Chapter 10 Woody Material

10-1 Introduction

WM plays a critical role in many Washington streams through its influence on stream geomorphic processes and aquatic habitat formation. This chapter determines when LWM is appropriate, and how to design WM features that meet habitat and stability objectives. The best approach for habitat enhancement and restoration is to mimic or replicate natural conditions to which salmon and other aquatic species have adapted. Site natural wood loading conditions provide a reference to guide quantities, sizes, and placement of WM as a component of habitat enhancement and restoration.

Installation of instream wood has become a common stream enhancement and restoration practice in Washington State. In many forested streams, wood is a fundamental driver of fluvial geomorphology—the shape of the stream channel and how it changes over time. The quantity, size, and function of WM, particularly large wood in many of these stream systems, have been altered through decades of timber harvesting, channel clearing, snag removal, and human alterations to stream channels and riparian zones, resulting in changes to stream channel form, function, and degradation of aquatic habitat. Placement of WM can achieve a variety of physical and biological benefits to stream morphology and aquatic habitat. WM can be used to directly provide habitat cover, complexity, and natural levels of streambank stability, or may provide indirect benefits through its influence on pool development, sediment trapping, hydraulic roughness, lateral channel dynamics, and maintenance of channel bedform.

This chapter provides policy on the use of WM in all water bodies—streams, rivers, lakes, and marine shorelines. WSDOT WM is divided into three categories: LWM, SWM, and slash. LWM can be designed to be stable or mobile. Mobile LWM is referred to as mobile woody material (MWM). See the Main Glossary of Terms for formal WSDOT definitions of the types of WM.

Section 10-1.1 gives an overview of the design process, while Section 10-2 describes reach assessments. Risk considerations are described in detail in Section 10-3, and detailed design is described in detail in Section 10-4. Design criteria, including using MWM, are discussed in Sections 10-4.1 and 10-4.2. Section 10-5 provides guidance on inspection and maintenance, and Section 10-6 provides the appendices.

Project designs that include WM require expertise in hydrology, hydraulics, and geomorphology and designs will need to be documented in a specialty report. Additional requirements about specialty reports are provided in Chapter 1. An FPSRD certificate number is required for all authors of any portion of a specialty report, if the project is related to fish passage barrier removal or scour. See Table 1-1 for a list of specialty reports and other requirements. An FPSRD certificate number is given to those who have viewed all of the training modules and successfully passed the comprehensive exam. Additional information, training resources, and the point of contact for this training can be found on the WSDOT Hydraulics Training web page. As WSDOT updates the FPSRD training modules a re-certification number is also required. Any updates to this training will be posted on the WSDOT Hydraulics Training web page.

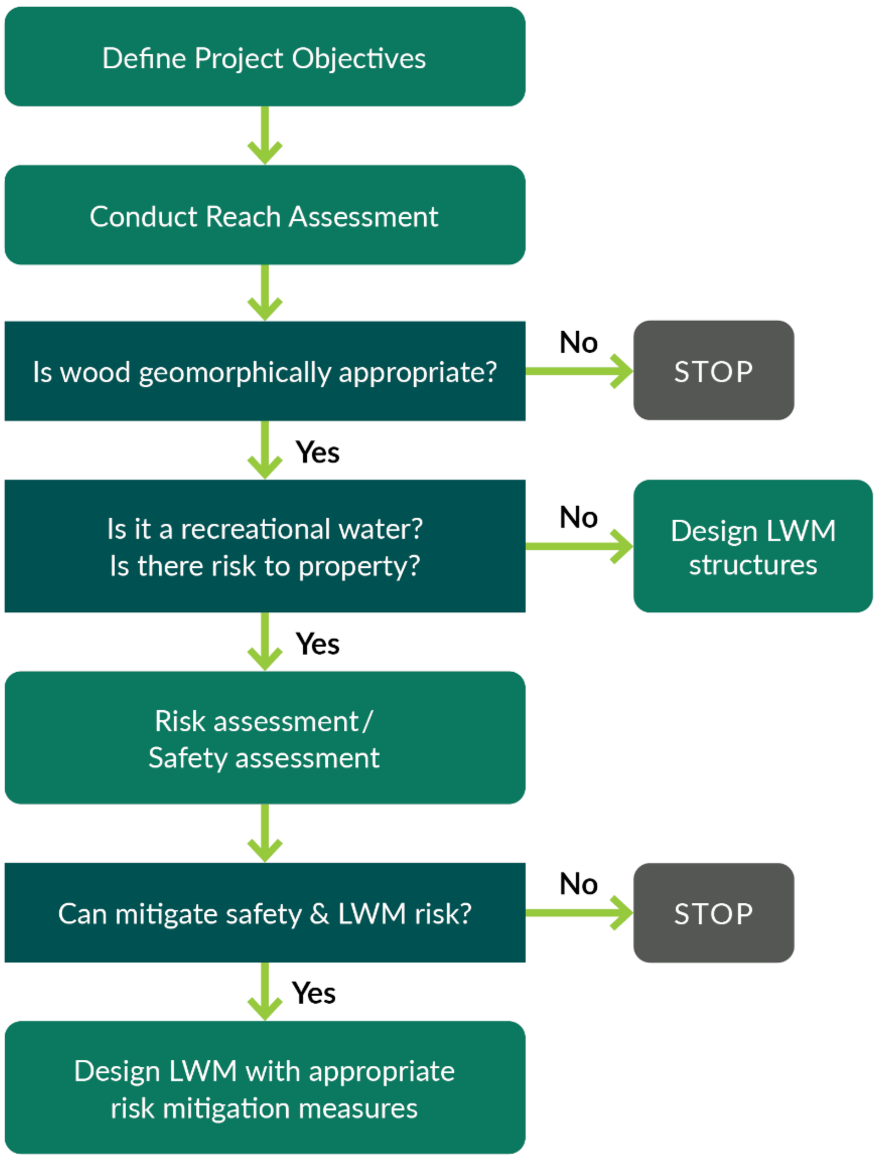
WSDOT is actively monitoring completed projects that include WM and will update this chapter as new information becomes available. Contact the State Hydraulics Office for additional or updated guidance.

10-1.1 *Design Process*

Design and placement of WM shall follow a geomorphic and ecological assessment of the watershed and a similar, more detailed assessment of the river reach and site to be treated, including an analysis of existing conditions and anticipated hydraulic and geomorphic responses. The following multi-step design process is shown in Figure 10-1:

1. The project objectives are identified.
2. A reach assessment describes the geomorphic and habitat conditions. It also informs habitat and bank stability objectives of the reach, the constraints, and the existing wood in the system and to determine if the use of wood is suitable for the site conditions (Section 10-2).
3. A risk assessment is completed to identify potential risks to infrastructure and the public, and to provide guidance to reduce potential risks (Section 10-3).
4. The design is created using general and project-specific design criteria.

Figure 10-1 Wood Design Process



10-1.2 *Guidance for Emergency Large Woody Material Placement*

Generally, failure of a water crossing or streambank requires rapid response to stabilize and prevent additional damage to WSDOT infrastructure and to restore a safe travel corridor. In these cases, regional maintenance staff likely need to act quickly and engineering judgment calls are needed during such situations. Incorporation of LWM could be considered a mitigation element for aquatic habitat impacts as a result of the emergency action. LWM shall be placed during emergency repairs only in consultation with the State Hydraulics Office. The maintenance or project office in charge of emergency repairs must also consult with WDFW and the appropriate tribal contacts for the area.

