream types can be found in the *Fluvial Geomorphology* appendix.

To ensure fish passage through a series of porous weirs, channel slope, maximum allowable head drop, length and depth of backwater, and length of thalweg created downstream should also be considered. For grade control, the minimum spacing should equal the maximum allowable head drop over the weir divided by the proposed channel slope. For example, the minimum spacing between 8-inch high weirs in a stream with a 2 percent slope will be 0.67 ft/ 0.02 = 33.5 feet. In general, the slope between the weir crests should not be flatter than that of the pre-project, low-flow water surface.

6.3 Shape and Configuration

Porous weirs should be installed with a relatively low profile, such that the tops of the boulders are exposed at low to average flows but submerged by higher flows. Cross-vanes and “W”-weirs span the entire width of the channel while rock “J”-hooks extend approximately 2/3 of the way across the channel width (see **Porous Weir Figures 1, 2, and 3**). Each is typically arranged to form an upstream-pointing arch in plan view, with the lowest point at the apex of the arch. Each arm of the arch of full-spanning porous weirs can have either equal or different lengths, depending upon the thalweg alignment as it approaches the weir and the desired thalweg alignment immediately downstream. The lowest point of the weir occurs at the apex of the arch and should be located far enough from the streambank so that the scour pool that develops will not undermine the bank; it is typically located in the center third of the channel. Note that the two apexes of a W-weir can be set at different elevations to accommodate different channel bed elevations or to increase flow through the one span. Locating the lower apex further upstream than the higher apex can further increase flow through that span.

Design guidelines provided by Rosgen and the NRCS both promote the use of a solid continuous row of footer rocks below and slightly in front of a top layer of “header” rocks that protrude from the streambed into the flow. Header rocks are responsible for creating the hydraulic effects of the weir, inducing scour, backwater, and redirection of flow. The primary function of footer rocks is to support the header rocks and prevent undermining of the structure. Footer rocks of full-spanning structures (not J-hooks) also provide grade control; their top elevation should be designed to correspond with the desired elevation of the channel bed. Note that a single row of rocks, rather than a double row of footer and header rocks, may be sufficient provided they are stable and extend deep enough into the bed to prevent them from being undermined.



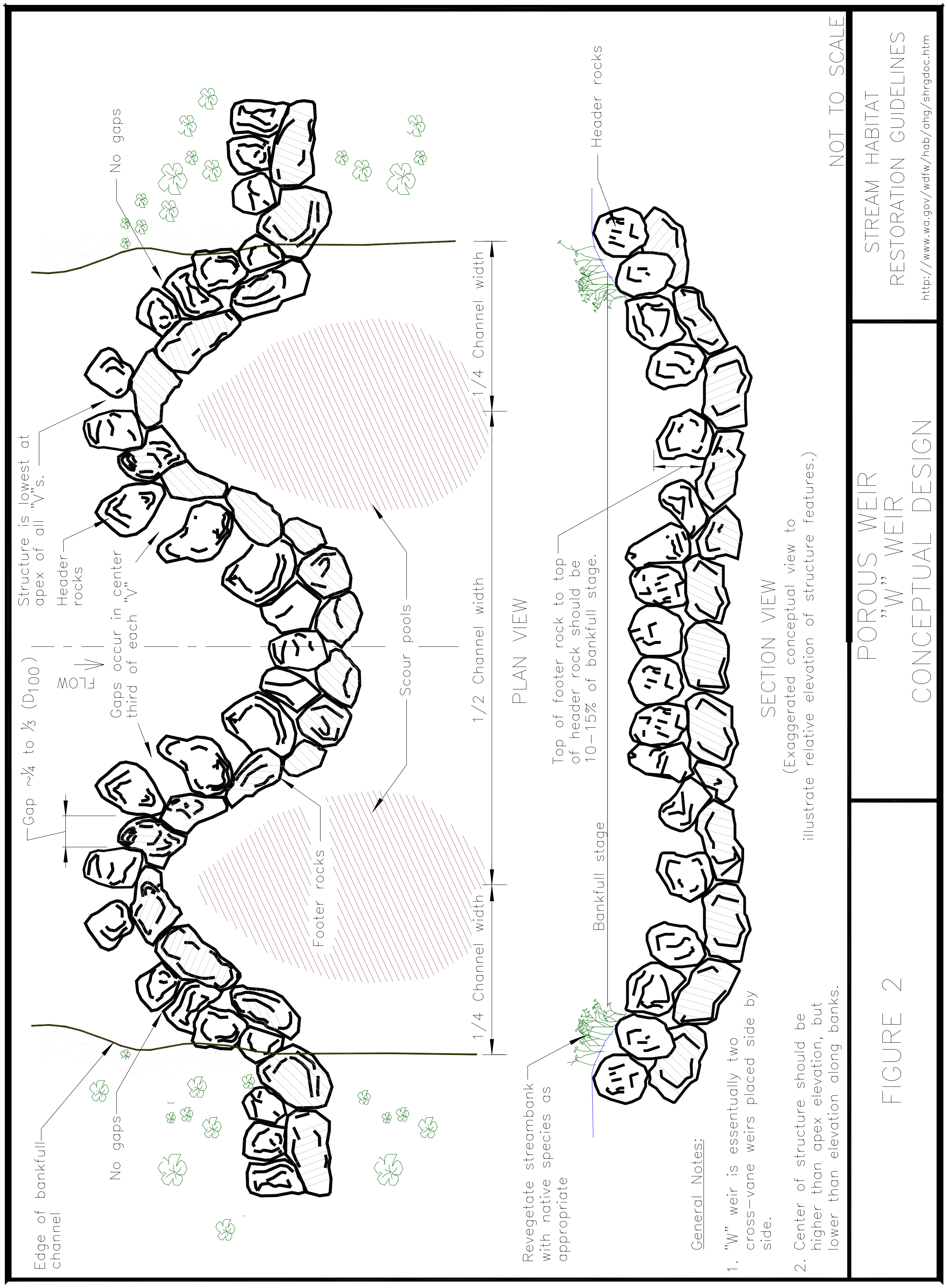
General Notes:

1. D_{100} = Max. rock size.
2. Avoid gaps between header rocks in vicinity of banks.
3. Typical recomended slope of the top of the vane is between 2 and 7 % (50H:1V to 15H:1V). Max. recommended slope is 20% (5H:1V).

FIGURE 1

POROUS WEIR
CROSS VANE
CONCEPTUAL DESIGN

STREAM HABITAT
RESTORATION GUIDELINES
http://www.wa.gov/wdfw/hab/ahg/shrgdoc.htm



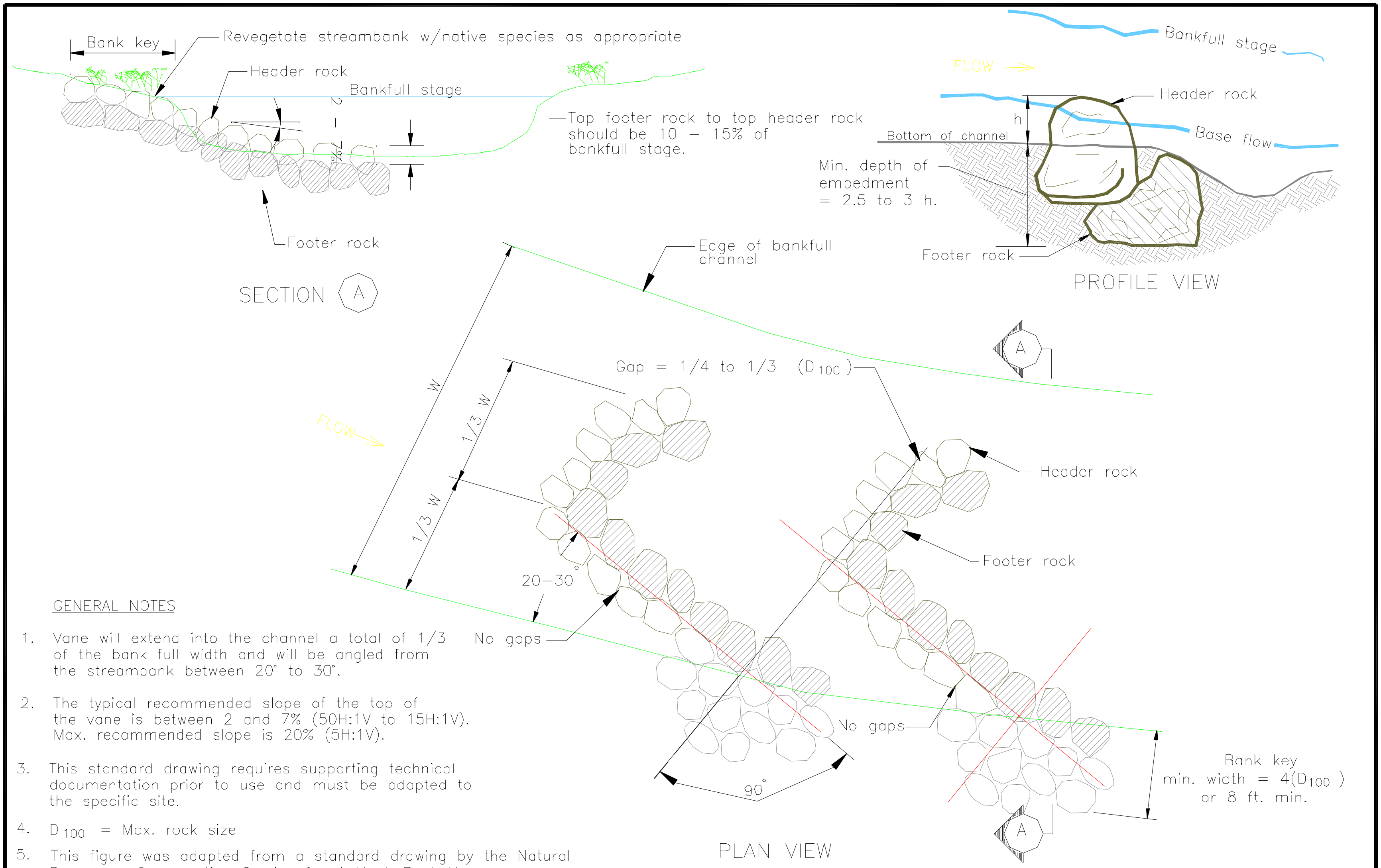
General Notes:

1. "W" weir is essentially two cross-vane weirs placed side by side.
2. Center of structure should be higher than apex elevation, but lower than elevation along banks.

STREAM HABITAT
RESTORATION GUIDELINES
http://www.wa.gov/wdfw/hab/ahg/shrgdoc.htm

POROUS WEIR
"W" WEIR
CONCEPTUAL DESIGN

FIGURE 2



GENERAL NOTES

1. Vane will extend into the channel a total of 1/3 of the bank full width and will be angled from the streambank between 20° to 30°.
2. The typical recommended slope of the top of the vane is between 2 and 7% (50H:1V to 15H:1V). Max. recommended slope is 20% (5H:1V).
3. This standard drawing requires supporting technical documentation prior to use and must be adapted to the specific site.
4. D_{100} = Max. rock size
5. This figure was adapted from a standard drawing by the Natural Resources Conservation Service for J–Hook Rock Vanes.

NOT TO SCALE

FIGURE 3

POROUS WEIR
J–HOOK ROCK VANE
CONCEPTUAL DESIGN

STREAM HABITAT
RESTORATION GUIDELINES
http://www.wa.gov/wdfw/hab/ahg/shrgdoc.htm

Weir angle.

The distance that the structure projects upstream varies with the angle of its alignment relative to a line tangent to the bank. Weirs with smaller angles are longer and project further upstream than those with larger angles. Therefore, more of the bank is protected and the discharge per unit length of weir is less. The later may benefit fish passage by providing a greater range of water depths and lower velocities to swim through. But the designer should also consider that weirs with smaller angles redirect flow more sharply towards the center of the channel creating deeper scour pools. This scour depth will need to be accounted for in footer rock design to ensure the structure is not undermined. Cross vanes and W-weirs typically project upstream at an angle ranging from 20 to 60 degrees. NRCS recommends that a hydraulic analysis be conducted for angles approaching 60 degrees. For J-hook vanes, a narrower range of 20 to 30 degrees is recommended. In a series of flume experiments, Johnson et al. found that structures with angles of less than 25 degrees were less effective at moving scour away from the bank.

Height of structure.

It is important to configure the porous weir such that it does not significantly backwater upstream reaches, particularly during flows that result in scour and habitat development. Excessive height can cause structural failure, trigger upstream aggradation and bank erosion, trap debris, and create a barrier to fish passage. To minimize backwater and to allow bedload to move through the porous weir with minimal restriction, the low point of the weir (situated at the apex) should not be placed higher than 15 percent of the bankfull channel height. This height is measured at the thalweg from the surface of the bed (or the top of the footer rock if it is higher than the bed) to the top of the header rock. From the apex, the crest of the porous weir should gradually but continuously slope up towards the bank such that the boulders nearest the bank are the last to be submerged as stage increases. Rosgen recommends a slope of 2 to 7% (50H:1V to 15H:1V). Due to the difficulty of achieving this relatively low slope in the field, especially for small streams, NRCS recommends the slope not exceed 20% (5H:1V). As the slope increases, so does the degree of channel confinement as more water is directed through the apex. Upstream backwater effects and downstream scour may increase in response. Guidance by NRCS and Rosgen suggest that the height of the porous weir near the bank should approach but not exceed the bankfull stage elevation. The relatively flat portion of the weir typically transitions into the bank at an angle of 1V:1.5H to 1V:2H. Hydraulic modeling can be used to quantify the degree of backwatering for a particular configuration. Excessive backwater effects will occur where the depth of bankfull flow over the weir is more than 120% of the average depth of bankfull flow. Fish passage may be obstructed at lower levels of backwater.

In fish bearing waters it is a requirement that any obstruction across or in a stream must freely pass fish [RCW77.55.060]. For fish passage to be achieved, the hydraulic drop over the structure must not exceed maximum criteria for fishways given in WAC220-110-070. To provide passage for adult steelhead and chinook, coho, and sockeye salmon, a 12-inch maximum difference in water surface elevation above and below the porous weir applies. But to allow passage for the weaker swimming fish, such as pink or chum salmon or adult trout, the difference in water surface elevations above and below the porous weir should not exceed 0.8 feet. If upstream juvenile salmonid passage is critical, the drop should not exceed six inches. Passage of other fish and wildlife species may require lesser drops.

Typically, the hydraulic drop over a weir placed in series is equal to the elevation drop between the tops of the footer rocks of two successive weirs, provided the conditions at each weir are the same. However, conditions may differ significantly if the degree of backwater upstream of the uppermost weir is higher than that for the lower weir, causing a greater drop to form over the structure. For this reason, it is recommended that individual weirs within a series have similar configurations. The hydraulic drop over an individual weir or the lowest structure within a series is governed by the amount of backwater created by the weir. The maximum allowable hydraulic drop must be satisfied at all flows between the low and high fish-passage design flow. The low fish passage design flow is the two-year, seven-day low-flow discharge or 95-percent exceedance flow during the migration months for the species of concern. The high fish passage design flow is the flow that is not exceeded for more than 10 percent of the time during the months of fish migration. The two-year peak flow may be used as the high fish passage flow when stream-discharge data is unavailable. The top elevation of the footer rocks may be installed below the elevation of the channel bed. However, if grade control is an additional objective, the elevation of the row of footer rocks should be designed to correspond with the desired elevation of the channel bed.

Gaps between rocks.

The location and size of the gaps between header rocks influence the hydraulic effects of the weir. Too large a gap will not create sufficiently high velocities through the gap needed to move bedload and dissipate energy. Too small a gap will constrict flows, trap sediment and debris, and may cause backwater conditions or impede fish passage. Guidance by Rosgen suggests that the gap between header rocks near the apex of the porous weirs (generally within the central third of channel width) should be between ¼ and 1/3 of the rock diameter. No gaps are recommended along the arm of the weir, as they tend to produce back-eddy erosion during large flood events that can erode the banks and compromise the integrity of the structure. Limiting gaps to the apex of the structure further concentrates water and may be desirable in areas with low base flows. The gaps in the weir can be modeled in HEC-RAS with the in-line weir option. For flows that overtop the rocks it may be necessary to use the velocity distribution option to determine flow velocities through the gaps. Using an iterative approach, the gap spacing can be designed to provide the desired hydraulic and scour conditions at design flows.

Depth of structure.

Boulders will “sink” into the bed as scour removes material from around their bases. To prevent the structure from being undermined, the bottom of the structure should extend below the estimated depth of scour. Numerous equations to estimate scour depth are provided in the *Hydraulics* appendix. These equations are often based on flume experiments and will provide an approximation. The depth of the scour pool increases with increasing degree of flow confinement, drop height, or channel slope, and with decreasing substrate size (e.g., from boulder to cobble, or from to gravel to sand).

Field measurements of similar scour conditions should be used to verify estimates of scour depth. (Be cautious that maximum scour depths occur at the peak of the hydrograph with infilling occurring on the receding limb of the hydrograph. Scour depths observed during low flows will be less then the maximum depth.) As a rule of thumb for gravel or cobble bed streams, NRCS guidance suggests that the expected scour depth associated with porous weirs may be estimated by:

$$\text{Scour Depth} = 2.5 * h$$

Where h is the height of exposed rock relative to the bed elevation. In sand bed streams, the depth of scour will be greater. NRCS suggests that estimated depth of scour in sand bed streams will be 3 to 3.5 *h. Rosgen recommends that footer rocks extend to a depth of 3*h in cobble and gravel bed streams and 6*h for sand bed streams. As a result, boulder placement in sand bed streams may be inappropriate.

6.4 Bank Key

Porous weirs (including footer rocks) should be keyed into the channel banks to prevent flanking of the weir at high flows. The key provides protection from scour associated with overbank flow spilling back into the channel. The bank key should be at least as high as the exposed portion of the porous weir at the bank. The extent to which the structure is keyed into the banks will depend upon bank, channel, and flow characteristics. Hydraulic modeling will indicate the flow depths and limits likely to occur for the expected range of flows. With this information the extent and height of the key can be determined for the specific site conditions. . The minimum recommended length for the bank key is four times the D_{100}, 1.5 times the height to the top of the bank, or eight feet (whichever is greater). However, in very stable channel systems with non-erodible banks, lesser keys may be appropriate. Longer keys may be necessary where banks are frequently overtopped.

For small streams, the key typically extends into the bank at the same angle as weir. On large streams, however, keys are often constructed perpendicular to the bank. The designer is encouraged to consider the hydraulic effects associated with the angle of the bank key should it become exposed. Material comprising the key should have the same dimensions as that used for the exposed portion of structure within the channel. Buried large wood can be incorporated into the bank key.

It is important to minimize bank disturbance and vegetation removal during construction. Revegetation of the bank at both keys is necessary for added structural strength and habitat needs.

6.5 Materials

Most porous weirs can be constructed wholly, or in large part, of stone. In general, the designer should strive to use natural materials as much as possible, and to use materials appropriate to the location and stream type. Porous weir structures should be designed to be rigid non-deformable features for flows up to some maximum design flow (a minimum of a 20-year flow is recommended). Flows that exceed the design condition may move some of the individual boulders or undermine the structure and cause it to deform. Material sizing guidance given in the *Drop Structure* technique also applies to porous weirs. Calculated rock sizes should be verified against those observed in the field.

Rock used in porous weirs should be sound, dense, and free from cracks, seams and other defects that would tend to increase its deterioration from weathering, freezing and thawing, or other natural causes. Angular rock is 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. The smallest dimension of an individual rock used in a porous weir should be greater than one-third its largest dimension[11]. 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.

6.6 Incorporating Large Wood into Porous Weir Structures

Large wood can be incorporated into porous weir designs for added habitat benefit, additional roughness, and flow realignment. It is sometimes incorporated directly into the structure itself by replacing header rock(s) near the bankline with tree trunks and attached rootwads or situated parallel to the bankline as added bank protection. However, the designer should note that placement of wood within the structure increases the risk of structure failure by creating voids in the rock fill, poor foundation conditions, and increased uplift forces. In addition, when adding wood in the vicinity of structures, consideration must be given to the scour, deposition, and flow patterns that are likely to develop. Care should be taken to ensure that flow is not directed to bypass or flank the next downstream structure and that the scour pool does not undermine adjacent infrastructure. Consideration should also be given to the fact that wood can create a constriction and additional backwater that may or may not be desirable. Wood may also recruit additional wood and other material moving downstream which can exacerbate constriction and backwater effects, impede fish passage over the weirs, and cause unexpected shifts in flow direction or scour and deposition patterns. For this reason, wood is most often placed in or along the fringe of the plunge pool created by the structure where it can provide critical in-stream cover, in the adjacent floodplain to provide floodplain refuge, or in the upstream or downstream channel away from the structures (the later two options pose the least risk of compromising the structure). Refer to the *Anchoring and Placement of Large Wood* appendix and the *Large Wood and Log Jams* technique for further guidance on wood placement.

7 PERMITTING

As installation of porous weirs involves in-channel work, stream bed and bank 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 Clearing and Grading Permit, Washington Department of Natural Resources Use Authorization, and an Endangered Species Act Section 7 or 10 Consultation may also be required. Refer to the *Typical Permits Required for Work In and Around Water* appendix for more information regarding each of these permits and checklists, and other permits that may apply.

8 CONSTRUCTION CONSIDERATIONS

As with all in-channel construction, the installation of porous weirs will result in considerable in-stream disturbance in the form of increased turbidity and rearranging of bed and bank material. General construction considerations relevant to all in-channel work, and ways to reduce them, are detailed in the *Construction Considerations* appendix. Principle construction issues relevant to porous weir construction include locating, transporting and installing boulders. Permit restrictions may require that additional factors be considered.

Construction of porous weirs requires careful excavation and placement of material within the stream channel and banks. Rock should never be dumped into the stream. Two types of equipment are typically used for placing boulders: 1) a hydraulic excavator fitted with a thumb and capable of excavating streambed materials and placing the largest rock size required for the project; and, 2) a loader to shuttle materials at the site. The equipment should be capable of placing rocks to insure that the rocks are interlocked and stable. Note that motorized wheel barrows, rock bars, winches, and other hand tools may be required where heavy equipment access is limited and to fine-tune boulder placement. Pre-construction planning in the field with the equipment operator during installation is very important to facilitate construction and achieve the desired results. Presence of the designer, or an inspector experienced in these structures, during construction is critical. Site specific conditions may arise that simply cannot be forecast and will require adjustment on the part of both the designer and the operator.

Except under special circumstances, construction will not be permitted to occur in flowing water due to the potential impacts to in-stream habitat and biota. To facilitate construction and meet regulatory restrictions the work area will need to be isolated from flowing water during construction using a diversion dike, flow bypass, or similar technique. Fish will need to be removed and excluded from the work area. Depending on site conditions, dewatering of the work area may be necessary during excavation of streambed materials and placement of footer rocks. Dewatering facilitates installation, prevents siltation of the stream during construction, and minimizes trampling and disturbance of aquatic life.

The number and location of access points must be selected to minimize damage to the existing riparian vegetation. At project completion, disturbed areas, including staging and access areas, will need to be graded smooth, seeded, and planted to repair damage and restore the riparian zone.

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). Low-flow conditions are ideal for the placement of boulders and may be essential for dewatering efforts. In-stream 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.

Porous weirs on small streams may be best contracted as time and materials contracts, as they will require considerable detail work. Structures on larger streams (greater than 20 feet wide) may be contracted as lump-sum contracts if sufficient detail is provided in construction plans and specifications. Use of an experienced contractor with a proven track record for constructing in-stream projects with minimal impacts to the environment can facilitate installation.

8.1 Cost Estimation

Porous-weir structures can be a relatively low-cost approach to improving habitat or reducing erosive energy along a streambank. The greatest cost factor is the size of the channel. Weir structures range in cost from approximately $75 per linear foot to $200 per linear foot. 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. Rock materials typically range in cost from $25 to $80 per cubic yard. Typical costs for installing rock range from $50 to $100 per cubic yard depending on source and access. However, it is not uncommon to have higher unit costs for very difficult sites. Dewatering, if required, may greatly increase the cost of the treatment. Additionally, access for large equipment may require either temporary access road construction or the use of specialized equipment, such as a spider hoe and tracked dump trucks, to cross riparian areas for channel access and materials delivery. Refer to the Integrated Streambank Protection Guidelines, *Cost of Techniques* appendix for further discussion of materials costs and construction costs.

9 MONITORING

Monitoring methods employed depend on project and monitoring objectives. At a minimum, monitoring should include annual evaluations of porous weir integrity and their ability to provide unobstructed fish passage to determine if maintenance is required. Inspections should note if there is any debris accumulation that may require clearing or more frequent inspection to ensure it does not become a problem. It should also note if infrastructure, public safety, or habitat is compromised or at risk as a result of the structure.

Long-term monitoring of other parameters (such as the impacts a porous weir has on the channel, bank stability, the abundance and favorability of stream habitat available to fish and other aquatic life, fish production, infrastructure, and water levels) will probably require both pre-project and post-project surveys. The level and frequency of monitoring required vary with monitoring objectives and the risks to habitat, infrastructure, and public safety that are associated with the presence or failure of the structure. Low risk projects may simply warrant annual site visits and a documentation of qualitative observations regarding bank erosion, flow characteristics, scour and deposition patterns, fish use, and the configuration and stability of header and footer rocks. On the other hand, projects that pose a relatively high risk to infrastructure, property, public safety, or habitat may require frequent quantitative physical and biological surveys to be conducted. Such surveys may include photo documentation from fixed photo points, detailed surveys of boulder dimensions, locations and bed and bank topography (including multiple cross-sections at, upstream, and downstream of the structure and spaced approximately one channel width apart) to document changes over time, pre- and post-construction snorkeling of the site and a reference reach to document fish use, or pre- and post-construction water level recording at multiple stream flows to document changes in flood elevations. Refer to the *Monitoring Considerations* appendix for guidance on developing and implementing a monitoring plan.

Habitat and fish usage monitoring protocols will likely require more rigorous and comprehensive monitoring plans than those required to evaluate the integrity of the structure as many must be tailored to fish life cycles. 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[12].

10 MAINTENANCE

Regular monitoring of the site after high flow events will identify any maintenance requirements. Maintenance of a porous weir project should not be required except in a few situations where the project is no longer meeting project objectives or unintended consequences have occurred and are unacceptable. Maintenance, when needed, may include re-positioning, replacement, or removal of individual boulders, removal of wood that has racked up against the boulders, or supplemental treatments of eroding banks. However, keep in mind that repositioning and replacement of boulders is only recommended after careful evaluation to determine what went wrong to avoid repeating the mistake. Note that any mitigation measures, such as the placement of large wood, may also require maintenance. This could include replacement or re-anchoring of large wood that was removed or loosened by high flows.

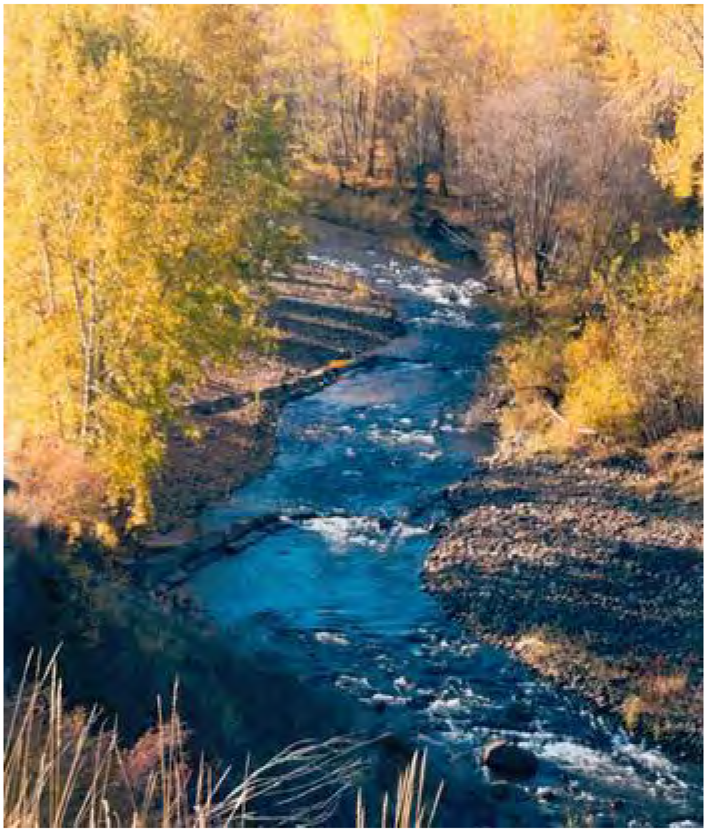
11 EXAMPLES

Porous Weirs Figure 4: Porous Cross Vane on Cedar Creek, Clark County, Washington.

