RECLAMATION
Managing Water in the West

Pacific Northwest Region
Resource & Technical Services

Large Woody Material - Risk Based Design Guidelines

U.S. Department of the Interior
Bureau of Reclamation
Pacific Northwest Region
Boise, Idaho

September 2014

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Photograph on front cover: Whitefish Island Project, Methow River, Washington, Methow Subbasin 2012.

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Authors:

M. Knutson, P.E., Bureau of Reclamation, Pacific Northwest Region, Resource and Technical Services, River Systems Analysis Group, Hydraulic Engineer
mknutson@usbr.gov, 208-378-5031

J. Fealko, P.E., Bureau of Reclamation, Pacific Northwest Region, Resource and Technical Services, River Systems Analysis Group, Hydraulic Engineer
jfealko@usbr.gov, 208-378-6540

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Table of Contents

Table of Contents (Continued)

List of Figures

Table of Contents (Continued)

List of Photographs

List of Tables

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1.0 INTRODUCTION

The Bureau of Reclamation (Reclamation) and Bonneville Power Administration (BPA) contribute to the implementation of salmonid habitat improvement projects in the Pacific Northwest to help meet commitments stipulated in the 2010 Supplemental Federal Columbia River Power System (FCRPS) Biological Opinion (BiOp) (NOAA 2010). The FCRPS BiOp lists Reasonable and Prudent Alternatives (RPAs), or a suite of actions, as requirements for implementation by Reclamation designed to protect listed salmon and steelhead across their life cycle. Habitat improvement projects in various Columbia River tributaries are one aspect of this RPA. Reclamation provides technical assistance to States, Tribes, Federal agencies, and other local partners for identification, design, and construction of stream habitat improvement projects that primarily address streamflow, access, entrainment, and channel complexity limiting factors. Reclamation’s contributions to habitat improvement are intended to be within the framework of the FCRPS RPA or related commitments.

This document outlines a risk-based process to be used by Reclamation, Pacific Northwest Region (PN Region), Resource and Technical Services, in the design and placement of large woody material (LWM) within rivers and streams throughout the Pacific Northwest. In meeting commitments to improve the physical processes and enhance stream habitat conditions, LWM placement within streams can be the preferred method in satisfying the required objectives; however, inherent risks exist within the stream environment and can be assumed with this type of construction material. These guidelines have been prepared to address these risks and to provide design guidance in a uniform and repeatable framework. The potential risks are identified from project formulation through project design. These guidelines provide documentation of the decision making process and follow a consistent evaluation methodology for describing the risk potential affiliated with design of LWM installations in a specific river or stream corridor for teams and individuals providing Reclamation designs.

1.1 Purpose and Need

In order to meet stipulated RPA requirements in the FCRPS BiOp, LWM placement may be required to achieve the appropriate level and functionality of habitat complexity. Currently, there are no official design or construction standards that exist for placement of LWM (Andrus and Gessford 2007). An effort to create national standards for the design and placement of LWM is currently being drafted by Reclamation at the Mid-Pacific Region’s Trinity River Office (Trinity) and by the U.S. Army Corps of Engineers (USACE). Due to the scope and review process, the completion of these guidelines will likely take several years. In the meantime, Reclamation, BPA, and USACE are required to design and implement projects through 2018 that meet BiOp commitments. These PN Region, Resource and Technical Services guidelines will provide design guidance until national or agency-developed guidelines are endorsed. Since this document will not be vetted through any national/official restoration or engineering community or society, it is not intended to be used as an official standard of practice for the design and installation of LWM. Rather, it is intended for use by Reclamation and project partners to provide a repeatable methodology for design of individual projects that document and present the inherent risks of LWM placement. The results of each of these assessments become part of the final work product that is agreed upon by all involved stakeholders documenting the acceptable risk factors in the design.

1.2 Background

Rivers are naturally hazardous and can be even more so with the increased complexity that is created with the placement of LWM within their banks. Montgomery (Montgomery et al. 2003) and others have shown that historically, rivers in the Pacific Northwest had vastly greater amounts of LWM in them and that LWM provided key structure for multiple ecosystem processes that evolved over thousands of years in this environment. Some of the identified benefits of long-term, stable LWM within rivers include development of complex habitat conditions for native fish and re-supply through dynamic feedback (Montgomery et al. 2003). Rivers and streams have been managed for multiple purposes since settlement of the Pacific Northwest, where human activities can often conflict with LWM in the river or stream. As such, LWM has been removed from streams and rivers on a vast scale (Montgomery and Abbe 2005). Additionally, streamside trees have been removed in many areas, which partially prevent the resupply of natural LWM and exacerbate the degradation of stream habitat conditions (Abbe and Montgomery 1996).

The use of LWM to construct engineered log jams (ELJs) is a relatively new approach to provide multiple ecological and hydraulic benefits for stream habitat conditions, but its use must also work in concert with other anthropogenic activities in the stream corridor. Some of the beneficial engineering uses for ELJs include:

(1) Improving and restoring aquatic and riparian habitat.

(2) Providing erosion control.

(3) Providing flood and grade control.

(4) Increasing sediment retention in a channel reach and/or river system (Andrus and Gessford 2007).

LWM is utilized in stream habitat improvement designs primarily to provide improved habitat conditions for salmonids and, as necessary, for protection of other corridor features to balance the many uses of the rivers and streams. It is becoming a more commonly used practice for restoration practitioners throughout the Pacific Northwest, specifically in areas where Reclamation has commitments to the BiOp.

1.3 Definitions

Large Woody Material (LWM)

LWM, as used in this document, includes any log of a diameter equal to or greater than 12 inches at breast height (DBH) and 10 or more feet in length, with or without their rootwads. This material is used for placement in a river or stream as stand-alone logs in the streambed or complex ELJs that include numerous logs of various lengths and sizes, bound together through weaving or with engineered fasteners and ballasted from floatation.

The Design Team

Improvement of altered rivers and streams is an emerging science and as such, it lacks defined guidance and procedure. Pioneers in this field have come from various scientific backgrounds, including earth and biological sciences. Currently, streambank stabilization and channel restoration work, including the design of LWM and ELJs, is often completed by an unlicensed scientist, rather than a registered professional engineer (Andrus and Gessford 2007). However, it is becoming increasingly clear that designed placement of LWM and ELJs likely falls under the umbrella of “practicing engineering” and, therefore, should follow state laws and ethical guidance governing such practice intended to safeguard public health and welfare. By providing technical assistance for the completion of construction documents that include specification and design of LWM to be placed in streams, Reclamation is, by definition, “practicing engineering” (State of Washington – Title 18, Chapter 18.43, Section 18.43.020). The practice of engineering is governed by each state with its specific requirements for registration and professional conduct that includes provisions with regard to design and the need to hold paramount the safety, health, and welfare of the public (ASCE 2013). As an example, Washington State’s provision for the practice of engineering begins as follows:

> “In order to safeguard life, health, and property, and to promote the public welfare, any person in either public or private capacity practicing or offering to practice engineering or land surveying, shall hereafter be required to submit evidence that he or she is qualified so to practice…” (State of Washington – Title 18, Chapter 18.43, Section 18.43.010).

In addition to holding a license to practice engineering, an engineer is typically required to “…perform services only in areas of their competence” (ASCE 2013). The design and placement of LWM within a stream or river corridor is typically a multidisciplinary effort, with design teams consisting of professionals with working knowledge of geology, fish biology, hydrology, fluvial geomorphology, sedimentation engineering, structural engineering, geotechnical engineering, hydraulic engineering, and river safety. Therefore, it is imperative that a multidisciplinary team be formed since these attributes of LWM design are not typically within one person’s area of competence. At a minimum, a designer will be required to get formal review of their decisions and designs by specific team members for LWM designs as outlined in Section 5.0 of this document, which describes minimal design team requirements based upon risk levels. In order to professionally seal the overall design product, a qualified professional engineer must engage in the design effort as responsible charge (Reclamation 2008b). This will minimally require a qualified licensed engineer to review necessary documents, including background materials, so that he/she is familiar with the individual site and design methods for appropriate review and acceptance. Engineering qualifications are detailed in Section 5.0 as appropriate to level of risk.

As stated earlier, the purpose of these guidelines is to provide a clear and consistent mechanism by which decisions can be made with respect to the design and placement of LWM. While this has not been adopted on an agency-wide or national level, it is Reclamation’s attempt to demonstrate transparency in the design development and risk assessment of these design elements.

2.0 HOW TO USE THIS DOCUMENT

The process outlined in this document is an attempt to perform design of LWM elements throughout Reclamation utilizing a risk-based approach, such that level and stringency of the planning and design effort is reflected by level of risk at the particular location. Initially, this document outlines a process of identifying potential risks to public safety and property that placement of LWM in a stream might present. A level of risk is assigned to project elements and the project as a whole for both public safety risk and property damage potential. Minimal design guidelines are then given for each risk combination for a design team to follow. Details of the design process and appropriate references are then given to lead a design team through to completion, resulting in a clearly vetted, documented, and finalized design for a LWM structure or project.

Initially, this process requires a design team to ask specific questions and to document their assumptions regarding risks associated with individual site location. Questions include specifics regarding the physical properties of the individual river reach, and how location and placement of an individual or group of LWM structures ultimately rank a project in terms of risk level. The intent of this design guidance is to provide designers working on projects utilizing LWM, consistent guidance from conceptual planning to final design that results in obtaining all project goals while also addressing and documenting public safety and property damage risks associated with LWM placement in the individual river reach.

The following steps outline the minimum risk-based design process for projects with LWM elements. Other necessary steps for project development and evaluation that include establishing clear goals and objectives of each project, along with plans for project monitoring and maintenance, are not included here, but need to be addressed separately. For LWM project elements, the following ten steps are intended to be completed methodically while understanding that as new information becomes available, some steps may need to be repeated so that risks are addressed in the design process in an iterative completion process:

1. **Step 1 – Pre project planning and site visit**

   The first step in a project is to establish ground rules that include goals and objectives, approximate budget limits, landowner concerns, regulatory concerns, timeline, design team roles and responsibilities, project stakeholders, and communication plans. All of this results in a project plan that is currently a requirement for all Reclamation projects for Reclamation's Columbia-Snake Salmon Recovery Office (CSRO). More details for development and necessary steps for a project plan are currently being developed and more information is available by contacting the CSRO office.

As part of the planning process, it is critical for members of the design team to meet with significant stakeholders and regulatory entities onsite for a project site walkthrough. This initial meeting and site visit should be utilized to establish ground rules for the project, along with initial identification of both project opportunities to address goals and potential limitations due to identified risks.

2. Step 2 - Reach level risk assessment

As outlined in Section 4.0, several risk factors to consider are reach-based and are not related to individual structure design. Reach factors can be defined from sources such as tributary assessments, reach assessments, geo-spatial data, aerial photography, river use studies, and local interviews. Definition of the reach factors up front will inform the design team as to the potential risks that the reach has with respect to LWM placement and should help to define the initial project concept so that the initial concept has some context as to acceptable risk. Minimal watershed and reach-based factors to consider include:

A. Property characteristics

- Existing in-channel structures (i.e., docks, pumps, intake structures, etc.).
- Existing floodplain structures in the reach (i.e., houses, out-buildings, etc.).
- Current and future potential land uses.

B. Reach-user characteristics

- Frequency of recreational or other use.
- Skill level of users.
- Access availability.
- Presence of children within reach.

C. Stream response potential

- Stream type.
- Riparian corridor conditions.
- Bed scour potential.
- Bank erosion potential.

D. Watershed conditions

- Watershed hydrology (hydrologic regime).

- Watershed vegetation including forest type and stage.
- Existing LWM levels in the watershed.
- Degree of impairment or alteration of watershed.

E. Biologic response potential

- Fish species and life stage presence.
- Target life stage and periodicity.
- Expected biologic response/benefit.

3. **Step 3 - Project concept development**

Once a reach-level assessment has been performed and design objectives have been clearly described, the project team can formulate a conceptual project to include LWM elements that can be evaluated within a risk assessment. Information regarding this critical step can be found in Section 3.0.

4. **Step 4 - Site level risk assessment**

As further outlined in Section 4.0, factors to consider at the site level include those previously described at the reach level, along with a more detailed evaluation of structure characteristics for potential public safety hazards, such as:

- Site-specific materials (i.e., geotechnical conditions, river features, etc.)
- Location of LWM structure within channel.
- LWM structure type and straining potential.
- Site egress during conditions in which people would normally encounter LWM structure.
- Sight distance for people to recognize hazard during conditions in which people would normally encounter LWM structure.
- Potential physical hydraulics at site of LWM structure.

5. **Step 5 - Risk level determination**

The design team completes the risk-matrix process to determine level of risk as outlined in Section 4.0.

6. **Step 6 - Define minimal design criteria including design team members**

The design team's needs and project specific design criteria are refined based upon risk assessment level as detailed in Section 5.0.

7. **Step 7 – Risk-based design**

   The design team designs each individual LWM structure based upon outcome of risk assessment and per requirements detailed in Section 6.0.