10-2 Reach Assessment

The reach assessment discussed in Chapter 7 is essential for developing and justifying the wood layout design. The reach assessment serves as the basis for applying large wood to aid in restoring, partially restoring, or enhancing geomorphic and biological processes at the project site. The reach assessment should provide the following context for developing the wood layout design:

- Reconstruct the historical processes that delivered large wood to the site and/or reach prior to floodplain settlement in North America during the 19th and 20th centuries (e.g., local recruitment via bank erosion, windfall, exhumation; wood supply delivered from upstream via debris flows, mass wasting)
- Reconstruct the geomorphic and biological impacts of removing large wood from the channel (e.g., impacts of log jam removal on channel incision, channel simplification, loss of pools), the floodplain (e.g., depletion of wood supply via loss of riparian forest), and possibly the watershed (e.g., clearcut logging)
- Document current conditions for large wood density, recruitment processes, wood sourcing, and geomorphic and biological functions within the project reach (if applicable, answer the question: “Why is wood absent?”)
- Assess risk of wood transport downstream to adjacent property owners and/or infrastructure

Effective design of the wood layout hinges on defining specific geomorphic functions to address:

- Is geomorphic grade control necessary to mitigate channel incision and knickpoint migration (e.g., channel-spanning buried large wood, channel-spanning log steps?)
- Is flow deflection and bank protection needed for protecting WSDOT infrastructure?
- Are engineered log jams (ELJs) recommended for pool formation, in-channel deposition, and gravel retention?
- Is surface and/or subsurface large wood needed to redistribute flow hydraulics (partition shear stress) and offer secondary stability to other design elements?

10-3 Risk Assessment

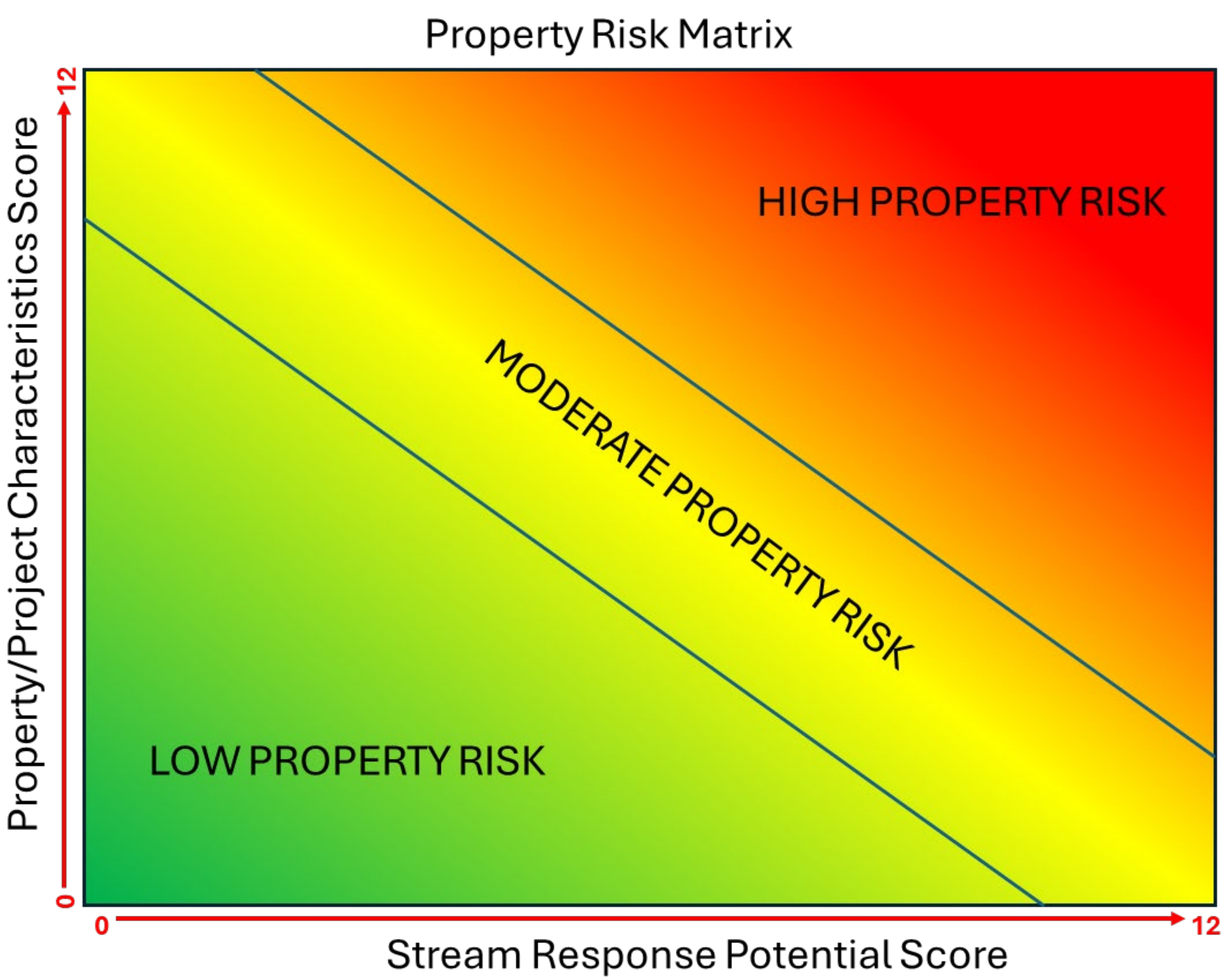
This section presents the risk assessment, including LWM and MWM, recreational water safety, and FEMA and local floodplain permit requirements.

10-3.1 *LWM and MWM Risk Assessment*

Risk shall be considered for all projects that propose WM and shall be incorporated into the PHD and FHD. There are two levels of risk evaluation—the first level is to assess whether adding large wood, in general, is appropriate for the project reach. This occurs during the site and reach assessment (Section 10-2). The second level is a more formal risk assessment, which shall address risks associated with infrastructure, MWM, long-term morphological changes, etc.

Some existing documentation providing guidance for evaluating risk includes the NOAA-produced guidance on conducting risk assessments for LWM placement (NOAA 2011). This document presents a risk matrix that is helpful in categorizing risk to infrastructure, even when risk cannot be quantified. This matrix is presented in Figure 10-2. NOAA 2011 discusses how to fill out the inputs on the X axis (stream response potential) and the inputs on the Y axis (property/project characteristics). In summary, the various factors affecting modification and movement of wood over time, along with the type and proximity of infrastructure downstream, are scored on the Y axis. The factors of stream response are scored on the X axis. The total score for each axis is plotted against each other, and the coordinates' location indicate the relative risk to infrastructure. The matrix has been modified somewhat from the original.