Porous Weirs Figure 5: Porous Cross Vane on stream in southeastern Washington.

Porous Weirs Figure 6: J-Hook Rock Vane on Omak Creek, Okanogan County. Photo provided courtesy of the Natural Resources Conservation Service.

Porous Weirs Figure 7: J-Hook Rock Vane on stream in southeastern Washington.



Porous Weirs Figure 8: Series of J-Hook Rock Vanes on the Tucannon River, Columbia County, Washington.

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BANK PROTECTION CONSTRUCTION, MODIFICATION, AND REMOVAL

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. 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 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 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 Chapter 6, *Bank Protection Techniques*.

6 REFERENCES

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INSTREAM SEDIMENT DETENTION BASINS

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.

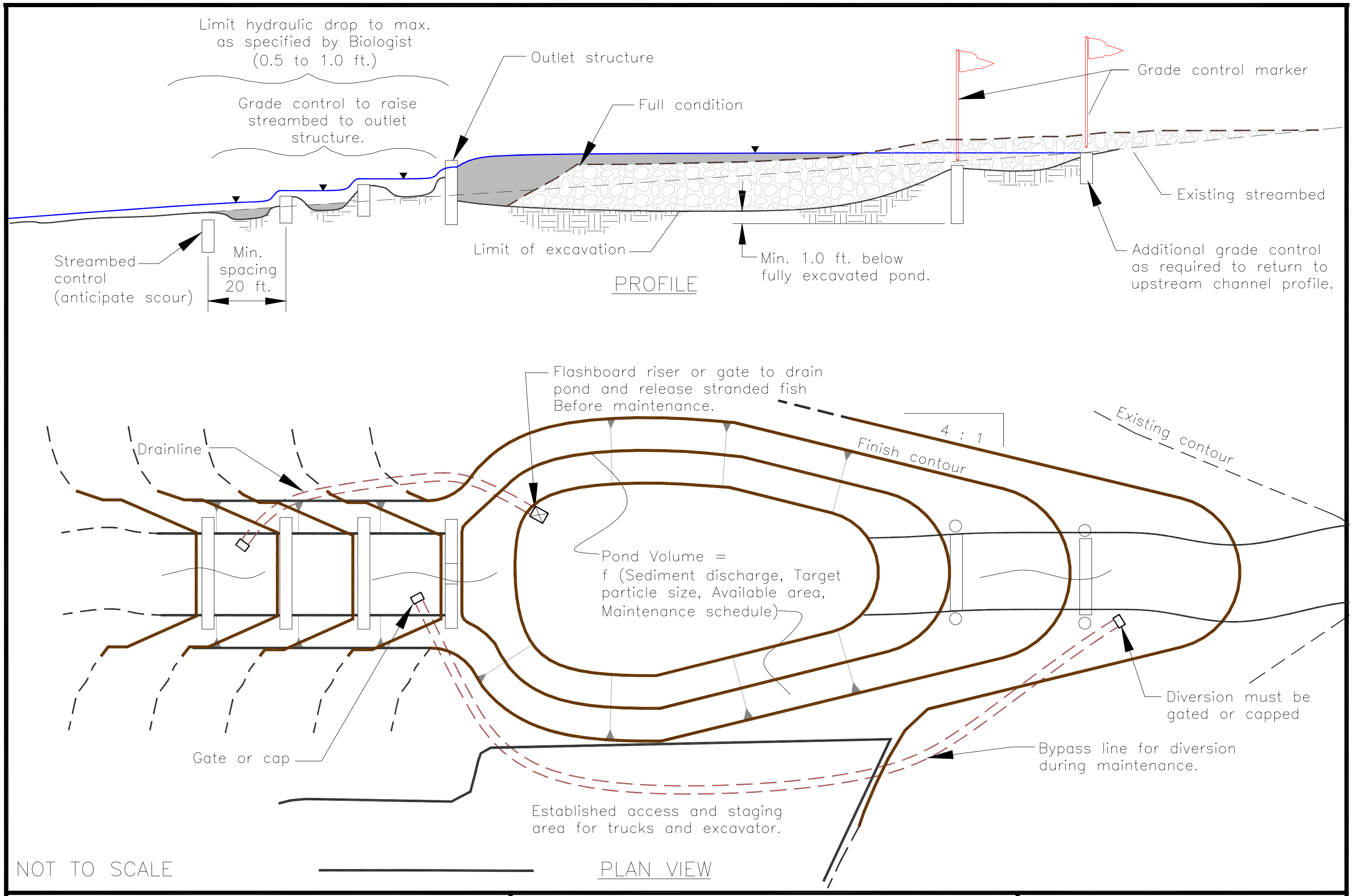

FIGURE 1

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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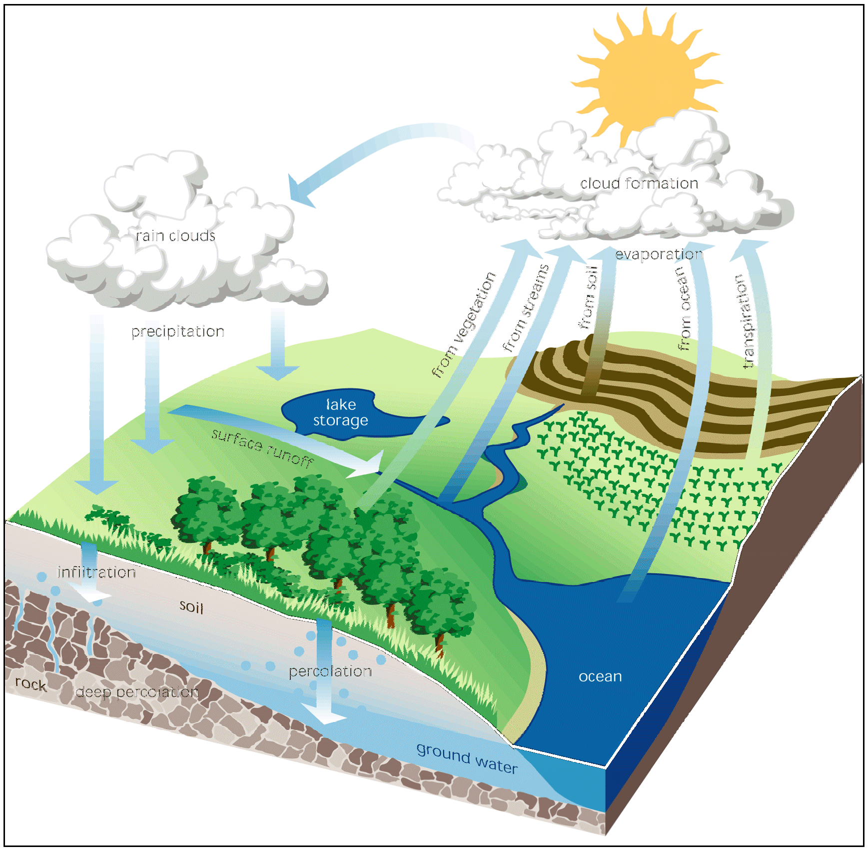
HYDROLOGY APPENDIX

The purpose of this appendix is to provide some understanding of the background and methods used in hydrologic analysis for stream restoration projects. It is intended to both inform the reader of important considerations for project design and direct further study to pertinent sources. It is not a substitute for research and detailed understanding of hydrologic processes in a particular project area. The reader should seek the advice and analysis of an experienced hydrologist or hydrogeologist for the development and review of project plans prior to site work.

References for sources and citations are listed at the end of the appendix.

1 HYDROLOGY

Hydrology is the science of water in motion. It includes the occurrence, movement, and storage of water in the atmosphere, on the land, and in the sea. The occurrence and movement of water is characterized in the hydrologic cycle shown below.



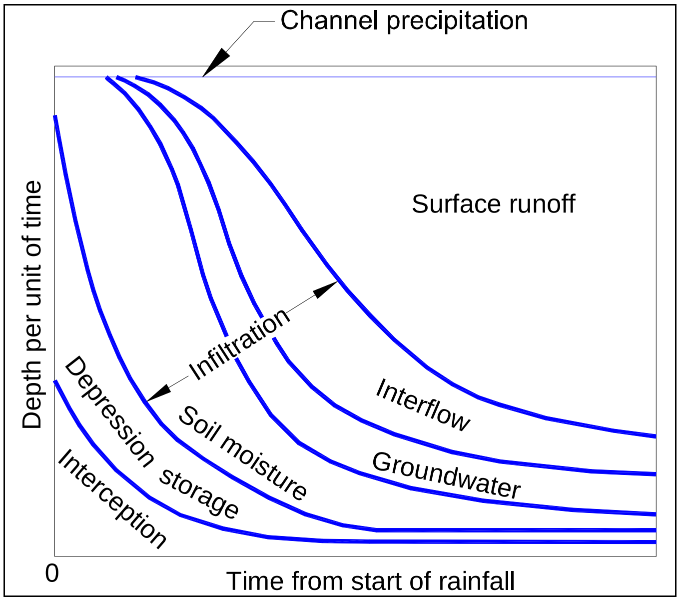
Hydrology Figure 1: Hydrologic cycle.
Source: Federal Interagency Stream Restoration Working Group. 1998. Stream Corridor Restoration: Principles, Processes, and Practices” [1]

The hydrologist studies processes and factors that influence the supply, movement, and forms of water in the landscape. Hydrologic studies include climate, geology, geomorphology, vegetation, and land use in varying scales of space and time. The science of hydrology also includes measurement of quantities and rates of movement of water, compilation of quantitative data, and studies to determine the principles and laws of the occurrence, movement, and work of water[2]. Hydrologic measurement requires accurate observations of nature while hydrologic study bases its conclusions on these observations.

"Understanding how water flows into and through stream corridors is critical to restoration. How fast, how much, how deep, how often, and when water flows are important questions that must be answered to make appropriate decisions about stream corridor restoration".

1.1 Runoff

Runoff is precipitation that appears in surface streams. When the rate of rainfall or snowmelt exceeds the rate of soil infiltration, water collects in small depressions until the excess moves downslope as overland flow, as shown below. Water that infiltrates the soil moves downgradient as subsurface flow. This movement may be quick (flashy) in saturated soils on steeper slopes or slow (delayed) in deeper soils and flatter terrain.

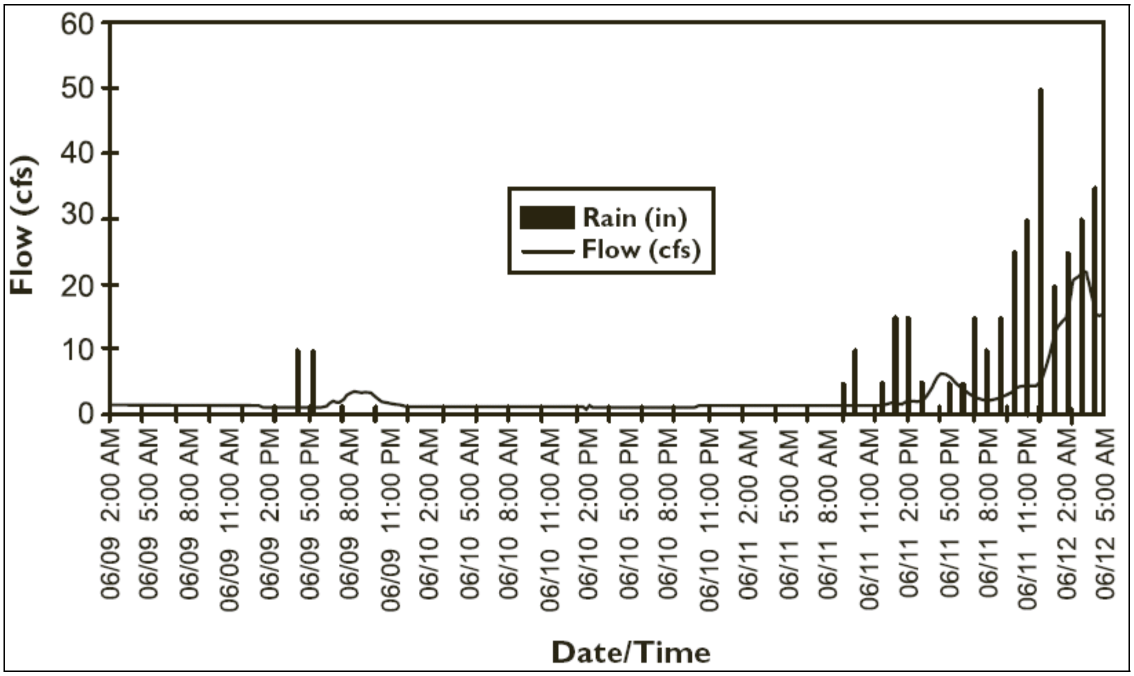


Hydrology Figure 2: Disposition of rainfall to runoff.
Source: Linsley R. K., Kohler M. A., and Paulhus J. L. H. 1975. Hydrology for Engineers.[3]

Water flowing in a stream represents the culmination of one or more runoff processes which transport water from different locations in the watershed by surface and subsurface pathways. Sources of runoff are 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 removed by 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 is 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 by processes described above.

Runoff may occur as overland flow, interflow (subsurface stormflow), or baseflow depending on watershed slope, roughness, and absorptive capacity. ***Overland flow*** spreads over a wide surface or slope before it is concentrated or confined to a channel. It occurs when the ability of the watershed surface to absorb water (***infiltration***) is exceeded by the intensity of the water input. Overland flow is commonly associated with soils having either moderate to high silt or clay content or impervious surface in urbanized areas. ***Interflow*** infiltrates the soil and is quickly transported to a stream channel. Interflow may begin shortly after the start of a storm and subside after precipitation ends. It forms the bulk of storm runoff in areas having moderate to steep slopes and highly permeable soils.

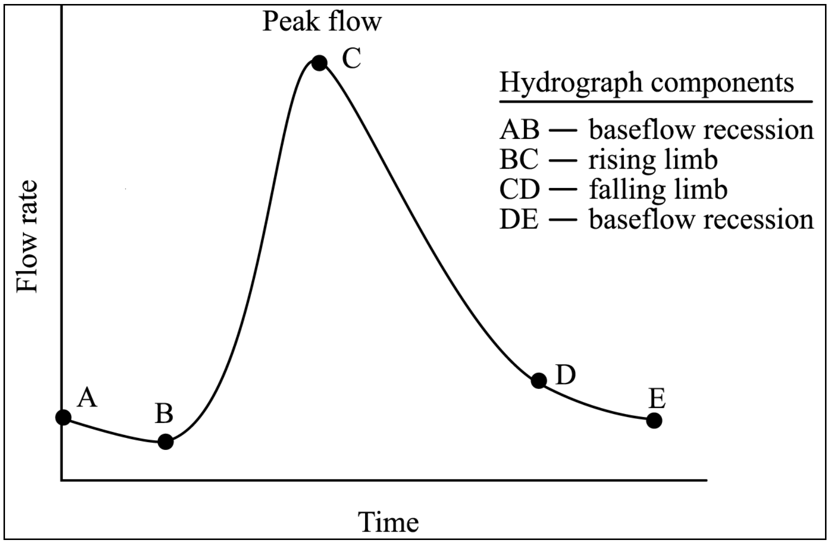
A storm ***hydrograph*** may depict runoff from rainfall in addition to baseflow, as shown below. The ***time-to-peak*** (time of rise) is from the middle of the rainstorm (when half the rainfall which contributes to runoff has fallen) to peak flow. It is an indicator of how rapidly runoff is delivered to that location. 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.



Hydrology Figure 3: Storm hydrograph.

Source: Dunne, T. and L. B. Leopold. 1978. Water in Environmental Planning.[4]

Specific components of a storm hydrograph are shown below. 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 "recession limb”), returning to baseflow (curve DE).



Hydrology Figure 4: Specific components of a storm hydrograph.

Source: Chow, V. T., D. R. Maidment and L. W. Mays. 1988. Applied Hydrology. McGraw-Hill Series in Water Resources and Environmental Engineering. [5]

1.1.1 Hydrologic Response

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. Factors that alter runoff can change the hydrologic response and may occur naturally (soil formation, beaver activity), or from human activity (diking, urbanization), or as a result of both (fire, or climate change).

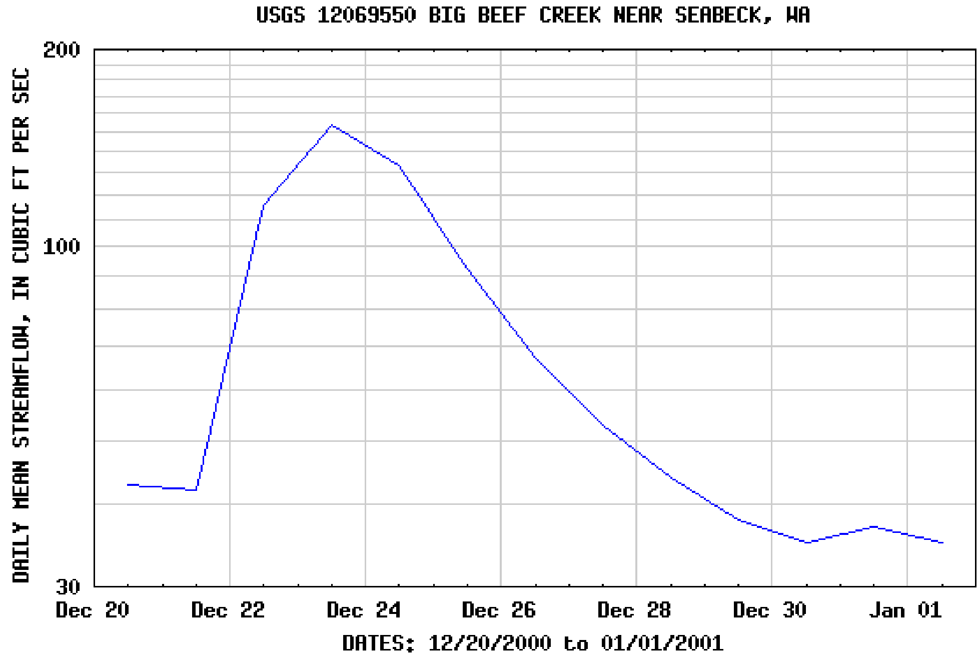
Structural projects in rivers and streams, including dams, diversions for irrigation and municipal/industrial water supply, transportation works, and flood control projects can significantly alter the conveyance element of hydrologic response. Changing land use, particularly urbanization, can alter runoff pathways and reduce watershed storage with potentially severe changes to a watershed’s hydrologic response. Isolation of a stream channel from its floodplain by diking and channelization (1) reduces natural flood storage capacity while (2) eliminating access to highly productive aquatic and riparian habitats. Aquatic habitat restoration projects are often designed to restore watershed storage capacity by removing impervious surfaces, restoring wetlands, replanting forested areas, removing levees, or adding structural complexity to stream channels and overbank areas.

1.2 Stream Flow

Streams may be ephemeral, intermittent, or perennial. Ephemeral steams flow mainly during storms and may or may not have a defined channel. Intermittent streams flow most of the year in most years and usually have a defined channel. Perennial streams flow all year in most years. Some perennial streams have sustained baseflow composed largely of groundwater discharge with additional storm runoff or snowmelt at various times of the year.

Water is in motion and it is natural that water levels go up and down. A change in water levels reflects a change in flow. Stream discharge is calculated by measuring flow through an area of channel. 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.

An annual hydrograph of discharge for a water year is shown below**.** Annual hydrographs are useful for establishing the seasonal variability and relative magnitude of stream flow over a year and can indicate the dominant sources of stream flow.



Hydrology Figure 5: Annual hydrograph.
Source: USGS. Water Resources of Washington.[6]

1.2.1 Gaining and Losing Reaches

Baseflows typically increase downstream due to accumulating groundwater discharge from shallow aquifers. This is known as a ***gaining*** (or *influent)* ***stream*** and is common in Washington. Baseflows may decrease downstream in a ***losing*** (or *effluent*) ***stream,*** as surface flow is lost to groundwater. Losing streams are common in arid climates where water tables are relatively deep below the ground surface.

Streams may have losing reaches alternating with gaining reaches as depth to the water table fluctuates with seasonal precipitation, groundwater withdrawal, or artificial recharge. Individual reaches can gain through the winter and springtime, lose through the summer and early fall, and "transition" between seasons. Channel boundaries between gaining, losing, and transition reaches may shift throughout the year.

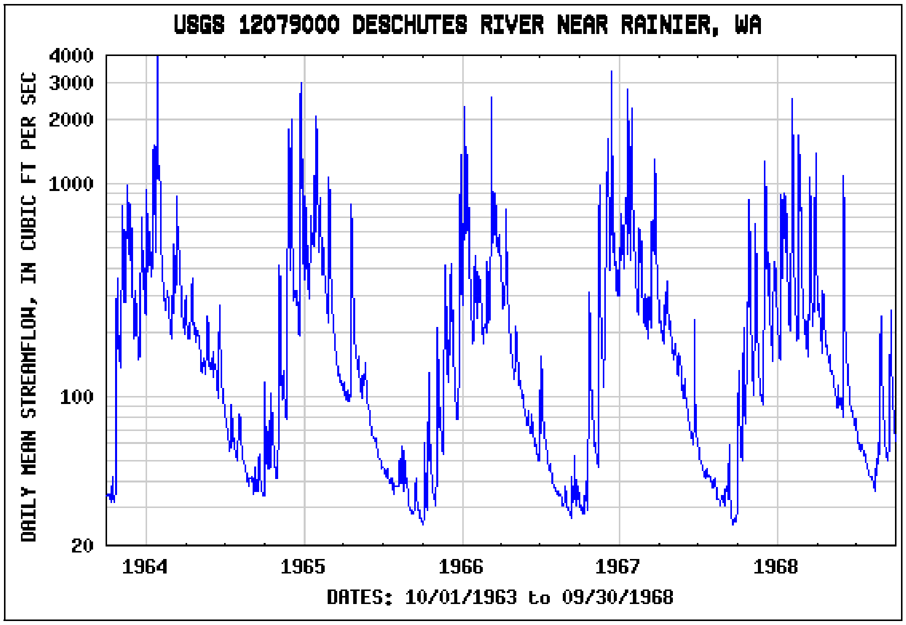
1.2.2 Hyporheic Flows

A ***hyporheic zone*** is defined as "saturated interstitial areas beneath the stream bed and into stream banks that contain some proportion of channel water or that have been altered by channel water infiltration"[7]. The extent of this zone may fluctuate daily, seasonally, and annually. Surface-water/groundwater interactions within the hyporheic zone provide ecologically vital physical, chemical, and biological functions. Bolton and Shellburg (2001)[8] 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

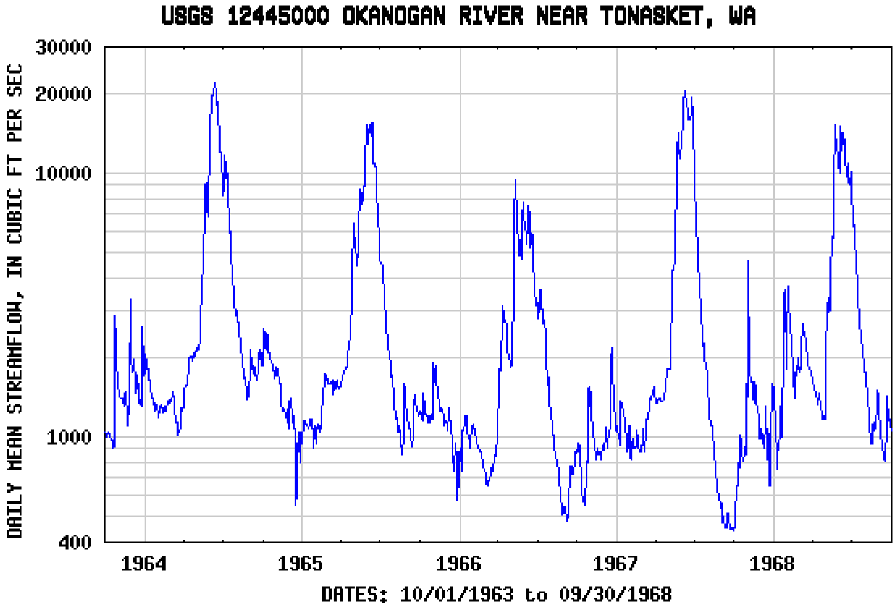
1.3 Hydrographs

Rain-dominated or rain-on-snow stream flow events (where rain and snowmelt simultaneously contribute to stream flow) appear on annual hydrographs as "spikes" extending over one-to-three days as shown below. These events are typical in western Washington streams.



Hydrology Figure 6: Rain-dominant hydrograph, 1964-1968. Deschutes River. Source: USGS. Water Resources of Washington. [6]

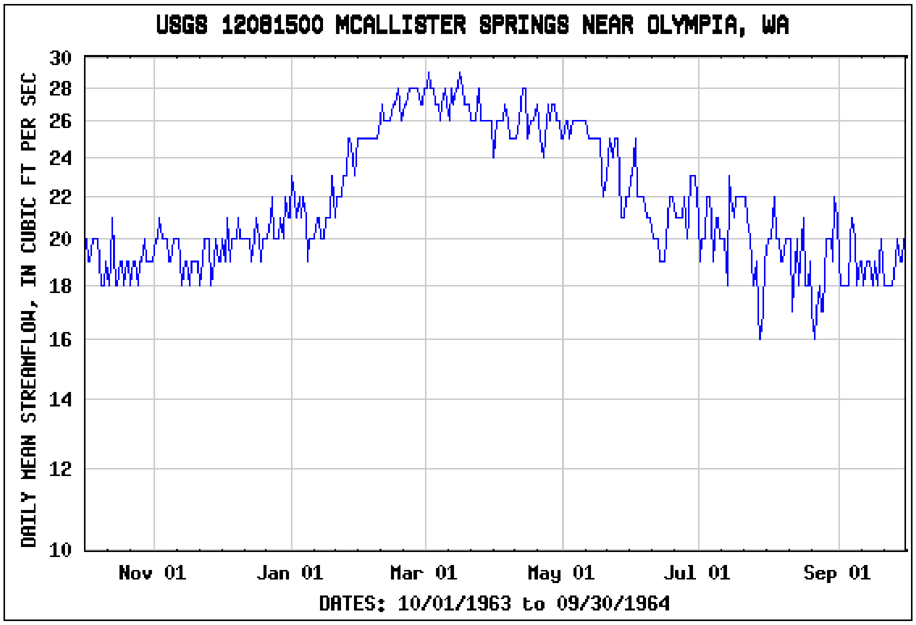
Stream flow from melting deep, high-elevation snowpacks typically creates a broader, smoother curve extending over weeks or months as shown below. This type of event is common in streams draining the east slope of the Cascades and the west slope of the Rocky Mountains in eastern Washington.



Hydrology Figure 7: Snowmelt-dominant hydrograph, 1964-1968. Okanogan River.

Source: USGS. Water Resources of Washington.

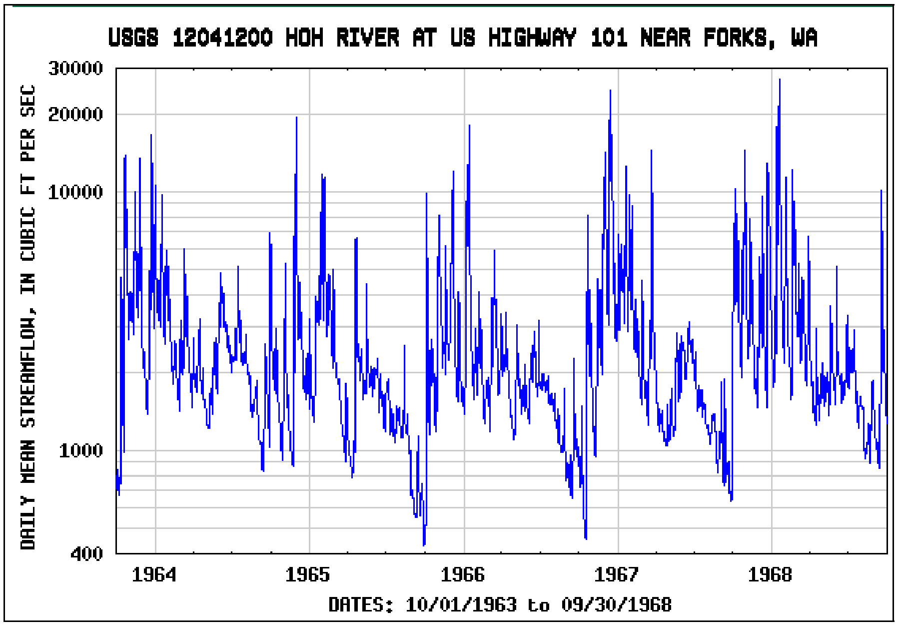
A stream that originates primarily from groundwater will have a moderated hydrograph indicative of sustained base flow, as shown below. Groundwater discharge may rise and fall in response to seasonal precipitation patterns.