8. **Step 8 - Design team review**

   The designs are reviewed and refined according to minimal criteria as discussed in Section 5.0 of this document, in addition to any necessary reviews required by current Reclamation design standards and project specific stakeholder requirements.

9. **Step 9 - Design completion**

   The designs are finalized with appropriate acceptance from stakeholders and required signatures as detailed in Section 5.0.

10. **Step 10 - Documentation**

    Entire process is documented in design memorandum with a risk assessment report and detailed in appropriate design drawings as discussed in Section 5.0.

3.0 Project Planning – Locating LWM Structures for Risk

Prior to developing a project concept, the project design team should consider potential risks for a particular project reach. In their site evaluation, the design team should look for indicators of such risk to include obvious signs such as public or private infrastructure, boat launches, and public gathering places. Some other, not so obvious signs to look for may include bank erosion, frequented pathways, lack of riparian vegetation, bedrock, potential swimming holes, and roadside access. This type of information, along with a quick literature or web-based search may alert the design team to potential recreational or other use and to property or infrastructure concerns. This information will aid the project design team in formulating an initial project concept. The closer the initial concept is to the risk acceptance level of local stakeholders, the less iterative the design and planning process may be.

3.1 Conceptual Design – Locating for Reduced Public Safety Risks

For those project sites that are in a reach with some public safety concern (i.e., frequent river usage), the project design team should consider how a river user may avoid a proposed LWM structure at the onset of their conceptual design and include factors such as stream currents (eddies) and bank conditions for ease of avoidance of a structure from a river user perspective. Design teams should seek to create the same river classification of rapids that existed prior to disturbance and should consult with recreational users of the reach regarding design features and reach use (Colburn 2012). For areas where there is floating or swimming recreational use by, sight distance may be a serious concern. Choosing LWM sites that are easy to see from the upstream user's perspective becomes more important. Additionally, the design team needs to consider the skill level of the users and determine if there is a safe and easily navigable way around the structure. This could be an easy exit from the stream at an eddy with a walkable pathway or a clear pathway within the stream that is easy to navigate through, remain within, or both (Colburn 2012).

The design team needs to consider seasonal use and river conditions to include typical velocities that may be encountered while users are present (approach velocity). The design team also needs to consider water levels relative to the LWM structure. Will the LWM structure be submerged and therefore, not recognized as a hazard? What will the hydraulic conditions be when users are present? These conditions may be distinctly different from those encountered during a site visit. All of these factors will be further examined through the risk matrix process, but an attempt at addressing some of the risks during the conceptual stages may save time in the planning process.

3.2 Conceptual Design – Locating for Reduced Property Damage Potential Risks

The design team will likely perform some relevant literature and geographic information system (GIS) data review, along with a kickoff site visit to the project reach, prior to initiating conceptual design. During this initial period, the design team should research basic information to help inform them about reach characteristics and increase awareness of property damage potential. Some helpful research could include the following sources (websites and GIS sources):

- Recent and Historic Aerial Photographs
    - Google Earth - www.earth.google.com
    - U.S. Department of Agriculture NAIP inventory www.fsa.usda.gov
- Soil Mapping
    - USDA NRCS Soil Survey - www.websoilsurvey.nrcs.usda.gov
- Road Network, Land Use, and Hydrography Data- Various State GIS Repositories
    - Oregon - www.gis.oregon.gov
    - Washington - www.fortress.wa.gov/dnr/app1/dataweb/dmmatrix.html
    - Idaho - www.gis.idaho.gov
- FEMA Floodplain Mapping
    - FEMA Map Service Center - https://msc.fema.gov
- Surface Water Right Locations and Rights to Divert - State Department of Water Resources
    - Oregon - www.oregon.gov/owrd/Pages/index.aspx
    - Washington - www.ecy.wa.gov/programs/wr/wrhome.html
    - Idaho - https://www.idwr.idaho.gov

Ideally, the literature and mapping reviews would occur prior to the initial site visit so that design team members are familiar with the area and know of the large-scale features in and around the reach (i.e., land use, bridge locations, vegetation conditions, etc.) and the physical features (i.e., geology, soil types, watershed area, watershed conditions, etc.) prior to the initial site visit. This knowledge should benefit the design team in conceptualizing a project to include LWM elements that meet initial project goals and objectives within the limits of budget and stakeholder constraints. A critical aspect of this process will be to identify potential property damage risks to existing or planned infrastructure and land use features, and to estimate the approximate level of planning and construction costs to ensure that damages are avoided. The design team should evaluate the site for potential property damage issues and make note of potential physical unknowns (e.g., geotechnical conditions, hydrology), which may require additional data collection or investigation prior to completing design.

3.3 Planning Process – Mitigating LWM Designs for Risk

Natural and man-made streams are inherently risky places for people and property. Natural stream channels transport water, sediment, and debris. Natural hazards include cold-moving water, vegetation, floating woody material, dumped material, eroding streambanks, boulders, and natural large wood accumulations. Design of dynamic habitat complexity in a stream is often contrary to public risk acceptance; therefore, it can be difficult to strike a balance between the two. Some project locations may be too risky to place large amounts of LWM within them and other locations may pose very little or no risk to doing so. These guidelines are intended to develop a procedural assessment of the potential risks when designing a project with LWM elements in an attempt to meet individual project objectives such as improved habitat complexity while addressing public and private stakeholder risks. This document does not cover processes or strategies for stakeholder or public involvement, but it is recognized as critical for project success. Stakeholder and public involvement is fundamental to project success and it is the intent of these guidelines to provide a basis for communicating both real and perceived project risks associated with LWM with all project stakeholders.

The risk-based design process is iterative and consists of conceptual design development, followed by a risk assessment utilizing these guidelines, followed by design adjustment, review, and re-evaluation of risks until acceptance of the project design is achieved by all team members and project stakeholders. It will be up to the individual project teams, landowners, project sponsors, local governments, and project funding entities to determine when they have met the necessary metric of public acceptance to move to project implementation. Along the path of this iterative process, there are likely a multitude of mitigating features and processes that may be more acceptable by eliminating or reducing some factors of risk for an LWM project. The following sections list some potential avenues in reducing risks and gaining further acceptance from project stakeholders. This list is not meant to be all inclusive as all projects are unique, but the list offers some potential avenues for exploring optional project components or placements to lessen risks for LWM projects.

3.3.1 Public Safety Risk Reduction Measures

Reducing risks posed by LWM features to river users typically includes alteration, movement, or removal of particular LWM elements. It can also include provisions for further educating the public regarding LWM features of a project so that risks are better understood. Some possible avenues to consider when attempting to reduce risks for a particular LWM feature or project may include the following:

- Moving LWM features from high risk areas or away from primary flow momentum.
- Removing protrusions in LWM feature and adding smooth "bumper" logs to upstream areas in which recreationalists may encounter the LWM.
- Placing signage in recreation areas to warn of potential risks.
- Creating or enhancing egress locations and clear paths around LWM features
- Reducing the number of LWM features.
- Placing fencing and removing easy access locations near LWM features.
- Creating or designing a persistent upstream bar depositional feature to deflect recreational users away from downstream LWM feature.

3.3.2 Property Damage Risk Reduction Measures

Structural Measures

Structural risk reduction measures may include additional project elements that are designed to prevent property damage and can include a multitude of options, depending upon the unique project circumstances. Whenever possible, additional project elements that are designed to reduce or eliminate property damage for a project should also attempt to further enhance the project objectives and can be made from natural materials to include additional LWM features and biostabilization techniques. Some potential examples may include:

- Debris deflectors - Structures such as log cribs or "flood fencing" structures that deflect the major portion of debris away from critical infrastructure (e.g., culvert, bridge pier, water intake) (FHA 2005).
- River training structures - Structures designed to "train" the river current in a specific direction such as stream barbs, which are typically designed to move current away from the near bank to reduce or eliminate erosion (NRCS 2005).
- Revetments - In some instances, bank armoring may be necessary and can consist of a wide range of materials, including rock or, more preferably, bio-engineering materials such as soil lifts and woody vegetation treatments.

Non-Structural Measures

Non-structural measures include establishing definitive planning and adaptive management protocols for the project that will ensure that monitoring and adaptive maintenance activities occur at critical periods during the life of the project. Specific details regarding monitoring plans are not included here, but are encouraged for multiple reasons such as reducing property damage risks and evaluating the project success at meeting its goals and objectives.

4.0 LARGE WOODY MATERIAL RISK ASSESSMENT

In 2007, Attorneys Beth Andrus and James Gessford documented the risks associated with ELJs and discussed the legal doctrines that govern liability for such structures in Washington State. In addition, they also included some recommended risk mitigation measures in a white paper (Andrus and Gessford 2007). In their paper, the following risks associated with LWM or ELJs were identified:

A. Hazard to river users or children

LWM or ELJs pose safety hazards to river recreationalists such as kayakers, rafters, swimmers, and fishermen. LWM can capture a recreational user who is unaware of the underwater snag and unable to see it or move away from it. Even properly designed and constructed ELJs can pose a risk of snagging or pinning a recreational user, particularly in fast moving rivers or streams. Similarly, children, who are curious by nature and unable to understand the risks posed by LWM, are likely to be drawn to play on or around a pile of wood or debris sticking out of the water. Therefore, LWM can present an especially dangerous risk as an attractive nuisance to the curious child exploring the river to play. Identification and design treatment for these hazards are addressed under Section 4.1, Public Safety Risks.

B. Structural failure and subsequent damage to infrastructure and downstream property

Even when properly designed, LWM or ELJs are susceptible to being dislodged during large storm events. As with naturally occurring LWM, this dislodged material can get hung up on or block culverts or bridge openings and cause pier and abutment scour, channel avulsion, or bridge overtopping, subsequently causing changes to the river form and hydraulics. Furthermore, the floating LWM has the potential to cause damage to downstream property and infrastructure, including streambanks, irrigation diversions, storm drainage outfalls, docks, and other bank protection projects. Identification and design treatment for these risks is covered under Section 4.3, Property Damage Risks.

C. Erosion

LWM placed in a stream, even when properly designed, can result in dynamic natural channel adjustments upstream and downstream of the ELJ structure. Channel erosion can include erosion of the streambed or banks, which can result in property loss and the addition of sediment to the stream. The addition of fine sediment can impair water quality. The susceptibility and associated risk for channel erosion is addressed in Section 4.3, Property Damage Risks.

D. Flooding

While not addressed in this document, LWM placed in the active floodplain or floodway has the potential to increase channel roughness, constrict channel width, and capture floating debris, all of which causes water to back up behind the structure. These effects can lead to increased flooding upstream or around the project area. This identified risk is not addressed in this document, but must be accounted for during the design by adhering to all local, state, and federal flood ordinances as typically established by cities and counties and minimally following FEMA flood insurance procedures at http://www.fema.gov/national-flood-insurance-program.

E. Occupation Health and Safety Issues

While not addressed in this document, safety risks to the health and well-being of personnel during the construction of ELJs within a stream or river were identified. This includes both construction and design personnel involved to ensure compliance with the design. This risk is not accounted for in this document as part of the risk assessment. However, it needs to be addressed through following established construction safety practices and procedures by all personnel onsite during construction at https://www.osha.gov.

Streams and stream corridor land uses are inherently diverse; therefore, all potential project sites differ with regard to their risks for placement of LWM in them. Prior to design, a risk assessment must be performed to identify potential issues associated with the placement of LWM at any given project site. As described, some identified risks to the public by placement of LWM in rivers can include risks to recreationalists within the river; risks to children playing in the river; risks of increased flood conditions; risks posed by channel migration; risks to infrastructure (bridges); risks to diversion facilities; risks of increased bank erosion; and risks caused by changes to channel form through aggradation or degradation. These identified risks are organized into two risk categories to address these concerns: (1) public safety risks and (2) property damage risks.

4.1 Public Safety Risks

Public safety risk evaluation addresses those risks posed by LWM within the wetted perimeter of a stream that can cause harm to people that are likely to be in and around the stream corridor. Two public groups have been identified as having the greatest potential risks for this category: recreational users and children. Recreational users include all groups or individuals that have been known in the past or planned in the future to utilize the particular stream reach for purposes of recreation (e.g., swimming, floating, and fishing). Risks to children include those reasonably known risks to the inherent curiosity and innocence of children that could be expected at the particular site. For the purposes of providing a repeatable methodology that assesses major public safety concerns, the two risks categories have been lumped into one public safety risk matrix for establishing the minimal public safety risk level.

The public safety risk matrix requires the designer to address several user groups and physical river process questions for each relevant LWM element in a project. Each response is weighted and plotted on the matrix to determine the minimal risk level of either low or high. The rating outcome is not necessarily the risk level assigned, but establishes the minimal risk level to the project. In some instances, a potential risk element may be severe (such as a project adjacent to an elementary school playground), but may not be reflected in the computed rating for public safety risk when all elements have been ranked in the matrix. Therefore, the design team and project stakeholders have the discretion of assigning a higher level of risk to a project than that shown by the minimal level assigned through the matrix evaluation process.

