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

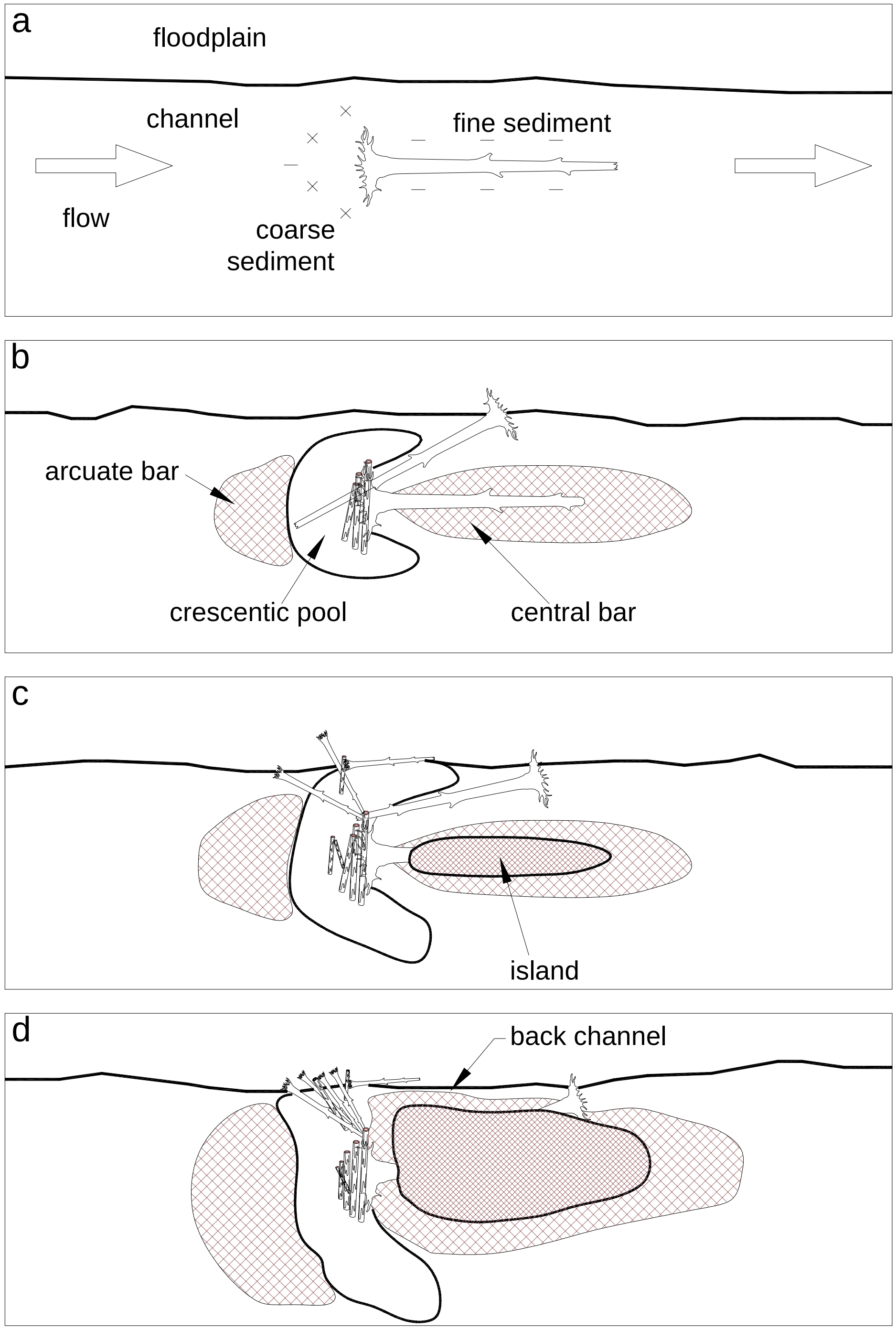
Large wood has a dominant influence on stream habitat and channel formation across the spectrum of time and space.[5] On a large scale, channel-spanning logjams can influence the routing of water, sediment, and wood as well as the processes of channel formation, floodplain formation, floodplain hydrology[6] 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™ 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.