Hydrology Figure 8: Groundwater-dominant hydrograph, 1964-1968. McAllister Springs.

Source: USGS. Water Resources of Washington.[6]

Stream flow influenced by glacial melt may still rise and fall daily during the summer months, as shown below.

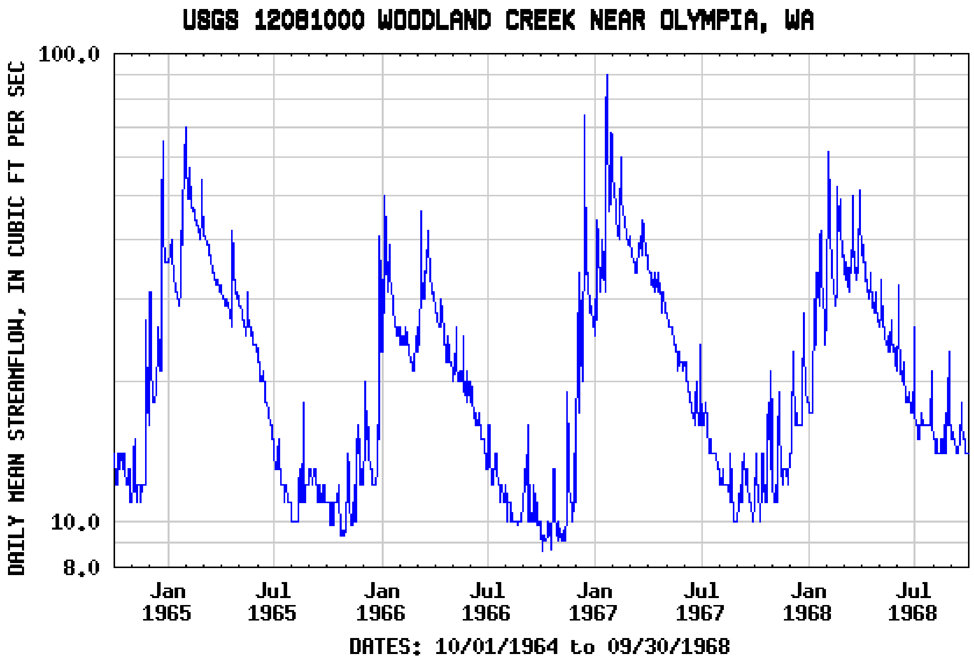


Hydrology Figure 9: Rainfall-dominant with glacial melt hydrograph, 1964-1968. Hoh River. Source: USGS. Water Resources of Washington.[6]

1.4 Hydrologic Regimes

1.4.1 Natural Hydrologic Regimes

A hydrologic regime is the sequence or pattern of low flows and high flows in a hydrograph. Hydrologic regimes are combinations of flow events (such as low flows, moderate high flows, and flood flows) and when they occur (fall rains, spring snowmelt) for annual hydrographs described in Section 1.3, *Hydrographs*. The magnitude, duration, frequency, and sequencing of variable flows can influence the physical and biological characteristics of a stream in several ways. Larger (flood) 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. Note the pattern of summer low flows, moderate spring and fall high flows, and winter flood flows in the rainfall dominant hydrologic regime shown below.



Hydrology Figure 10: Natural hydrologic regime. 1964-1968. Woodland Creek.
Source: USGS. Water Resources of Washington.

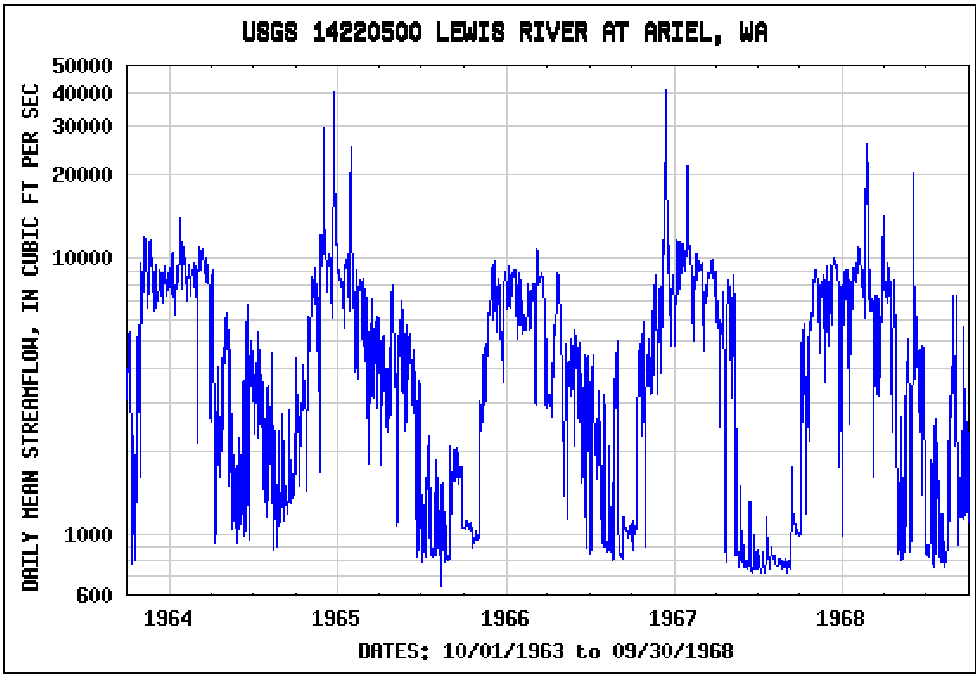
1.4.2 Regulated Hydrologic Regimes

Few major drainages in Washington are free of human influence. Many streams are affected by flow regulation that impounds, diverts, augments or modifies the natural flow. It is necessary to account for human-induced changes to a hydrologic regime when examining a hydrologic record in a regulated stream, Separating differences in the flow regime from pre-dam to post-dam conditions is necessary to plan and anticipate future conditions. Alteration of flow regimes during urbanization should also be evaluated for project assessments in urban areas.

Dams are built and operated for many uses, including hydroelectric power generation, storage for agricultural, industrial, and municipal use, flood control, and recreation. Regardless of the purpose of the dam, the effects of dams on a hydrologic regime can be dramatic. Some dams store large quantities of water and reduce stream flow during periods of high runoff. When stored water is released and used within a basin, flows may increase downstream due to return flows from water users.

Storing storm runoff reduces downstream peak flows. This effect is most pronounced for smaller to medium flood events and tends to diminish with larger events. The cyclic rise and fall of flow associated with storage and releases of water can affect channel morphology by altering erosion, deposition, and sediment transport. It can impact the presence, distribution, and survival of aquatic biota and riparian vegetation. In some cases, juvenile fish in the stream during summer low flows may be stranded or washed downstream by sudden flow releases.
Dams for hydroelectric power generation produce a highly variable hydrograph over short periods of time (a few hours to a few days) due to the release of stored water to meet demands

for electricity, as shown below. Once the demand is met, spring and summer flows are rapidly reduced which can strand fish and other aquatic organisms in the channel.



Hydrology Figure 11: Hydropower regulated hydrologic regime, 1964 – 1968. Lewis River. Source: USGS. Water Resources of Washington.

Agricultural diversions typically reduce stream flow and aquatic habitat during the irrigation season. Annual flow is generally decreased due to both increased evaporation from reservoir and soil surfaces and transpiration from crops. Peak water demand normally coincides with the summer low-flow period, creating conflicts between aquatic resources and agricultural requirements. In the extreme, streams can be completely dewatered during summer. Stream temperature problems are exacerbated by reduced flows, especially where groundwater pumping and loss of stream/floodplain connectivity has reduced or eliminated groundwater contribution to surface flows.

Municipal and industrial diversions do not usually exhibit the seasonal variability typical of irrigation diversions. Municipal uses are more year-round but may peak in the summer months due to extensive lawn and landscape watering. During a drought or in the driest months of the year, diversions may dewater a stream without in-stream flow requirements.

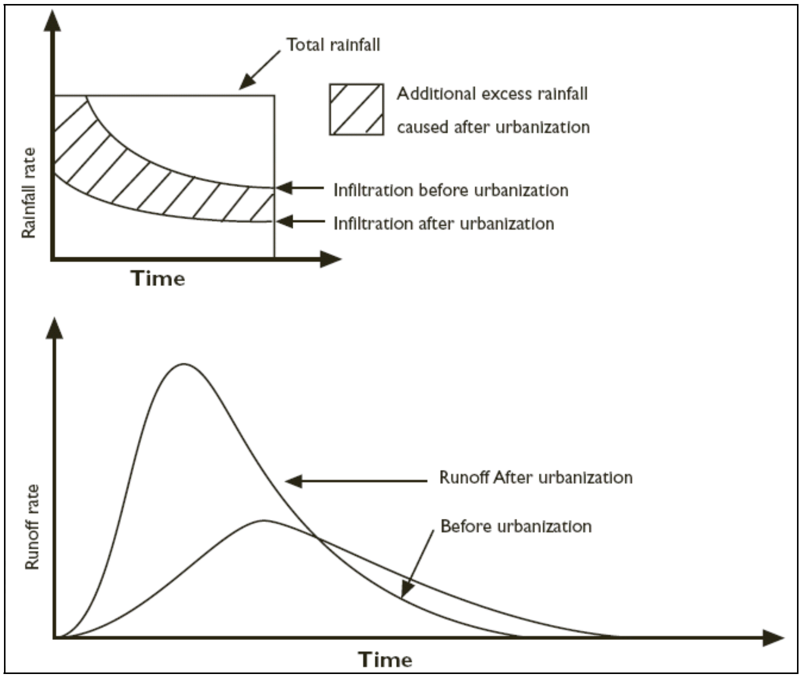
Flow augmentation is often practiced where the demand for water exceeds the natural supply. Augmentations take water from one drainage basin and divert it to another basin through tunnels, aqueducts, or open ditches. The discharge is usually to a natural stream channel or directly into a reservoir. Flow augmentations occur during spring and early summer runoff when water is abundant and reservoirs are filling. A watershed can show a dramatic increase in the magnitude, duration and frequency of flows if it is being augmented.

Channelization and construction of dikes, levees and other flood control works protect human infrastructure (roads, buildings, utilities, etc.) when a river or stream inundates its floodplain. Channelization is “the deliberate alteration of one or more of the interdependent hydraulic variables of channel slope, width, depth, roughness, or size of sediment load”. It typically includes such activities as channel widening, deepening, straightening, bank stabilization, and removal of live and dead vegetation from the channel and banks. Channelization may reduce the frequency and duration of overbank flooding through the channelized reach by increasing flow velocities through a straightened and shortened reach (as a result of increased slope) and by increasing the capacity of the main channel.

This effect is often obtained at the expense of non-channnelized areas downstream. These areas tend to experience increased magnitude and frequency of flooding due to more rapid delivery of flow and reduced flood storage. Channelization and levee construction often cause increased channel erosion, excessive deposition of bedload, and loss of channel capacity.

1.4.3 Urbanization

Urbanization of a watershed can have a profound impact on hydrographs as shown below.



Hydrology Figure 12: Conceptual hydrograph changes due to urbanization.
Source: Source: Chow, V. T., D. R. Maidment and L. W. Mays. 1988. Applied Hydrology. McGraw-Hill Series in Water Resources and Environmental Engineering.[5]

Increased area of impervious surface is a common cause of increased peak flow and reduced base flow. Impervious surfaces such as paved streets, parking lots, and roofs, can decrease soil infiltration, increase storm runoff and decrease groundwater recharge. As runoff in urban channels increases, the duration of high flows decreases because groundwater is no longer a major contributor to flow. New channels, curbs, gutters, and storm sewers create smoother conveyance and increase hydraulic efficiency of the drainage system. Runoff can reach the channel more quickly when it travels over smooth, hard surfaces and the lag time between rainfall and runoff is decreased. Increased peak flows result in more hydraulic force acting on a stream channel and increased bed and bank erosion. Storm flows may be captured in one watershed and released in a nearby watershed, changing watershed boundaries and runoff hydrographs. Storm flows captured in detention facilities and gradually released can reduce magnitude and increase lag time of peak flows in urban channels. Flow duration increases over that found in rural drainages and base flow may not be restored.

2 HYDROLOGIC ANALYSIS

Quantifying stream flow and evaluating frequency and duration of flows are two types of hydrologic analyses relevant to instream projects. Project designs are typically based on specific flow criteria such as low flows, dominant discharge, or flood flows. A number of methods can be used to quantify flow depending on available data and site information. These include direct measurements, estimates using Manning's equation, regional regression analysis, hydraulic models, and runoff simulation models.

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. The method may be direct or indirect and depends on available data. For example, peak flow data may be used directly if a project has a record of flood measurements. In other cases, data from neighboring stations can be regionalized and applied at a non-gaged site.

2.1 Stream flow measurements

Historic stream flow measurements at a gage can be used for hydrologic analysis if the period of record is long enough to be statistically significant or if any portion of the period of record is relevant. Gage data are usually reported as mean daily flows. Instantaneous peak flows rather than mean daily flows are used for deriving peak flow statistics if the project is an urbanized or suburbanized basin, or on a first- or second-order stream. Only a short period of record is usually relevant in an urban environment because rapid development and changing hydrologic conditions tends to make historic data obsolete. Segmenting data to represent existing or future conditions may be necessary but also may leave only a small amount of data to work with.

The United States Geological Survey (USGS) provides flow measurements for hydrologic analyses. USGS gaging stations are found on major drainages and can be important sources of flow data and information. Instantaneous maximum and minimum daily flow values are also reported for some gages. Historic records may be the only flow measurements available for a particular river where gaging stations are no longer in operation. Flow measurements for gaging stations are available from the USGS website. The USGS office may also help obtain more recent or historic data. 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.

2.2 Stream flow estimates

Stream flow can be estimated for ungaged streams by using the following methods:

1. *Manning's equation*. Manning's equation 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.

2. *Regional Regression Analysis.* Regional regression equations relate discharge to channel dimensions and watershed characteristics. Where gage data are insufficient, hydrologic parameters can be derived through analysis of precipitation events using data from other stations in the region. Regional analysis for non-gaged sites works well for flood-frequency correlated with meteorological or physiographic parameters. Floods at non-gaged sites can then be estimated from rainfall and size of the basin. 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.

3. *Hydraulic models.* Hydraulic models calculate flow in a channel using input parameters and equations discussed 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.

4. *Runoff and Stream flow Simulation Models.* Runoff and stream flow simulation models predict streamflow based on simulated runoff from storm events and other inputs. They are useful where there are no established streamflow gauges. They are most relevant in urbanized watersheds with hydrologic alteration due to impervious areas, flood control, and storm flow detention.

2.3 Stream Flow Calculations

2.3.1 Flow Frequency

Floods occur when stream flows exceed the capacity of the channel and overtop the channel banks. Incised channels often have significantly more capacity than natural channels and may contain the high flows. Aggraded channels have flood flows at greater frequency than non-aggraded channels. A 10-year, 50-year, and 100-year return period flow is often used in streambank protection designs. A 100-year flow channel design is often used for protection of infrastructure or public safety. Channel design projects may not be permitted if they increase the water surface elevation of the 100-year flood.

Flood flows may be reported as annual maximum flows with a return interval of a certain number of years (for example 10-, 20-, or 100-years). The probability of occurrence in any year is the inverse of the return interval. For example, the probability of occurrence of the 100-year flood in any year is 1/100 = 0.01 = 1%. The *annual maximum series* consists of maximum annual flood events. A *partial-duration series* consists of all peaks of record greater than some base magnitude during the year. The recurrence interval for a partial-duration series is based on the frequency of occurrence of floods of a given size. It is the occurrence of flows that equal or exceed a given discharge[9]. A partial-duration series or annual maximum series may be used for greater than the 10-year event.

Log Pearson Type 3 analysis is the federal standard for determining flood frequency. A complete discussion and reference for performing Log Pearson Type 3 analyses is available in Water Resources Bulletin 17B. Precipitation events of a certain probability do not necessarily result in stream flow of the same probability. A 10-year rainstorm may not produce a 10-year stream flow.

2.3.2 Flow Duration

Flow duration is the length of time a flow occurs. Flow-duration statistics based on frequency of occurrence are useful for projects that include habitat objectives for a specified life stage for target species. Flow-duration statistics require gage data for a specific season for which the design is relevant although USGS-derived flow-duration statistics are not generally season specific. Flow-duration statistics should be based on daily-flow data collected during fish spawning if a design objective is to sustain sufficient flows for fish spawning, Further information regarding derivation of flow-duration statistics is available in Dunne and Leopold.

2.3.3 Low Flows

Low flows typically reflect base flow conditions. An active low flow channel with sustained base flows may have distinct geomorphic features such as riffles and pools. 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 the depth and velocity of low flows. 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.

2.3.4 Dominant Discharge

This discussion of dominant discharge, effective discharge, and bankfull discharge is provided for informational purposes. Use of these geomorphic measurements is not recommended without careful study of their applicability on particular streams. Dominant discharge and related approximations are frequently uncertain distinctions on dynamic, alluvial-bedded streams of the Pacific Northwest.

Dominant discharge is defined as flow that produces the greatest morphologic effect over an extended period of time. It would control the shape and function of the channel in equilibrium (i.e., during periods the channel is not recovering from large floods or other severe disturbances) but it is frequently more concept than quantifiable value. Three methods commonly used to approximate dominant discharge are effective discharge, bankfull discharge, and return-period discharge. Each has limitations as to appropriate applications. Dominant discharge could be used for design of channel dimensions including cross-section, slope, and planform when a project goal is to mimic natural channel conditions although safety and property protection may require consideration of a larger design flow.

2.3.4.1 Effective discharge

Effective discharge is believed to transport the most bed load over time and is commonly viewed as a reasonable approximation of dominant discharge[10 11]. 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 flow records of daily mean flows in non-urban channels or instantaneous discharges in urbanized channels. A detailed methodology for calculation of effective discharge is provided in Biedenharn et al (2000).

2.3.4.2 Bankfull discharge

"Bankfull stage" is the water level at which a stream overflows the floodplain. It is defined as the elevation of a stream channel that "corresponds to the discharge at which channel maintenance is most effective, that is, the discharge at which moving sediment, forming or reforming bars, forming or changing bends and meanders, and generally doing work that results in the average morphologic characteristics of channels"[12]. It is hard to determine floodplain and channel boundaries in streams with numerous side channels and indistinct banks. Incised channels also do not have bank heights that relate to "bankfull" discharges[13] and where bankfull flow may significantly exceed dominant discharge. Guidelines for identifying bankfull indicators are provided in Dunne and Leopold (1978). A discussion of bankfull discharge and its relation to channel geometry in the Pacific Northwest is also provided in Castro and Jackson (2001).

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[14] guideline. It is important to consider that channel geometry represents current hydrologic and geologic conditions. 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[15].

2.3.5 Return-Interval discharge

Discharge with a given return interval may approximate dominant discharge when effective discharge cannot be calculated or when bankfull discharge is inappropriate due to an unstable channel or altered watershed. Recurrence intervals of 1.5 years or 2 years are commonly applied[16] . Studies have found some consistency between dominant discharge, bankfull discharge, and the 1- to 2-year recurrence interval discharge[9] [12]. 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. 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[17] [18].

2.3.6 Ordinary High Water Line

"Ordinary high water line" (OHWL) is defined in state law as "the mark on the shores of all waters 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 ordinary years, as to mark upon the soil or vegetation a character distinct from that of the abutting upland". It is a legal definition that does not always serve design needs well. The distance between ordinary high water marks on the bank is considered to be the ordinary high water width. It is similar to active channel width. A calculated discharge below OHWL can be used to approximate dominant discharge using Manning's equation and field measurement of channel cross-sections as detailed in the *Hydraulics* appendix.

2.4 Stream Flow Models

2.4.1 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:

- The US Army Corps of Engineers, HEC-1 model[19],
- The US Natural Resources Soil Conservation Service, Project Formulation-Hydrology model (Technical Release No. 20)[20]; and
- The US Natural Resources Soil Conservation Service, Urban Hydrology for Small Watersheds (Technical Release No. 55)

HEC-1 develops a series of interconnected sub-basins with hydrologic and hydraulic components of surface runoff, a stream channel, or a reservoir. HEC-1 calculates discharge but stage can be indirectly calculated from additional user input. The result of the model is a hydrograph at a specified location.

NRCS Technical Release 20 (TR-20) 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.

NRCS Technical Release 55 (TR-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.

2.4.2 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. The U. S. Environmental Protection Agency, Storm Water Management Model (SWMM)[21] 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.

2. The Hydrological Simulation Program – FORTRAN (HSPF)[22] 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 REFERENCES

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FLUVIAL GEOMORPHOLOGY APPENDIX

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 landform evolution related to stream systems. As an integrative field it includes the related disciplines of geology, hydrology and hydraulics, sediment transport, soil mechanics, and the mechanical effects of vegetation. Any project that potentially affects natural stream processes requires a basic understanding of the fluvial geomorphology of the system in question.

1 BASIC CONCEPTS IN FLUVIAL GEOMORPHOLOGY

1.1 Spatial and Temporal Scale

Stream channels are dynamic systems and are constantly changing both spatially and temporally. When evaluating a stream channel, it is important to consider both the spatial and temporal scale at which an evaluation or investigation is conducted, as well as the scale of the inputs and processes affecting the stream channel. There is a hierarchy of variables affecting stream systems. The foundation of this hierarchy is the triad of climate, geology, and topography[1]. This triad of variables determines the independent variables affecting stream channels – hydrology, sediment supply, and vegetation, which vary about fairly-constant averages in a temporal scale, but can change dramatically on a spatial scale within a watershed.

The variables that define channel process and form typically change downstream through a watershed, resulting in predictable spatial variability in habitat form and function. The downstream change in hydrologic regime through a watershed can be generally described as an increase in volume accompanied by a decrease in flow variability. Sediment transported can be generally described as increasing in volume downstream, but decreasing in particle size. Local variations in geology and bank material, as well as depositional patterns, may result in highly variable sediment character on a reach scale.

On a temporal scale, stream channel form and process are affected by climate change or cyclical fluctuation (such as drought), seasonal weather variations, and natural and anthropogenic disturbances to the channel and watershed. Climate change typically occurs over decades, though cycles of climate patterns may occur on a scale of years. Over short time scales (one to 10 years), some disturbances caused by human activities can be assessed. For example, overgrazing can affect hydrology and sediment load, potentially causing channel erosion and incision and resultant habitat degradation. Defining the temporal scale of observation, therefore, is essential for assessing relationships among various attributes of fluvial systems.

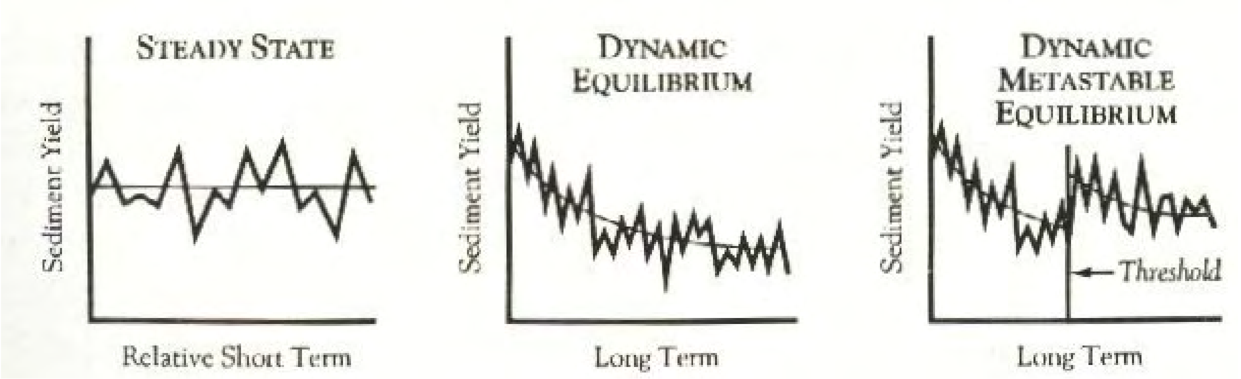
1.2 Equilibrium

One of the fundamental aspects of understanding stream channel behavior is that stream channels tend toward an equilibrium state in which the input and output of mass and energy to and from a specific reach are equal.[2] *The destabilization of streams typically occurs when the balance* *between sediment input and sediment output from a reach becomes altered.* A corollary to this is that overall channel morphology (sinuosity, channel width, and slope) remains relatively constant throughout the transfer of mass and energy, assuming inputs to the channel are relatively constant. The term equilibrium in the context of stream channels refers to the relative stability (defined below) of the channel system and its ability to maintain its morphological characteristics over some period of time and range of flow conditions, accommodating minor variations in inputs. In reality, perfect equilibrium does not exist in natural streams. However, natural streams do tend to develop channel sizes and shapes that accommodate and reflect the typical hydrologic regime and the character and quantity of sediment supplied by the watershed. These streams are said to be in a state of approximate equilibrium.[3]

Numerous authors[2 3 4 5] have presented discussions on and defined variations of the concept of equilibrium. Definition of the various forms of equilibrium is dependent upon the time scale under which equilibrium is scrutinized, and 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. Due to the complexity and variety of definitions of varying forms of equilibrium, these variations are not defined here. For further discussion of equilibrium, refer to Graf (1988)[2], and Thorn and Welford (1994)[6].

Stream channels commonly exhibit many forms of equilibrium, and are subject to changes in equilibrium resulting from anthropogenic influences, catastrophic events, and gradual changes in climate. For example, short-term fluctuations in a given variable, such as channel depth, may occur throughout a stream reach, but the longer-term, constant mean value of the variable is maintained. An example of this occurs when channels adjust to scour and fill associated with seasonal flooding. It is important to note that the time scale of observations is critical for defining an equilibrium state – if the time scale is too short, the mean value of the variable in flux will not be accurately determined. Following a low probability flood (e.g. a 50-year flood), a given reach of channel may exhibit bed incision and bank erosion. However, in subsequent years, the bed and banks may recover to previous channel dimensions. If observed only over a single year following a flood, the channel will not appear to be exhibiting equilibrium conditions. If observed over a decade following the same flood, the channel would otherwise exhibit equilibrium conditions.

Similarly, a stream may adjust its character gradually in response to gradual environmental change, such as a slow change in base level (the level below which a stream cannot erode, such as a lake at the channel mouth or a bedrock sill). In this instance, the stream undergoes a complex pattern of erosion, deposition, changes in sediment load and renewed incision as it adjusts to the new base level. The time scale through which equilibrium is exhibited may span hundreds or thousands of years. At any given point in time during the adjustment, the channel may exhibit equilibrium conditions; though over time the equilibrium changes. This is referred to as *dynamic equilibrium* (see **Geomorphology Figure 1**).



Geomorphology Figure 1: Concept of dynamic equilibrium expressed as a function of sediment yield – the total sediment derived from a watershed per year. From *California Rivers and Streams*, J.F. Mount[7]. Copyright permission is being sought.

Human influences on channels and their inputs can affect rapid destabilization of equilibrium conditions, or force rapid change of equilibrium values. Human influences are varied and complex and can affect all variables influencing channel equilibrium, channel processes and habitat. The most common and drastic human influences are related to urbanization, and include changes to the hydrologic regime and imposing constraints on the channel, such as levees, revetments or culverts. Removal of large wood from the channel is also common, and can have significant impacts on channel processes and habitat.

Most ‘healthy’ stream systems with high quality habitat and other attributes that we value are distinguished by complex energy dissipation mechanisms that include primarily channel roughness elements (e.g. large wood, boulders, complex channel planform and bedform). Equilibrium in such channels is maintained in part by the existence of these energy dissipation mechanisms that reduce the channel’s capacity to erode and transport sediment. In-channel roughness creates complex hydraulics and reduces flow energy. Floodplains play an equally important role during overbank events by increasing resistance to flow, rather than concentrating energy within the channel. Vegetation is particularly important to dissipating energy at channel bank margins and in floodplains. Vegetation provides critical stabilizing and roughening functions that make possible the existence of channels with high aquatic habitat value, that is, those with high hydraulic and structural complexity. Collectively, the energy-dissipating functions of in-channel wood, structural complexity, floodplains and vegetation are largely what maintain the system’s ability to balance the inputs and outputs of water, sediment, and kinetic energy.