A simple recreational risk identification matrix for LWM, used and modified by Reclamation, was presented at the River Restoration Northwest Conference in 2012 (Embertson and Monahan 2012). The resulting matrix plots two categories: the structure characteristics of each LWM structure versus the user characteristics for the project area. For each category, specific factors are evaluated and rated for each LWM structure (Figure 1). A point system is used for rating each factor that ranges between 0, equating to no risk, and 10, equating to extreme risk. For each category, the points assigned to each factor are summed and then averaged. Average values for each category are then plotted on the matrix against one-another to rate the individual LWM structure in the project. A minimum rating of either low or high is then assigned as the public safety risk for each structure based on the matrix exercise. With stakeholder input, the design team can then evaluate each structure and determine if the resulting rating reflects the risk for each LWM structure within a project. After this process, a final rating is assigned for use in the LWM structure design.

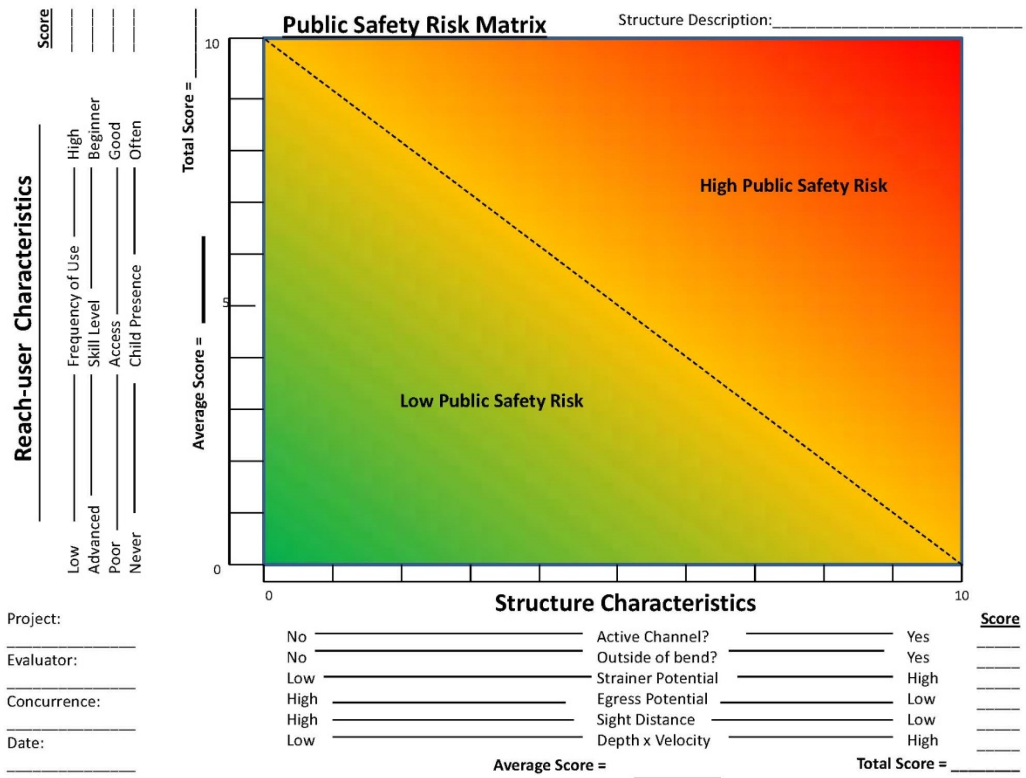


Figure 1. Public Safety Risk Matrix. (Refer to Appendix C for the full-size rating form).

4.2 Public Safety Risk Matrix

4.2.1 Public Safety Risk – X-Axis, Structure Characteristics

The X-axis of the Figure 1 matrix includes six factors for developing an average categorical risk. Each of the six factors is rated for each LWM structure proposed by the design team. As stated in Section 4.1, each factor should be assigned a rating from 0 to 10, which represents low to high levels of risk, respectively. Some guidance as to level of risk from low to high is given here; however, the design team shall rate each structure based on individual circumstances using best professional judgment. For river reaches with regular recreational use, designers are encouraged to float the project reach during conditions for expected use if properly equipped and trained to do so or utilizing properly trained river guides to do so.

1. **Active channel** - This factor rates the uncertainty of physical channel migration. The magnitude of risk for this factor is related to the anticipation of dynamic channel movement outside of the proposed design corridor. For example, if the structure is placed in a reach or channel that presently has obvious active channel migration or has evidence of such from recent records, the rating would be higher than a reach that is unlikely to change. This is also dependent upon the physical attributes of the corridor,

if it is alluvial or constrained by bedrock formations. If there is evidence of recent physical channel changes such as bank erosion, bar formation, or aggradation, this factor would be rated higher than if no evidence existed. However, barring evidence of such changes, the uncertainty can be evaluated using the physical attributes and processes anticipated within the reach. For example, a low rating (0) is appropriate if the reach is within a bedrock controlled channel and a high rating (10) is appropriate if the reach is located on an active alluvial fan. A moderate rating might be applied to an alluvial system that has changed in the past, but may not show obvious activity recently or is further confined due to other anthropogenic or natural features. Individual ratings must be decided by the project design team.

2. **Outside of bend** - This factor rates the location of the LWM structure design inside or outside of a bend. This factor rates the likelihood or potential that a recreationalist may be forced into the structure by the primary stream forces or flow characteristics within the channel. The smaller the radius of curvature of the bend (greater the tortuosity) or the greater percentage of stream momentum concentrated in the direction of the LWM structure, the higher this rating shall be. Individual ratings must be decided by the project design team.

3. **Strainer potential** - This factor rates the potential for a structure to pin or entrap a person against it. Structures that have some porosity or protrusions may have a higher potential to pin or entrap an individual. LWM elements may be designed to provide an amount of porosity with elements that are meant to snag flotsam in the river to enhance the habitat complexity and formation. LWM structures such as these would be rated high. Some LWM structures are filled with rock material creating a nearly solid structure and can contain smooth outer edges designed as hydraulic features for restoration needs. These structures can be rated low and the rating is dependent on the actual design features. Individual ratings must be decided by the project design team.

4. **Egress potential** - This factor rates the ease of avoidance for a person floating or swimming in the area of the structure. This includes avoiding the structure in terms of potential stream currents upstream and at the structure. Additionally, this factor should rate the ability to get around the structure through a clear navigable or walkable path. In a narrow stream with a LWM structure that extends significantly into the stream current, this factor could be rated high. For a wide river with uniform flow current and a small LWM structure placed on one bank, this factor could be rated low. Additional bank condition factors to consider might be a deeply incised channel or a channel with dense thorny vegetation on its banks where exiting and walking around a structure may be difficult. In these particular situations, the factor may be rated higher. Individual ratings must be decided by the project design team.

5. **Sight distance** - This factor rates the ability for recreationalists to see the structure and have the time to move away as they approach from upstream. This factor rates both

the ability to see the structure from upstream as well as the rate at which one approaches. This factor should be considered for periods in which recreationalists are either known or thought to utilize the stream reach (i.e., spring or summer rafting season, or fall fishing season). Sight distance should consider obstructions to view, slope of river upstream, velocity of river, width of river, and length of approach from LWM structure location when readily visible. A LWM structure located immediately around a bend with limited ability to see in a swift stream would be rated high for this factor. A LWM structure located in a straight and wide reach of a slow moving river that is clearly seen at all river flows could be rated low for this factor. Individual ratings must be decided by the project design team.

6. **Depth x velocity** - This factor rates channel approach velocity and depth to define the safety of standing and moving away or around the structure. For a situation where a person swimming in the stream and approaching the structure can reasonably stand and walk around the structure, a low rating could be applied. For any structure in which wading in the river as one approaches or arrives at the structure is difficult, a high rating would likely apply. As a guide, a low rating could result from a velocity-depth product of 0 to 2, a moderate rating could result from a velocity-depth product of 3 to 5, and a high rating could result from a velocity-depth product of 6 and above. However, the individual rating for this factor must be made by the design team for reasonable case specific circumstances to be encountered.

Once the six factors are rated and a numerical value has been assigned, the individual numerical ratings for the six factors should be summed and divided by six to determine an average structural characteristic rating used for plotting on the X-axis of the matrix. This should be done for each LWM structure.

4.2.2 Public Safety Risk – Y-Axis, Reach-User Characteristics

For the Y-axis of the public safety risk matrix (Figure 1), the following four factors are rated for typical recreational users and public presence in the project reach. As with the X-axis, each factor is rated on a scale of 0 (low risk) to 10 (high risk) by the project team. Guidelines for factor rating determination are given below, but should only be used as a guideline with deference to the project team, stakeholders, and supporting documentation.

1. **Frequency of Use** - This factor rates the level of use that can be expected within the project reach by recreationalists and is typically for those floating the river in a water craft; however, it can also account for people using the project reach for swimming and other in-river activities, as appropriate. Initially, potential use should be estimated through interviews of local user groups and a review of pertinent published guides and internet sources. For example, a reach of river that is frequented by an established guide company for use of inner-tubing or that is frequently used by the general public for such purposes would be rated high. Similarly, if the reach is known for intense

fishing or is listed as such within fishing guides or other sources, it would be rated a high score. Conversely, a reach of river where use is unknown and not documented as being used by anyone could be rated low. Individual ratings must be decided by the project design team and be based on local research of reach use.

2. **Skill level** - This factor rates the risk associated with the recreational skill level of users in the project reach and can be applied to people floating the reach or by swimming ability in locations where public tend to swim. For people floating the reach, craft type and safety equipment use could be factored into the risk assessment (i.e., low-skilled inner-tubers to highly-trained whitewater boaters). For example, a reach that is used by a range of individuals in which limited or no knowledge of river safety is practiced would be rated as low skill level and would likely receive a high numerical rating as having a greater risk hazard. Conversely, a reach that is only used by highly advanced and trained boaters with proper safety equipment would be rated as high skill level and could receive a lower numerical rating as having a lesser risk hazard if LWM conditions were already expected to be encountered in the reach. Individual ratings must be decided by the project design team and be based on local research of reach use.

3. **Access** - This factor rates the risk of having the public recreating in the project reach by accessibility. A reach with good access that is provided by a public boat ramp or park could be rated as high. A reach with access from nearby bridges or non-public, but utilized locations might be considered moderate, and a site with no nearby access provided by public roads and difficult terrain may be rated as low. Good access would receive a higher numerical risk rating, whereas poor access would receive a lower numerical risk rating. Individual ratings must be decided by the project design team and be based on local research of reach use.

4. **Child presence** - This factor rates the public safety risk at the project reach for the presence of children and is used to factor locations where children are known to be present and may be prone to investigate LWM structures to play on or near. As an example, a reach located adjacent to a summer camp for children would likely have a high numerical risk rating. Conversely, a location with difficult access and not near any location where children are known to be present would likely have a low numerical risk rating. Individual ratings must be decided by the project design team and be based on local research of local known uses.

Once these four factors are rated and a numerical value has been assigned, the individual numerical ratings for the four factors should be summed and divided by four to determine an average structural characteristic rating used for plotting on the Y-axis of the matrix.

4.2.3 Plotting the Matrix

Once each factor has been given a weighting, the factors for the X- and Y-axis are summed and averaged. The average values for each axis are then plotted where they intersect on the public safety risk matrix, which results in placement within either the low or high risk area of the matrix, representing the minimal risk assignment of a particular LWM structure (Figure 1). This area designates the minimal design standards, as described in Section 5.0, that are necessary for the particular LWM structure once assignment by the project team has been determined. If a higher risk rating is desired because of specific conditions or stakeholder concerns, the design team can choose to apply a higher rating. However, if a lower risk rating is desired, the project design team would need to consider changes to the conceptual LWM structure location or geometry that would result in a lower risk to public safety and document the decision.

4.3 Property Damage Risks

Rivers are dynamic and placement of LWM in them creates a changed condition. The river channel responds sensitively and quickly to any change (Leopold 1994.) Design teams must predict the potential dynamic changes that may manifest themselves through placement of LWM. Design for placement of LWM in rivers is governed by the anticipated desired response, either to maintain a conditional static form or to initiate a dynamic response. Given the dynamic nature of rivers and the multitude of independent variables associated with system response, predictions of response are probabilistic. Confidence in predicting responses is dependent on physical variables of the stream channel and its supporting watershed. Primary physical drivers for dynamic response potential include geology, hydrology, and vegetation (USFWS 2009). Therefore, risk potential for stream response at a project will depend on these physical variables. Additionally, as project complexity increases by either the complexity of LWM features or by the number of LWM elements, dynamic variability increases and response prediction becomes difficult.

In addition to stream response, the magnitude for potential property damages, including the mitigation costs and social values need to be considered. Some obvious features in and around a stream channel of value include instream structures such as bridges, water intakes, and docks. Damage can occur to floodplain structures such as houses or to agricultural lands, landscaped areas, and roadways. It is difficult to provide a single methodology to account for the multiple possibilities for property damage risk assessment associated with placement of LWM. Similar to the complexity of public safety risk, property damage risk potential can be assessed by categorization from low to high potential risk through a matrix exercise.