Figure 10-2 Large Wood Property Damage Risk Matrix (modified from NOAA 2011)



Stream Response Scoring (X-axis):

					Score (0-2)
Scale of problem					
Site	Reach	Multiple Reaches		Watershed	______
Landscape Sensitivity/Stream Type					
Bedrock	Colluvial	Alluvial	Incised Channel	Alluvial Fan	______
Riparian Corridor					
Continuous/wide		Discontinuous		Urbanized/levees	______
Bank Characteristics					
Bedrock/till		Erosion resistant		Highly erodible	______
Bed Mobility					
Low (Coarse/clay)		Medium (gravel)		Fine (sand/silt)	______
Dominant Hydrologic Regime					
Spring-fed	Snowmelt	Rain	Rain-on-snow	Thunderstorms	______
				TOTAL SCORE	______

Project/Property Characteristics Scoring:

					Score (0-3)
Project Scale					
Site Scale	Reach Scale			Multi-reach Scale	______
Wood Length (multiple of channel width)					
>2.5x with rootwad	2x	1.5x		<1.0x, no rootwad	______
Wood Properties					
High Density, Slow Decay				Low Density, Fast Decay	______
Infrastructure/distance downstream from crossing					
None/>1000'	Parallel Roads	Crossings <500'	Piers	Crossings <250'	______
				TOTAL SCORE	______

Additionally, NRCS's *National Engineering Handbook* (Technical Supplement 14J: Use of LWM for habitat and bank protection) provides discussion on the limitations of using LWM (NRCS 2010). The *National Large Wood Manual*, produced by USBR and the U.S. Army Engineer Research and Development Center (ERDC) (2016), provides additional discussion on projects involving WM.

MWM is used for habitat restoration and enhancement, recognizing that wood moves through aquatic systems across a variety of flow levels. However, MWM can pose risks to downstream infrastructure and properties. The use of MWM must be evaluated on a site-specific basis—the degree of mobility with the riparian corridor, the amount of natural wood recruitment, and the distance to the next downstream culvert and infrastructure are all factors. MWM shall not be placed when it could result in flood risk to infrastructure or properties, or damage to downstream crossings.

Studies on the transport of MWM in streams in the Pacific Northwest and northern California emphasize the differences between two distinct wood transport regimes: uncongested and congested (Braudrick et al. 1997). During uncongested transport, individual logs move without piece-to-piece interactions and generally occupy less than 10 percent of the active channel area. In congested transport, logs move together as a single coordinated mass or "raft" and can occupy more than 33 percent of the active channel area.

Congested wood transport can result in stream channel blockages because of its large effective size relative to its individual members and can result in channel migration, bank erosion, and blockages of downstream road-stream crossings. Congested wood transport is relatively rare; most accumulations of MWM tend to break apart and the pieces move individually (Diehl and Bryan 1993).

Studies of MWM blockages at culverts in small streams indicate that the plugging of culverts by MWM is initiated by one or more "initiator pieces" lodging across the culvert inlet during high flows (Furniss et al. 1998; Flanagan 2005). The point of contact with the edge of the culvert barrel then becomes a nucleation site for the continued accumulation of finer material—both wood and sediment. Wood accumulating over multiple floods will eventually result in diminished culvert capacity or complete blockage. Only 3.7 percent (2 out of 54) of initiator pieces in plugged culverts had lengths that were between 75 and 100 percent of the culvert width, and in both of those instances the initiator pieces had substantial rootwads attached that had lodged themselves on the barrel edges of the culverts. An additional study (Flanagan 2003) indicates that 99.5 percent of fluvially transported pieces of MWM through low-order channels are shorter than the BFW of the stream.

Based on the above research, MWM shall not be used when there is a potential to impact downstream infrastructure. SWM and slash by its nature does not pose a risk to infrastructure because of its mobility, size, and rate of decay relative to large wood pieces. However, the infrastructure present downstream of the project shall be considered, particularly if it is in close proximity to the crossing or reach in question. The quantity and placement of SWM used in the design may be constrained if there is risk to infrastructure. An example would be a tide gate flap or undersized culvert located within 100 feet of a project.

10-3.2 *Recreational Water Safety Risk Assessment*

WM may present risks to recreational users and these risks shall be considered in the planning and design phases of project development. The Recreational Water Safety Risk Assessment (RWSRA) shall identify the likely recreational activities that could occur at the site or in the project reach, and risks or hazards that WM may pose to recreational users. The assessment shall also determine if risk posed by WM can be reduced to an acceptable level. This type of assessment is often required by the Washington State Department of Natural Resources (DNR) for aquatic land use permits, if required, and shall include an inventory of nearby public access points, such as WDFW and USFS boating access sites. A review of regional paddling guidebooks will also help identify recreational water use. The American Whitewater Association (www.americanwhitewater.org) has a searchable database of recreational river runs.

The following types of water bodies are considered "recreational" by WSDOT for the purposes of this guidance:

- All rivers designated as "Wild and Scenic" rivers.
- All rivers and streams designated as navigational waters by the U.S. Coast Guard.
- All rivers and streams within state and national parks, national monuments, national

recreation areas, and wilderness areas.

- Rivers, streams, and other water bodies known to local law enforcement, fire departments, and other river rescue organizations to receive heavy recreational (boating/swimming) use. These organizations can be very helpful in determining the degree of recreational use and relative hazard.
- All streams with a BFW greater than 30 feet.
- All rivers and streams designated as State-Owned Aquatic Land by DNR.

An RWSRA is required if any the stream or river in question meets any of the above criteria.

When an RWSRA is required, the following must be considered to mitigate the recreational risk:

- WM placement in confined channels shall be limited to grade control on the streambed and not structures obstructing flow.
- WM structures shall not be placed where there is poor visibility from upstream. A minimum visibility of 50 feet or three BFWs, whichever is greater, must be maintained.
- WM structures shall not be put in channels that do not allow for circumnavigation.
- Larger LWM structures shall not be constructed in close proximity upstream or downstream (within 100 feet or three BFWs, whichever is greater) of boat ramps.
- Larger LWM structures, such as ELJs, shall not be placed on the outside of a meander bend where the curve ("tortuosity") of the bend is less than 3 using the formula $Rc/W<3$, where Rc is the radius of the meander curve, and W is the BFW in the upstream riffle.
- Signage shall be addressed on a case-by-case basis, particularly where upstream visibility is limited because of meandering channels, etc.
- Multi-log LWM structures shall be designed to limit flow-through characteristics by including an impermeable core to prevent "straining." Straining is a phenomenon by which swift water flowing through an LWM structure tends to draw floating objects toward and into it. The denser the core of the structure is, the less this tends to occur. LWM structures shall be designed to limit flow-through characteristics by including an impermeable core to prevent "straining."

At sites with heavy recreational use, public notification and involvement may be desired to minimize the risks of LWM structures. Public notification shall be handled on a case-by-case basis depending on the size and complexity of the project and the degree of public use of the water body. The public involvement procedures under the National Environmental Policy Act and State Environmental Policy Act shall be used as the primary mechanism for informing the public about WSDOT LWM projects. Guidance for these processes can be found in the *Environmental Manual*, Chapter 400. Additional guidance for public involvement can be found in WSDOT's *Design Manual*.

Basic engineering standards require consideration of safety and risk and, ultimately, design decisions regarding the use of WM in recreational waters must be left to the State Hydraulics Office. The methods and assumptions used for the recreational water safety assessment analysis will be fully documented in the project's Hydraulic Design Report.

10-3.3 *FEMA and Local Floodplain Permit Requirements*

Introduction of WM into a stream will change the WSELs in the immediate vicinity. While this is often desirable for habitat and hydraulic objectives, it may have an undesirable effect on adjacent property or infrastructure. During project designs, every project that includes WM shall evaluate the effects the WM has on the WSELs. If the stream has a FEMA-designated SFHA, the local flood manager may also require that the project meet specific floodplain requirements. The designer shall determine the FEMA designations for the stream and floodplain and ensure compliance with local and federal floodplain regulations.