Habitat form and function is also significantly influenced by and dependent upon disturbance to the channel system. White and Pickett[8] define disturbance as “any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment”. 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. Following a disturbance, the system undergoes a period of recovery to pre-disturbance equilibrium conditions. The rate of recovery is generally more rapid at first, slowing asymptotically as equilibrium is approached. Disturbance is most important to geomorphic form and process when this recovery time is greater than the time between significant disturbances.

1.2.1 Regime Theory and Channel Geometry

Prior to extensive use of equilibrium principles by geomorphologists, hydraulics engineers used the concepts of equilibrium in *regime theory*[2]. Regime theory is based on the tendency of a stream system to obtain an equilibrium state under constant environmental conditions (i.e. constant water discharge, as in a canal). It consists of a set of empirical equations relating channel shape to discharge, sediment load and bank resistance. The theory proposes that dominant channel characteristics remain stable for a period of years and that any change in the hydrologic or sediment regime leads to a quantifiable channel response (such as erosion or deposition). Stream reaches that are “in regime” (meaning “in equilibrium”[9]) are able to move their sediment load through the system without net erosion or deposition and do not change their average shape and dimensions over a short time period.[10]

Since real streams do not exist under constant conditions, regime theory is, by definition, not strictly applicable to them. However, even though the water discharge, and thus the sediment transport, in a real stream varies continuously over time, it can be shown that there exists a narrow range of discharges that, averaged over the long term, moves most of the sediment load. This *effective discharge* can in principle be said to mimic the *dominant* or *channel-forming discharge* used in the regime equations. As will be discussed later, more current research has focused on the *bankfull discharge*, and has attempted to implicitly equate bankfull with the dominant discharge used in the regime concept and the effective discharge that moves most of the sediment load. Thus, the older regime equations have been supplanted by equations that define the dimensions of the channel in terms of bankfull flow (to be defined later). In theory, then, there exists a *bankfull hydraulic geometry*, a predictable pattern, profile and shape of an alluvial channel determined by bankfull flow. 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 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.

Regime theory and its successor, bankfull hydraulic geometry, has formed the basis for a large body of work in fluvial geomorphology focusing on identifying and defining the geometric properties of equilibrium alluvial channels and their adjustments to discharge and sediment transport regimes.[11] According to R. D. Hey[10], there are nine measurable variables used to define equilibrium channel geometry. These characteristics are considered dependent variables for stream reaches in regime:

1. Average bankfull channel width (w),
2. Average bankfull depth (d),
3. Maximum depth (d_m),
4. Average bankfull velocity (V),
5. Height (Δ) of bedforms,

6. Wavelength (λ) of bedforms,
7. Channel slope (S),
8. Meander arc length (z), and
9. Sinuosity (P).

The six independent variables that control changes in channel dimension and shape are:

1. Discharge (Q),
2. Sediment load (Q_s),
3. Size of bed material (D),
4. Bank material and character,
5. Bank and floodplain vegetation (riparian and/or upland species), and
6. Valley slope (S_v).

Changes in any of these controlling variables may result in a new channel geometry that represents a stable morphology in a new equilibrium state.

1.2.2 The Bankfull 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[12].

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. 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. Finally, the floodplain is overflowed, on the average, several times per year, during moderate peak flow events (such as a 1.5-year or 2-year 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*. The bankfull channel refers to the channel cross-section below the elevation of the floodplain.

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.

It should be noted here that 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 flood), bankfull is defined by the floodplain geomorphic surface, in the field. 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 indicators are only valid if they have been “calibrated” by correlation with a floodplain or incipient floodplain nearby.

1.3 Channel Pattern

Researchers have variously classified channel patterns as straight, braided, meandering, or anastomosing based on the number of intersecting channel threads and the degree to which the channel meanders[3 13 14]. 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. Straight channels usually exist only in steep narrow valleys where geologic control prevents meandering and are dominated by sediment transport and colluvial processes. They tend to accumulate or store little alluvial sediment, and the banks and bed are usually dominated by colluvial material that enters the channel via erosion and mass wasting. Meandering channels, by contrast, wander back and forth across a valley and are typically alluvial. Both straight and meandering channels consist of a single thread channel. Braided channels differ in that they exhibit numerous channel threads separated by islands or bars, which are often submerged at high flow. Braided channels are dominated by sediment deposition processes and are alluvial. Multiple thread channels that are relatively narrow and deep, and are separated by well-vegetated, stable islands, are referred to as anastomosing. Many of the larger rivers in Western Washington were originally anastomosing channels, with large wood playing a dominant role in controlling channel and bar position, stability, and dynamics[15].

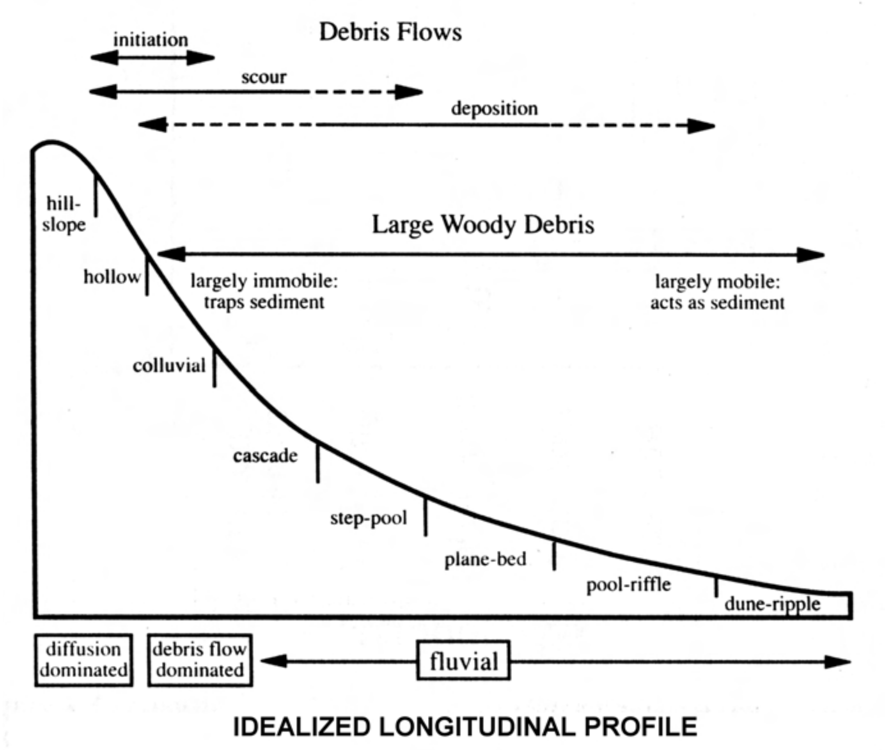
Channel pattern can be largely explained in most rivers by the interaction of channel slope, bankfull discharge, bed and bank material, vegetation, and available sediment load[16]. Channel patterns can exhibit similar forms in either equilibrium condition or in a condition of disequilibrium. For example, a braided channel may be considered in equilibrium condition across an alluvial fan, but may indicate a degraded condition in a lower gradient alluvial valley. As such, channel pattern can be a key indicator of severely degraded systems where factors leading to their degradation typically occur on a watershed scale. Differentiating between similar channel patterns in equilibrium condition or in degraded condition is best determined through reviewing historic channel condition with respect to changes imposed on the channel and its watershed.

1.4 Channel Classification

In the late twentieth century, several more-sophisticated schemes for describing river channels were developed. Some, such as the Channel Evolution Model (CEM)[17] discussed below, are highly useful but limited in scope to certain geomorphic settings. Others, such as those of Nansen and Croke[18], Whiting[19], and Brice[20] are potentially useful but have not gained widespread acceptance in this country. In the Pacific Northwest, the systems of Montgomery and Buffington[21] and that of Rosgen[22] are by far the most popular.

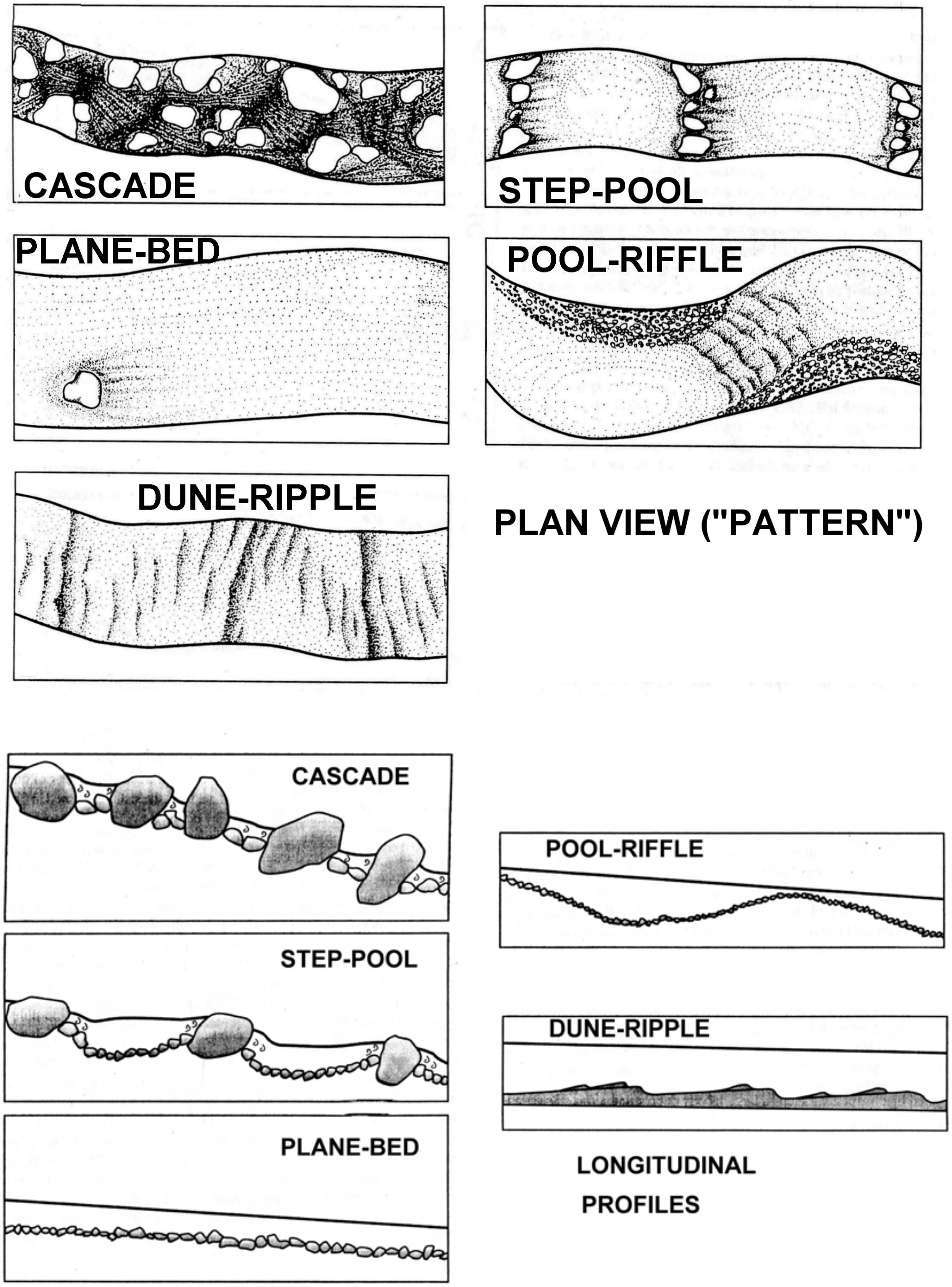
Montgomery and Buffington's classification (see **Geomorphology Figure 2**) is based on a hierarchy of spatial scales that reflect different geomorphic processes and controls on channel morphology. A conceptual, large-scale longitudinal view of the river channel from headwaters to lowlands is presented, in which a predictable sequence of 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 sour 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. The seven basic channel morphologies are arrayed in a way that reflects this continuum of process (see **Geomorphology Figure 3**). 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.

More broadly, Montgomery and Buffington see the river landscape as a continuum from "source reaches" to "transport reaches," and then to "response reaches." 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. In source reaches, steep channel slopes and proximity to catastrophic events such debris flows do not allow much fluvial sediment to accumulate in the channel. Transport reaches, like source reaches, function to efficiently route sediment delivered from upstream, and 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, 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.

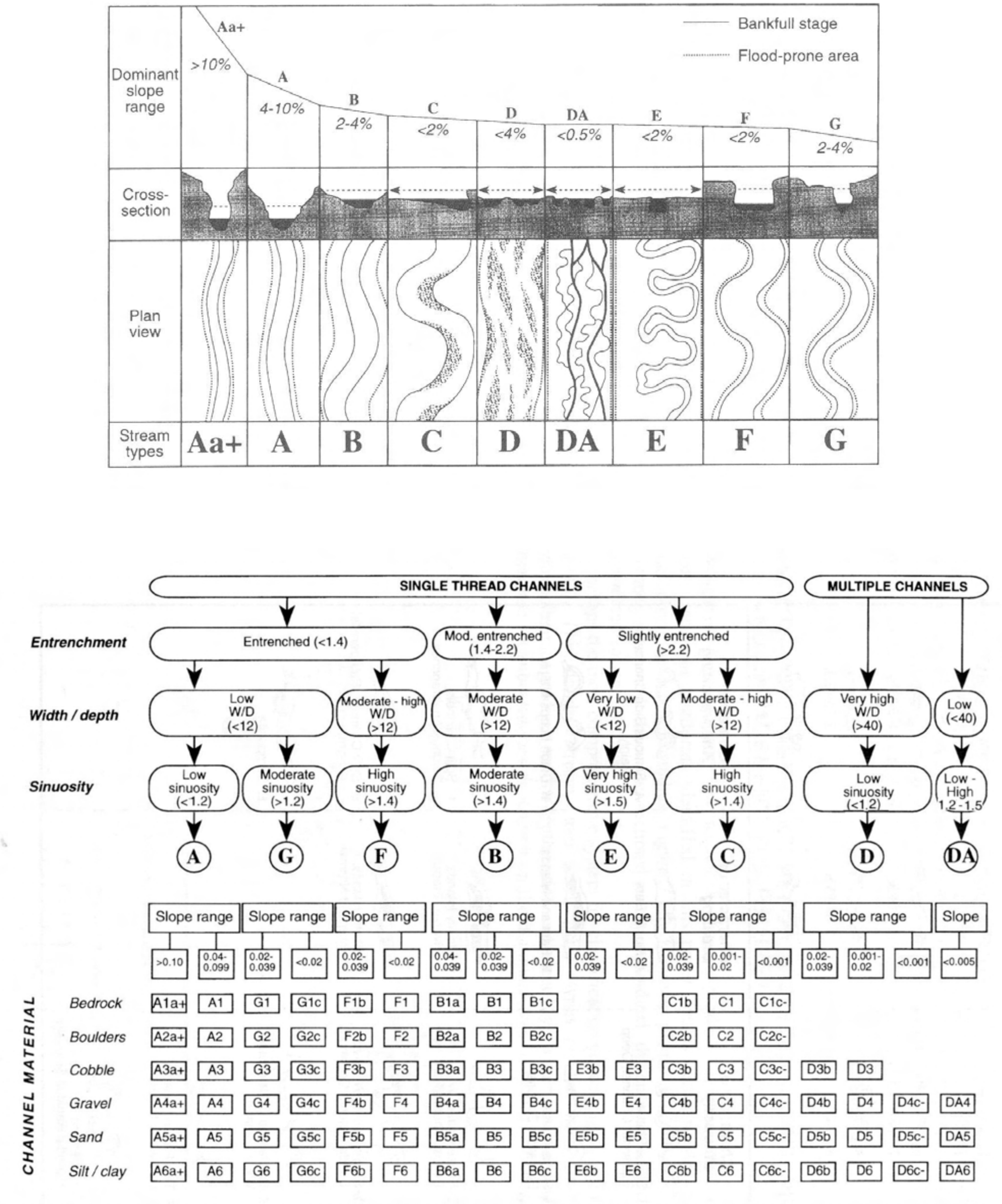


Geomorphology Figure 2: Montgomery and Buffington stream classification. Longitudinal view and watershed-scale process perspective. From *Channel-reach morphology in mountain drainage basins*, D. R. Montgomery and J. M. Buffington[21]. Reproduced with permission of the publisher, the Geological Society of America, Boulder, Colorado, USA. Copyright ©1977 Geological Society of America.

Rosgen's classification system (see **Geomorphology Figure 4**) 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 (a measure of confinement), width/depth ratio, and sinuosity. Within each of the eight basic types, the channel is further classified from 1 to 6 according to 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. Use of Rosgen's system is contingent on correct identification of bankfull, which was discussed earlier.



Geomorphology Figure 3: Montgomery and Buffington stream classification. Sketches of selected stream types. From *Channel-reach morphology in mountain drainage basins*, D. R. Montgomery and J. M. Buffington[21]. Modified with permission of the publisher, the Geological Society of America, Boulder, Colorado, USA. Copyright ©1977 Geological Society of America.



Geomorphology Figure 4: Rosgen stream classification. From *Channel Types and Morphological Classification*, C. R. Thorne[23]. Copyright 1977. © John Wiley & Sons Limited. Modified with permission.

Since form and process in river systems are interdependent, Rosgen's system, although strictly defined according to morphology, can be used to infer dominant process characteristics. Rosgen's system has the advantage of being more quantitatively objective than Montgomery and Buffington's, and is in more widespread use nationwide.

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. The Rosgen system includes these factors, but use of these variables in other *ad hoc* classification schemes is sometimes desirable depending on project objectives.

1.5 Geomorphic Thresholds

Short-lived states of disequilibrium often result when a geomorphic threshold is exceeded. A geomorphic threshold is a combination of the independent variables (such as described above) that results in a shift from one stable landform to another of a different type. This occurs 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. An example of a geomorphic threshold is the conversion of a narrow, meandering channel to a wide, braided channel when destruction of streambank vegetation results in reduction in root strength and loss of soil surface protection. Accelerated bank erosion follows, and the channel grows wider and shallower until shallowness and splitting of flows reduces the force of erosion to match the new, reduced, erosion resistance. The result is a different channel morphology, which may then evolve slowly back to a meandering channel as vegetation recovers.

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, and base-level changes. For example, 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 (see below). 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[24].

The most significant controls on channel stability over a period of years or decades are flow regime, sediment supply, and vegetation. 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.

1.6 Channel Responses to Change in Dependent and Independent Variables

Rivers are complex systems of inputs and responses whose features and form are rarely constant. Explanation and prediction of their behavior requires great depth in understanding of historic condition and current morphology and process, at times involves considerable educated speculation, and is always uncertain and prone to risk. In spite of the complexity of predicting or explaining geomorphic response, there are a number of common generalized channel responses that can be attributed, at least theoretically, to distinct causes. These include aggradation, incision, lateral migration, and avulsion, which are most commonly observed in alluvial systems that are free to adjust their channel boundaries.

1.6.1 Aggradation

Aggradation is the progressive accumulation of in-channel sediment resulting in increased channel bed elevation. Aggradation is a response to channel system changes that reduce the channel's capacity to transport the sediment delivered to it. Generally, this occurs as result of either increased sediment supply (load) or size (gradation), or diminished stream power (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 hillslope disturbances including vegetation removal, fire, and agricultural and other land use impacts
- Increase in sediment volume inputs from excessive bank erosion
- Increase in sediment volume inputs from excessive bed erosion from channel incision upstream

Aggradation associated with decreased stream power may occur in response to any of the following conditions:

- Increased channel width resulting in decreased unit stream power
- Large dams reduce duration of transport discharge
- Diversions reduce discharge
- Split flow within a channel reduces discharge in each split channel
- Reduced channel slope associated with local dams or grade control placed above grade (beaver dams, log jams, culverts, etc.)

1.6.2 Channel Incision

Channel incision is the inverse of aggradation and involves the progressive lowering of the channel bed relative to its floodplain elevation. Incised channels (also called entrenched or incised channels) occur when stream power exceeds the channel bed's resistance, 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
- Decrease in sediment delivery to the stream system

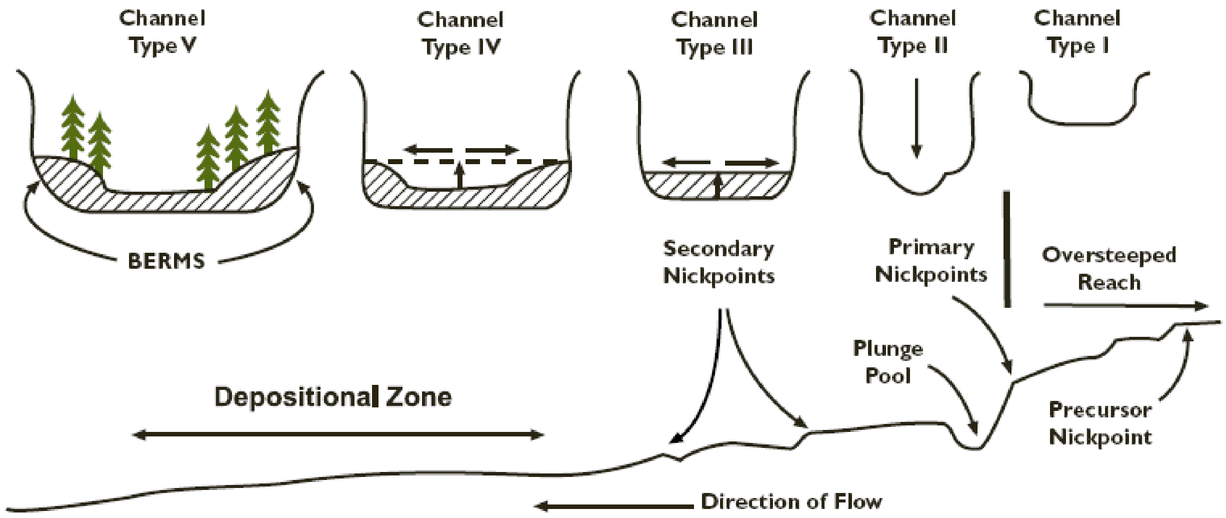
Incision associated with increased stream power may occur in response to any of the following conditions:

- Stream channelization and straightening causing a steepening of the channel profile
- Decreased channel roughness due to channelization, stream cleaning, large wood removal, and splash damming.
- Lowering of base level, such as the lowering of a lake, removal of grade control (culvert, bedrock, log controls)
- Increase in peak flows due to land use changes
- Increase in duration of transport flows associated with vegetation removal, urbanization, or other forms of land development that increases runoff rates and volumes
- 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 stream power necessary to mobilize it
- Diversion of storm water or sewer discharge into the stream

Regardless of the causes of incision, 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. Schumm and others [25], used such a model to develop 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 **Geomorphology Figure 5**) 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, rather than dissipating on the floodplain. Additionally, bed erosion can destabilize stream banks by oversteepening the slope and undermining 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. The combination of increased energy within the channel and reduced bank stability often leads to rapid bank 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 **Geomorphology Figure 6**). 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. Other effects include unstable banks due to over-steepening, bank instability due to groundwater discharge, increased shear stress because of low-probability flows being contained within the channel, and loss of wetland/floodplain habitat and backwater areas. 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 armored to prevent further erosion.



Geomorphology Figure 5: Diagram of a channel evolution model. From *Fluvial processes and morphological thresholds in incised channel restoration,* M. D. Harvey and C. C. Watson[26]. Copyright permission is being sought.

Geomorphology Figure 6: Channel incision. An example of channel instability in an incising channel. Columbia Creek, Oregon. Photo provided courtesy of Inter Fluve, Inc.

For a complete discussion of channel incision and incised river channels, refer to:

- Darby and Simon, 1999[27].
- Knighton, 1998[28]
- Schumm, Harvey, and Watson, 1984[25]

1.6.3 Lateral Channel Migration and Erosion

Channel migration is the progressive movement of a channel across a valley and involves bank erosion and transport of eroded materials. Lateral channel migration may occur 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, a point bar develops across the channel, thereby maintaining channel form. However, lateral migration may also occur in response to disturbance or external changes in input variables resulting in widening of the channel and other changes in channel form.

Lateral migration 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 resistance
- Excessive saturation of banks during low flow periods due to irrigation
- Rapid drawdown and saturation failures related to dam releases

1.6.4 Channel Avulsion

Channel avulsion is a process whereby a channel shifts its location by cutting across adjacent terrain. Avulsion occurs naturally in meandering streams, most commonly cutting off a mature meander bend during long-duration or extreme overbank flows. The occurrence of avulsion can also be brought about by channel manipulation, by armoring channel banks, or as a result of changes in external variables. The mechanism by which avulsion occurs is 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. Aggradation within the main channel or a blockage of the main channel is 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. 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.

Avulsion occurs in numerous types of channels[29]. Highly sinuous meandering channels may avulse due to insufficient sediment transport, which results in channel aggradation and further loss of channel capacity. Under equilibrium conditions, this is part of the normal channel processes of meander development. The meander elongates due to erosion of the cut bank and deposition on the point bar; slope, velocity and sediment transport capacity are gradually reduced. 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 (creating a variety of habitat, including backwater habitat, 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. Finally, all channels are prone to avulsion if they become perched relative to their floodplain. This is common in alluvial-fan environments or along relocated channel segments.

2 VEGETATION AND LARGE WOOD IN FLUVIAL PROCESS

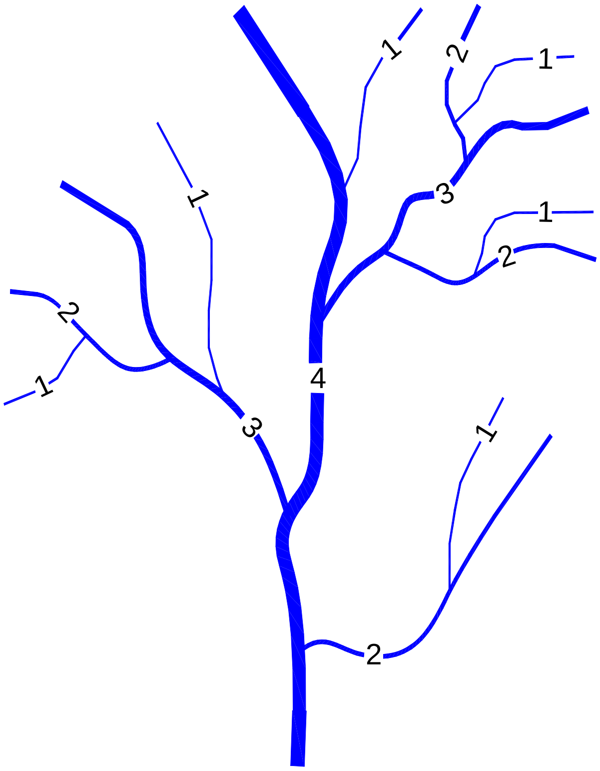
Vegetation affects the geomorphic process and resultant channel forms by increasing resistance to erosion of channel banks (riparian vegetation) and by interrupting and redirecting channel flow (in-channel wood). The character of riparian vegetation can act as a key independent variable in determining channel form and process. (The type of vegetation that occurs naturally is a function of geology, topography, and climate.) 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 streams. Willows commonly stabilize newly deposited materials in bars and thereby facilitate the creation of new floodplain area. Upland vegetation also can play a role in channel process by controlling hillslope erosion, thereby reducing sediment input to stream channels.

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 potential component of channel design[30][31]. Large wood in streams represents large roughness elements that divert flowing water and influence the scour and deposition of sediment in forested streams throughout the world. 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.[32] 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[32];
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. Increasing in-channel hydraulic complexity, thereby increasing channel habitat complexity;
4. Improving fish habitat by increasing types and sizes of pools[33] (pools associated with wood may be deeper and have more depth variability than free-formed pools[34]);
5. Inducing hydraulic head differential to promote hyporheic flow;
6. Forming channel bars and creating inducing sorted gravel deposits important to spawning (this influence has not been extensively studied)[35];

7. 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;[36]
8. Retaining small wood and organic detritus;
9. Promoting floodplain connectivity and periods of inundation by increasing channel roughness; and,
10. Stabilizing backwater and side-channel areas (chute cut-offs and oxbows).