4.3.1 Property Damage Risk Matrix

A risk identification matrix was developed by Reclamation to identify risks to property including public infrastructure, private infrastructure, and private lands as a variable of potential dynamic stream response (Figure 2). This matrix was based on modification to the 2-axis screening matrix developed for evaluating project proposals (RiverRAT) by the National Marine Fisheries Service (NOAA Fisheries) and U.S. Fish and Wildlife Service

(USFWS) in assessing a project's potential risk for negative impacts to environmental resources (USFWS 2009). Originally developed for evaluation of a project's risk relative to negative impacts to environmental and wildlife resources, the matrix was adapted to evaluate a project's risk to potential property damages. Much like the screening matrix developed by NOAA Fisheries and USFWS for RiverRAT, the property damage risk assessment matrix is qualitative.

The 2-axis matrix shown in (Figure 2) evaluates property damage risk potential for all LWM structures of a project by weighing the two categories of property/project characteristics and stream response potential against one-another. On the X-axis, the stream response potential is used to evaluate the inherent sensitivity of the stream to natural or anthropogenic disturbance. On the Y-axis, the property/project characteristics are used to evaluate the complexity of the project, the type of land use, and the number of potentially affected in-channel and floodplain structures within the immediate reach of the project.

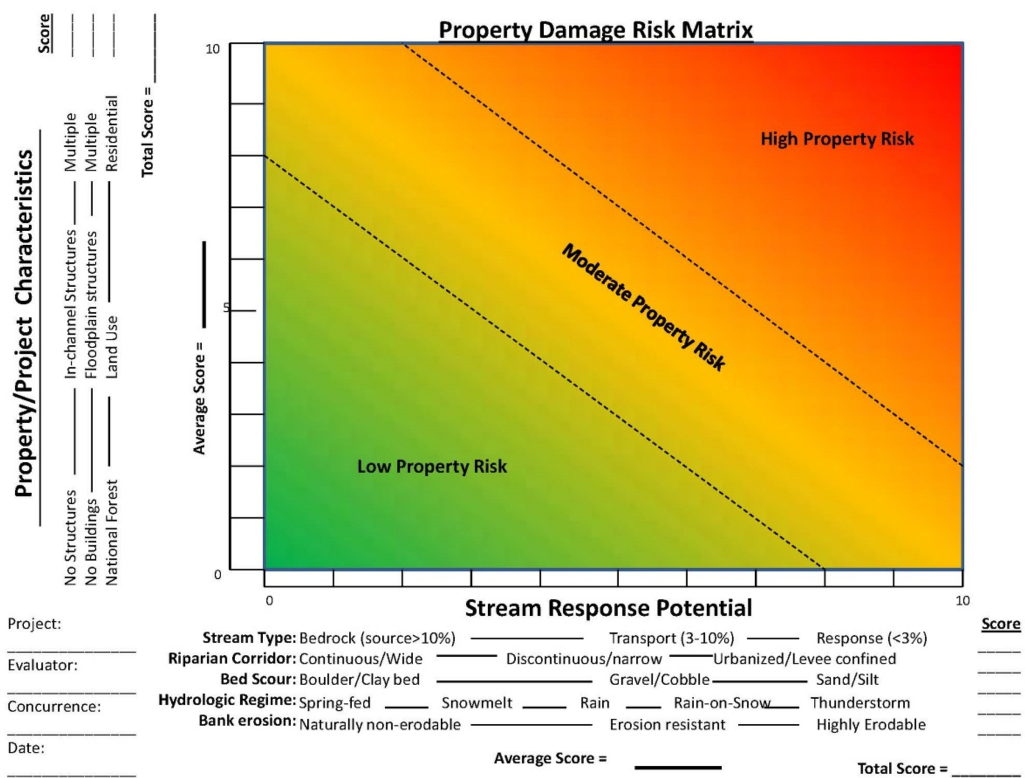


Figure 2. Property Damage Risk Matrix. (Refer to Appendix C for the full-size rating form).

4.3.2 Property Damage Risk – X-Axis, Stream Response Potential

This matrix is intended to provide a repeatable methodology for various design teams to assess property damage risk potential for projects and communicate that risk to stakeholders in a repeatable fashion. There are no right answers in defining levels of risk, but a number is assigned to each factor to assess property damage potential. Five weighting factors are considered for evaluation of stream response risk, which are defined by Reclamation for purposes of property damage risk assessment of a potential LWM structure. More information on each of these physical stream response factors can also be found in documentation for using RiverRAT at http://www.restorationreview.com.

The X-axis weighs the potential for a LWM structure to influence or cause physical changes within the stream channel, which has been termed as stream response potential. For each of the five project factors, a value between 0 and 10 (no risk to very high risk) is chosen based on physical conditions and hydrologic drivers. Each factor is weighted evenly and an average of all five factors is determined for plotting on the X-axis of the property damage risk potential matrix (Figure 2).

1. **Stream type** - This factor rates the potential for stream response based on the stream's type and slope within the project reach. Identification of the stream type can be used to determine a stream's potential sensitivity to disturbance. Using Montgomery and Buffington's classification system (Montgomery and Buffington 1998) or other methods, one can estimate a stream's physical sensitivity to change. A project located in a source reach with a bedrock channel and a high slope may be rated as having a very low sensitivity. A project located in a response reach within an alluvial channel and low slope may be rated as having a high sensitivity. Individual ratings must be decided by the project design team.

2. **Riparian corridor** - This factor rates the project reach's ability to respond to change through natural riparian resilience. The capacity of the stream to absorb disturbances without harm to habitat or property, often referred to as resilience, generally increases with the width of the riparian corridor (USFWS 2009). Additionally, the probability that the stream may be adversely affected increases when the riparian corridor is narrow or discontinuous. A project in a location with a relatively wide riparian corridor in comparison to stream width would be rated low. Whereas, the risk associated with morphologic response is greatest in urban and levee-confined streams that lack the space necessary to respond to disturbances (USFWS 2009). Individual ratings must be decided by the project design team.

3. **Bed Scour Potential** - This factor rates the project reach's physical susceptibility to bed changes. Channels with highly mobile or erodible bed material such as sand or loose gravel will respond to disturbance more rapidly and to a greater degree than

those with less erodible bed material. Coarse sediment, particularly immobile material such as boulders, creates streams with much lower scour risk. Individual ratings must be decided by the project design team.

4. **Bank Erosion Potential** - This factor rates the project reach's physical susceptibility to bank erosion based upon bank material composition. Bank erosion is lower in channels with naturally non-erodible bank materials, such as rock or highly cohesive clay. Conversely, erosion is higher in channels with banks that are highly erodible due to their material composition such as sand or loosely deposited alluvium. This factor rates the project reach's physical susceptibility to bank changes. Individual ratings must be decided by the project design team.

5. **Dominant Hydrologic Regime** - This factor rates the stream's temporal hydrologic variability. Stream systems with evidence of high variability in their hydrograph have a much greater potential for system response and hence a relatively lower channel stability (USFWS 2009). For example, spring-fed stream systems that have little discharge variability and hence are highly stable and predictable and would be rated low. In contrast, convective thunderstorm-driven hydrology that results in streams with high variability and more frequent high flows could be rated high. Additionally, streams that show evidence of hydrologic regime shift from climate change or other factors such as from snowmelt driven to rain-on-snow events are especially susceptible to change and should be rated high. Individual ratings must be decided by the project design team.

4.3.3 Property Damage Risk – Y-Axis, Property/Project Characteristic

For each of the three project factors, a value between 0 and 10 (no risk to high risk) is chosen based on proposed project and its unique site conditions. Each of the three factors is weighted evenly and an average of the three factors is determined for plotting on the Y-axis of the property damage risk potential matrix (Figure 2).

1. **In-channel structures -** This factor weighs the amount, type, and vulnerability of in-channel structures present in or near the project to LWM. In-channel structures can include bridges, piers, docks, intakes, pumps, fish screens, and any other placed features in the channel area. The distance for evaluation of structures upstream and downstream of the LWM project must be decided by the design team and based on physical conditions and project stakeholder consideration. A project with no structures located in the determined damage area of a project could be rated as 0. A project that has multiple vulnerable structures in the determined potential damage area or a structure with multiple piers and no freeboard could be rated 10. Individual ratings must be decided by the project design team. The decisions on the distance to consider for potential damages needs to be clearly documented by the design team.

2. **Floodplain Structure**s - This factor weighs the amount, type, and vulnerability of structures within the 100-year floodplain influenced by the project to flood changes. A project that has no constructed structures in the 100-year floodplain could be rated low. A project that has multiple residences within the 100-year floodplain and at or only minimally above it could be rated high. Individual ratings must be decided by the project design team.

3. **Land Use -** This factor attempts to determine the property damage potential by land use category. A qualitative assessment is performed by the design team and is based on project stakeholder input. Flood prone land uses that are highly susceptible to either flood effects or channel migration would receive higher ratings than natural land uses. For example, an area in which floodplains are used for agricultural of high value crops that are grown during a common flood season may receive a higher rating than an area where natural uses are predominant. As another example, a project that is completely located on National Forest lands may be rated as low. A project that is within an urban area with exposed channel banks could be rated as high. Significant farm land or rural residential may receive a moderate rating. Individual ratings must be decided by the project design team.

Once each factor has been given a rating, the factors for the X-axis are summed and averaged and the factors for the Y-axis are summed and averaged. The average values for each axis are then plotted where they intersect on the property damage risk matrix, which results in placement within low, moderate, or high risk areas, representing the minimal risk assignment that a particular project has (Figure 2). Minimal design standards are then necessary as described in Section 5 for addressing property damage risks for the project once assignment by the project team has been determined. If a higher risk rating is desired because of specific conditions or stakeholder concerns, the design team can choose to apply a higher rating. However, if a lower risk rating is desired, the project design team would need to consider changes to the conceptual project or geometry that would result in a lower risk to potential property damages.

5.0 LWM Minimal Design Guidelines for Risk

Ratings for risks associated with public safety concerns and potential property damages result in a low or high and low, moderate, or high risks, respectively. This guideline establishes six combinations of risk categories that a LWM structure in a project reach can have. For each combination, a design guideline has been given in (Table 1). These guidelines are for the design of LWM elements and are in addition to standard design processes for Reclamation designs as outlined in Reclamation Manual – Directives and Standards (Reclamation 2008b).

5.1 Standard Design Guidelines

All LWM structures designed by or in support of Reclamation's Pacific Northwest Regional Office are required to follow the following minimal guidelines.

1. **Principle in Charge (PE)** - Designs containing LWM elements require an appropriate professional engineer responsible charge and approval. A qualified professional civil engineer with education and experience in river hydraulics or structural design of LWM must perform or oversee the design minimally following standard Reclamation procedures for design review and approval processes (Reclamation 2008b). In addition, the PE must ensure that all other required design team members have reviewed and approved of the project prior to final approval (signature by the PE).

2. **State and Local Established Guidelines for LWM Structures** - Some municipalities, counties, and States within the Pacific Northwest Region have specific rules and regulations regarding the design and construction of LWM structures. As LWM restoration continues to evolve, new rules may apply within specific local or regional jurisdiction. It is the design team's duty to research applicable local and regional laws and to follow additional guidance, as necessary. For instance, Washington State passed House Bill 1194 in 2013 as protection for project landowners against liability from property damages resulting from habitat projects involving LWM elements on their property. In order for a landowner to be indemnified of liability, specific design guidance must be followed as outlined in Appendix B.

5.2 Risk-Based Design Guidelines

Once a risk assessment is completed for a project with LWM elements, the resultant risk combination for public safety and property damage potential risks are then evaluated for their required design criteria. Table 1 lists required minimal design criteria to complete the project to include stability design discharge, river-use survey requirements, geomorphic assessment requirements, and design team requirements.

5.2.1 Definitions

Stability Design Discharge Criteria

The criteria are the minimum annual peak flood design discharge to maintain structural stability of proposed LWM feature. Peak flood design discharge will be based upon a flood frequency analysis as required (see Section 6.2, Hydrology and Section 6.3, Hydraulics for the appropriate methods to develop discharge-frequency relationship and evaluate stream hydraulics).

River-Use Survey Needs

A river-use survey is required to document current and potential uses of the river corridor by the local landowners and the public. There are two categories dependent upon the result of the public safety risk matrix evaluation: literature reviews and public interviews. Both require documentation of literature found regarding current or potential use, while the latter requires a more formalized public process.

- Literature Review – For those projects that appear to have a low public safety risk, it is a requirement to, at minimum, define the current use of the river corridor through documenting rationale used in the public safety risk evaluation process, which should be minimally completed following a literature review. This review should minimally document any guide books, publications, websites, and the local sponsor's knowledge of the reach pertaining to river use.

- Public Interview - For those projects that appear to have a high public safety risk, further survey needs to be completed (if not already completed during the risk evaluation). In addition to a literature review, a public river use survey needs to be conducted through the project sponsor. The intent of this public survey is to get direct public feedback from river users and stakeholders. The process in which this survey is conducted is not explicit in this document, but must include direct feedback from a diverse mixture of pertinent public users. The river use survey must document current river use and potential river use through such means as public survey, public interview, open house, or similar means as identified by the appropriate project sponsor.