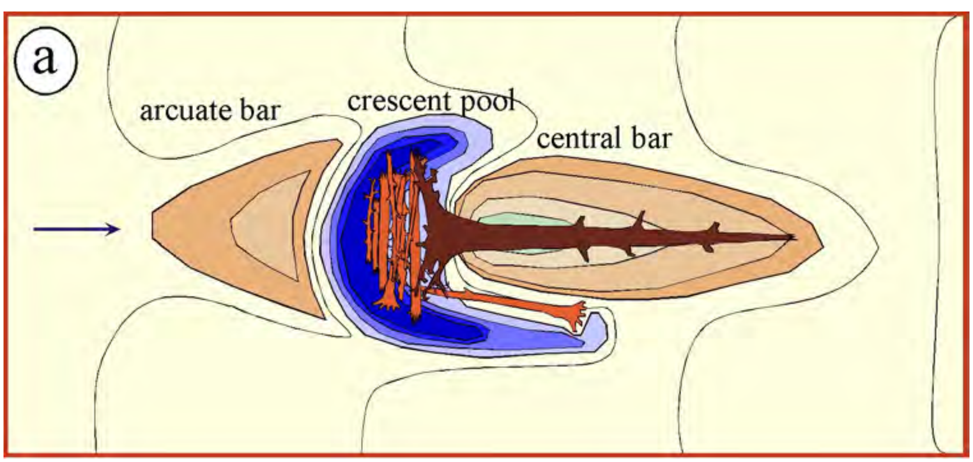
Min Log Diameter (m)	**Bankfull Width 0 to 5m**	**Bankfull Width 5 to 10m**	**Bankfull Width 10 to 15m**	**Bankfull Width 15 to 20m**
	Minimum Length (m)			
0.50	6	13	31	---
0.55	5	11	26	---
0.60	4	9	22	32
0.65	3	8	19	28
0.70	3	7	19	24
0.75	3	6	14	21
Min Volume (m^3)	1.0	2.5	6.0	9.0

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)

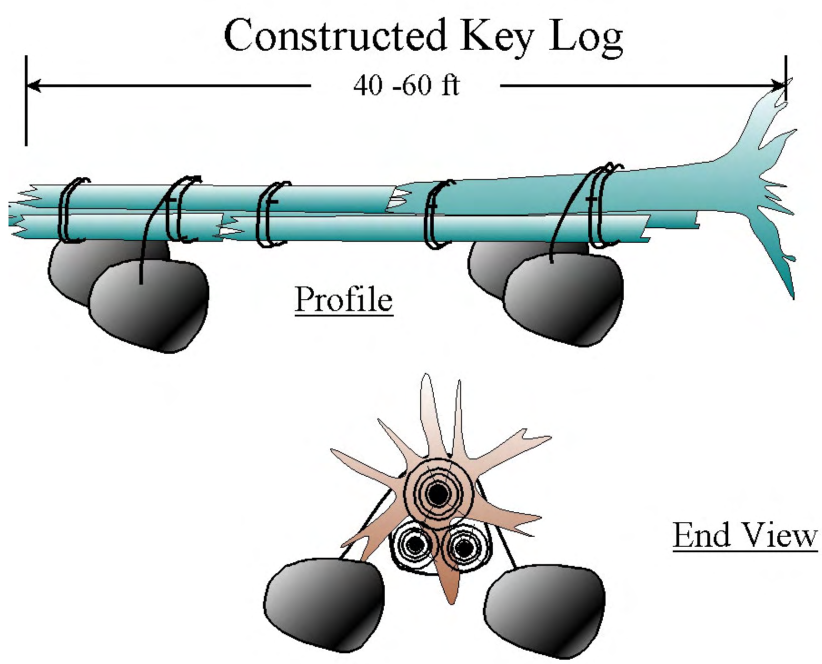
Large Wood and Log Jams Figure 7. LW complex on the Little Hoko River anchored by wedging LW between trees on the bank. (Little Hoko River, Clallam County, Washington)

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™, 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™ is most appropriate in small streams (less than 200 cfs average maximum flow)[4]. This study comparing ELWD™ 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.