The geomorphic effects of wood vary with stream size. In low-order, headwater streams (first and second order), large wood often spans the channel, or, if submerged, induces local sediment storage and steps in the water surface profile. In mid-order streams (e.g. third and fourth order), large wood is large relative to the stream and may cause significant channel migration or widening along with sediment storage. In high-order streams (e.g., forth or fifth order) (see **Geomorphology Figure 7**), where large wood is small relative to the channel, wood accumulations may increase channel migration and the development of anastomosing or secondary channels, although islands formed as a result of large woody deposits may actually be quite stable[32].



Geomorphology Figure 7: Stream order. First order streams are headwater streams. As headwater streams combine to form larger streams, the order increases.

3 ASSESSMENT METHODOLOGIES

3.1 Baseline Geomorphic Analysis: Evaluation of Existing Conditions and Historic Change Where Restoring Historic Configuration is Appropriate

The most important components of geomorphic analysis include:

- Assessment of past channel change,
- Determination of causes of channel change,
- Assessment of current channel conditions, including morphology, stability and departure from conditions expected for the given stream type,
- Assessment of probable future channel evolution,
- Reduction of uncertainty in key assumptions regarding management, design, processes or conditions, or effects on habitat or critical species

Habitat restoration, streambank protection, and other instream construction projects will likely be unsuccessful if the driving forces of channel adjustments are not recognized and addressed. Consequently, projects designed to mimic or alter natural channel processes require an understanding of the causative agents of change.

3.1.1 Characterizing Existing Channel Conditions

The initial characterization of the project reach should be based on plotted bed and floodplain profiles and maps or aerial photographs that show channel planform. The project reach should be described in terms of channel slope, pattern, sinuosity, and cross-sectional dimensions. Infrastructure controls should be identified and their geomorphic relevance indicated, such as fixed-bed elevations (pipelines, weirs, bridge aprons) or areas of channel or floodplain encroachment (roads, development, bridges, culverts, levees).

3.1.1.1 Channel Longitudinal Profile

Channel slope is defined as the vertical fall of a stream over a given distance. It is typically reported as a percentage (ft/ft) or as feet of drop per mile (ft/mile). Channel profiles (elevation vs. distance plots) depict slope trends on a stream system. The most accurate means of determining the slope of the channel is by surveying the channel thalweg elevation (the deepest thread in the channel bed), the water surface, and the elevation of bankfull (best, if possible) or other high water indicators through a reach (such as “ordinary high water”). Longitudinal profiles may sometimes be obtained from the Federal Emergency Management Agency if a hydraulic model has been developed for flood-insurance studies. Channel profiles determined from topographic maps may provide approximate channel slope, but will not be detailed enough to provide a longitudinal profile since the scale of the contour lines is generally too coarse, and for smaller streams may actually represent the canopy cover. Furthermore, topographic maps are based on survey data that may predate significant changes in the valley topography and the channel.

Channel slope is always measured in terms of the channel distance, rather than the valley distance, and can be calculated by the following equation:

$$S=(E_2-E_1)/D$$

Where, S = channel slope, E_2 and E_1 = bankfull elevations (or water surface, in feet or meters) at two similar geomorphic points along the thalweg, and D = channel distance between E_2 and E_1 (in feet or meters). A more accurate representation of channel slope will be attained if survey points are located from the top of one riffle to the top of another riffle (thereby including the entire channel unit), rather than between a riffle and a pool. By surveying the beginning, middle and end point of each channel unit, the riffle slope and pool slopes can be determined, as well as maximum and average riffle and pool depths if the thalweg is surveyed as well. Ratios of maximum to average depth can then be compared to expected regional means as a tool to detect departure from stable conditions. The longer the survey length, the more accurate the slope calculation will be. If a significant valley control is crossed, the survey should be analyzed as two distinct reaches.

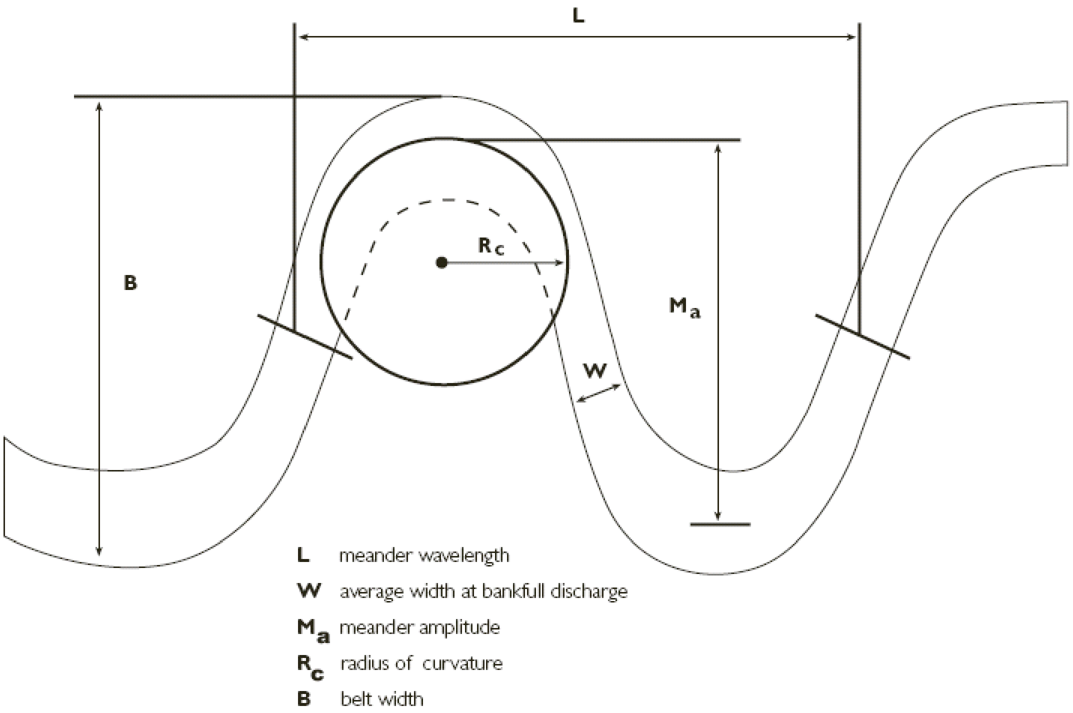
3.1.1.2 Channel Planform

Channel planform is the form of a stream as seen in map (aerial) view. In streams with meandering patterns, planform is quantitatively described in terms of sinuosity by the equations:

$$P=D_c/D_v \text{ or}$$
$$P=S_v/ S_c$$

Where P = sinuosity, D_c = channel length (feet or meters), D_v = valley length (feet or meters), S_c = channel slope, and S_v= valley slope. Channel length is theoretically best measured along the channel thalweg or, if necessary, the centerline, but can be measured along one bank or the other for small channels.

Other parameters that describe channel planform are the belt width, wavelength, amplitude, and radius of curvature of an individual meander bend (**Geomorphology Figure 8**). Collectively, these planform characteristics can be compared to historical conditions in order to assess channel behavior over time, and to expected ranges of values for channels of the same type in the same physiographic province. Radius of curvature is particularly important, as overly sharp radii greatly increase the near-bank shear stress and erodibility.

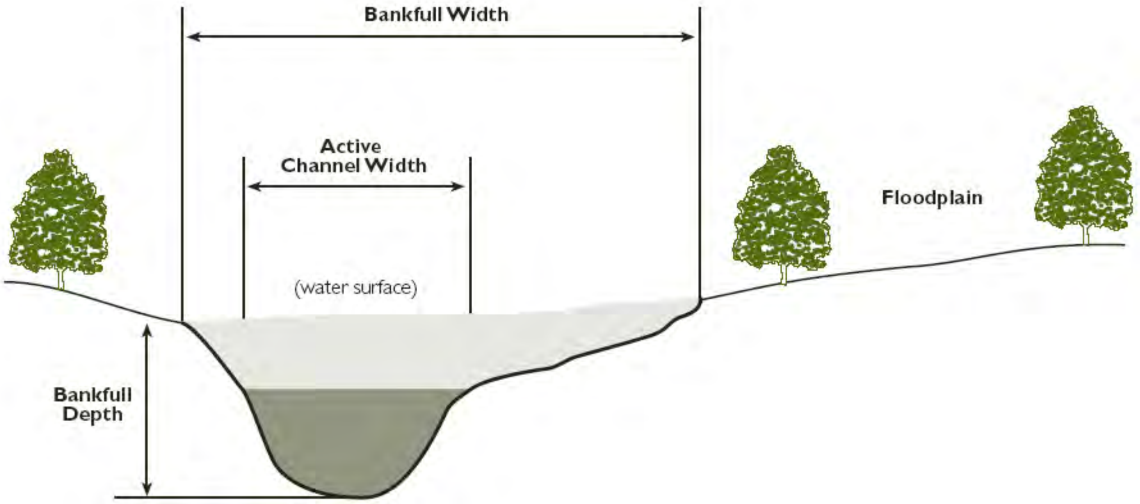


Geomorphology Figure 8: Channel planform characteristics.

3.1.1.3 Channel Cross-Section

Channel cross-section reflects the two-dimensional view across the channel, 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. Typically, the elevation at twice the maximum riffle bankfull depth will encompass the 50-year flood[37]. 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 (**Geomorphology Figure 9**).

In addition to 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."



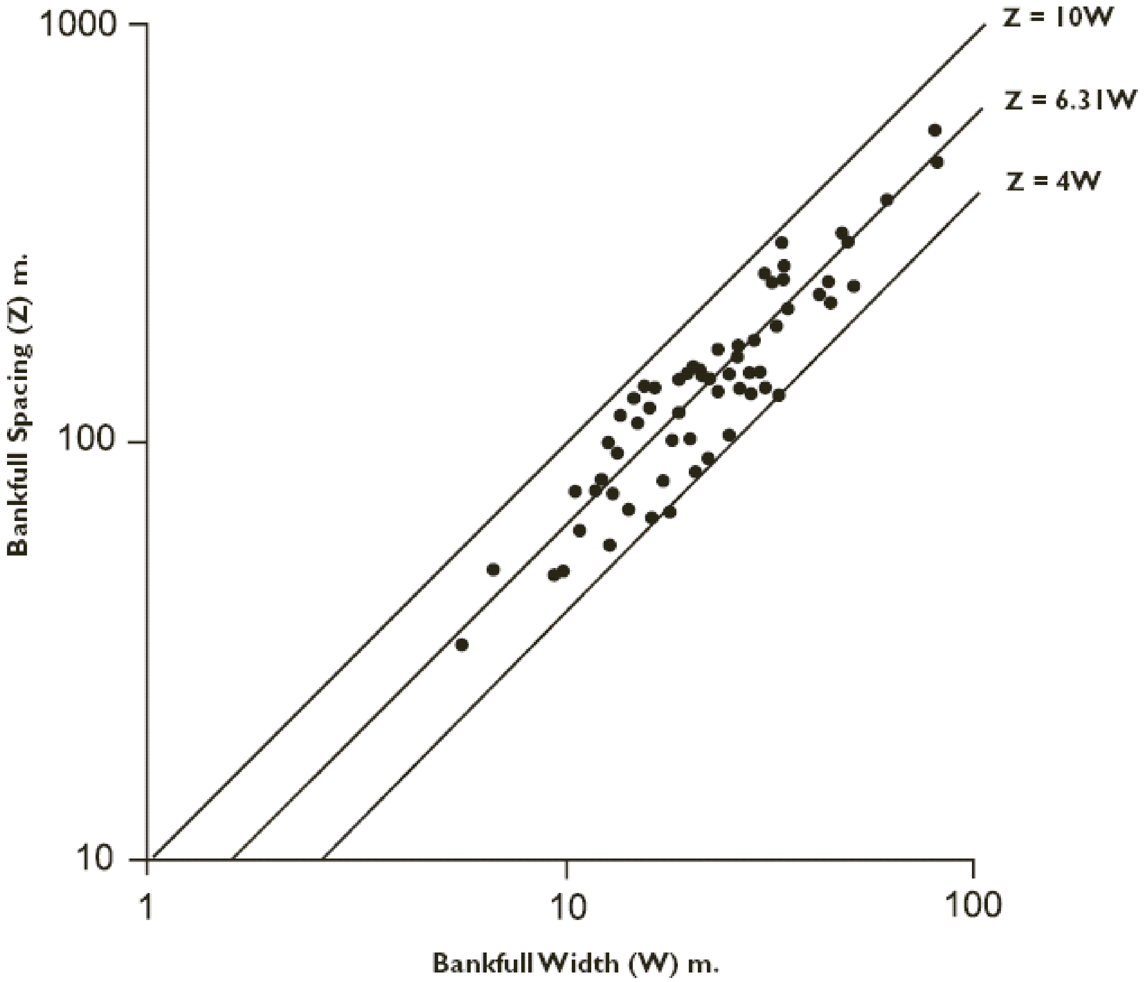
Geomorphology Figure 9: Channel cross-section.

3.1.1.4 Pools and Riffles

Pools and riffles generally occur at relatively constant spacing in alluvial streams. A pool-riffle sequence is a dynamic response of the channel to a large-scale, non-uniform distribution of three variables: velocity, boundary shear stress and sediment[38]. Leopold and others[39], determined that riffle spacings were consistently on the order of five to seven times the channel width (**Geomorphology Figure 10**). This empirical deduction is consistent with a theoretically predicted spacing of 2π (6.28) times the channel width determined by Hey[40]. Hey and Thorne[41] further substantiated the correlation between width and riffle spacing, predicting riffle spacing as:

$$z = 6.31\ W_{bf}$$

where z = the distance of riffle spacing (meters), and W_{bf} = bankfull width (meters)[41]. This definition of riffle spacing is based on work in Great Britain on gravel bed rivers with single-thread channels and a mix of straight, sinuous, and meandering planforms. The coefficient of determination for this data set is 0.88, and the overall range of riffle spacing for the majority of sites is between four and ten times the channel width[41]. Along with pool-riffle spacing, the average and maximum pool and riffle depths, and the ratios of maximum to average depths can be obtained from the longitudinal profile. All of these factors become clues to departure from stable or expected morphology, and ways to track changes over time.



Geomorphology Figure 10: Riffle spacing as a function of bankfull width. From *Fluvial Processes in Geomorphology*, L. B. Leopold, M. G. Wolman and J. P Miller[39]. Copyright permission being sought.

3.1.1.5 Substrate Analysis and Sediment Transport

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 active alluvial material. 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 (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}), 84th percentile (D_{84}), percentage of fines and maximum particle size (D_{100}) are determined.

Some investigators prefer to assess sediment using a pebble count procedure, such as the 100-point Wolman pebble count or the more statistically-defensible 400-point grid sample. Pebble count information is useful for 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.

3.1.2 Channel Classification

A classification of stream reaches can aid in visualizing and describing the project site[23]. Channel classification can also aid in deciding which channel morphology, and consequently what array of project design possibilities, are appropriate to the geomorphic or valley setting. Furthermore, classification serves as a tool for assessing the sensitivity of the channel to human modification or natural disturbance, and the risk of project failure. Finally, in some types of projects, such as channel modification, the use of natural analogs (“reference reaches”) requires matching of similar channel types, which in turn requires consistent channel classification.

Which system is used is largely a matter of professional judgment. The systems of Rosgen[22], and of Montgomery and Buffington[42] have been described previously. Each of these systems requires some formal training and practice for consistent application. Sometimes, it is desirable to develop an *ad hoc* classification system, such as when the stream of interest not well described by existing schemes (e.g. estuaries).

It is important to note that most classification systems are based on the existing channel morphology of a stream, which may or may not be in equilibrium. In other words, they best describe only existing conditions, not historic conditions or the functional potential of a stream system. A classification system must be used with the understanding that fluvial systems are constantly adjusting and evolving in response to changes in slope, hydrology, land use and sediment supply.

3.1.3 Assessing Historic Channel Change

3.1.3.1 Aerial Photography and Historic Maps

When available, sequential aerial photos of a stream channel provide a historical record of channel planform changes. Sequential air photos are often available dating back to the 1930s, while other historic photos can sometimes be found in historic archives dating back to the last century. Historic land survey maps often show details of river location and form as well. This information, coupled with hydrologic data from stream gages, is extremely valuable for understanding how the particular channel responds to floods. An evaluation of historic channel change may reveal previous channel conditions that provided quality habitat or channel stability, which may then be used as the basis for project objectives. However, an aerial photo provides a snapshot in time and does note necessarily imply channel stability. The stream may have been responding to significant changes in the watershed, or may have been stable under different watershed conditions. Early photography from the 1930s represents a period of significant landscape alteration (grazing and timber harvest) that often exceeds current disturbance levels. There is no reason to assume that a past morphological form will be stable under current hydrologic and landscape conditions unless watershed conditions have remained relatively constant, which is rarely the case.

Aerial photographs for the western United States are recorded in a database maintained by the U.S. Geological Survey Earth Science Information Center (the USGS will search for historical photography at *1-888-ASK-USGS*). Access to maps and photographs produced by USGS can be found at http://mapping.usgs.gov. Aerial photographs of your region can be obtained from the Washington State Department of Natural Resources, the Washington State Department of Transportation, the Federal Bureau of Land Management, the U.S. Forest Service, the U.S. Army Corps of Engineers and the Natural Resources Conservation Service.

3.1.3.2 Ground Reconnaissance

Field observations provide valuable information regarding flood history and channel response. This information is especially valuable when combined with hydrologic data regarding flood-recurrence intervals – for example, the effects of a recent 10-year or 25-year recurrence-interval event might be directly observed in the field. Ground assessment of stream channels may include observable flood impacts, such as abandoned channels, natural channel cutoffs or the accumulation of wood on mid-channel bars. Many geomorphic channel features can be roughly dated according to the age of riparian vegetation that is present. For example, an abandoned side channel with 10-year-old cottonwoods present may represent the impacts of a flood documented 10 to 11 years ago. Ground reconnaissance is an essential part of a geomorphic assessment and can provide useful information on the geomorphic effects of large flows in a particular channel reach.

Another important tool available for geomorphic assessment is the observations of long-time residents and others who have been involved with the system over time. Local historical societies often have collections of photos for various streams in their area, which provide general information on riparian vegetation and potentially other stream attributes. When assessing the reliability of anecdotal accounts, consider that memory of specific numbers representing dates, water levels, water extent, etc. is highly fallible. However, memories that are tied to specific activities or informal physical benchmarks (e.g. walls of buildings) may be very accurate.

3.1.4 Channel Stability Analysis

Channel stability is assessed by measurements capable of detecting excessive bank erosion, excessive streambed erosion or scour, or excessive deposition. Here “excessive” means outside the expected range of variability for the given stream type and setting. If excessive erosion or deposition is occurring, the channel is in a state of transition from one type to another, i.e. it is changing its basic shape, pattern and/or longitudinal profile. Vertical instability (incision or aggradation) is often coupled with lateral instability (excessive bank erosion and accelerated channel migration or avulsion rates).

Channel incision is commonly indicated by:

- headcuts or knick points, which are steep breaks in channel longitudinal profile. In coarse-bedded streams, headcuts are more subtle (spread out) than in fine-textured systems, and often require a longitudinal profile for definitive identification.
- Over-steepened or vertical banks with evidence of gravitational failure (geotechnical instability, as opposed to surface erosion)
- Previous engineering activities such as extensive channel armoring
- Conversion of moist-site vegetation to dry-site vegetation as the floodplain becomes “perched” and the water table falls

Channel aggradation may be indicated by:

- Pool infilling (often, a mass of finer material may reside over an older, buried coarse pavement layer)
- Excessive overbank deposition, especially, overbank deposits of medium or coarse gravel as opposed to sand and silt
- Fresh avulsions
- High width to depth ratio where a lower ratio is expected
- Excessive mid-channel bar formation, or transverse bars that direct flow into the streambank
- Excessive locally-derived large wood recruitment
- Substrate characteristics indicative of high bedload (poorly developed pavement layer, matrix-supported subpavement layer, buried pavements, sand dunes or other bedforms in a coarse-bedded stream)

Lateral instability can be assessed by indices that quantify near-bank shear stress and bank erosion potential, such as Rosgen’s Bank Erosion Hazard Index, by width to depth ratio, and by measured bank erosion rates from surveys (bank pins, toe pins, or cross-sections) or aerial photos.

4 SUMMARY

A geomorphic assessment of a reach where habitat restoration, instream engineering work, or streambank stabilization projects are intended will provide quantitative understanding of the processes that continue to shape the channel over time. Any geomorphic assessment should have clearly defined objectives, and the information gathered and analyzed should address these objectives. Geomorphic analysis allows projects to be designed in such a way as to account for, and work with, natural 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.

5 GLOSSARY

Active channel -- The active channel is that portion of the channel within the bankfull channel that is defined by the lower limit of perennial vegetation.

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SEDIMENT TRANSPORT APPENDIX

1 SEDIMENT TRANSPORT PROCESSES

1.1 General

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) and bedload (the coarse-grained fraction transported along the channel bed). 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.

1.2 Sediment Transport Processes and Aquatic Habitat

The caliber, 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.

1.3 Sediment Transport and Stream Morphology

1.3.1 General

Sediment transport and storage count among the major interdependent variables that determine stream morphology. Many channel features, including depositional bars, riffles, and dunes are manifestations of sediment transport and storage. **Table G1** 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.

As seen in **Table G1**, the characteristic features of various channel types are often, to a great degree, the product of the balance between sediment supply and transport. For instance, cascade and step pool channel morphology is maintained by the stability of large, relatively immobile bed materials[4]. Smaller bed material readily moves through these channels during lesser flow events. Such channels are considered to be in a sediment “supply-limited” state, meaning that only a relatively small amount of readily transportable sediment is available. In contrast, dune ripple channel morphology is indicative of a sediment “transport-limited” situation, in which transportable sediment is readily available, and equilibrium between sediment deposition and mobilization is established. Significant bed load transport occurs in dune ripple channels over a broad range of discharges, including relatively low flows. Plane bed and pool riffle morphologies include a mix of transport- and supply-limited characteristics, with the presence of depositional bars in pool riffle systems suggesting a tendency towards transport-limited conditions. Channel bars represent temporary sediment storage in the stream channel, and also represent the incipient floodplain that may become established if additional sediment is deposited on the bar and vegetation takes hold. Bedrock channels tend to be supply-limited, and alluvial materials tend to occur only in “shielded” areas such as scour holes and behind obstructions. However, in contrast to cascade channels or step-pool channels, bedrock channels may owe their supply-limited character to a current lack of large form-resistance elements such as large wood that would retain alluvial sediment. Colluvial channels are strongly influenced by hillslope processes, and the majority of long-term sediment flux from these channels appears to be the result of debris flows.

Table G1. Channel types, characteristic features, and corresponding sediment transport processes based on Montgomery and Buffington.[3]

Channel Type	***Characteristic Features***	***Corresponding Sediment Transport Processes***
Cascade	• "Disorganized" bed material typically consisting of cobbles and boulders • Small, irregularly spaced pools less than a channel width apart	• Large, bed-forming materials typically become mobile only in large flood events (i.e., 50-100 yr events) • Gravel stored in low energy sites is transported by lesser floods • Sediment conditions are probably supply-limited
Step Pool	• Discrete steps formed by large-diameter material separating pools containing finer materials • Pool lengths generally equal 1-4 channel widths	• Like cascade channels, large, bed-forming materials typically become mobile only in large flood events • Gravel stored in low energy sites is transported during lesser floods • Sediment conditions are probably supply-limited
Plane Bed	• Characterized by long stretches of featureless bed • Composed of sand to boulder sized materials (typically gravel to cobble)	• Seem to be a transitional state between sediment supply- and sediment transport-limited channel form
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 • Substrate varies from sand to cobble (typically gravel)	• Display both sediment supply- and transport-limited characteristics, but the presence of depositional bar forms suggest that they are more transport-limited than plane bed channels
Dune Ripple	• Typically low gradient, sand bed channels containing relatively mobile dunes, bedload sheets, and ripples	• Sediment conditions transport-limited
Bedrock	• Bedrock bed • Often, some alluvial material stored in scour holes and behind obstructions	• Generally reflect a high transport capacity relative to sediment supply or current lack of large roughness elements for sediment retention capacity
Colluvial	• Small headwater streams founded on colluvial fill	• Weak or ephemeral fluvial transport • Long-term sediment flux from these channels appears to be dominated by debris-flows

1.3.2 Effects of Vegetation on Sediment Transport

Vegetation has a profound effect on sediment transport, from the supply of sediment delivered from the uplands to quality and quantity of sediment transported and stored in the channel. The strength and roughness created by vegetation on the channel banks and across the floodplain (or the lack of it) greatly affect channel geometry and flow hydraulics, thus influencing the processing of sediment. By increasing bank strength, particularly in medium- to fine-textured soils, vegetation makes possible the evolution of relatively deep, narrow channel cross-section and meandering plan forms. Through its influencing channel geometry, vegetation strongly affects channel complexity and capacity. Both of these characteristics in turn affect sediment transport. Channel complexity provides both form roughness that reduces the energy available for erosion and transport, and hydraulic complexity that causes sediment sorting during deposition. By limiting channel capacity, vegetation increases channel-floodplain interactions, thereby limiting the erosive energy at high flows and delivering finer sediments to the floodplain for capture, storage, and stabilization. Thus, the dynamic interactions among flow, sediment, vegetation, and energy build and maintain stream/floodplain ecosystems.

1.3.2.1 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, and because of its form roughness is extremely important for energy dissipation. In general, 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[5],[6],[7],[8]. Wood can actually "force" pool riffle and step pool channels by inducing the formation of pools, bars, and steps. In extreme cases, logjams may force the presence of alluvial beds in otherwise bedrock reaches. 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.

1.3.3 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 there is just enough energy 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 natural channel capacity. Typically, diking and other activities that restrict or eliminate floodplain connectivity disrupt the equilibrium, often leading to increased erosion within the diked reach, and excessive sediment deposition downstream.

Furthermore, during high flows, when the 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.

1.3.4 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. In effect, as long as a weir or dam acts as a sediment trap, it produces a "decoupling of the sediment transport conveyor belt."[9]. 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[10]. Below large dams, this bed immobility is further accentuated by the controlled release of water, which mutes peak flows. 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 natural stream channel design in bedrock dominated channels, alluvial channels, colluvial channels, and wood-controlled channels alike. As a design component, sediment transport analyses focus on providing for sediment continuity, a factor that is repeatedly cited as a condition for true channel stability.[11] 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.[12]

Sediment transport analysis poses many challenges. Most sediment transport analyses and design methods focus on channel competence, or the capability of a channel to transport bed material of a given size. Just as important as competence, but less frequently addressed, is consideration of the volume (capacity) of sediment that a channel is capable of transporting. Measurement and prediction of sediment mobility and transport volumes are notoriously difficult and, in most cases, inaccuracies can be by orders of magnitude.[13] Regression equations based on sufficient sampled data provides the most accurate rating curves of sediment discharge to stream flow. Whenever possible, sediment sampling data should be used to calibrate or aid in selection of transport equations. Model results 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 currently accepted sediment transport analysis approaches and techniques are presented below.

2.2 Estimating 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, sieve analyses, or suspended sediment measurements. The most commonly used method of sampling coarse riverbed material is that developed by Wolman.[14] Despite the development of more sophisticated statistical techniques for bed material analysis, the pebble count method remains widely used due to its simplicity and almost universal acceptance.[15] 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 collected either at random or within a grid[16]. This sample represents the armor layer, and the resulting particle size distribution will generally be coarser than the average bed material distribution.