Geomorphic Assessment Needs

Geomorphic assessment need refers to the scope and scale of detailed geomorphic assessment required for the project.

- **Reach Scale Assessment** - Reclamation currently has an assessment process in place to assess both past and present physical properties of a natural river system that is meant to characterize the natural and anthropogenic physical attributes that a stream (tributary scale or reach scale) currently has and its potential in terms of natural physical conditions. Many river reaches that Reclamation works in have published tributary or reach scale assessments in place, while others do not (all completed assessments can be found at http://www.usbr.gov/pn/fcrps/habitat/projects/index.html). For those locations where a Reclamation or similar reach scale assessment has not been documented, the project team is required to provide a level of assessment similar to that of a Reclamation reach scale assessment. The project team is not required to document this assessment in a stand-alone document, but is required to document their work in the design report. Individual project locations will vary in their necessary detail. It is up to the project design team, including the fluvial geomorphologist, to determine the requirements of this project reach scale assessment to ensure that resource and project risks are well understood.

- **Rapid Site Assessment –** A rapid site assessment is minimally performed by a fluvial geomorphologist, fish biologist, and a project engineer. It typically consists of a single site visit to include a project reach walkthrough along with a rapid, web-based historical and literature search of pertinent physical site information.

Design Team Needs

This section discusses the required team members to provide design and/or review of LWM features of a project dependent upon level of risk assigned.

- Required Team Members -
    - **PE**: Professional civil engineer with knowledge of design of LWM structures to include appropriate design of hydraulic, structural, and geotechnical engineering components. The Principle in Charge minimal needs, as stated in Section 5.1, is required to minimally oversee all design work and ensure that all required reviews are adequate and complete prior to final signatory authority of design based upon state licensure and Reclamation signatory requirements (Reclamation 2008b).
    - **FG**: Fluvial geomorphologist with professional expertise in river and stream morphology and experience in evaluating rivers in the Pacific Northwest.
    - **FB**: Fish biologist with professional expertise in fish habitat for typical species found in the Pacific Northwest to include salmonids.
    - **HE**: Professional hydraulic engineer is defined as a professional civil engineer with expertise as a hydraulic engineer. A hydraulic engineer has expertise in complex open-channel flow to include developing hydraulic computer models of stream hydraulics and sediment transport, with additional knowledge of

flood hydrology. The hydraulic engineer must possess unique experience in evaluating river systems in the Pacific Northwest.

Hydraulic Model Requirements

Refers to the complexity of hydraulic model required to analyze and assess channel hydraulics at instream LWM features – see section 6.3.

Table 1. LWM Risk Rating Design Requirements for Reclamation Projects (see above for definitions).

Public Safety Risk	Property Damage Risk	Stability Design Flow Criteria	River Use Survey Needs	Geomorphic Assessment Needs	Design Team Needs	Hydraulic Model Requirements
High	**High**	100-year	Public Interview	Reach Scale	PE, FG, FB, HE	2 dimensional
High	**Moderate**	50-year	Public Interview	Rapid	PE, FG, FB, HE	2 dimensional
High	**Low**	25-year	Public Interview	Rapid	PE, FG, FB	2 dimensional
Low	**High**	100-year	Literature Review	Reach Scale	PE,FG, FB, HE	2 dimensional
Low	**Moderate**	25-year	Literature Review	Rapid	PE, FG, FB	1 dimensional
Low	**Low**	10-year	Literature Review	Rapid	PE, FB	No requirement

5.3 Documenting Risk-Based Design

The process of defining the risk level to public safety and potential property damage posed by placement of LWM in rivers and streams throughout the Pacific Northwest will serve to establish the acceptable parameters for design and placement of LWM within each unique river corridor and recognize the physical river conditions, public usage, and land uses within the proposed reach. Populating the matrices in this guideline will further document risk evaluation and acceptance. However, each project is unique and design teams will differ in their assessment and final risk rating. The intention here is to provide a methodology and documentation procedure that serves as the basis for design decisions regarding risk, resulting in similar project rankings when using different design team members. Therefore, in addition to documenting all design computations, a risk assessment report for all projects containing LWM is also produced as part of the complete design package. Risk assessment reports will vary in size and length depending on the complexity and risks associated with each project, but should document each risk factor and describe how individual values were assigned, all assumptions that were made, and risk score for each determination. Additionally, the document will provide details regarding all local and stakeholder involvement in the ratings or ranking for this process, including documentation of all pertinent communications. For example, if a designer contacted a local raft guide company regarding recreational usage of a stream reach for which a project with LWM was proposed, the communication, whether a phone call, interview, or e-mail should be documented, dated, and included in the appendix of the assessment report. A signature page (see Appendix A, example signatory page) is placed at the beginning of the document to show concurrence among all required design team members during the design process.

Review and Signatory Requirements

In addition to Reclamation specific (Reclamation 2008b) or other design requirements for design review, each required team member listed in Table 1 must review and approve of the design at critical milestones to include:

1. **Risk assessment** - Once the initial risk assessment matrix exercise is completed and all team members and stakeholders are satisfied with the risk rating (i.e., high-high or other), each required team member shall sign the risk assessment rating produced for file in the project report (see Appendix A - example signatory page).

2. **Sixty percent design** - In addition to other required reviews, the mandatory design team members (i.e., PE, FG, FB and HE as required) must all provide review of this interim design product. The 60-percent design shall minimally show all LWM elements, their plan location and profile views, and their structure configurations. It should also show details of channel hydraulics with the structures in place through appropriate hydraulic modeling techniques (see Section 6.3, Hydraulics). Each team member shall provide documented comments regarding the design, which shall be addressed in final design considerations.

3. **Final Design** - As stated previously, the final design documents (plans, specifications, and design report) are to be signed by the responsible charge, which shall be a Professional Engineer (PE) per Reclamation standards (Reclamation 2008b) and individual state requirements. The PE must first ensure that all other required team members are satisfied with the final design through formal review and signature from each team member within the design report (see Appendix A - example signatory page). Once all required team members have accepted the final design and the PE is satisfied with the design documents, the documents are signed according to Reclamation and individual entity requirements, including the PE signature as responsible charge of design.

6.0 ENGINEERING DESIGN OF LWM STRUCTURES

This section covers the general engineering considerations for design of LWM structures. Typical forces acting upon LWM structures are detailed, as well as how those forces are treated for various conditions. The appropriate hydrologic considerations are discussed and minimal hydraulic analyses for LWM projects are established. Additional references to published design guidance for further clarification in the design process are given. This section describes the minimal standards for factors of safety to be applied to structures for varying levels of risk. Reclamation designers along with those contracted to perform LWM design for Reclamation projects will be required to minimally follow these guidelines. For unique structures or site conditions that do not fit the guidance provided, variances to these guidelines may be allowed, but must be approved by Reclamation's Resource and Technical Services Management prior to final design and implementation.

6.1 Types of Structures and Free-Body Diagrams

Abbe and Montgomery identified repeating patterns of naturally occurring LWM formations that they classified into ten types (Abbe and Montgomery 2003). We have simplified different LWM accumulation types into five distinct groups based on their location and elevation within or adjacent to the river channel. Mid-channel structures are LWM structures located in the channel or at the head of an island or bar and usually encourage split flows around the structure (Figure 3).

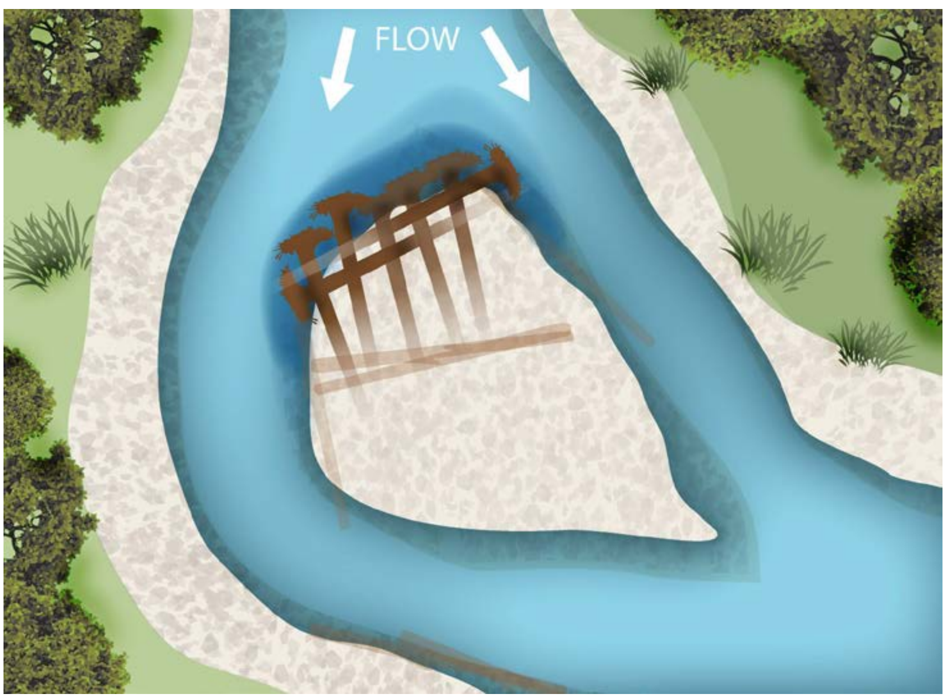


Figure 3. Illustration of a mid-channel LWM structure type.

Bank structures are located along a channel bank and are often embedded into the bank (Figure 4). These LWM structures can deflect flow away from the bank and are often used for bank protection to reduce bank loss rates.

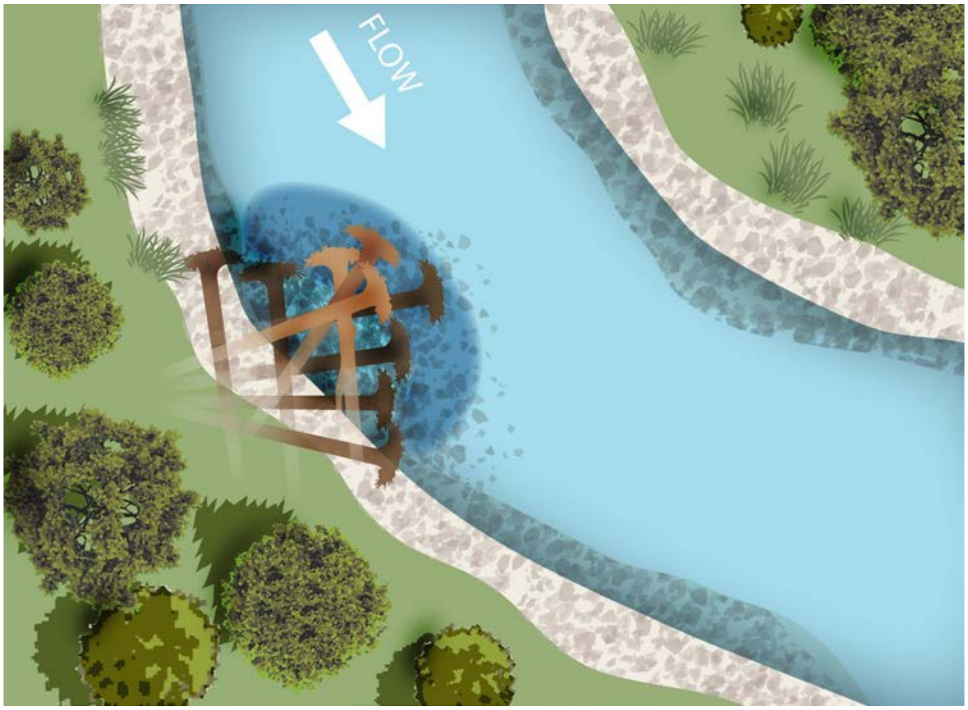


Figure 4. Illustration of a bank LWM structure type.

Channel-spanning structures are wood structures that span the entire width of the channel (Figure 5). These LWM structures are usually above grade and replicate multiple logs falling across a channel. These can also be utilized to limit flow through certain channels.