10-4 Design

The design of WM structures requires a comprehensive understanding of hydraulics, geomorphic, and ecological factors to achieve project objectives. A successful design ensures that WM placements are stable as intended, functional, and align with project goals. Key considerations include selecting appropriate materials; evaluating forces acting on the structure; and incorporating safety measures to mitigate risks to infrastructure, the environment, and public safety. The stream design engineer shall ensure that banks opposite any WM are appropriately stabilized against erosion. For WM intended to be used as grade control, the stream design engineer shall coordinate with the State Hydraulics Office for approval. This section outlines the design principles, criteria, and methodologies for designing WM structures.

10-4.1 *Bank Protection Design Criteria*

WM influences river systems by increasing flow resistance, reducing velocity, and decreasing sediment transport. Designers can recreate this natural function to protect streambanks by using wood-dominated features like ELJs or log crib walls. These features function by increasing hydraulic roughness along the streambank and thereby protecting the underlying material from erosion. When designed and constructed appropriately, they are effective at addressing lateral instability but are not suitable as a scour countermeasure for critical infrastructure like bridges or walls. WM shall be placed outside of any scour countermeasure footprint. WM shall be placed such that it does not conflict with the scour policies presented in the *Bridge Design Manual*, nor with Chapter 4 or Chapter 7 of this *Hydraulics Manual*.

Extensive guidance exists for numerous techniques for bank protection, from rock to revegetation. See Section 4-6 for guidance on using rock for bank protection. Some of the most pertinent guidance documents are listed below:

- HEC-23, Volume 1 and Volume 2
- ISPG (WDFW 2002)

- *Bank Stabilization Design Guidelines* (Baird et al. 2015)
- WDFW's *Stream Habitat Restoration Guidelines* (Cramer 2012)

10-4.1.1 Wood Selection

Where WM is to be incorporated into bank protection design, the decay and degradation of the wood over time shall be considered. Coniferous species of wood are acceptable for bank stability design, aside from western hemlock. The density of the wood species used must be accounted for in the stability calculations. Per the WSDOT GSP for "Woody Material," western red cedar is disallowed. However, if the density is accounted for in the stability calculations, then it may be used. Deciduous trees, which are prone to decaying sooner, shall not be used for bank stability. Refer to Section 10-4.3 for additional information regarding WM stability analyses. See Table 10-1 below for the relevant properties of different species to use in stability analyses.

Table 10-1 Physical Characteristics of Woods Found in the Pacific Northwest

Common Name	Genus	Species	Green Wood (moisture content ~ 30%)			Dry Wood (moisture content ~ 12%)		
			Specific Gravity[a]	Modulus of Rupture N/m^2	Modulus of Elasticity N/m^2	Specific Gravity[a]	Modulus of Rupture N/m^2	Modulus of Elasticity N/m^2
Subalpine fir	*Abies*	*lasiocarpa*	0.31	3.40E+07	7.20E+06	0.32	5.90E+07	8.90E+06
Western red cedar	*Thuja*	*plicata*	0.31	3.59E+07	6.50E+06	0.32	5.17E+07	7.70E+06
Black cottonwood	*Populus*	*trichocarpa*	0.31	3.40E+07	7.40E+06	0.35	5.90E+07	8.80E+06
Engelmann spruce	*Picea*	*engelmannii*	0.33	3.20E+07	7.10E+06	0.35	6.40E+07	8.90E+06
Grand fir	*Abies*	*grandis*	0.35	4.00E+07	8.60E+06	0.37	6.10E+07	1.08E+07
Sitka spruce	*Picea*	*sitchensis*	0.37	3.90E+07	7.40E+06	0.40	7.00E+07	1.08E+07
Ponderosa pine	*Pinus*	*ponderosa*	0.38	3.50E+07	6.90E+06	0.40	6.50E+07	8.90E+06
Red alder	*Alnus*	*rubra*	0.37	4.50E+07	8.10E+06	0.41	6.80E+07	9.50E+06
Silver fir	*Abies*	*amabilis*	0.40	4.40E+07	9.80E+06	0.43	7.30E+07	1.19E+07
Yellow cedar	*Chamaecyparis*	*nootkatensis*	0.42	4.40E+07	7.90E+06	0.44	7.70E+07	9.80E+06
Mountain hemlock	*Tsuga*	*mertensiana*	0.42	4.30E+07	7.20E+06	0.45	7.90E+07	9.20E+06
Western hemlock	*Tsuga*	*heterophylla*	0.42	4.60E+07	9.00E+06	0.45	7.80E+07	1.13E+07
Bigleaf maple	*Acer*	*macrophyllu*	0.44	5.10E+07	7.60E+06	0.48	7.40E+07	1.00E+07
Douglas fir	*Pseudotsuga*	*menziesii*	0.45	5.30E+07	1.08E+07	0.48	8.50E+07	1.34E+07

Notes:

N/m^2 = newton per square meter.

a. Specific gravity computed from oven-dry weight (0% moisture) and volume at 12% moisture content.

10-4.1.2 Design Flows

LWM bank protection features are intended to function over a long project design life (50 years or longer), and therefore the design flood event shall be the 1 percent annual exceedance probability (AEP) (100-year) used for the stability analysis. For complex wood structures, such as ELJs, flow deflectors, or wood incorporated into a combined rock and wood bank protection, the design flood shall be the 2080 100-year projected flood. Anchoring techniques, which are described in Section 10-4.3.1.4, may be necessary to ensure that the WM does not mobilize during the design flood event. Refer to Section 10-4.3.2 for additional information regarding required Factors of Safety for design as part of the stability analysis.

10-4.1.3 Placement Criteria

As noted previously, wood-dominated features can be effective at addressing lateral instability but are not suitable as a scour countermeasure for critical infrastructure like bridges or walls. WM shall be placed outside of any scour countermeasure footprint and such that it does not conflict with the scour policies presented in the *Bridge Design Manual*, nor with Chapter 4 or Chapter 7 of this *Hydraulics Manual*. The risks described previously in Section 10-3 shall also be considered when evaluating whether bank protection design incorporating WM is appropriate.

During design, the appropriate extents for the bank protection in plan view, as well as the top and bottom elevations necessary for design features to provide full bank protection, shall be evaluated. This evaluation shall be conducted by an interdisciplinary team and include hydraulic modeling, scour analysis, and floodplain analysis. A risk assessment shall also be conducted on the design features to evaluate longevity (for example, pile failure, erodible bank materials, and/or long-term WM integrity). The bottom elevation of the bank protection shall be designed to accommodate scour at the design flood. The top elevation of the bank protection shall extend a minimum of 1 foot above the scour design flood.

Several examples of bank protection designs including WM are included in the appendix.

10-4.2 *Habitat Enhancement Design Criteria*

WSDOT performs stream habitat restoration or enhancement to reconstruct stream corridors through new water crossings. Habitat restoration or enhancement may also occur in road widening or realignment projects or as an element of wetland or aquatic habitat mitigation projects. Permitting agencies will often require WSDOT to incorporate wood into these projects as sustainable habitat features. These features increase channel complexity and diversity of habitat necessary to support a healthy aquatic ecosystem. They must be designed based on the expertise and input from all members of a project's Stream Team (defined in Chapter 7-1), including a stream design engineer, geomorphologist, and biologist.