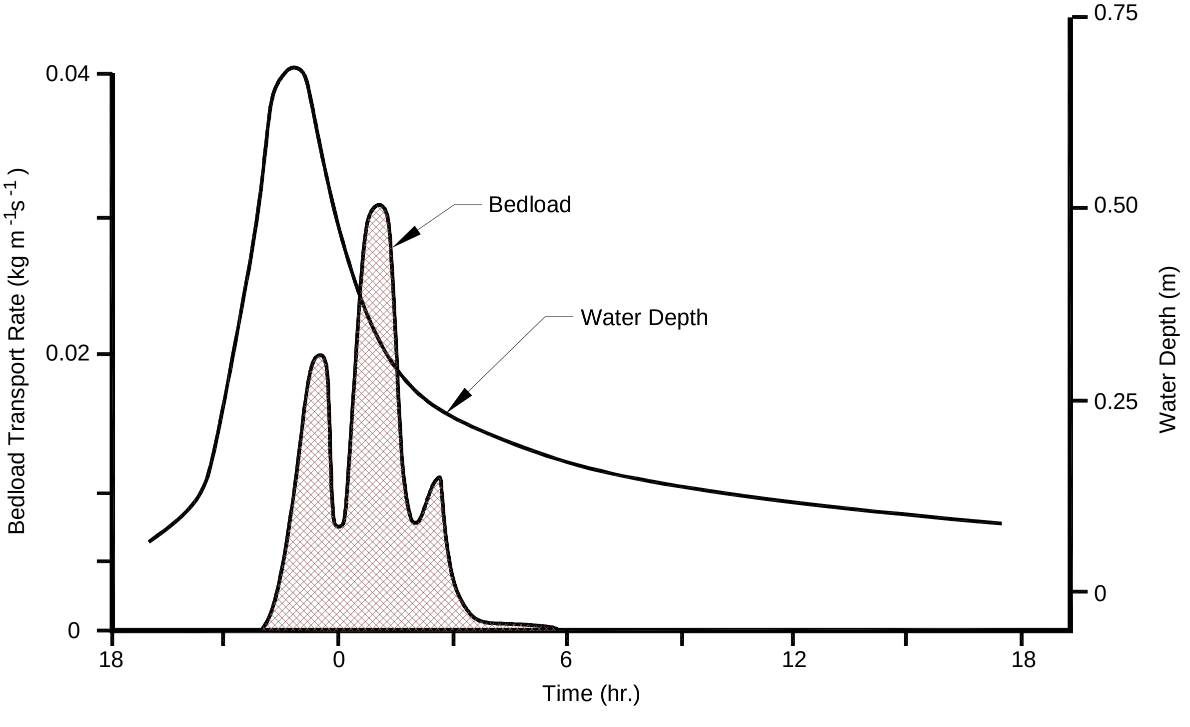
Note that some authorities do not recommend pebble count sampling for sediment transport computations[17],[18]. Pebble counts tend to be biased towards larger particle sizes, and as such are well suited to hydraulic roughness determination, but underestimate the presence of smaller size fractions, which 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 chose a larger, more palpable particle during the sampling process.

To avoid this bias, volumetric sampling with sieve analysis is necessary. The "barrel sampler" method is a standard volumetric sampling technique,[19]. Sieve analysis is conducted on bulk samples taken from the field, and consists of sifting sediment through several standard sized sieves[20]. The amount of sediment remaining on each sieve is then weighed to determine the percent of the total weight of a given size fraction. 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. 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 measurements are necessary. Suspended sediment measurement is usually done by pipette analysis[21]. Sediment sampling allows for estimation of size gradations in motion at given flows and provides useful information on design elements relative to substrate size.

2.3 Bedload Movement

Sediment in fluvial systems tends to move in a series of slugs, pulses, or waves[22],[23].



Generally, the coarser the sediment the more infrequent and concentrated in time the movement is. For example, in a study on the East Fork River in Wyoming, Meade[24] concluded that sediment moved in three pulses over a one-year period. The movement of each pulse was correlated with the pulse of water discharge resulting from snowmelt. This study also suggested that sediment is transported downstream in a series of waves; when discharge increases, material stored in riffles moves to the next riffle downstream. Such wave-like or pulse-like movement is typical of semi-arid streams (or streams with coarse bed-load) and it may be less common in humid environments.

2.4 Incipient Mobility of Sediment

The assessment of sediment mobility within a channel requires an understanding of the sediment size gradation present, as well as the transport energy available to mobilize that gradation. In many cases, the evaluation of the transport energy available to transport the size fraction present is deemed sufficient for channel design[25]. This is referred to as "incipient mobility", and addresses mobility purely in terms of sediment size mobilized, rather than sediment volume mobilized. In more complex cases, however, such as those in which the incoming sediment volumes are either excessively large or small, the more difficult calculation of transport volumes may be necessary. Sediment volume is typically a function of stream power, which represents the energy needed to transport sediment in a channel, or, equivalently, a function of hydraulic shear stress, which refers to the force on the streambed. Stream power is a representation of channel capacity, or the quantity of material that the flow is able to transport. A thorough review of various stream power equations is provided by Rhoades[26].

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 shear stress at incipient motion is called the critical shear stress.

Shear stress is a measure of the erosive force exerted by flow on the channel boundary. Total shear stress created by flow along meandering rivers with natural topography is partitioned into shear exerted on bed, banks, bed forms, wood, vegetation, etc.[27] 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. Bank shear stress can be estimated by multiplying the average shear stress value by a coefficient (see Lane, 1955, or Chang, 1988). Maximum bank shear, based on a wide, trapezoidal channel, is approximately 0.75 times the maximum bed shear at a distance 1/3 up from the channel bed. Different channel shapes and bends will also affect the values for bank shear. A more thorough discussion of shear and methods to calculate shear is provided in the *Hydraulics Appendix*.

Shear stress calculations determine the force of the water on the channel particles. By knowing the amount of shear stress in a stream, the particle size necessary to withstand these forces can be found. This is important when designing a channel to withstand a certain design flow or flood flow. Average shear stress is calculated by the equation,

$$\tau = \gamma R s$$

where τ is the shear stress, γ is the specific weight of water (specific weight of water is inversely related to water temperature), 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. Shear stress is commonly expressed in units of pounds per square feet (psf). The water depth is a function of flow magnitude and channel geometry.

Shear stress will therefore be greatest in steep streams during high flows.

Critical shear is the shear stress required to mobilize sediment of a particular grain size. In order to calculate critical shear stress, the Shields equation is used:

$$\tau_c = \tau_c^*(\gamma_s-\gamma)D$$

where τ_c^* is the dimensionless Shields parameter for entrainment of a sediment particle of size D, and γ_s and γ are the unit weights of sediment and water, respectively, expressed in pounds per cubic foot. 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. The Shields parameter is dependent on particle size and packing, and may range from 0.01 for loosely packed gravel to 0.1 for imbricated deposits (imbricated deposits have been arranged in a shingled fashion by stream flows and are particularly difficult to mobilize). 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[28]. Their work suggests that the lack of universal Shields parameter values warrants great care in selecting those values in mobility assessments.

In incipient mobility assessments, the critical shear value is generally calculated using the D_{50} of the sediment gradation present. The use of the D_{50} to characterize the bed material size in mobility analysis is based on the hypothesis of equal mobility[29]. Originally proposed by Parker et al, (1982), this hypothesis assumes that the "*bed-load* size distribution is approximated by that of the *substrate* for all flows capable of mobilizing most available gravel sizes" (emphasis added). Note also that "substrate" here refers to the subsurface[30], 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 is still widely used in incipient motion analysis[31],[32],[33]. This is probably due to the added level of complexity, and perhaps uncertainty, involved in analyses that allow for bed-load size characteristics to vary with discharge.

A perhaps more significant aspect of the equal mobility hypothesis is its relation to the dynamic pavement concept of Parker et al. for gravel bed streams,[34]. In this view, the coarsened surface layer (termed "pavement," rather than armor, to distinguish it from immobile surface layers) persists at all flows, even though all available particle sizes are present in the bedload. The surface coarsening "hides" smaller particles from the flow, thus rendering them less mobile, while coarser particles project into the flow. Thus, the critical shear stress for smaller and larger particles tend 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. This "hiding factor" has been expressed mathematically, and can be used to predict critical shear stress of any particle size from that of the D_{50} size, and to estimate the D_{50} critical shear stress from the ratio of pavement to subsurface D_{50}[35].

Sediment mobility has been described in terms of shear stress ratio, which (adopting the equal mobility hypothesis) is the ratio of the shear stress present to the critical shear required to mobilize the D_{50}. Wilcock and MacArdell[36] estimated that a shear stress ratio of 2 is needed to mobilize the entire bed of a channel (although this depends to some extent on the particle size distribution). Channel stability was defined by a bankfull shear stress ratio of 1 in the assessment procedure developed by Johnson et al.[37]. 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 limited and aggradation is likely. Many practitioners consider incipient motion for the D_{84} at bankfull as a "rule-of-thumb" design parameter [38]. Channel design allowing incipient motion for the D_{50} may result in channels that aggrade over time. Other practitioners use incipient motion for the D_{100}, the largest alluvial particle, as a target design criterion[39].

2.5 Channel Competence-Based Methods of Sediment Transport Analysis

Incipient motion analyses can be used to assess channel competence and to design channel components (including habitat structures constructed with rock) to be stable under a given discharge. USDOT, 1988[40] is a useful reference for utilizing tractive force (shear stress) analysis for design. Shear stress is not, however, a practical measure of tractive force in steeper channels, 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].

2.5.1 Tractive Force Analysis

Analysis of tractive force, a generalized measure of shear stress, can be used to determine channel geometry (considering primarily depth) based on the mobility of bed sediment[42]. Using this approach, incipient motion analysis as described in "Incipient Mobility of Sediment" (above) is used to assess the mobility of the streambed and bank materials. Because the theoretical mobile particle size is calculated, the tractive force method can be used to design a channel that is essentially rigid (non-erodible) at the design discharge. Tractive force analyses can also be used to design channel components, such as banks, to withstand the shear forces associated with a given design discharge. USDOT, 1888 includes information on the calculation of shear in-channel bends and on the shear resistance of various materials commonly used in channel design. A summary of these calculations and materials is provided in the *Hydraulics Appendix*. Alternatively, if a mobile channel bed is desired, tractive force analysis can be applied to determine a fraction of the bed material that is mobile at a given design discharge. Two methods for addressing mobile channel beds in design are addressed below.

2.5.2 Mobile Channel Bed Under Fixed Slope Conditions

This approach can be applied when slope is fixed due to vertical constraints as well as lateral floodplain constraints. Analysis of moving (or 'live') beds with a known or constrained slope most often makes use of extremal hypotheses. Extremal hypotheses state that a stable channel will adopt dimensions that lead to minimization and maximization of certain parameters. For instance, extremal hypotheses include the minimization of stream power, maximization of sediment transport, minimization of stream power per unit bed area, minimization of Froude number, and the maximization of friction factor. These hypotheses and their application to river design are summarized in Chang, 1988. Chang combined several of the extremal hypotheses, along with standard hydraulic analysis, to generate a numerical model of flow and sediment transport, the FLUVIAL 12 model. The model was used to make repeated computations of channel geometry with various values for input variables. Results of the analysis were used to construct a family of design curves that yield channel depth and width when given discharge, slope, and bed material size.

2.5.3 Mobile Channel Bed Under Known Sediment Concentration

Using this approach, design will ensure that the sediment entering the reach is transported out of the reach by manipulating channel dimensions. Upstream stable channel dimensions can be used to calculate an assumed sediment supply. 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. The hydraulic design package 'SAM' performs this series of analyses for alluvial channels and is available for public use[43].

2.6 Limitations of Competence-Based Methods

Sediment size and incipient motion particle size are relatively easy to characterize from deposited bed sediments and hydraulic analysis (see the discussion of "tractive force" above). However, as previously mentioned, sediment volume is much more difficult to quantify. Sediment volume is typically calculated using sediment transport equations, which are notoriously inaccurate. There are numerous sediment transport equations, each of which was developed for specific types of conditions and purposes. As such, they are only applicable to specific types of channels.

Modeling of sediment transport remains one of the central thrusts of fluvial geomorphic and hydraulic research. It is likely that quantification of sediment volume will eventually become a routine part of channel design once the limitations of sampling and characterization are reduced. 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, river channel design.

3 SEDIMENT TRANSPORT EQUATIONS AND MODELS

There are numerous sediment transport equations, each of which was developed for specific types of conditions and purposes. **Table G2** 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. Whenever possible, the use of measured sediment loads for testing and calibration of the chosen equation(s) is preferred. Actual equations and detailed descriptions are available in standard sediment transport texts, (e.g., Chang).

Table G2. 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[44],[45]	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[46]	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[47]	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.[17],[34]	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[48]	1973	N/a	Uniform sediments Ds > 0.04mm Ds < 28.1mm	Flume: depth < 0.4m Fr < 0.8	Total load
Engelund and Hansen[44]	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.[49]	Total load; Sand bed w/ dunes
Laursen[50]	1958	0.00043-0.00210	s.g. ~ 2.65 Dm = 0.011mm – 4.08mm Distributions ranged	Based on various flume tests by others: Flumes ranged from: 10.5in wide x 40ft	

			from well sorted to well graded	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.[51],[52],[31]	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

Another approach, which yields greatly improved accuracy with little increase in modeling complexity, is to use a site-calibrated sediment transport model[18],[52],[53]. Here, one of the above models, such as Parker et al.[18], is calibrated to one or more bedload measurements 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. Standard procedures for bedload sampling are available[54]. Although bedload sampling is somewhat time consuming, the sampling and calibration procedure is much less costly for the improved accuracy than the more-elaborate 2-D or 3-D modeling discussed below.

In addition to the specific sediment transport equations, there are several sediment transport numerical models available for use in river engineering applications. The most common approach to sediment transport modeling is a steady state, 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. Based on the quantity of sediment transported for the given flow, the channel elevation (i.e., slope) is adjusted via a routing scheme. The program either performs calculations for a given range of flows, or for a given flow, the model continues until there are no more channel adjustments (i.e., equilibrium conditions). This modeling approach is the basis for the Corps of Engineers HEC-6 model[55], and is widely used. The primary limitation of the HEC-6 approach is that it is a one-dimensional model. There are a number of inherent assumptions including: steady, uniform flow and rigid boundaries with no changes allowed in the channel width and no lateral migration.

The next level of modeling is the semi two-dimensional modeling approach. In two-dimensional models, a similar coupled hydraulic and sediment routing scheme is used, but at the end of the routing run an estimate is made as to whether or not channel width adjustments are appropriate. Several methods are used to estimate stable channel widths: extremal hypotheses as described earlier (GSTARS 2.0, FLUVIAL 12)[27], or bank stability estimated from stable slope angles (GSTARS 2.0, CONCEPTS)[27]. These models add a significant feature of width adjustment without adding significantly to data or analysis efforts needed. In all, these are felt to be the most appropriate approaches for most river restoration designs, particularly those projects that will involve significant modification to channel alignment, slope, or sediment loads.

The third level of modeling is the fully two-dimensional or three-dimensional modeling approaches. These models represent significant improvements in describing fluvial erosion and hydraulic processes, but this comes at a significant increase in the level of effort needed both in terms of data and analysis requirements beyond current capability. In fact, while utilization of 2-D modeling is beginning to become more widespread for large projects, application of 3-D modeling continues to be impractical due to technological limits such as computer capabilities and high input requirements.

4 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.

The appropriate volume/extent of sediment storage is best determined using an analog (reference) reach. 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.

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HYDRAULICS APPENDIX

1 INTRODUCTION

Relevant to the discussion of habitat restoration, hydraulics can be defined as the laws governing the movement of water within a channel and the forces generated by this movement. Hydraulic effects result in movement of sediment, erosion of channel banks and scour of the channel bed. These processes help form, as well as respond to, the geomorphic conditions of the stream. This appendix describes how to calculate hydraulic conditions at a section and discusses one-dimensional models for characterizing flow along a reach, shear stress (erosive forces along a bank or bed) and scour depth in stream channels.

Although the material presented in this appendix is intended for engineers experienced with hydraulics, it may be beneficial reading for anyone involved with stream restoration. Readers unfamiliar with basic hydraulics are referred to the "Recommended Reading" section at the end of the appendix. 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.

2 MANNING'S EQUATION

Manning's Equation is probably the most commonly used formula for basic hydraulic calculation in natural channels. In its most basic form, the equation relates flow velocity to hydraulic radius, hydraulic roughness and channel slope. Using Manning's Equation in its various forms, one can determine:

- Average water velocity given cross-sectional geometry, depth, slope, and roughness;
- Channel discharge given cross-sectional geometry, depth, slope, and roughness;
- Channel roughness given cross-sectional geometry, slope, depth, and discharge;
- Channel slope given cross-sectional geometry, discharge, depth, and roughness; and
- Channel depth given cross-sectional geometry, discharge, slope, and roughness.

Manning's equation assumes steady and uniform flow. When the velocity at any given point remains constant with respect to time, then a flow is considered *steady*. If flow depth does not change with location along the channel, then the flow is *uniform*. In reality, steady and uniform flow is practically nonexistent in natural settings. Nonetheless, Manning's equation is commonly used as a relatively simple and convenient tool for hydraulic analysis of natural streams. It is generally understood and accepted that the results are approximate, and designers should keep this in mind when applying its results.

Manning's Equation can be written in either velocity or discharge terms as follows:

$$V = (1.49/n)(R_h^{2/3} S_e^{1/2}) \qquad \text{(Equation 1)}$$

$$Q = (1.49/n)(A R_h^{2/3} S_e^{1/2}) \qquad \text{(Equation 2)}$$

Where: V = average cross-sectional velocity (ft/sec)
n = Manning's roughness value
Q = discharge (cubic ft/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)

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* are typically estimated based on tables for *n* developed through empirical study. Methods for calculating *n* are also available. Guidance for determining appropriate n values can be found in most hydraulic analysis/design references including Chow (1959) [1] and others[2,3,4].

2.1 Continuity

The modification of Manning's equation from the form shown in equation (1) to that shown in equation (2) is based on the fundamental relation:

$$Q = VA \qquad \text{(Equation 3)}$$

Where: Q = discharge (cubic ft/sec)
V = average cross-sectional velocity (ft/sec)
A = cross-sectional area of flow (ft^2)

Assuming the cross-sectional area of flow "A" is measured normal to the flow direction, the relation expressed by equation (3) holds true for any cross-section on a stream. If discharge is constant throughout a stream reach, then the flow is considered to be *continuous*, and the following relation is true (Chow, 1959).

$$Q = V_1A_1 = V_2A_2 = \ldots \qquad \text{(Equation 4)}$$

Where the subscripts denote different locations within the reach (Chow, 1959). Equation (4) is commonly known as the *continuity equation.* The continuity equation holds true as long as discharge within the reach is constant (there is no additional water flowing into or out of the reach).

2.2 Modeling Backwater Effects

With the exception of long uniform stream reaches, flow along a stream is often controlled by downstream (during subcritical flow regime) or upstream (supercritical flow regime) channel conditions. Backwatering occurs when a downstream flow control such as a constriction, higher bed elevation (e.g. crest of riffle downstream of a pool) or increased roughness creates a ponding effect that forces a higher water surface elevation at an upstream section then would occur in a freely draining condition. The Manning's equation is not capable of modeling backwater effects caused by downstream flow control. One-dimensional models are necessary to quantify backwater effects. One-dimensional numerical surface water models are based on continuity and momentum and they assume cross-section averaged flow, in steady state conditions, and a flat water surface elevation across each cross section.

Examples of these models include:

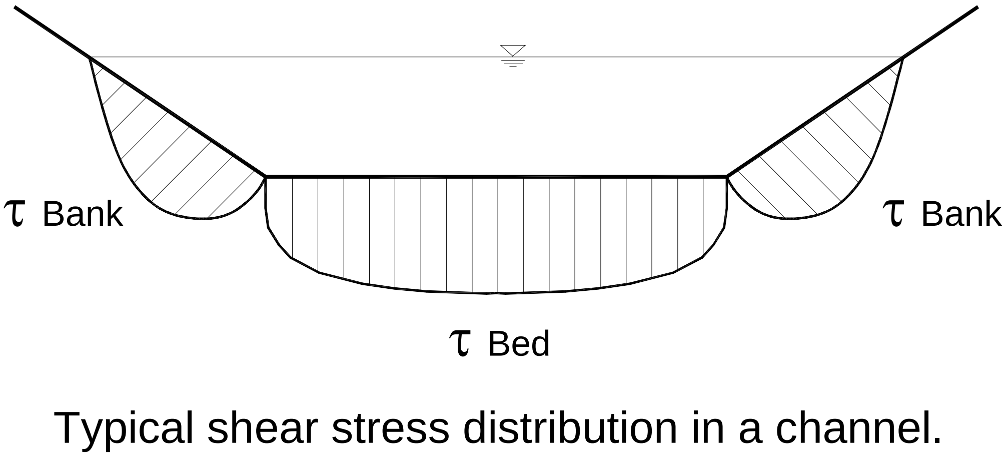
1. US Army Corps of Engineers (USACE), Hydrologic Engineering Center, River Analysis System Model, (HEC-RAS). HEC-RAS analyzes networks of natural and man-made channels and computes water surface profiles for subcritical or supercritical flow based on steady or unsteady one-dimensional flow hydraulics. 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 with HEC-RAS version 3.0 using the flow split optimization option.
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, gradually varied, and 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.

Occasionally projects will require predictions of complex flow patterns warranting the use of two-dimensional hydraulic models. Examples of such projects include: wide shallow streams, bays, estuaries or braided streams or when secondary currents are important such as around bends or groins. Two-dimensional models in use include Finite Element Surface-Water Modeling System (FESWMS) from FHWA and RMA-2 (USACE).

3 SHEAR STRESS

Shear stress is an important parameter in habitat restoration design, because all materials, whether manufactured or natural, used for habitat restoration must be able to withstand the expected shear stress at the design discharge. Thus, in design, all materials and vegetation types are chosen based on the expected shear for a given flow (for example, the 50-year discharge) at their point of installation. Shear stress is typically measured in units of pounds per square foot (psf).

On any given bank, the material and vegetation types required to resist erosion may vary with location. Lane’s diagram, **Hydraulics Figure 1**, shows theoretical distribution of shear stress on streambed and banks on a straight section of trapezoidal channel. Based on Lane’s diagram, materials and plants of greater shear resistance are required lower on the bank, while a lighter-duty treatment 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 (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.



Hydraulics Figure 1. Theoretical distribution of shear stress on bed and banks.

Typical permissible shear stresses for various materials are shown in **Hydraulics Table 1**. As can be seen in the table, the range of materials for which such information is available is limited. Often, the information listed in **Hydraulics Table 1** must be extrapolated or used merely as an aid in estimating the shear resistance of similar plants and materials that do not appear there. In addition, there is no standardized testing procedure that accounts for the effects of weather, repetitive inundation, and long-duration inundation. Therefore, the values in **Hydraulics Table 1** should be applied using professional judgment and considering site variables of the project location. Fischenich[5] provides additional information in Stability Thresholds for Stream Restoration Materials.

Hydraulics Table 1.
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)
Class A vegetation Weeping lovegrass: excellent stand, average height 30” Yellow Bluestem Ischaemum: excellent stand, average height 36”	3.7
Class B vegetation Kudzu: dense or very dense growth, uncut Bermuda grass: good stand, average height 12” Native grass mix (long and short midwest grasses): good stand, unmowed Weeping lovegrass: good stand, average height 13” Lespedeza sericea: good stand, not woody, average height 19” Alfalfa: good stand, uncut, average height 11” Blue gamma: good stand, uncut, average height 13”	2.1
Class C vegetation Crabgrass: fair stand, uncut (10” – 48”) Bermuda grass: good stand, mowed, average height 6” Common lespedeza: good stand, uncut, average height 11” Grass-legume mix: good stand, uncut (6” – 8”) Centipedegrass: very dense cover, average height 6” Kentucky bluegrass: good stand (6” – 12”)	1.0
Class D vegetation Bermuda grass: good stand, cut to 2.5-inch height Common lespedeza: excellent stand, uncut (average height 4.5”) Buffalo grass: good stand, uncut (3” – 6”) Grass-legume mix: good stand, uncut (4” – 5”) Lespedeza sericea: very good stand cut to 2-inch height	0.6
Class E vegetation Bermuda grass: good stand, cut to 1.5-inch height Bermuda grass: burned stubble	0.4
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.[6]

3.1 Estimating Shear Stress

Shear equations presented in this appendix allow the designer to estimate bed and bank shear in straight stream reaches and bends. In addition, a means of estimating shear as a function of height in the water column is presented. It is assumed that persons utilizing the equations presented in this appendix are well versed in hydraulic analysis and familiar with the concepts of shear and scour. It is recommended that hydraulic analyses be carried out only by a qualified hydraulic engineer or someone with equivalent experience.

3.1.1 Bed Shear Stress in a Straight Reach

Shear stress on the bed is[6]: $\tau_{bed} = \gamma S_e R_h$ (Equation 5)

γ = the specific weight of water = 62.4 lbs/ft^3,

Therefore: $\tau_{bed} = 62.4 S_e R_h$ (Equation 6)

Where:

τ_{bed} = maximum bed shear stress in lb/ft^2 (psf)

R_h = hydraulic radius in ft. (see below)

S_e = energy slope in ft/ft (see below)

S_e is the slope of the energy grade line. This slope is usually similar to the hydraulic grade line (water surface) and bed slope (gradient) and is typically replaced by bed slope in hand calculations. By definition, the slopes are equal for steady, uniform flow. 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. Zero flow points are the points in the bed that would control the pools upstream of major riffles if there were no water flowing in the channel. They are the low points at the head of riffles. In a braided channel, or channels without defined riffles, the mean bed elevation should be used. The mean bed elevation should be determined from several closely spaced cross-sections. The U.S. Army Corp of Engineers hydraulic program, HEC-RAS, can output bed shear stress as well as energy slope.

R_h is the hydraulic radius, which is the cross-sectional area of the wetted channel (A) divided by the length of the wetted channel perimeter (P), at the design flow being considered. This value is occasionally replaced by depth of flow, y, but this should only be done when the width of the channel far exceeds the depth of the channel. HEC-RAS will always correctly use A/P. As a rule of thumb, always use $R_h = A/P$.

A common application of the equation is for maximum bed shear stress is:

Maximum bed shear stress in a straight reach: $\tau_{bed} = 62.4\ (S_e)\ (A/P)$ (Equation 7)

where:
τ_{bed} = maximum bed shear stress in lb/ft^2 (psf)
A = cross-sectional area of flow (ft^2)
P = wetted perimeter (ft)
S_e = energy slope in (ft/ft)

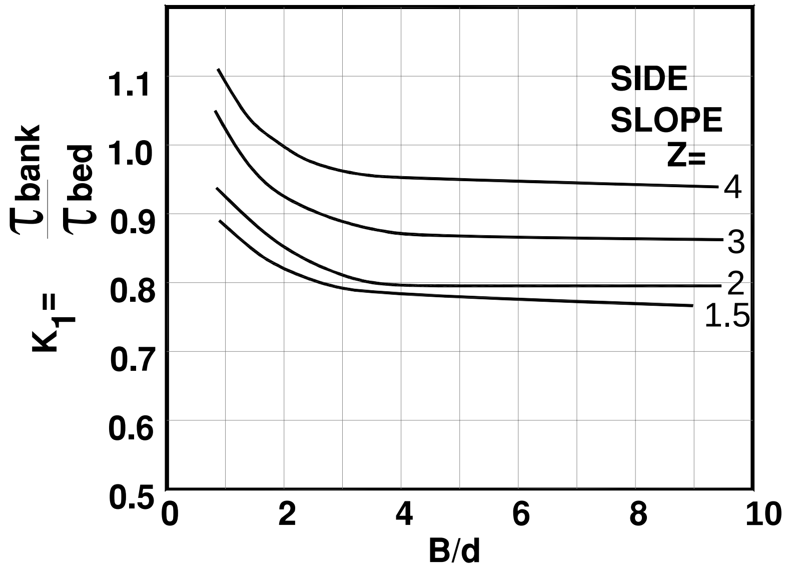
This calculation gives a quantitative measure of the erosive force acting on the bed of the channel.

3.1.1.1 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 Lane's Diagram, **Hydraulics Figure 1**). This factor, K_1, varies based on channel side slope and the ratio of bottom width to depth as shown in **Hydraulics Figure 2**. This approximation applies only to a relatively straight reach of stream.

Maximum bank shear stress in a straight reach[6]. $\tau_{bank} = K_1\ \tau_{bed}$ (Equation 8)

where:
τ_{bed} = maximum bed shear stress in lb/ft^2 (psf)
K_1 = ratio from **Hydraulics Figure 2**.



Hydraulics Figure 2. Side slopes, depth/width ratio[6].

Shear stress on the upper bank can be estimated using Lane's Diagram shown in **Hydraulics 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 (psf)
τ_{bed} = maximum bed shear stress (psf)
C = coefficient from **Hydraulics Table 2**
y = stream depth (ft)

Hydraulics Table 2. Coefficient "C" vs. depth

Distance X (feet from stream bottom)	***C (From Lanes)***	***C (Recommend for design)***
y	*0.0*	*0.0*
0.9 y	*0.14*	*0.14*
0.8 y	*0.27*	*0.27*
0.67 y	*0.41*	*0.41*
0.6 y	*0.54*	*0.54*
0.5 y	*0.68*	*0.68*
0.4 y	*0.79*	*0.79*
0.33 y	*0.8*	*0.8*
0.2 y	*0.7*	*0.8*
0.1 y	*0.5*	*0.8*
0.0 y	*0.0*	*0.8*

Note: Although Lane's shear diagram indicates zero shear at the base of the bank, 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.