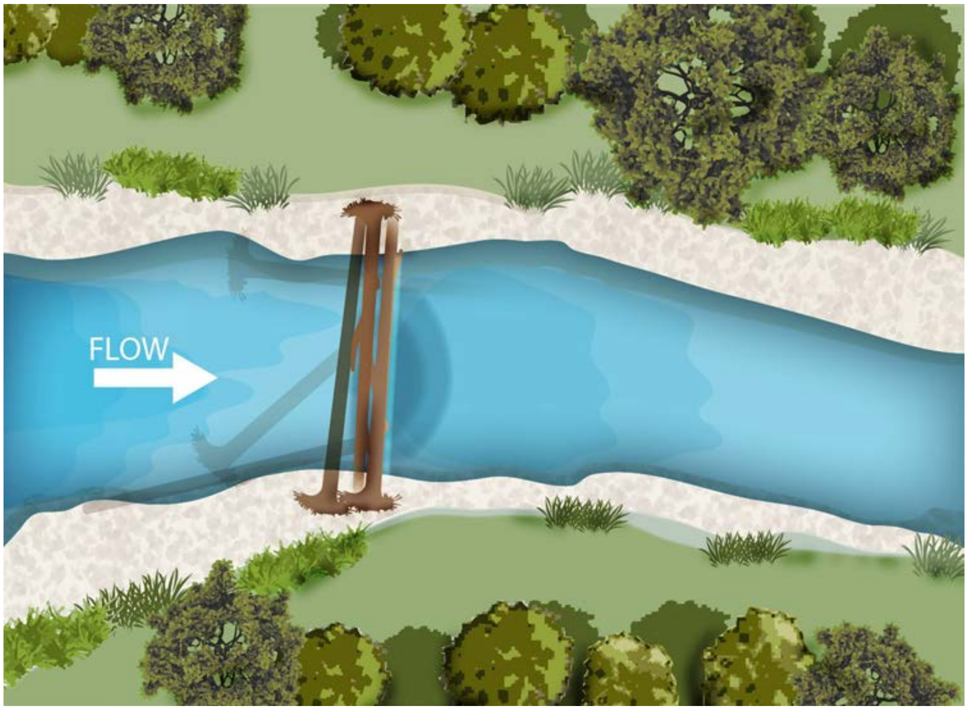


Figure 5. Illustration of a channel-spanning LWM structure type.

Grade-control structures are channel-spanning structures that are embedded into the channel bed to form a hardened point along the channel bed to maintain elevation (Figure 6).

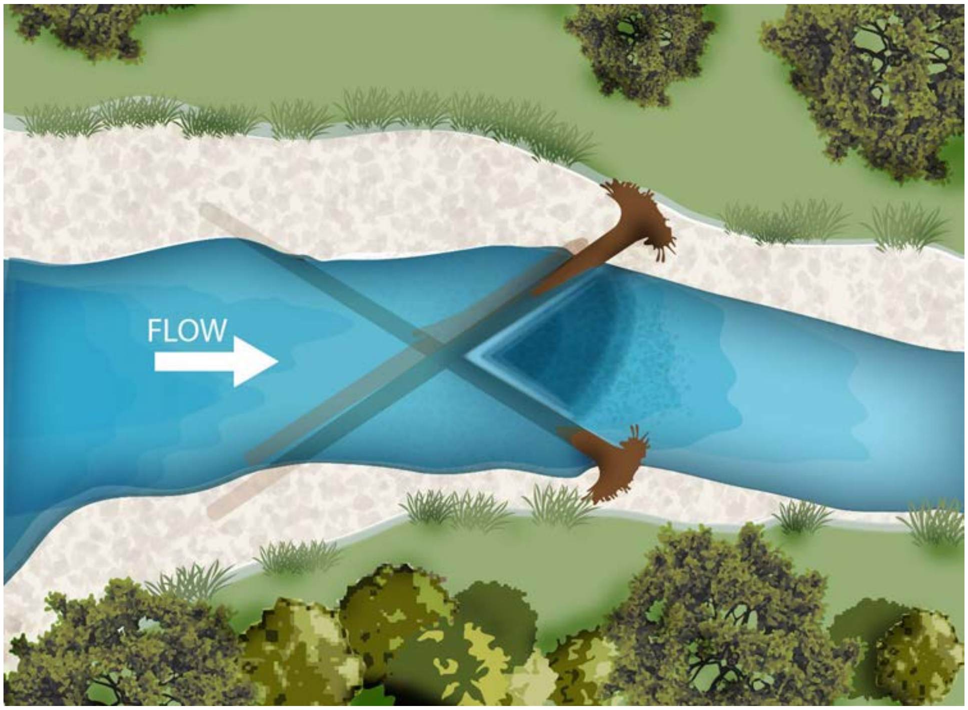


Figure 6. Illustration of a grade control LWM structure type.

The last types are floodplain structures which are located completely out of the channel and on the adjacent floodplain (Figure 7). These LWM structures are intended to roughen up the floodplain and reduce overbank erosion.

Figure 7. Illustration of floodplain LWM structure type.

6.2 Hydrology

The importance of hydrology in river design cannot be overstated. Much of the uncertainty in design of LWM structures may lie in the lack of hydrologic information in the form of long-term and reliable gage data. Additionally, as the overall climate changes, reliability on the recent past hydrologic information becomes more suspect (IPCC 2012). The current and potential future hydrologic regime must be understood to predict stream hydraulics that may be encountered during the design life of a proposed LWM structure. This section does not cover the extensive subject of river hydrology since there are many excellent references for further exploration, but further defines Reclamation's minimum requirements for hydrologic criteria for design of LWM. Additionally, this section briefly covers some important hydrologic considerations that should be made along with a brief overview of applicable techniques for estimation of project-scale hydrologic conditions.

6.2.1 Hydrologic Regime

Understanding and predicting the environment and forces that may act upon any project in a river requires an understanding of the potential hydrologic conditions of the river. Hydrologic regime is a term used for the relationship of precipitation inputs and streamflow outputs in a drainage basin, measured across a range of temporal and spatial scales (Post and Jones 2001). Careful evaluation of the annual hydrograph provides indicators to the hydrologic regime of a particular watershed. An understanding of the historic discharge pattern and magnitude is critical to project success. It is critical for design teams to attempt to predict the potential hydrologic conditions that may impact a LWM project. Ideally, a project site will be located on a stream with historic gage information; however, in many instances, gage data does not exist. In such instances, the design team should evaluate nearby, regional gages for annual patterns that likely reflect patterns associated with the stream of interest. A plot of the annual discharge over a long period of record can reveal patterns to help the design team define the probable conditions that will impact a LWM structure. Some patterns to look for include:

1. **Peak flood events**: Do peak flows occur seasonally in a defined prolonged period such as snowmelt? Do they occur sporadically in a spiked pattern in the fall or winter such as rain-on-snow? Sporadically in the late spring or summer indicating thunderstorm activity? Or do all of the above apply?

2. **Drought periods**: Does stream discharge stagnate at low or very low flows for prolonged periods? How will this affect proposed habitat or revegetation plans?

3. **Outliers**: Are there well-defined patterns broken by extreme events that could have been caused by hydrologic regime shifts from snowmelt to rain-on-snow events, from ice jam flood events, or other anomalies that deserve further investigation?

4. Is there a shift in pattern from year-to-year? Are there indicators towards possible hydrologic regime shifts to be considered in the design process?

5. Duration of events: How long do flood events last? What about low periods?

Beyond defining the stresses that a structure will undergo, this exercise can help predict other significant factors to include in the design process, such as seasonal habitat needs for aquatic species of concern, potential conditions during recreational usage periods, and long-term trends. Uncertainty in prediction of hydrologic conditions from lack of historic gage data, climate change, or other reasons should be accounted for in design through sensitivity analyses in hydraulic force definition, increased structural factors of safety, or both.

6.2.2 Annual Peak Discharge Exceedance Probability (AEP)

Table 1 lists minimal design guidelines for LWM structures based upon risk level, which includes minimal criteria for stability design discharge. This represents the minimum annual peak discharge exceedance probability (AEP) that a structure must withstand through the design process. For Reclamation projects that include LWM structures, the AEP ranges from the 10 percent to 1 percent annual probability of exceedance (10-year to 100-year flood). Development of the AEP curve for a given project location requires either real or synthetic gage data to include a record of historic peak flow events for a stream. Several published techniques are available to predict the annual peak discharge exceedance probability curve for a given stream location, all of which vary in their uncertainty. In general terms, methods that utilize historic discharge data are preferred, especially stream gages with a longer period of record (POR) or stream gages on the stream of interest near the project location.

The most widely utilized method for statistically classifying and developing flood flow frequency curves (AEP curve) is outlined in the historic publication *Flood Flow Frequency Guidelines – Bulletin 17B* (USGS 1982). This method relies on fitting the peak flow data (either annual or partial) to the Log-Pearson Type III distribution, which is the preferred method for determining flood-frequency curves for Reclamation projects. Additional resources are published in this reference that include proper methods to handle historic flood events, partial peak flows, regional skew, and combined probability. Designers should be familiar with this historic guideline as it serves as the basis of most discharge-frequency computational methods currently in use (i.e. USGS StreamStats at http://water.usgs.gov/osw/streamstats/). Development of flood-frequency curves requires investigation and proper treatment of peak flow events. For instance, peak flood events should fit within the same population (hydrologic regime) in order to be properly treated as the same statistical population. Historic estimated peak flows should be included within flood frequency estimates, but must be treated as detailed in Bulletin 17B guidelines.

As mentioned, all estimates for flood frequency curves have uncertainty associated with them. Often times, no gages exist on or near project sites. Estimates must be made from other synthetic means to include published regional regression estimates, transference from nearby gaged locations, or hydrologic modeling of watersheds. The designer must pay attention to the methods used in development of the flood frequency curve as uncertainty can range by orders of magnitude. For all estimates, error bars should be published based upon level of uncertainty. Channel hydraulics can then be estimated for the range of uncertainty (for a given AEP) and a sensitivity analysis can be performed (see Section 6.3, Hydraulics). Uncertainty in the flood frequency curve can and should be transferred into the factor of safety for projects as determined by the design team and project risk rating.

6.2.3 LWM Design Life and Stability Design Discharge

When developing a LWM project, the design team needs to consider the design life of each LWM feature. The design life of a LWM structure can vary for several factors to include intent of a specific project. Design life will depend upon materials, delivery methods, construction methods, climate conditions, and hydrologic conditions. Wood elements naturally decay at variable rates dependent upon their species, size, and their environment (Abbe et al. 2003). Few data exists for absolute decay rates of different types of wood in fluvial environments (Abbe et al. 2003). Designers must utilize wood species that fit the intended design life of each project, which should also be consistent with the level of risk and stakeholder understanding of the project. For the most part, Reclamation should specify the use of Douglas fir or better for LWM projects as it is fairly abundant throughout the Pacific

Northwest and provides excellent material properties for a significantly long design life. It has been estimated that Douglas fir will decay by approximately 20 percent over a period of approximately 30 to 50 years in a forest environment (Harmon et al. 1986). In a riverine environment, decay rates can vary substantially (Young 2007). Saturated logs under soil with little interaction with moving water may last centuries (Young 2007), while logs exposed to continual wetting and drying along with abrasive flows in a stream with high sediment loading may decay quite rapidly. Abbe presents a figure of decay rate (by mass) over time for both Douglas Fir and Cottonwood that may be useful for design life prediction (Abbe et al. 2003). Predicting future local environmental conditions is therefore critical to approximating the design life of key components of a LWM structure. For higher risk situations in which design life may be critical, designers should utilize the expertise of fluvial geomorphologists, plant ecologists, and foresters to estimate the design life of a particular structure.

Structures designed to persist for longer terms are more prone to experiencing conditions in which meets or exceeds their intended stability design discharge. The probability of the stability design discharge being met or exceeded during the design life of a structure is based upon statistical probability theory as shown in Equation 1:

$$P = [1 - \left(1 - \frac{1}{T}\right)^{n}]\ x\ 100 \qquad \textbf{\textit{Equation 1}}$$

Where, P = Probability of an T-year event occurring over a period of n years

The probabilistic nature of the design life for LWM structures should be communicated upfront with project stakeholders by the design team on the expectations of project performance and the potential need for monitoring and maintenance. The unique nature of individual projects to include environmental conditions precludes the ability to place requirements upon the design life of LWM structures. Instead, design teams must establish design criteria to include the design life of individual project structures for each project. This information is critical to communicate with project stakeholders for a multitude of reasons. Australian design guidelines state that the design life of LWM structures can be assumed to be 50-years or longer (Brooks et al. 2006). Based on these guidelines, the potential design life for LWM structures may range between approximately 10 to 50 years. Table 2 gives some guidance on the probability of the stability design discharge being met or exceeded during the listed design life of a LWM structure.

Table 2. Probability of experiencing design discharge during design life of project.

Stability Design Discharge	**during Design Life**		
Design Life:	***10-years***	***25-years***	***50-years***
10-Year Flood	65%	93%	99.5%
25-Year Flood	34%	64%	87%

Stability Design Discharge	Probability in percent of Design Discharge being met or exceeded during Design Life		
50-Year Flood	18%	40%	64%
100-Year Flood	10%	22%	40%

As one would expect, the longer a project is expected to perform, the more likely it may experience one or more flood peaks with a discharge that meets or exceeds the stability design discharge. As such, LWM structures that are expected to persist and provide particular design attributes for longer periods of time must have more planned monitoring and potential maintenance throughout their design life. A monitoring and maintenance plan is recommended for LWM projects; however, it is beyond the scope of these guidelines.

6.3 Hydraulics

6.3.1 Acceptable Methods for Stream Hydraulics Prediction

The laws of physics that govern the three-dimensional nature of fluid flow, which define the numeric prediction of stream channel hydraulics are well known, but extremely complex to apply. Several methods exist to numerically predict channel hydraulics, all of which have their own limitations. Basic methods include the use of the one-dimensional open channel flow equations such as the Manning's equation or the energy equation. More complex methods solve the Saint-Venant equations for conservation of mass and momentum (Litrico and Fromion 2009).