Conceptually, stream restoration refers to restoring or partially restoring geomorphic processes that were present at the site prior to Euro-American settlement. For example, WSDOT has several stream crossings that traverse alluvial fans. The streams are often confined between berms and levees upstream of the crossing. The disruption of alluvial fan processes frequently results in excessive, chronic sedimentation at the highway crossing. Repetitive dredging is usually required, often under emergency conditions. Berm or levee removal, partial or complete restoration of alluvial fan floodplain processes, and/or road relocation are examples of stream restoration by reestablishing alluvial fan processes to decrease sedimentation at the crossing.

The concept of stream enhancement refers to improving or enhancing geomorphic processes and biological conditions at a site that may not result in full restoration of a site. For example, a stream may have been relocated from its lowland, floodplain environment (pool riffle morphology) to flow over a steep glacial escarpment. If the highway was constructed through the floodplain (burying the original channel course), channel design of the affected reach will need to reflect the appropriate target morphology of the steeper gradient (e.g., step pool or cascade morphology). Because restoration or partial restoration of a pool riffle system is not possible, the channel design will need to enhance geomorphic and biological conditions appropriate to its current governing conditions (e.g., slope, confinement, and so forth).

All channel designs should go beyond consideration of flow conveyance to include continuity of sediment and wood transport processes. In moderately confined and unconfined alluvial systems, stream enhancement or restoration will incorporate floodplain and channel migration processes. For example, sediment yield and sediment transport are critical to consider for sizing a crossing span width and vertical clearance in a response reach affected by debris flows draining an upper watershed composed of weak bedrock.

Many streams have been severely impacted by land clearing, channelization, stream relocation, wood removal, and urban development. Channel incision is a common consideration in urbanizing systems. The impacts of changes to watershed hydrology, sediment transport regime, loss of streambank vegetation, and channel alterations are critical to understand for defining the objectives of a wood layout design. Stream enhancement or restoration upstream of crossings can help to reduce risks by capturing mobile wood that might otherwise cause blockages. Stream enhancement or restoration can also be instrumental in preventing channel incision and knickpoint propagation through a new crossing.

Stream enhancement and restoration activities include the following:

- Construct channels with the appropriate planform, grade, width, depth, and channel substrate, as discussed in Chapter 4 and Chapter 7
- Construct overbank and floodplain areas, where appropriate
- Stabilize the channel banks and disturbed floodplain and upland areas with revegetation and bioengineering

Wood provides habitat and geomorphic functions within a stream, including the following:

- Create stable obstructions that capture organic debris and form log jams
- Form pools
- Contribute to eddy creation and flow complexity
- Cause the deposition of finer sediments to create substrate diversity

- Enhance hyporheic flow by locally increasing hydraulic head
- Provide cover for aquatic organisms
- Provide woody substrate for invertebrates and other aquatic species
- Accumulate mobile wood and other organic debris
- Activate side channels with flood flows

Note that all vegetation to be cleared on a site shall be evaluated for use for habitat purposes and so used if determined to be acceptable quality.

10-4.2.1 Wood Selection

The type of WM used for habitat enhancement is based on the size or mobility of the wood as defined below, as well as in the *Hydraulics Manual* Main Glossary of Terms and "Woody Material" GSP. Acceptable species for these types of WM are included below.

- **Large woody material (LWM):** LWM and MWM consist of trees and parts of trees including any variation of logs, rootwads, or stumps greater than 4 inches in diameter and larger than 6 feet in length. These shall be of a native coniferous tree species. Western red cedar cannot be used unless the density is accounted for in the stability calculations (see Table 10-1). Deciduous trees obtained from clearing or grubbing on site may be used for stable LWM or MWM if approved by the State Hydraulics Office.
- **Small woody material (SWM):** A random assortment of branches, trees, brush, and treetops of the following native species: western red cedar (*Thuja plicata*), Douglas fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*) coniferous trees, or various hardwood trees. The maximum diameter of any piece of SWM shall be 4 inches. The maximum length of any piece of SWM shall be 6 feet. SWM shall not contain any material that causes turbidity.
- **Slash:** A random assortment of branches, trees, brush, and treetops of the following native species: western red cedar (*Thuja plicata*), Douglas fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), Sitka spruce (*Picea sitchensis*) coniferous trees, or various hardwood trees. The maximum diameter of any piece of slash shall be 2 inches. The maximum length of any piece of slash shall be 6 feet. Slash shall not contain any material that causes turbidity.

10-4.2.2 Design Flows

LWM used for habitat enhancement or restoration shall be designed and placed with specific project objectives in mind. The appropriate design flood event must be determined based on habitat objectives, hydraulic opening width, and on-site constraints (see Section 10-4.2.3 for additional information related to placement considerations). Maintenance clearance requirements and the potential for scour countermeasures must also be considered. Stable LWM shall be designed based on the 1 percent AEP (100-year) flood event. For complex wood structures, the design flood shall be the 2080 100-year projected flood; contact the State Hydraulics Office for additional information. MWM shall be designed based on a target flood event and is in alignment with the results of a risk assessment and use of MWM shall be approved by the State Hydraulics Office prior to incorporating into the design. Refer to Section 10-4.3.2 for additional information regarding required FOSs for design as part of the stability analysis.

10-4.2.3 Placement Criteria

Before laying out an aquatic habitat enhancement design, it is important to have some understanding of the species that use the stream and what habitat features the design will provide based on the reach assessment completed (see Section 10-2). The Stream Team needs to identify what kind of fish and habitat is needed and whether the channel has been impacted by the loss of functional wood. The reach assessment (see Section 10-2) shall assist with evaluating this. For example, many channels experience incision or downcutting after wood is removed, which can impact water crossings. To provide the best certainty for fish habitat, natural configurations and spatial organizations known to foster adaptations by salmonids shall be mimicked. For example, see Fox (2003) and Abbe and Montgomery (1996).

Knowing the species life history and habitat needs, as well as an understanding of the stream system, helps to identify an appropriate wood configuration. For example, wood located at the outer limits of the bankfull channel may provide high flow refuge but provide little rearing habitat or summer thermal refugia as it may be well away from the active low-flow channel. Conversely, wood placements low in the channel to enhance low-flow habitat values may not provide high-flow refuge. The purpose of the overall design, including the intended function of proposed wood structures, shall be documented by the Stream Team in a hydraulic design report.

Habitat-limiting factors shall be considered for some types of projects, such as ones addressing certain chronic environmental deficiencies or restoration-based projects. Common limiting factors in Washington's waterways include water quality (temperature, sediment), stream flow, instream structure and complexity, pool size and/or frequency, spawning habitat, overwinter habitat, rearing habitat, and interaction with floodplain. Assessments identifying the limiting factors for a stream or basin have been completed for about half of Washington's watersheds in accordance with the 1998 Washington State Watershed Management Act. Links to studies and reports for each WRIA can be found at Ecology's website.

Wood placement includes orientation, dip angle, and spacing. The configuration of wood will depend on the project objectives and specifically the intended objective for each log. Configuration of LWM for bank protection is different from that for aquatic or floodplain habitat enhancement. WSDOT expects a diversity of wood sizes, orientations, and elevations that are appropriate for the channel size. Wood can be placed in single logs or multiple-log groupings, depending on the intended purpose and both short- and long-term function. Complex placements with multiple logs with interlocking pieces of wood provide better habitat and mimic wood accumulation (log jams) over time. Channel-spanning WM may be included but requires approval by the State Hydraulics Office.