3.1.1.2 Shear Stress in Bends[6]

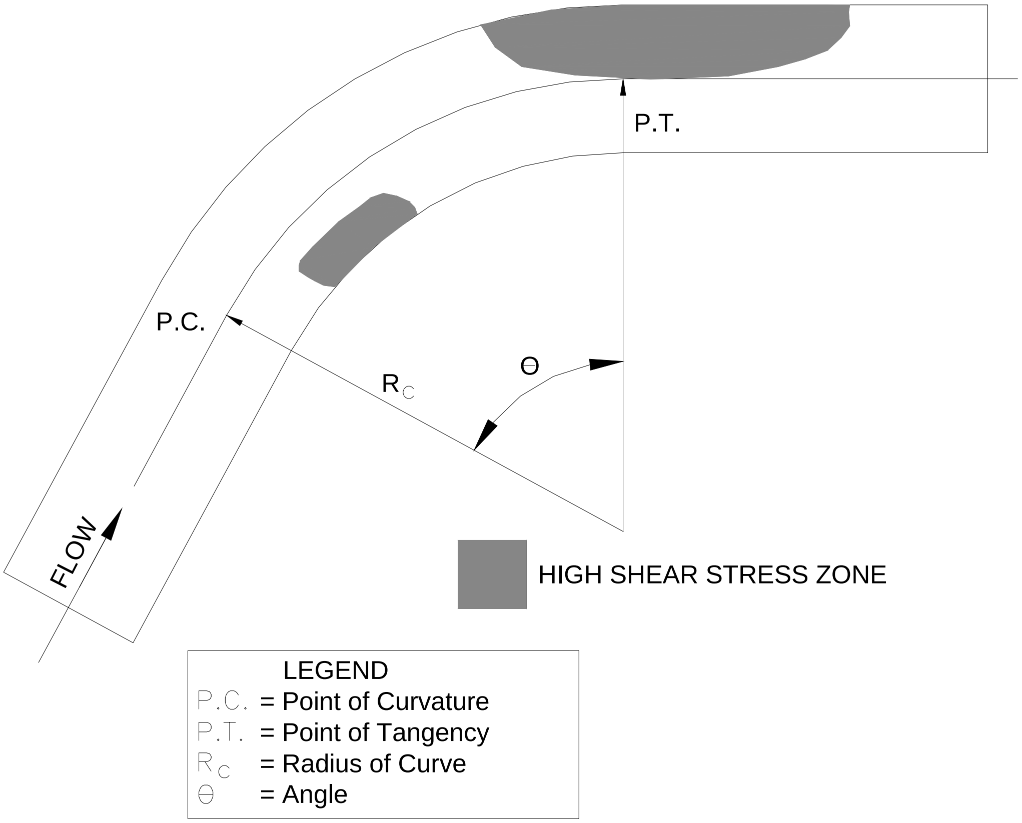
Flow around bends creates secondary currents that exert higher shear forces on the channel bed and banks than those found in straight sections. Several techniques are available for estimating shear stress in bends. A relatively simple and widely used method estimates maximum shear stress on channel banks 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:

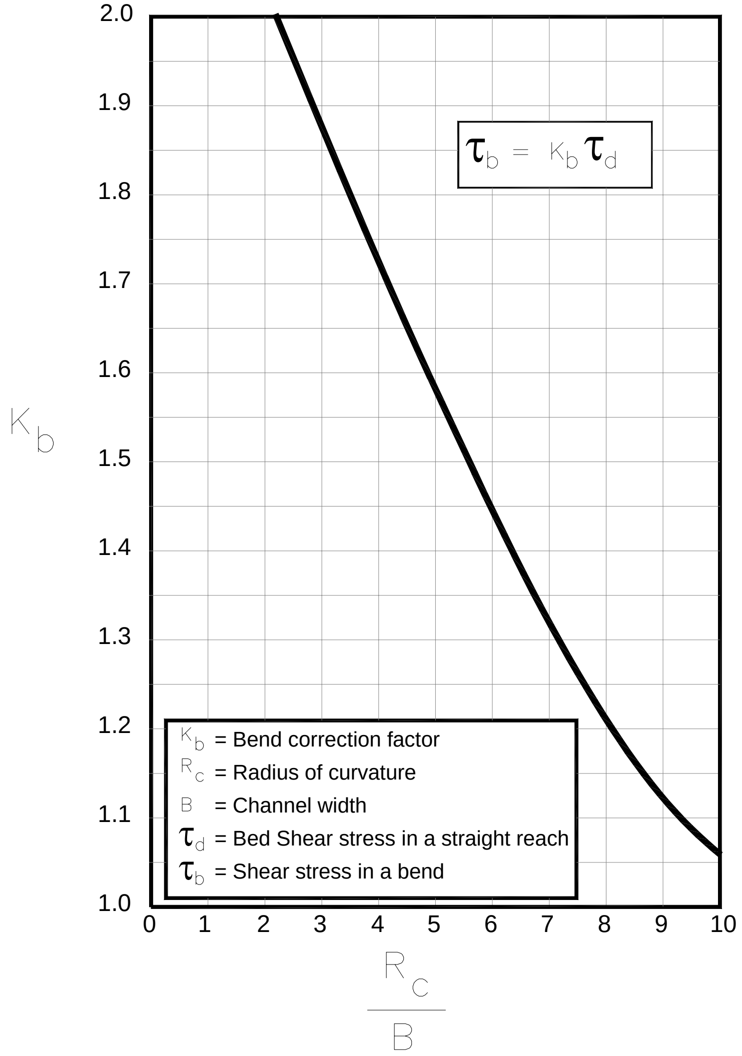
$$\tau_{bend} = K_b\ \tau_{bed} \qquad \text{(Equation 10)}$$

where: τ_{bend} = maximum shear stress on bank and bed in a bend (psf)
τ_{bed} = maximum bed shear stress in adjacent straight reach (psf)
K_b = bend coefficient (dimensionless)
and: $K_b = 2.4\ e^{-0.0852(Rc/b)}$ (alternatively, K_b can be determined from **Hydraulics Figure 4**)

where: R_c = radius of curvature of bend (ft)
b = bottom width of channel at bend (ft)



Hydraulics Figure 3. Shear stress distribution in a channel bend.



Hydraulics Figure 4. 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 (**Hydraulics Figure 3**).

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:

$$\Delta y = V^2 W / (g R_c) \qquad (\textit{Equation } 11)$$

where:
Δy = super-elevation of water surface (ft)
V = average velocity of flow (ft/s)
W = channel top width (ft)
g = acceleration due to gravity (32.2 ft/s^2)
R_c = radius of curvature of bend (ft)

3.2 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[7,8]. Sites that are subject to very frequent scour have less habitat value than areas subject to moderately frequent scour events.[9]

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 phenomenon 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[10] 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.”

3.2.1 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.

3.3 Types of Scour

Five types of scour are defined below[11]: 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 patter 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[12]. 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 to the outer corner of the channel and pronounced bend scour occurs near the outer edge of the channel. 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[7].

Constriction Scour – Constriction scour occurs when features along the streambank create a narrower channel than would normally form. Often the constricting feature is “harder” than the upstream or downstream bank and can resist the higher erosive forces generated by the constriction. Bedrock outcrops often form natural constrictions. 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 or bridge abutments are common examples of features that cause constriction scour. 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, crating 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 associated deposition. Accordingly, clear-water conditions usually produce deeper scour depths than live-bed conditions.

3.3.1 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.

3.3.2 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 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[13]. 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) (**Hydraulics 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 as defined below

Note that for the special case of round-nosed piers aligned with the flow:

$d \leq 2.4$ times the pier width for $Fr \leq 0.8$
$d \leq 3.0$ times the pier width for $Fr > 0.8$

K_1 = Correction factor for pier nose shape:

For approach flow angle > 5 degrees, $K_1 = 1.0$ (**Hydraulics Figure 5**)
For approach flow angle ≤ 5 degrees:

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	$K_1 = 0.9$

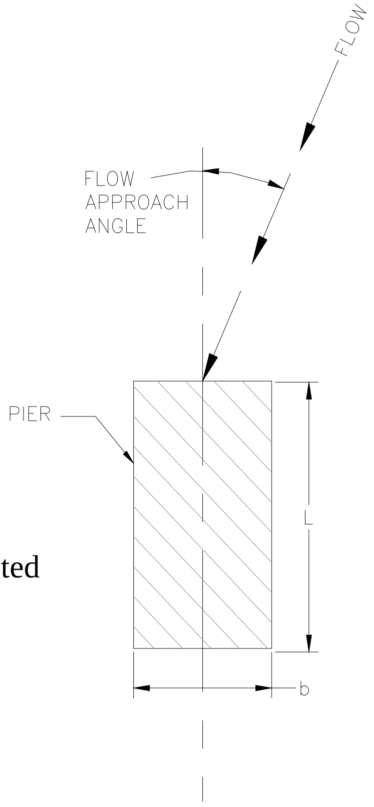
K_2 = Correction factor for approach flow angle

$$K_2 = (\cos \theta + L/b \sin \theta)^{0.65}$$

where:
K_2 = correction factor from **Hydraulics Table 3**
L = length of the pier which is being directly subjected to impinging flow at the approach angle (m) (**Hydraulics Figure 5**)
θ = flow angle of approach to pier (in degrees)
Maximum $L/b = 12$

Hydraulics Table 3. K_2 vs. 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



Hydraulics Figure 5.
Pier scour flow approach angle.

K_3 = Correction factor for bed conditions, based on dune height, where dunes are repeating hills formed from moving sand across the channel bed. See **Hydraulics Table 4**.

Hydraulics Table 4. K_3 based on bed conditions

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 D90 bed material size (m/s)
V_{c50} = critical velocity for D50 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)

3.3.2.1 Top Width of Scour Hole at Pier

USDOT[13] 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.

3.3.2.2 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[14] 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[13] presented below 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 alignment of the abutment
$\theta > 90$ degrees if embankment points upstream
$\theta < 90$ degrees if embankment points downstream

L’ = length of abutment projected normal to flow (m)
L’ = A / y
Where: A = flow area of approach cross section obstructed by the embankment (m^2)

Fr = Froude number of flow upstream of abutment

$= V / (g\ y)^{0.5}$
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.

3.3.2.3 Clear-Water Scour at an Abutment

USDOT recommends using the live-bed equation presented above to calculate clear-water scour.

3.3.3 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.

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[15]. This estimate will be somewhat conservative for mild bends.

3.3.3.1 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[15] 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.

$$d/y_1 = 1.07 - \log(R_c/W - 2) \qquad \text{for } 2 < R_c/W < 22 \qquad \text{(Equation 14)}$$

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
R_c = channel radius of curvature at channel centerline (m or ft)

The width of flow 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[16] 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)
R_c = centerline radius of bend
W = width of 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 that cause overbank flow exceeding 20% of channel depth.
- There is no safety factor incorporated into this equation- this is the mean scour depth based on the sites measured.
- A safety factor of 1.08 is recommended by Maynord.
- 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

$d_s/D = \alpha + \beta\ (W/R_c)$ (Equation 16)

Where: $\alpha = 0.361\ X^2 - 0.0224X - 0.0394$

$X = \log_{10}(WS^{0.2}/D)$

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);

$\beta = 2/(\pi\ 1.226\ ((1/\surd f\ ) - 1.584)\ x)$

f = Darcy friction factor

$x = 1/\ [\ 1.5\ f\ \{(1.11/\surd f\ ) - 1.42\}\ \sin\sigma + \cos\sigma\ ]$

$\sigma = \tan^{-1}[\ 1.5\ f\ ((1.11/\surd f) - 1.42)]$ = Darcy friction factor = 64/Re

where Re = Reynolds number

Notes:

- Results correlate well with Mississippi River data and under predicted 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

3.3.4 Constriction Scour

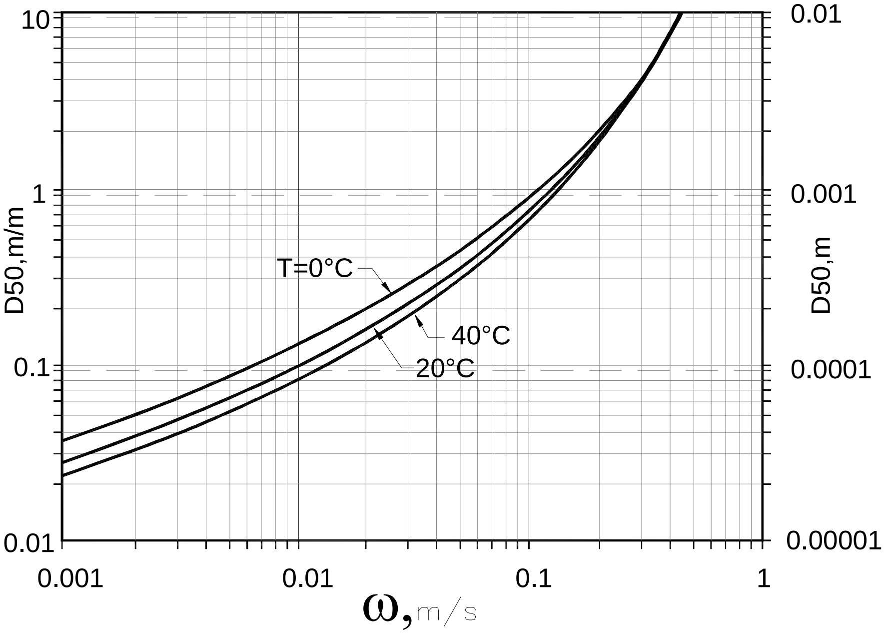
Constriction Scour equations were primarily developed from flume tests with the constriction resulting from bridge abutments. However, these equations apply equally well to natural constrictions or constrictions caused by installation of instream structures such as groins.

3.3.4.1 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 **Hydraulics Figure 6**, provide scour depth estimates for streams with gravel-sized bed materials.

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 next section) be calculated and that the smaller of the two calculated scour depths be used. 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.



Hydraulics Figure 6. Fall velocity of sand sized particles.

Laursen Equation for Live-Bed Conditions[13]

$y_2 / y_1 = (Q_2/Q_1)^{0.86} (W_1/W_2)^A$, $d = y_2 - y_0$ (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/s)
Q_1 = flow (m^3/s) 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 **Hydraulics Table 5**

Hydraulics Table 5. 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

ω = fall velocity (m/s) of bed material based on D_{50} (see **Hydraulics Figure 5**)
U_* = shear velocity = $(g\, y_1\, S_e)^{0.5}$ (m/s)

where: g = acceleration due to gravity (9.81 m/s^2)
S_e = slope of energy grade line in main channel

Notes:

1. As presented here, this equation assumes that all stream flow passes through the constricted reach.

2. 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.

3.3.5 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.

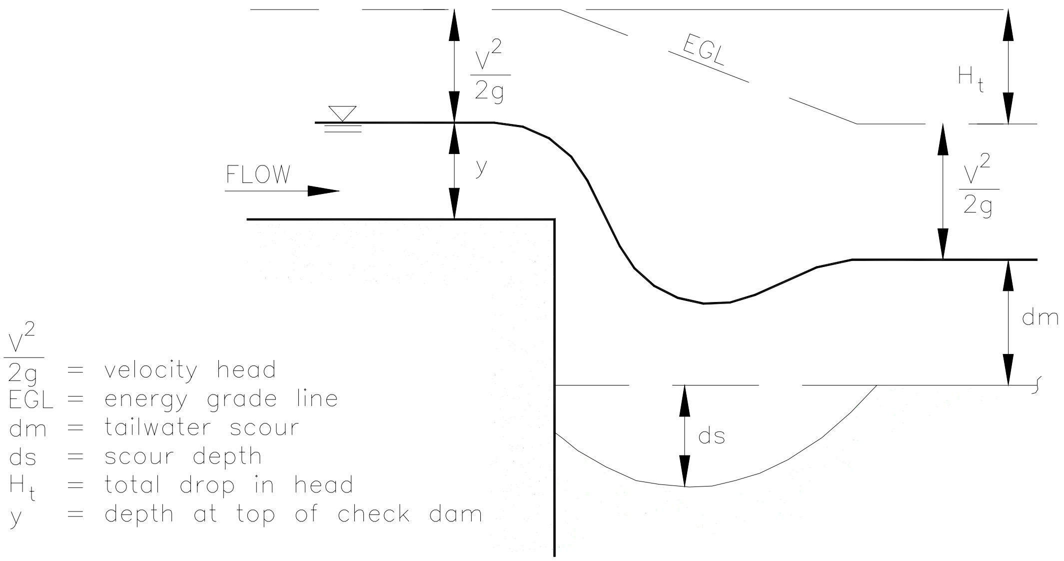
Laursen Equation for Clear-Water Conditions[13]

$$y_2 = \{ 0.025\, Q_2^2 / [D_m^{0.67}\, W_2^2] \}^{0.43}, \quad d = y_2 - y_0 \qquad \text{(Equation 18)}$$

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)

3.3.6 Drop/Weir Scour

Two equations are presented here for estimating scour depths for a flow pouring over a weir, step pool, grade control structure, or drop structure. **Hydraulics 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.



Hydraulics 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.

U.S. Bureau of Reclamation Equation – Vertical Drop Structure[10]

$$d_s = KH_t^{0.225}q^{0.54} - d_m \qquad \text{(Equation 19)}$$

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[17]

$d_s = \{ [4 (y_c/D_{50})^{0.2} - 3 (R_{50}/y_c)^{0.1}] y_c \} - d_m$ (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.

3.3.7 Jet Scour

Although 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[18] for guidance. Please refer to the Recommend Reading section of this appendix.

3.3.8 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

3.3.8.1 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.

Note: Units are metric or English

$y_s = y_{bi}\ (q_{di}/q_{bi})^m$ (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.

Note: Units are metric or English

$y_L = 0.47\ (Q/f)^{0.33}$ (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} is in millimeters

D_{50} = mean grain size of bed material (must be in mm)

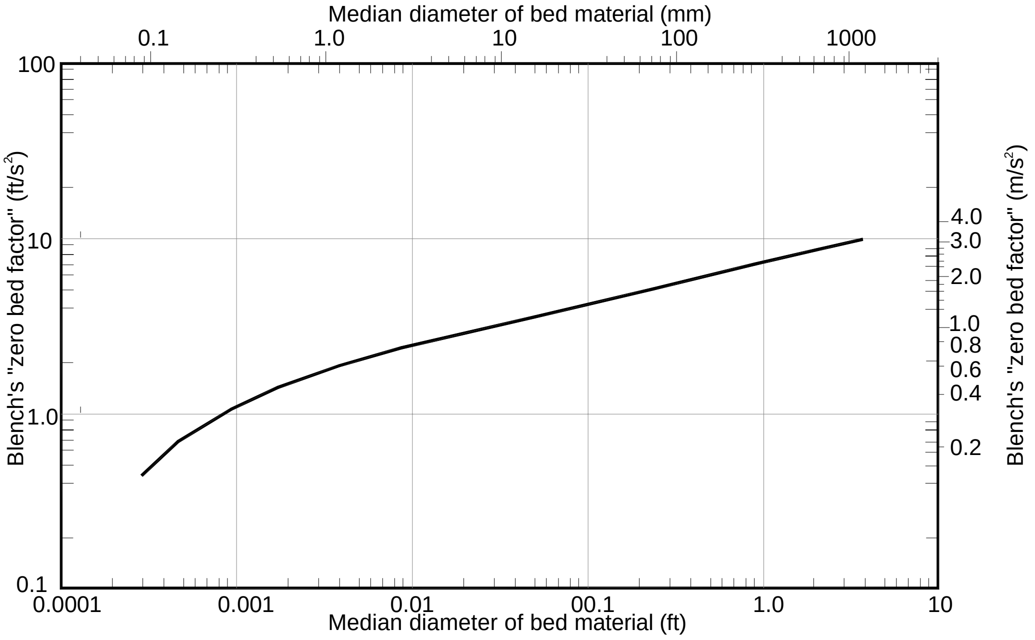
Blench Equation

For zero bed factor (clear water scour)

Note: Units are metric or English

$y_B = q_d^{0.67} / F_{bo}^{0.33}$ (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_{bo} = Blench's zero bed factor, from **Hydraulics Figure 8** (ft/s^2 or m/s^2)



Hydraulics Figure 8. Chart for estimating F_{bo}.

STEP 2

Adjustments to Neil, Modified Lacey, and Blench Results

$$d_N = K_N\, y_N \qquad \text{(Equation 24)}$$

$$d_L = K_L\, y_L$$

$$d_B = K_B\, y_B$$

where: d_N, d_L, d_B = depth of scour from Neil, Modified Lacey, and Blench equations respectively;

K_N, K_L, K_B = adjustment coefficients for Neil, Modified Lacey, and Blench equations as shown in **Hydraulics Table 6**.

Hydraulics Table 6. Adjustment coefficients based on channel conditions

Condition	**Neill - 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

3.4 Additional Reading

The following texts are recommended reading for those interested in learning the fundamentals of hydraulic analysis.

Chaudhry, M. H. 1993. Open-channel flow. Prentice Hall, Inc., New Jersey. 483 p.

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[15] Hoffmans, G. J., and Verheij, H. J., 1997. Scour Manual, A. A. Balkema Publishers, Brookfield, VT.

[16] Maynord, S. 1996. "Toe Scour Estimation in Stabilized Bendways", Journal of Hydraulic Engineering, ASCE, v122, n8, p460.

[17] Laursen, E. M., and M. W. Flick, 1983. Final Report, Predicting Scour at Bridges: Questions Not Fully Answered – Scour at Sill Structures, Report ATTI-83-6, Arizona Department of Transportation, 1983.

[18] Simons & Senturck, 1992. Sediment Transport Technology, Water Resources Publications, Littleton, CO.

CONSTRUCTION CONSIDERATIONS APPENDIX

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.

This appendix is intended to provide a broad overview of construction considerations. Because site-specific conditions and project-specific criteria influence construction approaches significantly, a comprehensive discussion of construction techniques is beyond the scope of this appendix. 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.

1 SITE LIMITATIONS

Site limitations such as terrain, location of utilities, land ownership, infrastructure, sensitive landscapes, stockpiling/disposal and access are constructability issues that may influence many design components. For this reason, site limitations should be considered during all phases of design and implementation and are best 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.

1.1 Site Access

While some types of stream restoration or rehabilitation projects can be constructed solely with hand labor, the construction of most projects will require heavy equipment at the project site. Site-access considerations include ingress and egress for construction staging, access to the stream and any planned stockpile areas (e.g., construction and waste materials), and dewatering and sediment-control systems.

Construction Considerations Figure 1.
Heavy equipment access for a log cribwall construction on Beaver Creek.
Source: Inter-Fluve, Inc.

- use an existing access point,
- construct an access point,
- construct a temporary construction platform adjacent to the stream,
- create an in-channel access point during low-flow conditions or where the channel has been dewatered such that the work area is dry (e.g., exposed gravel bar), or
- use a spider excavator, a floating platform or heavy equipment as construction access within a wetted channel.

Construction Considerations Figure 2.
Spider Excavator placing rocks and logs in Whatcom Creek.
Source: Inter-Fluve, Inc.

Access through a riparian area should be carefully marked to minimize impacts and to aid in the subsequent restoration efforts. Mitigation for construction activities will be necessary. See

Chapter 4, *Developing A Restoration Strategy* for more information about mitigation.

1.2 Access Roads

Temporary access roads may need to be constructed to transport materials and equipment to the site. 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 vegetation and habitat character. 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.

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.

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 no impact to underlying vegetation or soils. Similarly, dry conditions reduce many impacts associated with soil compaction and soft soils.

In summary, the following circumstances should be considered in designing and timing construction access to the site:

- refueling location and frequency,
- sensitivity of landscape soils and vegetation,
- size and character of equipment,
- frequency of ingress/egress, and
- season and soil moisture.

1.3 Construction Platform

Construction of most bank-protection projects will require some degree of heavy-equipment mobility along and near the bank. 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, the majority of 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.

Construction Considerations Figure 3.
Construction platform for a major streambank reconstruction on the Little Miami River in Ohio**.**
Source: Inter-Fluve, Inc.

Between-bank construction platform. When site restrictions require that construction must occur within the channel banks, there are a number of options. 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.

1.4 Utilities

Utilities are often found near or within a project 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 should 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.

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 if it increases or decreases cycle time for construction operations.

Construction Considerations Figure 4.
Stockpiling logs and soils on Beaver Creek.
Source: Inter-Fluve, Inc.

2 CONSTRUCTION PERIOD

The timing of construction will often be determined by regulatory mandates intended to reduce water-quality impacts to critical 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's Area Habitat Biologist for information on work windows (see Appendix B, *Washington Department of Fish and Wildlife Contact Information*). 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 Hydrology and Precipitation

Hydrologic analyses that can be helpful in determining an appropriate time for construction include analyses of seasonal variations in average and extreme 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 Appendix D, *Hydrology*.

Hydrologic analyses should also be conducted to determine the appropriate method and design for dewatering. Dewatering systems must be designed not only to handle average flows, but also to handle anticipated high flows associated with storms or other hydrologic events during the construction period. 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 bank-protection project, the potential consequences of inundation due to high seasonal flows should be estimated and the risk of such occurrences calculated using hydrologic statistics. These analyses can be conducted for any stream using daily gauge data. They are further discussed in Appendix D.

2.2 Revegetation

Successful revegetation is largely determined by the timing of revegetation efforts. Ideally, revegetation components of a bank-protection project will be conducted to maximize the potential for survival of the plant materials installed and to enhance their ability to grow quickly. Furthermore, 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. For further discussion of planting considerations, refer to Appendix H, Planting Considerations and Erosion-Control Fabrics.

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. 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.

Construction Considerations Figure 5. Installing rooted willow cuttings during fabric encased soil lift construction. Source: Inter-Fluve, Inc.

2.3 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 Appendix D).

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 (see Appendix H). The Washington State Department of Ecology has guidance on erosion-control techniques in the *Stormwater Management Manual for Western Washington*[1].

In addition to 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.

3 DEWATERING

Dewatering a streambank construction area may be essential for constructability and to provide a required degree of sediment control for water-quality protection. The design and implementation of dewatering systems is often underemphasized. At a minimum, dewatering systems must be able to divert one-year flows anticipated during the period of construction. A one-year flow is the greatest flow that has a 100-percent chance of occurring every 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 one-year flow may be appropriate; but, during the winter, preparation for a greater-magnitude flow event will likely be required. The possibility of inundation should be planned for in the design of dewatering systems. The probability of a dewatering system being overwhelmed by storm flows can be determined using standard hydrologic analyses. When available, the analyses should be based on data sets derived from peak flows covering the construction window for 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.

Dewatering can be accomplished on small streams by diverting flow around a project. On larger streams, cofferdams can be used. 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. 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[22] and National Marine Fisheries Service specifications to prevent loss of fish. Any diversion will similarly require a recovery plan for fish left behind when the water is gone. Fish can be recovered manually from remnant pools and transferred by bucket to downstream reaches.

Construction Considerations 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.

3.1 Cofferdam Isolation

An alternative to diverting a channel is to use a cofferdam, which isolates the project site from the water in the channel (see variant of this technique in **Construction Considerations Figure 6** above). 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. **Construction Considerations Figure M-1** shows an example of a cofferdam. 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.

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.

3.2 Partial Isolation - Working in Wet

An alternative to dewatering solely for the purpose of sediment control is the use of partial isolation (see **Construction Considerations Figure M-2**). Partial isolation is still applicable even when dewatering is not necessary for installation purposes. This method 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.

4 HEAVY EQUIPMENT

There is a wealth of heavy-equipment types 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).

Construction Considerations Figure 7.
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 **Construction Considerations 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. They can be practical and cost-effective for any imported earth materials, including wood, large boulders, fabric or artificial materials.

Construction Considerations *Figure 8:* 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.

Horses. Horses can also be used for transporting materials and as a substitute for heavy equipment in many remote or access-limited areas.

5 REFERENCES

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ANCHORING AND PLACEMENT OF LARGE WOOD APPENDIX

1 INTRODUCTION

This appendix describes methods and design considerations for anchoring wood in waterways, including passive anchors, flexible anchors, and rigid anchors. Structures made of single or multiple pieces of large wood, boulders and other materials are commonly used in streams and rivers as habitat features, fish-passage structures and bed- and channel-stabilization features. The 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 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 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, disturbance plays a pivotal role in channel evolution and habitat productivity. In reference to bank protection, the movement of wood is undesirable, whereas restoration activities should accommodate and encourage disturbance where possible[1].