In most instances, river hydraulics are numerically predicted by averaging two of the three dimensions and predicting the "one-dimensional" stream hydraulics in the direction of flow. In more complex or risky situations, stream hydraulics are numerically predicted in two-dimensions (depth averaged), which requires more experience and knowledge. Occasionally, problems are so complex that only three-dimensional numeric models or physical models can predict hydraulics. However, for most LWM projects, either one-dimensional or two dimensional numeric models are used for stream hydraulic prediction. There are many one-dimensional and two-dimensional numeric modeling tools available for use in predicting stream hydraulics. Discussion of various hydraulic models is beyond the scope of this document. Currently, two hydraulic models are typically used for Reclamation projects with LWM components. A brief discussion follows with references to additional information.

One-Dimensional Modeling

The most frequently used one-dimensional model in the United States is likely USACE's Hydraulic Engineering Center's River Analysis System (HEC-RAS) model (USACE 2010). The HEC-RAS model has a graphical user interface (GUI) that allows the user to interact with the model using a geospatial mapping platform. The model can use either the energy equation or the momentum equation for predicting one-dimensional stream hydraulics based upon user preference and temporal conditions. This model is free and supported by the USACE to include regular updates and added features. It is recommended that design teams utilize this model for most one-dimensional applications. Application of this model minimally requires knowledge of open channel hydraulics and input of both site specific geometric and flow data to include:

Geometric data inputs for the HEC-RAS model consist of cross-section geometry data, reach lengths, energy loss coefficients, and any pertinent hydraulic structure data (e.g., bridges, weirs, culverts). A thorough discussion of this information, as well as modeling approaches is beyond the scope of this document; however, such information can be found in appropriate user manuals and model documentation (USACE 2010). A brief description of each of these modeling data follows:

Cross-section geometry is the representation of the ground surface perpendicular to the direction of flow. Cross-sections are located along a watercourse to define the conveyance capacity of the main channel and the adjacent floodplain. Cross-sections are required at representative locations throughout the watercourse and at distinct locations where changes occur in discharge slope, shape, or roughness, or at a location where hydraulic structures are located.

Reach length is the measured distance between cross-sections. Reach lengths are provided for the main channel measured along the thalweg, and for the left and right overbanks measured along the anticipated path of the center of mass of the overbank flow.

Energy loss coefficients estimate losses caused by the resistance to flow from the bed-surface, turbulence, vegetative roughness, channel irregularities, channel alignment, obstructions, and by the contraction and expansion of the flow. Adjusting these coefficients (Manning's roughness and expansion/contraction coefficients) allows hydraulic effect simulation of horizontal and vertical channel irregularities including LWM features.

Hydraulic structure data is the geometric representation of structures that influence the water surface profile within a watercourse, such as bridges, culverts, spillways, diversion structures, and weirs. The information required to define each structure varies. For a bridge structure, the dimensions of the bridge deck, piers, and bridge abutments are the inputs. There are more information and subroutines (see *HEC-RAS Applications Guide – USACE-HEC*, January 2010) that allow for coding of debris accumulation on these structures to include ice. Users should become familiar with hydraulic structure modeling to include ice as possible avenues to modeling similar conditions for LWM structures.

The need for accurate survey data cannot be overstated since the hydraulic model will only be as good as the survey data that created the model geometry. One can develop a one-dimensional hydraulic model from multiple survey sources, including detailed topographic and bathymetric survey of the project reach or from surveyed cross-sections at specific locations throughout the project reach. Locating cross-sections for a hydraulic model is very important and requires research and observation of the project reach, along with an understanding of open-channel hydraulics. Cross-sections need to be located at hydraulic controls throughout the project reach to accurately predict one-dimensional channel hydraulics. Additional cross-sections need to be located at project feature locations including potential LWM sites. Cross-sections should extend both upstream and downstream of the area of interest as the model boundaries are theorized and should not be within areas analyzed. Further discussion on the appropriate model layout can be found in the *HEC-RAS Reference Manual* (USACE 2010). Particular attention should be paid to modeling of bridges as this reference provides excellent guidance in the application of the HEC-RAS model to obstructions from bridge piers and abutments which can have similar hydraulic effects as LWM elements. Additional guidance can also be found for unique model applications similar to LWM elements in the HEC-RAS Applications Guide (USACE 2010).

Flow inputs are derived from a hydrologic analysis as described in Section 6.2, Hydrology. The HEC-RAS model requires the discharge in the watercourse and the flow conditions at the boundaries of the model. Multiple discharges can be run in one simulation. For LWM elements, design discharges are based on both stability discharge guidance given in Table 1 along with additional hydraulic analysis of varying discharges over the typical range for the site and determining which discharges create worst case conditions. For each discharge, a representative boundary condition must be applied at the upstream and downstream cross-sections for the model. Boundary conditions are ideally the known water surface elevations or known water surface slopes for the given discharge. Other options include estimated water surface slope or critical conditions at the model boundary as discussed further in the HEC-RAS Reference Manual (USACE 2010).

Two-Dimensional Modeling

Two-dimensional modeling requires expertise in numerical modeling and hydraulic theory and is beyond the scope of this document. Only a brief description and recommendation of the Bureau of Reclamation's Sediment and River Hydraulics two-dimensional model (SRH2D) follows.

There are many two-dimensional models available. For modeling of river hydraulics, one will typically utilize a model that simulates flow in the two-dimensional horizontal plane (X and Y) averaged over the depth. Reclamation's model SRH2D as developed by Reclamation's Technical Service Center (TSC) in Denver, Colorado is a robust depth-averaged two-dimensional model that has been used to simulate multiple rivers throughout the Pacific Northwest (Reclamation 2008a). This model is free to use and is supported by the TSC (http://www.usbr.gov/pmts/sediment/model/srh2d/). Several other models exist and are capable of simulating two-dimensional hydraulics of rivers (i.e., River2D, RMA-2, FESWMS); however, Reclamation recommends that SRH2D is utilized for Reclamation projects whenever possible. The SRH2D model requires a detailed three-dimensional terrain surface for the project reach to extract geometric data for hydraulic modeling. Model geometry consists of two-dimensional geometric elements (triangles and polygons) that form the finite element mesh of the model geometry. For SRH2D, these elements are created utilizing third-party model mesh preprocessing software such as the Surface Water Modeling System (SMS), which provides a GUI and automated processes in multidimensional model mesh development (http://www.aquaveo.com/). Three-dimensional points are extracted at the nodes of each model element from the terrain surface. Other inputs include Manning's roughness values for elements of the mesh, boundary conditions at upstream and downstream nodestrings and selection of a turbulence solution method and initial conditions (more information on the SRH2D model can be found in the SRH2D User Manual found at http://www.usbr.gov/pmts/sediment/model/srh2d/).

Public safety and property damage risk potential can best be understood by a thorough examination of existing and proposed stream channel hydraulics. This requires knowledge of both expected hydrologic conditions and channel hydraulics, which can be estimated through numerical modeling. Numerical models have become increasingly easy to use with minimal inputs and GUIs. However, like any other tool, confidence in application of these tools requires specific knowledge and experience. Reclamation's risk-based minimum standards for numerical prediction of channel hydraulics in evaluation of projects with LWM elements are shown in Table 3:

Table 3. Numerical hydraulic modeling requirements by LWM project or feature risk rating.

Public Safety Risk Rating	Property Damage Risk Rating	Minimum Hydraulic Study
High	High	2-dimensional model
High	Moderate	2-dimensional model
High	Low	2-dimensional model
Low	High	2-dimensional model
Low	Moderate	1-dimensional model
Low	Low	No requirement – recommend 1-dimensional model

6.3.2 Hydraulic Modeling of LWM Elements

LWM features are designed to be static and to influence stream hydraulics in particular ways through design geometry, location, and orientation to flow. These three-dimensional features are difficult to model with one- and two-dimensional modeling tools. In addition, little research has been published to describe hydraulic effects of the multiple conditions that may occur for these elements. Currently, stability calculations are often performed for LWM structures based upon static theory and scour prediction is based upon empirical data derived from research for bridge piers. All engineering calculations for force stability and channel effects for LWM features require inputs of local channel hydraulics to include water depths and velocities at the LWM feature. Typically, LWM features are modeled as obstructions in either the flow cross-section or two-dimensional model mesh, which decreases available channel conveyance and increases local water surfaces and near boundary velocities.

One-dimensional models produce average cross-sectional results and are inherently limited in prediction of local effects at LWM elements. Two-dimensional models are much better at prediction of local hydraulic effects, but do not predict the three-dimensional complexity associated with these features. Designers must be cognizant of these limitations and apply appropriate factors of safety based upon their confidence in hydraulic prediction methods. For one-dimensional models, average channel energy (force) can be accurately predicted; however, how that force is oriented at particular elements of a LWM feature and how that force is partitioned as either potential energy (water depth) or kinetic energy (water velocity) must be locally assumed. For two-dimensional models, force vectors in the X and Y direction can be obtained, and the designer must assume force partitioning in the Z (depth) direction.

Hydraulic loading refers to the force of water applied to an LWM structure in a stream. Hydraulic loading is a direct function of the size and orientation of surface area that a LWM structure blocks a stream's current. Design teams must determine the most appropriate hydraulic loading conditions that an individual LWM structure should be designed to and must communicate those assumptions to stakeholders for acceptance. Determination of hydraulic loading conditions is not trivial since LWM structures are often designed to capture flotsam and additional woody material to create additional habitat benefits. Even in situations where LWM structures are not meant to capture additional material, they may. Additional material can range from natural trees or branches dislodged by the stream during high flow conditions to anthropogenic material such as tires, plastic sheeting, and building materials washed into the stream during flood conditions. Some regions of the Pacific Northwest can also experience problems associated with ice. Ice can form upstream of or at the LWM structure and create additional loading and impact stresses. Estimating the probability of various hydraulic loading conditions is not possible in most locations as data on variables such as tree loading and ice conditions is typically not available. Design teams must research a stream's history through the reach assessment process and must make design assumptions accordingly. In addition to risk and consequences, design life of each LWM structure must be considered in these assumptions.

6.3.3 Hydraulic Loading Conditions and Sensitivity

For stability, generalized flood peak flows may not create worse case conditions and other potential factors must be considered to include floating debris, ice formation, bed entrainment and scour, along with combined effects of multiple project elements to alter hydraulic forces. This section is not intended to provide an authoritative view on these subjects, but will provide an introduction to these issues and recommend methods to produce a sensitivity analysis in hydraulic calculations to ensure structural stability during multiple potential hydraulic loading scenarios throughout the lifespan of the designed structure.

Debris Loading

As debris floats downstream, it has the potential to hang up and rack on islands, bridge piers, and other LWM structures. Engineered structures that are placed within the river channel should be evaluated for the potential to accumulate additional material and should be designed to be structurally stable at the design flows given these additional loads. The dominate force in this type of loading condition is additional drag force, but dynamic loading due to impact of debris can also be significant.

LWM structures should be evaluated for the potential to receive delivery of drift material. If a structure is located where it has the potential to collect debris, the hypothetical accumulations of debris should be calculated and analyzed as described in Section 6.3.3. Debris loading has typically been studied more completely on bridge infrastructure including piers and superstructures. Studies have determined that debris jams have the ability to grow to a width of approximately the "sturdy log length" that can be delivered to the site. A sturdy log is defined as the log length above which logs are inadequately abundant, or inadequately strong throughout their full length to produce drift accumulations equal to their length. The sturdy log length can be estimated as the smallest of the three following values (Diehl 1997):

- The width of the channel upstream from the project feature.
- The maximum length of sturdy logs.
- In much of the United States, 30 feet plus one quarter the width of the channel upstream from the site.

Local knowledge should be used when selecting a maximum sturdy log length (design log length) for analysis of debris loading on a LWM structure as the Pacific Northwest has a wide range of potential materials that could determine the maximum sturdy log length. Figure 8 is recreated from Diehl (1997) and shows the minimum design log length for the Olympic Peninsula and the eastern United States.