WM can pose a risk for critical infrastructure as noted in Section 10-3. Wood shall be located so that it does not create scour that could compromise bridge members (e.g., piers, abutments), road embankments, walls, or scour countermeasures. State Hydraulics Office approval is required for any projects with stable LWM proposed within a water crossing. If stable LWM is proposed within the channel under a permanent water crossing, appropriate scour countermeasures are required and must be designed to protect the structure's foundations in accordance with the *Bridge Design Manual* and Chapter 7 of this *Hydraulics Manual*. The inclusion of MWM in a design requires approval from the State Hydraulics Office. SWM and slash is generally acceptable without State Hydraulics Office approval.

Maintenance and freeboard requirements shall be taken into account by the Stream Team when proposing WM near or through a permanent water crossing. Refer to Table 7-3 and Table 7-4 in Sections 7-3.6.1 and 7-3.6.2, respectively, for additional information on these requirements. Localized aggradation occurs upstream of WM and shall be considered when determining minimum required freeboard.

As described in Section 10-2, WM can play a significant role in affecting reach-scale processes within a stream, including the channel's overall gradient. Depending on the arrangement and stability of wood pieces or jams, they may function as grade control for the system. The Stream Team must contact the State Hydraulics Office if using WM as a permanent grade control feature is being considered for a project. Less stable forms of grade control also occur naturally, consisting of matrices of smaller pieces of wood, sediment, and other debris. Section 7-3.9.4 includes guidance for designing deformable grade control features.

Constructing WM structures as designed can be challenging based on site-specific conditions. The State Hydraulics Office must be contacted if a Stream Team's designed layout is modified during construction. The modifications shall not substantially alter the intent of the design or redirect the expected flow path for the waterway in a manner that could put the structure or scour countermeasures at greater risk.

Several examples of habitat enhancement designs are included in the appendix for reference.

10-4.2.4 LWM Targets

For WSDOT projects LWM targets apply as a starting point in stream restoration design. These targets are adopted from the recommendations in Fox and Bolton (2007). The targets need to be adjusted based on site-specific constraints and considerations and shall not create risks to infrastructure or fish passage. Target values need to be adjusted based on what is geomorphically appropriate for the project site. This could be an increase or decrease from the Fox and Bolton starting point. The hydraulic design report shall include documentation for the proposed targets used for the stream restoration design and discussed with co-managers.

Fox and Bolton (2007) measured several parameters of wood in streams of various widths and in various environments. Because this is the most detailed study of LWM in Washington, the *Hydraulics Manual* uses it as a reference. Additionally, when LWM is being used to emulate habitat functions in a newly created reach of stream, the 75th percentile of four key metrics found by Fox and Bolton (2007) is the LWM target. This was identified by the authors of that study to compensate for cumulative deficits of wood loading due to development. The four metrics are:

- Key piece volume
- Key piece density
- Total number of LWM pieces (key and non-key)
- Total volume of LWM (key and non-key)

Table 10-2 shows the LWM targets for each of the four metrics, by BFW, and forest zone of the categories of streams. A “log metrics calculator,” a spreadsheet tool supplied by the State Hydraulics Office, is available and shall be used to tabulate proposed LWM compared to these targets.

Table 10-2 Large Wood Target Metrics

<table>
<tr><th colspan="2">KEY PIECE VOLUME</th><th colspan="3">KEY PIECE DENSITY</th><th colspan="3">TOTAL LWM VOLUME</th><th colspan="3">TOTAL PIECES OF LWM</th></tr>
<tr><th>BFW class (ft)</th><th>volume (yd3)</th><th>Forest zone</th><th>BFW class (feet)</th><th>75th percentile (per/ft stream)</th><th>Forest zone</th><th>BFW class (feet)</th><th>75th percentile (yd3/ft stream)</th><th>Forest zone</th><th>BFW class (feet)</th><th>75th percentile (yd3/ft stream)</th></tr>
<tr><td>0-16</td><td>1.31</td><td rowspan="3">Western WA</td><td>0-33</td><td>0.0335</td><td rowspan="3">Western WA</td><td>0-98</td><td>0.3948</td><td rowspan="3">Western WA</td><td>0-20</td><td>0.1159</td></tr>
<tr><td rowspan="2">17-33</td><td rowspan="2">3.28</td><td rowspan="2">34-328</td><td rowspan="2">0.0122</td><td rowspan="2">99-328</td><td rowspan="2">1.2641</td><td>21-98</td><td>0.1921</td></tr>
<tr><td>99-328</td><td>0.6341</td></tr>
<tr><td>34-49</td><td>7.86</td><td rowspan="3">Alpine</td><td>0-49</td><td>0.0122</td><td rowspan="3">Alpine</td><td>0-10</td><td>0.0399</td><td rowspan="3">Alpine</td><td>0-10</td><td>0.0854</td></tr>
<tr><td rowspan="2">50-66</td><td rowspan="2">11.79</td><td rowspan="2">50-164</td><td rowspan="2">0.0030</td><td rowspan="2">11-164</td><td rowspan="2">0.1196</td><td>11-98</td><td>0.1707</td></tr>
<tr><td>99-164</td><td>0.1921</td></tr>
<tr><td rowspan="2">67-98</td><td rowspan="2">12.77</td><td rowspan="2">Douglas Fir/Pond. Pine (much of eastern WA)</td><td rowspan="2">0-98</td><td rowspan="2">0.0061</td><td rowspan="2">Douglas Fir/Pond. Pine</td><td rowspan="2">0-98</td><td rowspan="2">0.0598</td><td rowspan="2">Douglas Fir/Pond. Pine</td><td>0-20</td><td>0.0884</td></tr>
<tr><td>21-98</td><td>0.1067</td></tr>
<tr><td>99-164</td><td>13.76</td><td colspan="9" rowspan="2"></td></tr>
<tr><td>165-328</td><td>14.08</td></tr>
</table>

To account for portions of the channel where infrastructure may limit LWM placement (e.g., under a buried structure), a higher density may be needed in some channel segments to achieve the target density for the entire restored segment if this is considered appropriate.

Density targets assume that the LWM will be engaged with instream flows so that it functions to create habitat such as pools, low-velocity refugia, cover, capture sediment, or sediment retention. To best achieve these functions, LWM shall be placed within the low-flow channel.

Using the BFW, the LWM designer first selects the corresponding 75th percentile key piece volume, then the 75th percentile key piece density, and 75th percentile total LWM volume. When using the log metrics calculator, when BFW, length of regrade, and forest zone are entered, the target metrics for the project reach are automatically calculated.

When the LWM targets are determined, the designer then enters log dimensions (midpoint diameter and length) and number for each log type to match the proposed design. The log metrics calculator helps the designer quickly determine target numbers and how the proposed design compares to the targets. Contact the State Hydraulics Office for additional or updated guidance.

10-4.3 *Stability*

Stability of WM in the aquatic environment refers to the ability to remain in place under hydraulic forces throughout its intended lifespan. Stability analysis evaluates the vertical, horizontal, and rotational forces acting on WM and their interactions with anchoring and resisting forces. Section 10-4.3.2 provides an overview of suitable FOSs and Section 10-4.3.1 provides an overview of performing stability analysis on WM.

10-4.3.1 Stability Analysis

A WM stability analysis consists of a static evaluation of the forces acting upon the WM using a free-body analysis. Vertical and horizontal forces are analyzed separately, with rotational forces considered for bank protection and stable LWM structures. The vertical and horizontal forces acting upon the WM are compared with their resisting forces, like anchoring and ballast, to determine an FOS for the vertical, horizontal, and, if applicable, rotational force components.