The selection of correctly sized large wood is fundamental to the success of a project because it minimizes the need for anchoring, although stability is enhanced by proper placement and anchoring. Naturally stable wood is discussed in the *Large Wood and Log Jam* section of these guidelines. Complex placements that emulate natural conditions are best because they have the greatest flexibility in adapting to changing channel and flow conditions with long term stability[2]. Gravel ballast of similar size to what occurs naturally in the stream bed is the first anchoring option that should be considered, followed by other types of passive anchors, flexible anchors, and finally rigid anchors. As risks associated with large wood increase, more highly engineered solutions may be required.

Successful large wood projects have used many types and methods of anchoring. Site conditions, project objectives and economic constraints govern which types are used.

2 FORCES ON WOOD IN STREAMS

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, and the unpredictable potential for a structure to collect additional debris. In addition, partially buried logs extending into the current are often subjected to substantial oscillation and vibration, which are complex and difficult forces to calculate. 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 2.0 is recommended for situations that present risk to life or infrastructure. Factors of safety as low as 1.0 may be appropriate for enhancement projects in remote areas. Professional judgment is necessary and public safety concerns, including boat use, should always be addressed in the application of instream projects.

The analysis of wood stability is in part dependant 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 dependant on stream order[3], something that we should 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 a natural system that the simplified engineering discussed here only indirectly grasps.

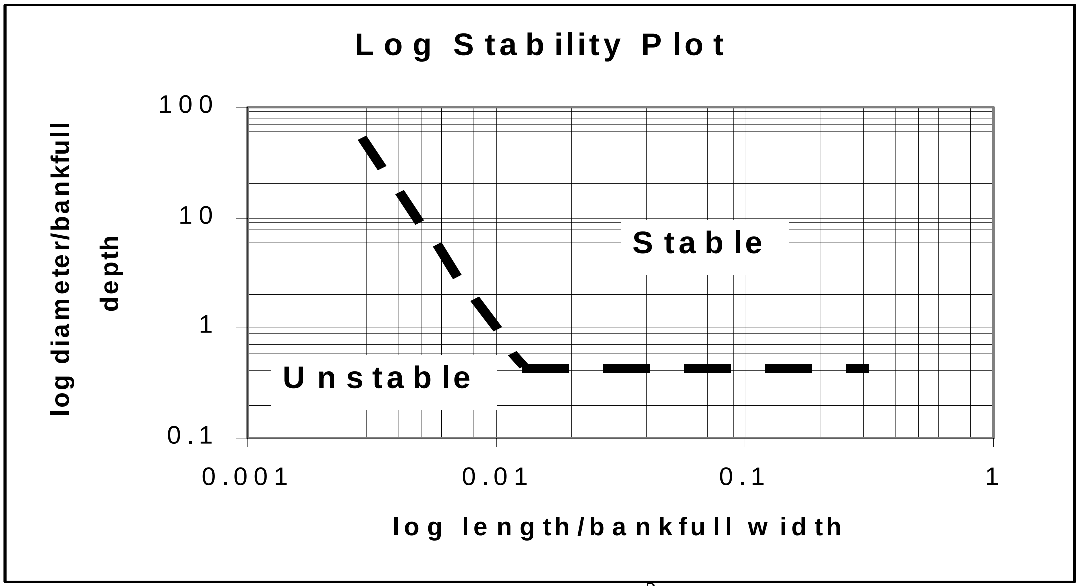

Figure 1 Example log stability plot, from Abbe[3].

For projects on major rivers, or those that involve the placement of a large number of pieces, an empirical approach used by Abbe[4] should be employed. Abbe surveyed and cataloged existing wood pieces at study sites, measuring size and channel geometry and determining stability. A dimensionless plot of log length/bankfull width vs. log diameter/bankfull depth was developed which differentiates stable and unstable zones (see **Figure 1**). Bankfull width and depth should be determined for the reach where natural, stable wood is measured. This simple relationship does not substitute for thorough stability analysis but will serve as a planning tool and will provide verification of results.

A complete analysis of forces on wood in streams can only be accomplished with momentum and energy analysis in combination with flow studies. At present, too little is known of the various coefficients and the role of specific forces to justify such a detailed analysis. Designing and building instream structures with large wood is a rapidly evolving science, so the practitioner should stay aware of advances in modeling that could place complex analyses within easy grasp. The current standard approach to analyzing the stability of wood in streams is to view logs or log jams as flow obstructions. 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. **Figure 2** below shows the location and direction of some of the forces acting on a log or structure.

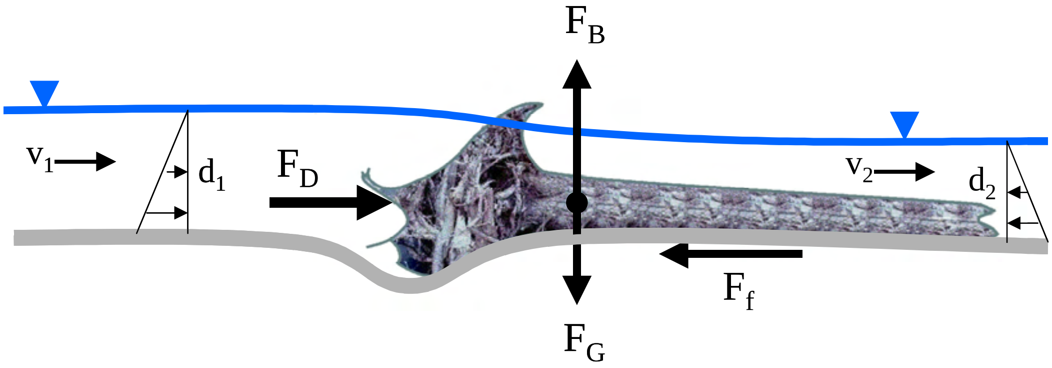

Figure 2 Forces acting on a submerged log.

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 displaced by the log. Wood will not float provided that the buoyant force does not exceed the weight of the log. These forces are calculated as follows:

Equation 1

$$F_G = Vol_{wood} \gamma_{wood}$$

Equation 2

$$F_B = Vol_{woodSubmerged} \gamma_{water}$$

where (γ is the unit weight of wood (ρg, or density times gravity) and water as indicated and *Vol* is the volume of total wood and submerged wood as indicated. The 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. The volume of the submerged log must be determined from predicted flood elevations. Many designers have assumed the fully submerged condition for ballasted log jams in the worst-case scenario. Castro and Sampson suggest 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 describe in detail ballast boulder design. Drury[7] outlines a gravel ballast design method which, though not discussed in detail here, 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 dimension a frictional force is balanced against fluid forces on the upstream face of the log or root wad. Friction, F_f is developed between the log and channel substrate, the submerged 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, $\mu = \tan\phi$:

Equation 3

$$F_f = \mu F_N$$

The coefficients of friction range from 0.4 for fine sand to 0.9 for gravel and boulders. Coefficient of friction is the tangent of the angle of repose for the material. There is no empirical data to justify the application of this model to real situations, although all of the references cited here employ 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 determined with the empirical relationship,

Equation 4

$$F_D = \left(\frac{v^2}{2g}\right) A_{SW} C'_D \, \rho_w$$

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). 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[8, 5,] . 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 .

The drag coefficient is strongly influenced by boundary conditions, particularly when the blocking ratio, B, is greater than about 5 or 10 percent . The blockage ratio is:

Equation 5

$$B = \frac{Ld}{A}$$

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

Equation 6

$$C_D = 0.997 C'_D (1 - B)^{-2.06}$$

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, although 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) found that in streams less than 16 feet 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]:

Equation 7

$$\sum F = \rho Q (v_2 - v_1)$$

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:

Equation 8

$$F_P = \frac{1}{2} \gamma d^2$$

where (is the unit weight of water and *d* the depth. Shear may be neglected if it is negligibly small, 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 would be 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].

2.1 Types of Anchors

There are four common alternatives for the placement of large wood in a river. In order of preference for habitat formation, they are:

1. **No anchors** -- where wood is supplied to the stream and allowed to be naturally stable or, as conditions develop, moved by the flow.
2. **Passive anchors** -- where the weight and shape of the structure is the anchor, and movement at some flow level is acceptable (includes ballast).
3. **Flexible anchors** -- such as tethering the structure so there is some degree of movement flexibility with varying flows.
4. **Rigid anchors** -- holding the logs permanently in place with no movement allowed.

2.1.1 No Anchors

In the sphere of restoration activities, wood placement without the benefit of specific structure or anchoring is preferred when the restoration of ecosystem functions is a specific goal. Wood movement and the disturbance it causes are part of a productive ecosystem[15] where one looks at landscape level restoration[16]. Passive anchoring is a part of natural wood stability, but it is an anchoring method when we specifically employ it to create a stable wood structure. The no-anchors method simply states that one assumes full liability for risks incurred from mobile wood in a stream system. This approach works well in remote areas or for projects with a large land area and a single landowner (e.g. industrial timber).

2.1.2 Passive Anchors

Passive anchors use the weight and shape of a structure itself to provide resistance to movement. Logjams can be anchored by large wood pieces (whose own weight will stabilize them), rootwads, and frictional resistance with the bed (see Section 2, *Forces on Wood in Streams*). Bracing one or both ends of a log against trees or bedrock is also a form of passive anchoring (pinning, **Figure 12**). Individual boulders can be placed within a woody matrix without cabling because they provide additional weight for structural stability. Ballasting a structure with gravel is also passive anchoring (see **Figures 3, 4,** and **5**). A debris structure can be considered passively anchored as long as they are cabled or pinned in a rigid matrix but remain unattached to any exterior anchors.

The structure may 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.

2.1.3 Flexible Anchors

Flexible anchors or tethers use materials that are similar to those used in rigid anchors, however, in this case, they allow the large wood structure to shift with changing flow stage or direction (see **Figure 9**). 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. In certain circumstances this may be considered a desirable outcome, although in most situations local scour is not acceptable and the tether must be designed to prevent the structure from moving near the bank. Secure tethering requires that anchors be attached at several points on the structure to prevent unlimited twisting. Tethered structures float and allow flood flows to pass under them until the depth of water exceeds the length of the tether, presumably reducing stress on the structure[17]. Gippel notes a decrease in the coefficient of drag with increasing log height over the bottom, reaching a minimum when it is floating. However, flexible anchoring introduces dynamic forces that add stress to the anchoring system. Structures are often tethered to points both on the bank and in the channel. Flexible anchors are appropriate for backwater and other low velocity areas, but should not be used in high-energy stream channels. Flexible anchors also pose the greatest risk to public safety due to floating wood and exposed cable.

2.1.4 Rigid Anchors

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. Some structures that are embedded in the bank can lead to continued bank failure if they shift or move downstream. Due to the anticipated permanence of this approach, it is important that the structure being anchored is properly designed and positioned. The anchoring methods most commonly used include cabling or pinning to a deadman, bedrock 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 is an example of a rigidly anchored restoration or mitigation project. Logs embedded in a barb, groin, rock toe and revetment are examples of rigid-anchor bank protection structures (see **Figure 11**).

2.2 Methods of Anchoring

There are seven common methods of anchoring large wood including:

1. **Ballast** -- the addition of weight to the structure.
2. **Pilings** -- trap large wood behind or between wood poles driven into the bed or banks.
3. **Cabling or Chaining** -- secures large wood to itself or other objects.
4. **Pinning --** trap large wood in existing vegetation or pin one log to another with

rebar pins or bolts.

5. **Deadman Anchors** -- buried objects secured to the large wood that resist removal by virtue of the weight of the soil mass above it.
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

2.2.1 Ballast

Any object that adds to the weight and frictional resistance of a structure is considered ballast. The most commonly used ballast material is rock ranging from gravel to boulders. If ballasting with gravel, risk of failure can be high, considering that if the gravel is the same size or smaller than the streambed alluvium, then it could be washed away by floods, releasing the log. This creates a risk to downstream property, a reduction in mitigation value and a loss to the restoration project at that location. Careful design reduces this risk. Sediment transport off of the structure can be minimized if the top of the structure is designed to match the floodplain elevation. By mimicking natural floodplains, vegetation will become established and sediment deposition will occur during most flood events.

Ballasting log jams with gravel has become standard practice (see **Figures 3, 4,** and **5**). Since gravel has over twice the bulk density of wood, gravel ballast placed over the jam counteracts buoyancy[18]. This leads to long-term stability by providing a substrate for plants to grow and form persistent features in the same fashion as vegetated bars or islands. Individual logs imbedded in gravel are much more stable, resisting incision and general bed scour. The factor of safety also improves over time due to saturation of the wood and a subsequent increase in density.

A log structure can also be anchored by confining it with boulders, without direct, permanent connection between the various parts. Examples include logs imbedded in a boulder cluster or in a groin (see **Figure 11**) or burying the log in the bank with added boulders for ballast (see **Figure 6**). Buoyancy as well as hydraulic forces must be accounted for in design. When calculating ballast requirements, use the submerged weight of the material. For common rock materials, the submerged weight is 60 percent of its weight in air.

Another approach to ballasting is to stack additional logs on top of a structure. Logs that remain above the designed 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 the large wood using cables or chains. This increases the log's submerged weight and its friction with the bed. Concrete blocks can also be used but, because they are unnatural features, they are not preferred; if concrete blocks are used it should be in locations where they will remain completely buried. 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. In addition, concrete is not allowed in many bank protection or mitigation projects. See *Cabling and Chaining* below for risks.

2.2.2 Pilings

Where equipment access allows and soils are appropriate, structures can be anchored with piles (see **Figure 7**). Pilings are appropriate in streams with moderate to fine-sized bed material. Hard clays, cemented hardpan and bedrock will obstruct pilings. Very coarse, cobble/boulder substrate will prove difficult for piling placement. Pointed steel caps will aid in driving log pilings into a gravel/cobble bed. Sharpening one end of the log and driving it in with an excavator bucket may be sufficient in streams with fine-grained bed material. Pilings can also be pushed horizontally into banks as long as soil composition is able to provide appropriate structure.

In streams that have bed and bank material that is too large or compacted for this approach, pile-driving equipment can be used, although it is not a common practice. Other pile types are possible, for instance steel H-pile or pipe, but this is not frequently applied either. Pilings have also been installed by excavating a hole, installing the pile and backfilling the hole. This may lead to increased erosion of the disturbed soil and failure of the pile.

The matrix of pilings, logs, sediment and vegetation may be all that is necessary to hold a structure together. If necessary, pins or cables are used to attach materials to pilings. Logs can be wedged between pilings and held in place by water pressure or ballast. This approach has also been used successfully for building log jams. Cable strung between a number of pilings has been used to hold woody debris in place. This has been particularly successful in holding small debris in scour holes to promote the deposition of fine sediment.

Typical piling anchor designs require one-half to two-thirds of the piling length 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 and forces acting on the piles. Additional pilings away from the scour zone may be required as they are in some designs of engineered log jams (see example drawings in the discussion about Engineered Log Jams in the *Large Wood And Log Jams* Chapter). For critical applications with high risk factors, a professional engineer should determine the structural requirements for using pilings as anchors.

2.2.3 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. Rope or straps of synthetic material may 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 the structure itself is under too high a stress and should be reevaluated. The designer should ensure that more natural methods, like ballasting, cannot be applied effectively to the situation.

Cable is available in galvanized and non-galvanized forms. Galvanized cable has the advantage of being resistant to corrosion but should still be cleaned prior to the use of adhesives such as epoxy. 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.

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 clamps ranges from two for 3/8-inch-diameter cable to five for one-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.[19]

When attaching cable to logs, always remove the bark from the area enclosed by the cable, otherwise the cable will loosen as the bark rots. To prevent the cable from slipping along the log, insert the cable through a drilled hole in the log or create a notch around the log using a chainsaw or axe. If rigid anchoring is required, a winch is necessary to tension the cable properly before tightening the attachment hardware. Following the placement 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, care should be taken not to girdle the tree.

Cable leading to buried anchors through a rip rap blanket becomes abraded as the wood moves with changing flow. There are numerous instances 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.

2.2.4 Pinning

The word “pinning” has entered the restoration idiom with two different meanings. One is a steel 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 (see **Figure 12**). This latter meaning recognizes an often-observed natural method that should be employed whenever possible. Often, increasing hydraulic forces increase the pinning effect and resulting stability. If there are opportunities to apply this technique, it should be preferentially used.

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 structure to fail catastrophically. However, the use of pins leaves less non-native material in the channel after failure.

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 or 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 variable 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.

2.2.5 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 pushes against a wedge of undisturbed soil when tensioned. 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 set by providing tension on the anchor. The tension causes the deployment of legs or plates, which actually provide the anchorage. These anchors depend entirely on the shear strength of the soil and, therefore, are not acceptable in 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 more rapidly and gain inroads behind a structure or into undisturbed areas. 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.

Designing deadman anchors requires information on soil characteristics, such as the strength and tightness of soil, which will determine the style and number of anchors required. In design, a simple pullout analysis should be completed to determine the appropriate depth and style of anchor for a particular application. In addition, the manufacturer’s specifications should always be followed for commercial anchor systems.

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.

2.2.6 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 8** and **9** 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. There are many types of anchor adhesives 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’s 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[20]. 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.

2.2.7 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 **Figure 10**) or a log jam may be piled up to an elevation above the floodplain and buried in gravel ballast (see **Figure 4**). 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. Creatively using 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 natural 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.

2.3 Placement Considerations in Streambank Restoration 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 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. It has been found that fish use increases when large wood is included in rock revetment projects[21, 22]. 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 [23] 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. **Figures 9, 10,** and **11** show several bank-protection projects successfully incorporating large wood.

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[24] 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.

2.3.1 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[25] and a greater diversity of channel features with associated aquatic communities[26]. 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 erode, 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 end of a bend as momentum resists wood transport through the lower third of the meander bend. This is a good place to expect wood recruitment on placed large wood.

2.3.2 Large Wood in Rock Toes or Revetments

Engineered log jams provide immediate, stable habitat and bank protection. Logjams that have been installed in front of rock toes or revetments as mitigation have provided some habitat value. With the effective use of wood in streambank protection on the rise, it is wise to consider using wood instead of rock if possible. Trees with rootwads are the best material to use.

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.

Based on a review of recent riprap revetment projects with large wood, two techniques show the most promise for stability and habitat. In low energy streams large logs are embedded in a boulder toe with rootwads extending in the channel. The logs are 30 feet long, placed at the elevation of the streambed, embedded 15 feet into the bank and ballasted. The upstream angle can be from 30 to 50 degrees and other logs can be attached to them to create greater complexity. In confined streams with deep flood flow, additional logs are placed higher to collect debris. The second technique involves the construction of log jams independent of the rock face to avoid jeopardizing rock placements and bank protection. See the Logs and Log Jams Technique for further information.

2.3.3 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 11**). However, there are a few added complications. 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. A good understanding of large wood transport/supply, hydrology, hydraulics and geomorphology are important. If the structure is properly designed, large wood will stay intact and improve habitat. Risk analysis and design requirements will help determine the applicability of wood in barbs at a given site.

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. There is usually more rock in groins than in barbs, so wood can be held more securely.

Figure 1 North Fork Stilliguamish River, Snohomish Co., log jam using gravel ballast.

Figure 2 North Fork Stilliguamish River, Snohomish Co., log jam using gravel ballast.

Figure 3 Gorst Ck., Kitsap Co., log bank protection using gravel ballast.

Figure 4 E. F. Issaquah Ck, I90 Sunset interchange, King Co., habitat logs anchored in bank with additional boulder ballast.

Figure 5 Salmon Ck, Jefferson Co., channel restoration project. Piling used to increase stability of log jam.

Figure 6 Boulder anchor. Cable should be protected from abrasion with hydraulic hose or similar protection.

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Figure 7 Sauk River side channel near SR 530, Skagit co. Large wood tethered on long cables to large drilled boulders.


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Figure 8 Samish River, Skagit Co. Large wood anchored using a combination of techniques; rock ballast, cabling, and pilings.


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Figure 9 Cedar River, Darre Dam project, King Co. Large wood anchored in groin.

Figure 10 Bear Ck. Pacific Co. Log pinned by existing live tree.

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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 Office of Permit Assistance can help you determine which state and federal permits are needed for your project. The Office of Permit Assistance may be reached by phone at 360-407-7037 or (800) 917-0043, or on line at http://www.ecy.wa.gov/programs/sea/pac/index.html. The Office of Permit Assistance also publishes The Permit Handbook: Commonly Required Environmental Permits for Washington State[1], available on line at the above web address. 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 should be contacted for an authorization to lease state land. Early contact not only prevents construction delays, it can result in a better project. Delays in involving the necessary agencies increase the likelihood of project rejection or costly design modifications.

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 permit process, including any environmental review under the State Environmental Policy Act (SEPA) or National Environmental Policy Act (NEPA), combined with the relatively short allowable work period for many types of in-stream construction projects, should be carefully considered when developing project planning, design, and construction schedules. Project proponents must plan ahead, especially when time sensitive grant monies are utilized. In addition to 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, while 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 and current information.

1 HOW THE ENDANGERED SPECIES ACT AFFECTS PROJECT PERMITTING

Recent listings of several salmonid fish species in Washington State under the ESA have added complexity to obtaining permits for work in or around water. The Endangered Species Act (ESA) applies to everybody subject to the jurisdiction of the United States, including state and federal agencies, cities, counties, tribes, and individuals. The purpose of the ESA is to ensure the long-term survival of native fish and wildlife and the ecosystems upon which they depend. One component of ESA compliance requires obtaining a permit for any action that may "take" 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 Fisheries (formerly the National Marine 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 has jurisdiction over all fish and wildlife species whose life cycles reside mainly in the marine environment. 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 positively or negatively affect any listed fish, wildlife, or plant species require review by NOAA Fisheries 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. **Section 7 Consultation**
   A section 7 consultation is required whenever a federal nexus exists for a project; that is, for all activities carried out, funded, or permitted by a federal agency. 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 and/or USFWS, as appropriate[3]. That federal agency is referred to as the "action" agency.

   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:

   a. "No effect" indicates there is no probability of any effect on listed species by the proposed activity. A "no effect" determination does not require NOAA Fisheries 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 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. NOAA Fisheries 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 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.

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 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 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 Habitat Conservation Plan (HCP) to NOAA Fisheries 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 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]

3. **Section 4(d) Rule**
   Section 4d of the ESA allows NOAA Fisheries 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 4d exemptions may apply to different species or runs of fish. Project proponents should contact NOAA Fisheries 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 and USFW, 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!

2 COMMONLY REQUIRED PROJECT PLANNING CHECKLISTS, 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 is a summary of that provided in The Permit Handbook: Commonly Required Environmental Permits for Washington State, where more detailed information is available. Another good source of information is Guide for the Acquisition of Permits Commonly Needed for Salmon Habitat Restoration or Enhancement Projects in the State of Washington[5]. This is a comprehensive document on permit acquisition. It provides guidance on permits commonly required for salmon habitat restoration projects, information required for permit applications, the content of environmental review under the State Environmental Policy Act, and compliance with the ESA (including preparation of a biological assessment).

2.1 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. In the case of 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. 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). Refer to WAC 197-11-922 through 938 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, after which, permit processing can proceed if no further 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. The Lead

Agency will begin the process by issuing a determination of significance (DS)/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 there are likely adverse environmental impacts 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.

2.2 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 environmental impact statement (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.)

2.3 Joint Aquatic Resource Permits Application (JARPA) and Associated Permits

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.

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 state waters. This approval is issued by the WA Department of Fish and Wildlife.

- *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 WA Department of 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 the Section 404 permit. *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 the Section 10 permit.
- *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 fish habitat enhancement and watershed restoration projects. They are:

1. **Streamlined Process for Fish Habitat Enhancement Projects**
   Projects qualifying under RCW 77.55.290 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 Washington Department of Fish and Wildlife and local government have 15 days to determine if the project qualifies under RCW 77.55.290. If the project qualifies, Washington Department of Fish and Wildlife must approve or deny the HPA within 45 days.

   To qualify for the fish habitat enhancement expedited permit application process, projects must accomplish one or more of the following:

- Removal of human-made fish passage barriers; or
- Restoration of an eroded or unstable stream bank using bioengineering techniques; or
- Placement of woody debris or other in-stream structures that benefit natural reproducing fish stocks
- <u>and</u> must be approved in one or more of the following ways:
- By WA Department of Fish and Wildlife, 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 WA Department of Fish and Wildlife, as a department-sponsored fish enhancement or restoration project,
- Through the review and approval process for Conservation District sponsored projects, where the project complies with design standards established by the Washington Conservation Commission through interagency agreement with the U.S. Fish and Wildlife Service and the Natural Resource Conservation Service, or
- Through a formal grant program established by the legislature or the Washington Department of Fish and Wildlife 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. The 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 which 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 Office of Permit Assistance for more information regarding the expedited permit process.

2.4 Aquatic Use Authorization

Anybody wishing to use state-owned aquatic lands (including owners of adjacent lands) must get authorization from the Washington Department of Natural Resources (DNR). In addition to 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.

3 OTHER PERMITS THAT MAY APPLY

The following is not an all-inclusive list, but covers most other permits that may apply. Again, contact the Office of Permit Assistance for further information.

3.1 Forest Practices Approval

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 permit is issued by the Washington Department of Natural Resources.

3.2 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. The Washington Dept of Ecology reviews the certification and the proposed project for compliance with state environmental requirements.

3.3 Noxious Aquatic and Emergent Weed Transport Permit

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.

3.4 Short-term Water Quality Modification

Required for the use of aquatic herbicides or pesticides, including those used to control noxious and non-noxious aquatic plants. The WA Department of Ecology issues this permit.

3.5 Stormwater Discharges from Construction Sites

Required for construction that disturbs five or more acres. The Washington Department of Ecology issues this permit.

3.6 Hazardous Waste Release Notification

The Washington Department of 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.

3.7 Archeological Excavation Permit

Required when excavating, altering or removing archaeological resources or Native American gravesites. The Washington Department of Community Development, Office of Archaeology and Historic Preservation issues this permit. Historic settlements were often located near waterways.

3.8 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 9 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.

3.9 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 REFERENCES

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[1] Washington Department of Ecology. 1998. Permit Handbook: Commonly Required Environmental Permits for Washington State. Publication Number 90-29. 75 pp. http://apps.ecy.wa.gov/permithandbook/

[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.

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[4] U.S. Fish and Wildlife Service and National Marine Fisheries Service. 1996. Habitat Conservation Planning Handbook. Washington, D.C.

[5] Ecocline Fisheries Habitat Consulting LTD. 2001. Guide for the Acquisition of Permits Commonly Needed for Salmon Habitat Restoration or Enhancement Projects in the State of Washington. Prepared for People for Salmon, North Bend, Washington. 158 pp. http://www.peopleforsalmon.org/permits.html

MONITORING APPENDIX

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 Protect Streambank	Channel cross sections
	Streambank profile
	Bank pins to measure rate of bank erosion
8.1.1.2 Improve aquatic habitat	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

The following references provide details on how to use each of the monitoring variables identified in the above table:

Bain, Mark and Nathalie Stevenson, editors. 1999. Aquatic habitat assessment: common methods. American Fisheries Society, Bethesda, MD.

- This document provides methods for measuring stream cross-sections, stream longitudinal profiles, bank stability, fish passage barrier assessment mostly on culverts/, bed material composition, large woody debris survey, pool/riffle composition, riparian vegetation surveys, and temperature. Governor's Watershed Enhancement Board. 1993. Photo plots: a guide to establishing points and taking photographs to monitor watershed management projects. Salem, OR. 16p. Harrelson, Cheryl, C.L. Rawlins, and J. Potyondy. 1994. Stream channel reference sites: an illustrated guide to field technique. Gen. Tech. Rep. RM-245. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 61p. www.stream.fs.fed.us/PDFs/RM245.PDF

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- This document provides methods for measuring stream water quality variables, cross sections, width/depth ratio, bank stability, macroinvertebrate, macrophyte and fish surveys, bed material, large woody debris, water depths, pool parameters, and riparian vegetation. Moore, Kelly, Kim Jones, and Jeff Dambacher. 1998. Methods for stream habitat surveys: aquatic inventory project. Oregon Department of Fish and Wildlife: Natural Production Program. Corvallis, OR. 35p.

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- This document provides methods for measuring streambank and channel stability, % vegetation overhang and cover, and riparian vegetation species density and distribution. Rosgen, Dave. 2001. A stream channel stability assessment methodology. Proceedings of the Seventh Federal Interagency Sedimentation Conference, Vol. 2, pp. II - 18-26, March 25-29, 2001, Reno, NV

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- This document provides methods for measuring streambank stability. Winward, Alma H. 2000. Monitoring the vegetation resources in riparian areas. Gen. Tech. Rep. RMRS-GTR-47. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 49p.

- 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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[2] 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.

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