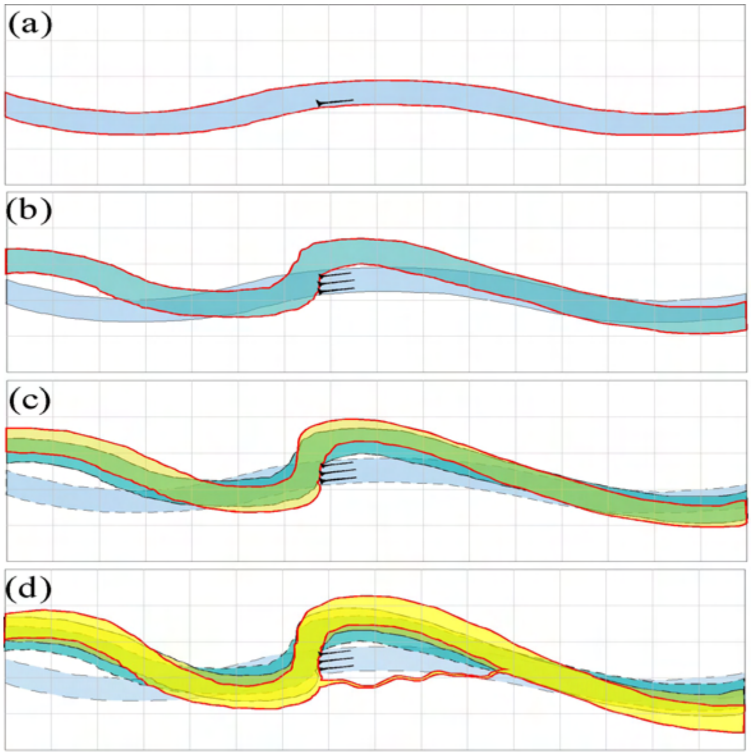
Flood-peak jams. These jams are often mobile during large floods or dam-break events. They may temporarily obstruct the channel and cause a significant backwater, followed by re-mobilization of the accumulation. They frequently deposit in the floodplain against standing trees or shrubs.

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.

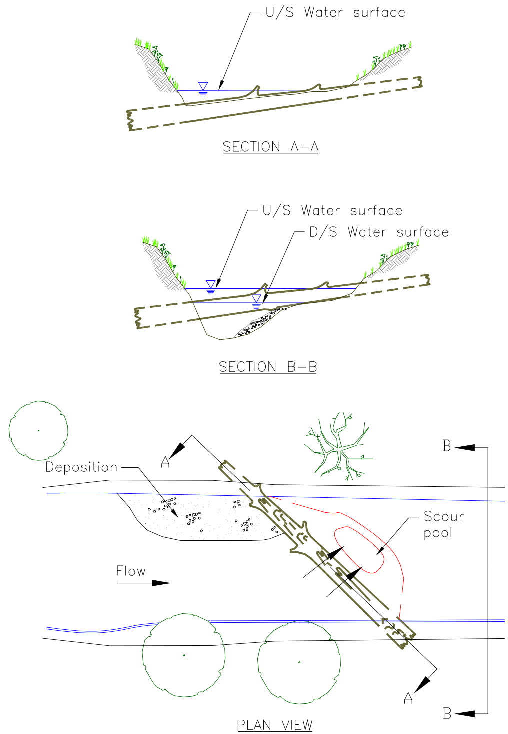
Log sills, or weirs, can be found at many orientations to the flow in natural channels and that approach should be encouraged in small-and-medium-sized stream restorations. Natural sills do not often have a level crest. A sloping-crest sill can both constrict the flow laterally and create plunging flow (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.