Numerous guidance documents deal with the stability analysis equations for estimating these forces. A description of applicable equations and their use can be found in *Large Woody Material – Risk Based Design Guidelines* (USBR 2014), NRCS (2007), and *Large Woody Debris Fish Habitat Structure Performance and Ballasting Requirements* (D'Aoust 1991). More recently, USFS has published the *Computational Design Tool for Evaluating the Stability of Large Wood Structures* (Rafferty 2016). The WSDOT-approved methodology for assessing WM stability is a modified version of the Rafferty (2016) spreadsheet. Contact the State Hydraulics Office to obtain the most up-to-date copy. Other methods may be acceptable upon review and approval by the State Hydraulics Office.

A discussion of vertical, horizonal, and rotational forces, as well as the design and selection of anchoring techniques, is provided in the sections below. Designers are responsible for selecting appropriate methods and documenting all assumptions and calculations, including determining the applicable horizontal and vertical forces acting upon the WM. The State Hydraulics Office may request that additional forces be considered in the WM stability analysis based upon project-specific considerations.

Bank protection and stable LWM stability analyses shall consider anticipated short- and long-term lateral and vertical channel changes. WM for habitat enhancement shall also consider these scour components. Assumptions for these channel changes and how they impact WM stability shall be documented in the hydraulic design report.

10-4.3.1.1 Vertical Forces

Vertical forces on WM are driven primarily by buoyant force, which acts upward and is determined by the submerged volume of the wood and its unit weight. An additional upward force, lift, arises from flow velocity and the lift coefficient of the WM. Lift forces are typically a small component to the overall vertical force acting upon the WM, but it can still influence stability.

These upward forces are counteracted by resisting forces that act downward. Key resisting forces include the weight of the WM, vertical soil loading, and anchoring. In multi-log structures, interactive forces between individual logs may contribute to resistance or, in some cases, add to the upward forces.

Further discussion of anchoring techniques and interactive forces is included in Section 10-4.3.1.4.

10-4.3.1.2 Horizontal Forces

Horizontal forces on WM are driven primarily by drag, which acts along the direction of flow and results from the interaction between the submerged portion of the WM and the water's velocity. The magnitude of the drag is influenced by the flow velocity, the cross-sectional area of the submerged wood, and its drag coefficient.

Additional driving horizontal forces that may arise in site-specific scenarios include impact from MWM striking the structure during high flow events, hydrostatic force caused by water surface differential across the structure, debris loading from accumulation of transported material against the structure, and ice loading.

Resisting horizontal forces counteract these driving forces and provide stability to the WM. Common resistance mechanisms include friction from the interaction between the channel bed and WM, passive forces from soil surrounding the WM, and lateral resistance provided by anchoring systems such as timber piles or boulders.

Interactive forces with other WM pieces can act as either driving or resisting forces. Further discussion of anchoring techniques and interactive forces is included in Section 10-4.3.1.4.

10-4.3.1.3 Rotational Forces

Rotational forces on WM occur when loading on the WM is asymmetrical, creating moments that may cause the structure to rotate. These forces are most relevant for WM placed along channel banks or in configurations where flow is unevenly distributed.

A rotational force evaluation assesses the driving and resisting moments acting on the WM. A rotational force analysis is required for all bank protection and stable LWM structures. For MWM structures, a rotational force analysis may be requested by the State Hydraulics Office based on project-specific considerations.

10-4.3.1.4 Anchoring and Interacting Forces

Anchoring techniques include a variety of design elements that help WM structures achieve the target FOS for vertical, horizontal, and rotational forces. WSDOT prioritizes the use of "self-ballasting" WM, which achieves the intended FOS at the design flow event without additional anchoring. However, in high-risk sites or when additional stability is required, anchoring or interactive forces with other stable logs may be employed to achieve the necessary FOS.

A variety of anchoring techniques may be employed depending on site-specific conditions, design requirements, and project constraints. It is the responsibility of the stream design engineer to select the most appropriate technique and document that basis for the selection and analysis. Factors influencing anchoring technique selection may include project permit conditions, constructability, geotechnical conditions, required FOS, and other project-specific factors. Commonly used anchoring techniques include soil ballast, boulder ballast, wood ballast, and boulder anchors. Additional anchor techniques that are not commonly used but may be considered based upon case-by-case approval by the State Hydraulics Office include dolosse-timber, earth anchors, and timber piles. For any anchoring technique that uses ferrous hardware or material, stainless-steel cable and components shall be required. Chain is not allowed within WSDOT projects or projects within WSDOT ROW. No galvanized hardware shall be used below the 100-year WSEL.

WM designs often include multiple logs, ranging from small-scale structures with a few logs to complex arrangements with hundreds of logs. In multi-log structures, interacting forces play a critical role by redistributing forces from more stable logs to less stable ones. This interaction can enhance the stability of both individual elements and the structure as a whole. For example, a log placed on top of a complex structure can transfer vertical forces downward to the logs beneath it, or timber piles placed directly behind a log can counterbalance the drag forces acting on the upstream side of the structure. For all interacting forces, the stream design engineer is responsible for determining appropriate assumptions, documenting these assumptions, and providing supporting calculations.

In simpler structures with relatively few individual logs, force interactions can be explicitly analyzed for each individual log using tools such as the *Computational Design Tool for Evaluating the Stability of Large Wood Structures* (Rafferty 2016). In larger structures, where it is impractical to account for individual forces on each log, designers may need to assume force distribution across the structure and treat it as a cohesive unit. Approval must be obtained from the State Hydraulics Office prior to adopting this approach.

10-4.3.2 Factor of Safety

Design criteria for WM are covered in Sections 10-4.1 and 10-4.2 with the following section providing an overview of selection of suitable FOS for WM design. FOS is defined as the ratio of the resisting forces divided by the driving forces and is evaluated for vertical, horizontal, and rotational forces separately. Selection of FOS for WM design is influenced by the site-specific purpose of the WM placement, risks to public safety and property damage, and the desired lifespan of the WM. Differing FOSs may be required for different WM placements within a single project based upon the risks to public safety and private property and design intent of the WM placement. Additional resources for evaluating risks to public safety and property damage are included in Section 10-3.

10-4.3.2.1 Bank Protection

Design of WM for bank protection is covered in Section 10-4.1. The application and placement of bank protection structures are often included in a project design to protect existing or proposed infrastructure along a river or streambank in a manner that provides improvements to habitat conditions within the stream and increases overall wood loading in the project reach. As this type of design is typically in locations where risks to public safety and/or property damage are higher, a higher FOS is required for structure design. Bank protection structures shall be designed to a minimum FOS of 2 for the vertical and 1.75 for horizontal and moment FOS components. Additionally, bank protection stability analyses require stability analyses to account for impact to the structure from MWM. Refer to Section 10-4.3.1 for further details on WM stability analysis.

10-4.3.2.2 Habitat Enhancement

Design of WM for habitat enhancement is covered in Section 10-4.2. Habitat enhancement WM structures are intended primarily to provide benefits to aquatic habitat rather than protection of banks or infrastructure. Habitat enhancement structures can be placed in conjunction with bank protection structures to provide a variety of habitat and infrastructure protection goals in a project design.

10-4.3.2.2.1 Stable Large Woody Material

The primary purpose of stable LWM is to serve as a key structural element in habitat enhancement WM structures. Stable LWM can be placed as individual pieces or small assemblages to increase wood loading within a project reach, contributing to ecological and hydraulic benefits.