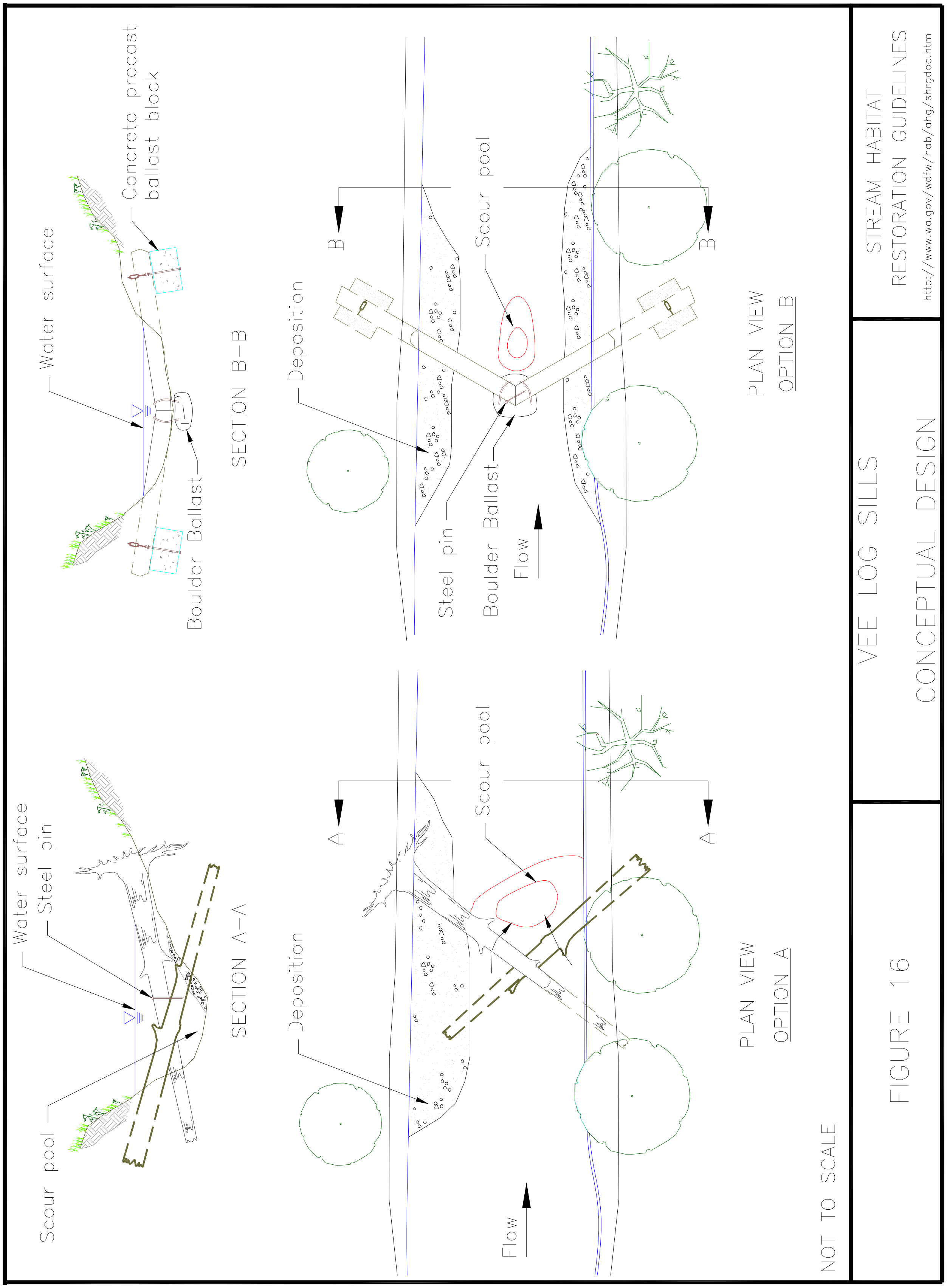
Horizontal-crest log sills develop scour through plunging flow, with the depth of scour dependent on the height of drop and substrate size. Although the horizontal crest aids in log longevity by keeping it continuously submerged, no thalweg develops in the upstream deposition zone. Adding single or double 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.

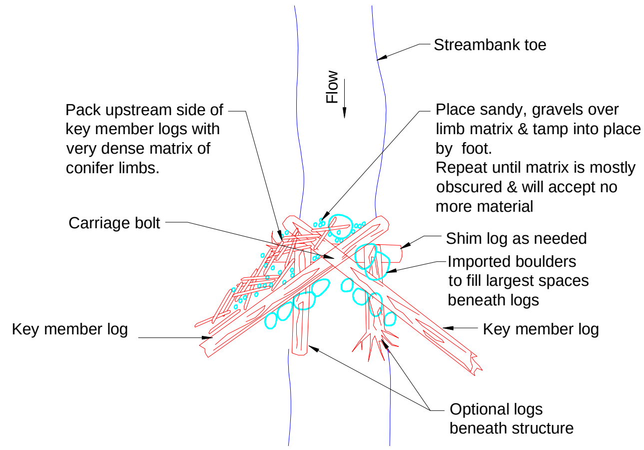
V-shaped sills (in plan view) can be built by burying the ends of two crossing logs somewhere in the center half of the streambed (see **Large Wood and Log Jams Figure 16**). The crests should slope down to the point of the V. Another method is to saw-cut the logs and pin them together at the point of 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.


Scour pool
Water surface
Steel pin
SECTION A-A
Deposition
Scour pool
A
A
PLAN VIEW
OPTION A
Flow
NOT TO SCALE
Water surface
Concrete precast ballast block
Boulder Ballast
SECTION B-B
Deposition
Scour pool
B
B
Steel pin
Boulder Ballast
Flow
PLAN VIEW
OPTION B
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).

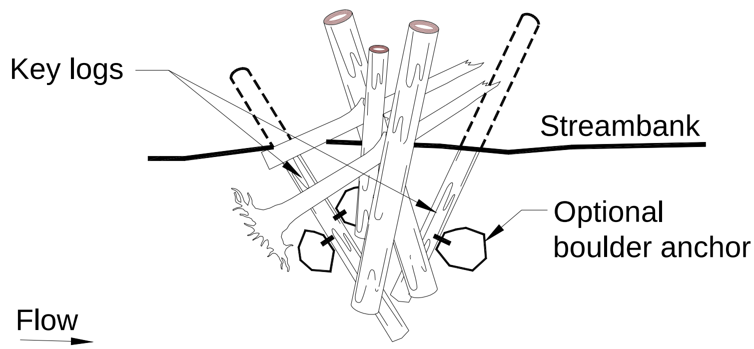
In low gradient or spring-fed channels (low energy systems) both individual logs and LW complexes are used to improve habitat. The low energy or limited vertical drop (hydraulic head) available means that greater constrictions are necessary to create scour. Often 50% or more of the cross-section needs 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.

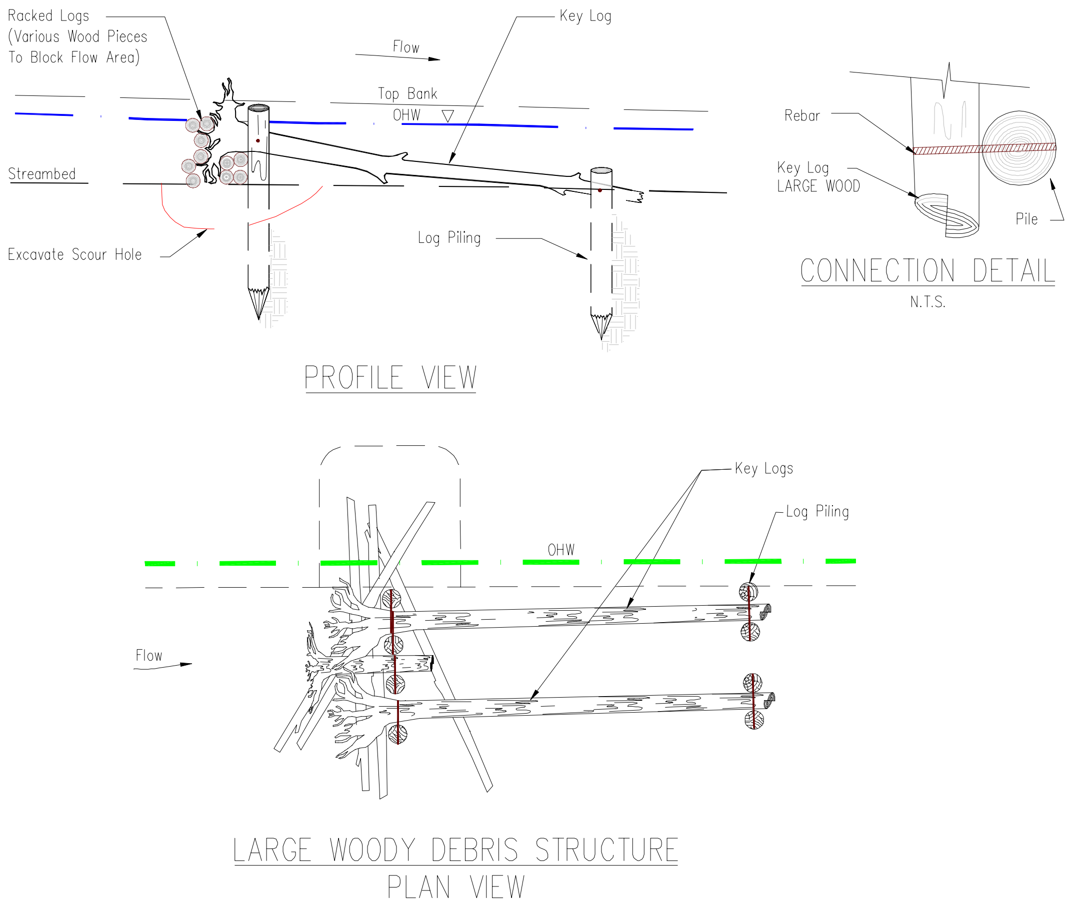
Stabilizing a logjam may require excavation of the streambed or bank to provide a trench for the key piece(s). The depth of excavation depends on channel hydraulics, substrate characteristics, bank material, channel dimensions, existing vegetation and the size of wood. Once a key piece is placed in a 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*

Name of particle	*Size Range 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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