Stable LWM may be placed in locations with varying levels of risk and therefore must have a minimum FOS of 1.5 for the vertical, horizontal, and moment components. Higher FOS may be appropriate because of site-specific considerations. Additionally, stability analyses shall consider impact to the structure from MWM. Refer to Section 10-4.3.1 for further details on WM stability analysis.

10-4.3.2.2.2 Mobile Woody Material

MWM is LWM that is designed to move at target design flood events. MWM placements are intended to be applied in low-risk settings where the movement of MWM pieces is anticipated to occur over the lifespan of the project. MWM shall be approved by the State Hydraulics Office. MWM shall not be placed where movement of individual or multiple pieces, including out of the project, would pose a risk to public safety or private property. FOS for MWM shall be set to 1 for both the vertical and horizontal FOS components at the target design flood event. Target design flood events shall be approved by the State Hydraulics Office. For stability analysis of MWM, moment and impact forces may be disregarded.

Designs shall not incorporate a large quantity of MWM. Designers shall provide a design where MWM mobilizes at a variety of flow events and consider rootwads on some pieces to prevent mass mobilization of all the placed MWM at the same time.

10-4.4 *Scour*

Scour is the principal failure mechanism of many instream structures, and it is also a primary threat to wood structures. Scour at wood placements creates important habitat features but can also cause undesirable movement or destabilization of logs and/or streambanks. Bank protection projects incorporating WM must be designed to accommodate anticipated scour conditions including, but not limited to, bendway scour, long-term degradation, and lateral migration. WM for habitat enhancement shall also consider these scour components when evaluating the FOS based on the required stability. Appropriate anchoring methods shall be used to minimize the risk for wood structures intended to be stable from mobilizing (see Section 10-4.3). Stability analyses using soil ballast as an anchoring technique shall evaluate and take into consideration the potential for the overburden/backfill material to erode. Bioengineering techniques shall also be considered whenever it is expected that the placed WM will direct flow toward the opposite bank.

Reliable methods for estimating local scour near WM have not yet been developed in either the engineering or scientific communities. In some cases, equations developed for bridge piers and abutments have been used to predict scour around wood structures, but these are overly conservative for gravel bed streams found in much of Washington and may not accurately represent the unique geometry of wood. Scour analysis for LWM projects will therefore often rely heavily on engineering judgment and lessons learned from practical experience. It is always worthwhile to measure residual pool depths (the difference in depth or bed elevation between a pool and the downstream riffle crest) in a project reach to get minimum estimates (during flood flows these pools may deepen). The methods and assumptions used for the project analysis shall be fully documented in the project's hydraulic design report.

Additional guidance may be found in Chapter 6 of the *National Large Wood Manual* (USBR 2016). This document also cites the following references as being useful for specific situations:

- **Empirical formulas for scour:** WDFW (2012), Arneson et al. (2012), Shields (2007)
- **Scour analysis applied to LWM:** Brooks et al. (2006), Abbe and Brooks (2011)
- Scour computations for ELJs: Papanicolaou et al. (2018)

10-5 Inspection and Maintenance

As wood members decay, they lose strength and may ultimately fail and then may be transported. LWM may also capture MWM transported from upstream in which the accumulation of wood becomes a hazard by either redirecting flow or constricting the channel. Although LWM used for fish passage projects is intended to mimic natural channel wood, it may also be used to provide bank protection or bank stability and needs to be inspected to ensure that it provides the function intended and does not become mobilized or present a risk to infrastructure.

If a maintenance or repair action is identified, the RHE shall coordinate with the State Hydraulics Office to determine an appropriate course of action. Additional guidance will be provided in future revisions to the *Hydraulics Manual*.

10-6 Appendices

Appendix 10A Woody Material Structure Examples

Appendix 10A Woody Material Structure Examples

10A-1 Self-ballasting Large Wood Structures

These structures are for habitat primarily but can be used to encourage natural processes to enhance a stream system, such as encouraging aggradation in a degraded system. A log of sufficient size, relative to the stream, and placed correctly, can be stable without anchors.

Figure 10A-1 Self-ballasting Large Wood Structure, Swauk Creek, Kittitas County

10A-2 Rootwad Habitat Structures

As the name implies, these structures consist of logs with rootwads or a series of logs with rootwads located to interact with the channel at low and high flows to provide habitat variability and structure in the stream corridor. These may or may not have anchors.

Figure 10A-2 Rootwad Habitat Structures, Evans Creek, King County

10A-3 Log and Rock Revetments

These revetments consist of a rock revetment with one or two layers of logs with rootwads at the toe of the streambank. These structures provide roughness, energy diffusion, some habitat value, and minor flow deflection. They are relatively simple to install and often can be done with WSDOT Maintenance resources.

Figure 10A-3 Log and Rock Revetments, Newaukum River, Lewis County

10A-4 Crib Walls

Crib walls are constructed with logs in a rectilinear array, with voids backfilled with mineral and/or organic soils. Wood or steel piles may be integrated for additional stability. They provide contiguous protection to the bank with a great deal of roughness and complexity. Crib walls are narrow in profile and minimize encroachment into the channel. They are especially useful in narrow channels/banks that cannot accommodate wider structures. Depending on the scour risk, the design may include wood or steel piles for added stability. Several examples of crib walls are shown below.

Figure 10A-4 Crib Wall with Wood Piles, Beaver Creek, Okanogan County

Figure 10A-5 Crib Wall with Steel Piles, Sauk River Side Channel, Skagit County

Figure 10A-6 Crib Wall with Soil Lifts (No Piles), Sauk River, Skagit County

10A-5 Flow Deflection Jams

Flow deflection jams consist of a series of logs with attached rootwads (key members) and often include large volumes of material. These are sometimes linked with revetments or crib wall structures where contiguous protection is desired.

Figure 10A-7 Flow Deflection Jams, Hoh River, 2004, Clallam County

10A-6 Apex Bar Jams

Apex bar jams are crescent- or fan-shaped structures constructed at the head of islands or gravel bars. Apex bar jams act to split and turn flows. Bars forming downstream of them tend to grow and become persistent. Apex bar jams recruit large volumes of additional wood. The potential for major changes in hydraulic and geomorphic functions resulting from wood recruitment is an important risk factor than must be considered in design.

Figure 10A-8 Apex Bar Jams, Hoh River, 2004, Clallam County

10A-7 Dolotimber

The use of dolotimber structures, or other ballasted prefabricated LWM structure matrices, may be considered in situations with extreme high flows and imminent danger to infrastructure. They offer excellent interstitial habitat and are extremely effective at reducing near-bank shear stress (Abbe and Brooks 2011).

Figure 10A-9 Dolotimber Structures, Skagit River, Skagit County

10A-8 Log Jacks

Log jacks are discrete structural units that are composed of four to six logs that hold a central ballast rock. The logs are connected to each other with cable, threaded rods, or chains. The rock in turn is connected to the logs with a wire rope cradle, and secured with wire rope clips or brackets. They can be assembled in a nearby spot with ample work space and then moved into position on the water body. Each log jack is a component of a larger array of log jacks. The array is deformable, and can respond to scour.

A major advantage of log jacks is that they can be deployed without flow diversion. Being modular, log jack design can be easily adapted to various scenarios/terrains. A potential disadvantage is that portions of the log jacks that are subaerially exposed can degrade quickly over time, and may come apart. However, when used in a river with significant recruitable wood, log jacks can rack and trap wood, which can reinforce the array's stability.

Figure 10A-10 Log Jacks, Wynoochee River, Grays Harbor County