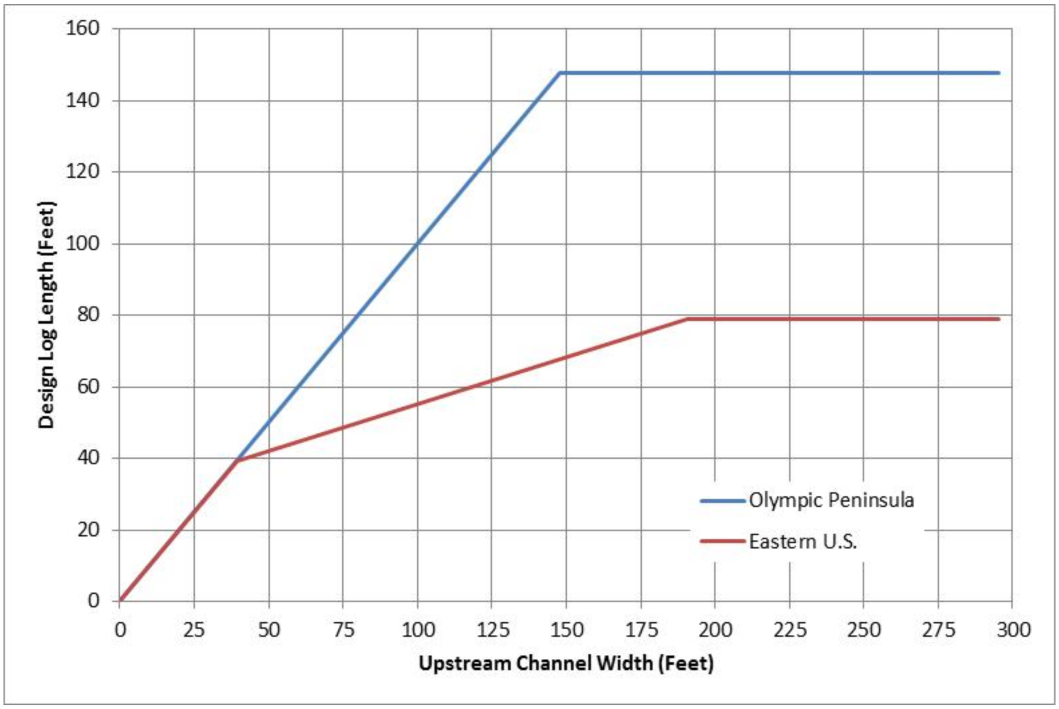


Figure 8. Design log length for the eastern US and the Olympic Peninsula (Diehl 1997).

Drift typically accumulates at the water's surface for the first key member and smaller pieces of drift grow along the upstream and edges of the debris. Debris can start growing down and toward the river bed as debris is washed under the jam at the upstream edge, or debris can start building toward the streambed by collapsing due to compression as hydraulic forces exceed the compressive strength of the wood (Diehl 1997). Australian design guidelines recommend that a blockage is as wide as the design log length and has an associated depth equal to 4 feet (Brooks et al. 2006). New Zealand design guidelines recommend a blockage that is equal to the design log length (not to exceed 50 feet) and an associated depth equal to half the flow depth, but not greater than 10 feet (Diehl 1997). In the United States, Diehl (1997) noted that few accumulations on single piers were more than 50 feet wide and in narrower channels, such accumulations tend to be narrower than the channel. In worst case scenarios, the depth of a blockage could roughly form a rectangle which extends the width of the design log and the depth of flow based on potential for abundant drift, prolonged flooding, or multiple floods without drift removal (Diehl 1997).

For design purposes it should be assumed that a drift debris jam should be as wide as the sturdy or design log length. The depth of the blockage should be evaluated by the design engineer and should be based on the waterways potential to deliver drift, the extent and duration of a high flow event, and the potential for multiple floods within a short period of time. This could create depths of blockage that range from the Australian and New Zealand guidelines all the way up to the full depth of flow. This could result in a formation of a rectangular or triangular blockage based on the designers' recommendations. This blockage should be analyzed with the hydraulic model to determine the hydraulic effects of the structure.

Ice Loading

Ice loading is a difficult condition to project for the future. There are four different ways that ice can interact with a LWM structure: (1) ice sheets being carried downstream by stream flow can enact dynamic pressures on LWM structures (impact loading); (2) static pressures can result due to thermal movements of ice sheets; (3) pressures can result from hanging ice dams or jams of ice; and (4) static uplift or vertical loads can result from ice adhering to the structure in fluctuating water levels. Ice formations, size, position, and height are best estimated from field investigations, review of public records, aerial surveys, or other suitable means (AASHTO 2012). Ice loading conditions should be applied only to hydrologic and hydraulic conditions that would be present during icing conditions. For example, ice loading would not apply for peak flows if the site is snowmelt dominated and peak flows typically occur in May and June when icing conditions would not exist. Icing conditions should be evaluated for flows that would be typical in the timeframe that icing potential would be the highest. In analyzing hydraulic forces associated with ice loading, the most typical is pressures and blockages associated with ice jams. These would be modeled as blocked flows or obstructions in a hydraulic model to estimate hydraulic conditions during an ice jam.

6.4 Structural Stability

LWM material jams are naturally occurring and build and deteriorate throughout their life as wood inputs and hydraulic forces vary throughout the years. In certain situations, this natural formation of jams is desired and little emphasis is placed on structural stability since movement within the system is desirable. However, the more typical scenario is that there is a risk or perceived risk associated with wood material being placed within a channel and then migrating downstream or into the floodplain. To ensure a LWM structure meets the constraints of its location and associated risks, a structural stability evaluation of its key members is required for all structures placed within the channel and active floodplain. Often secondary and racking members are designed to be less permanent and more mobile. The designer should use professional judgment to decide whether to evaluate stability of secondary and racking members.

A quantitative assessment of site conditions and a force balance analysis can provide the means to evaluate the stability of a proposed LWM structure and help determine where an artificial ballast is appropriate (Abbe et al. 2003). A structure's stability can be evaluated with fairly simple or complex equations and scenarios depending on the risk rating. The ultimate identifier of a structure's stability is its individual factors of safety. The factor of safety is the metric used in this analysis to measure the stability of a structure and these factors vary depending on the calculated risk.

6.4.1 Factors of Safety

Safety factors for structural stability are the ratios of resisting forces to driving or acting forces. Due to the level of uncertainty in computations of both driving and resisting forces associated with LWM structures, safety factors during the selected critical design event should accommodate level of uncertainty and be increased as risk increases.

D'Aoust and Millar (2000) completed a study of wood stability of 90 structures throughout the Pacific Northwest and Canada. This study showed that single log structures were typically stable with factors of safety greater than 1.1. As structure complexity increased, the required factor of safety increased toward 1.25 to reduce instabilities. This increase in the required factor of safety for stability is likely due to uncertainties associated with coefficients, design velocities, impact loading and additional loading from racking LWM. Based on this work, minimum factors of safety in British Columbia range from 1.5-2.0.

Based upon the findings from the D'Aoust and Millar (2000) study, a minimum factor of safety of 1.25 is recommended to be applied to sliding, overturning, and rotation, while a minimum factor of safety of 1.5 is applied to flotation (note: in some unique circumstances, interior wood members may be allowed to be designed to float). As the level of risk increases, the factors of safety should increase as well. Table 4 provides minimum recommended factors of safety based on public safety and property damage risks.

Table 4. Minimum recommended factors of safety.

Public Safety Risk	Property Damage Risk	Stability Design Flow Criteria	$FOS_{sliding}$	$FOS_{bouyancy}$	$FOS_{rotation}$ $FOS_{overturning}$
High	**High**	100-year	1.75	2.0	1.75
High	**Moderate**	50-year	1.5	1.75	1.5
High	**Low**	25-year	1.5	1.75	1.5
Low	**High**	100-year	1.75	2.0	1.75
Low	**Moderate**	25-year	1.5	1.75	1.5
Low	**Low**	10-year	1.25	1.5	1.25

As more studies are completed that address the stability of LWM structures and working professionals develop more accurate ways of estimating variables, these factors of safety could be further reduced for structures in low-low risk areas.

6.4.2 Resistance to Flotation (Buoyancy)

Flotation is typically caused by the buoyant force and the lift force acting on the wood material from water passing over its surface, like air passing over the wing of an airplane.

The buoyant force is the force due to the volume of water displaced by the placement of wood. Most wood has a density that is less than the density of water, which causes it to float.

Flotation and lift forces are countered by vertical forces transferred to LWM structures through the placement of ballast, native backfill, and wood above the water surface elevation, which rely on skin friction to oppose vertical lift forces. The ballast must overcome the buoyant force of the LWM structure to ensure vertical stability. If these vertical forces do not overcome buoyancy, the LWM structure will float up and may move downstream as either a raft or individual pieces of wood, depending on the design. The following sections provide greater detail regarding each of the forces acting in the vertical direction.

Large Wood Material Force

Equation 2 represents the vertical force that accounts for the volume of wood in the LWM structure that is submerged. Equation 3 represents the force associated with the portion of the LWM structure that is dry during the design discharge event. Some LWM structures are designed to overtop during their design discharge event, while other structures are built and designed to never be overtopped. The submerged volume is multiplied by the difference between the specific weight of the wood and the specific weight of water (buoyant weight), while the dry wood volume is multiplied only by the unit weight of wood.

$$F_{LWMs} = V_{LWMs} * (\gamma_{wood} - \gamma_w) \qquad \textbf{Equation 2}$$

V_{LWMs} = volume of submerged large wood material

γ_{wood} = unit weight of wood

γ_w = unit weight of water

$$F_{LWMd} = V_{LWMd} * \gamma_{wood} \qquad \textbf{Equation 3}$$

V_{LWMd} = volume of dry large wood material

As LWM structures dry and wet based on the annual hydrograph, the LWM structures are possibly in a dry state immediately prior to flooding. It is recommended that the dry unit weight of the wood be utilized in these calculations. The dry unit weight of various woods can be found from references including *Research Note NRS-38 Specific Gravity and Other Properties of Wood and Bark for 156 Tree Species Found in North America* (USDA 2009), or the G*eneral Technical Report FPL-GTR-190 Wood Handbook: Wood as an Engineering Material* (USDA 2010). If a less conservative approach regarding the weight of wood is desirable, any wood buried below the thalweg could be assumed to be fully saturated if situated in a perennial water body. This will greatly decrease the uplift force associated with the submerged large wood.

If the submerged LWM force is negative, the LWM structure will float because the resultant forces are acting upwards in a vertical direction. If the submerged weight of the LWM is positive, the wood weighs more than water and sinks with the resultant force acting down in the vertical direction.

Lift Force

As water flow impacts a LWM structure, forces are generated that can lift the structure. The lift forces are a function of the wood area and approach velocity, as seen in Equation 4. Typically, the lift coefficient is small and ranges from 0.1 to 0.2 (0.18 for cylinders with a maximum of approximately 0.45). Lift forces are greatest when the wood is in contact with the channel bed and declines toward zero when the gap between the bottom of the log and the bed exceeds half the log diameter (Alonso 2004). Lift forces have been typically neglected in the design of LWM structures since it is assumed that scour and deposition quickly reshape the local topography (Wallerstein et al. 2001).

$$F_L = -\frac{C_L * A_{LWM} * \gamma_w * U_o^2}{2 * g}$$ **Equation 4**

C_L = lift coefficient

A_{LWM} = area of large woody material perpendicular to flow

u_u = upstream channel velocity at design event

g = acceleration due to gravity

Boulder Ballast Force

Due to the increased density obtained through competent rock versus soil backfill, boulders are often used as ballast material to counter the buoyant forces of LWM. Boulders are often placed directly on top of the pieces of wood, then backfilled around and above the boulder ballast. Boulder ballast can be located above and below the design event water surface elevation and can be estimated from Equation 5.

$$F_{boulder} = F_{bouldersub} + F_{boulderdry}$$ **Equation 5**

$$F_{bouldersub} = N_{bouldersub} * \frac{\pi}{6} * d_{bouldersub}^3 * (\gamma_{boulder} - \gamma_w)$$ **Equation 6**

$N_{bouldersub}$ = number of submerged boulders

$d_{bouldersub}$ = effective diameter of submerged boulders

$\gamma_{boulder}$ = unit weight of boulders

$$F_{boulderdry} = N_{boulderdry} * \frac{\pi}{6} * d_{boulderdry}^3 * \gamma_{boulder}$$ **Equation 7**

$N_{boulderdry}$ = number of unsubmerged boulders

$d_{boulderdry}$ = effective diameter of unsubmerged boulders

The unit weight of boulders is typically estimated based on the specific gravity of 2.65. The specific gravity can then be utilized to estimate unit weight of the individual boulders.

Soil Backfill

LWM structures are often embedded into banks or the substrate to obtain additional structural resistance to lateral and vertical forces. Soil backfill is incorporated between log members and ballast and is typically compacted in lifts to ensure adequate compaction as the structure is buried. The resistant force associated with soil backfill of a LWM structure can be estimated from Equation 8.

Average dry unit weights of soil can be estimated from Table 5 for different soil classifications, or the dry unit weight can be estimated from Equation 11. Soil below the design water surface elevation is fully saturated and is also susceptible to buoyant forces since it is fully submerged. Soil above the design water surface elevation should be assumed to be dry. This assumption is based on typical gravel and cobble banks for free-flowing western rivers that have little capillary rise capabilities.

Table 5. Substrate and soil properties, reproduced from Rafferty (2013).

Grain size (mm)	Sediment Class	Average Dry Unit Weight (lb/ft^3)	Internal Friction Angle (degrees)
Bedrock	Bedrock	165	-
256-2048	Boulder	146	42
128-256	Large Cobble	142	42
64-128	Small Cobble	137	41
32-64	Very coarse gravel	131	40
16-32	Coarse gravel	126	38
8-16	Medium gravel	120	36
4-8	Fine gravel	115	35
2-4	Very fine gravel	109	33
1-2	Very coarse sand	103	32
0.5-1	Coarse sand	98	31
0.25-0.5	Medium sand	94	30
0.125-0.25	Fine sand	93	30
0.063-0.125	Very fine sand	92	30
0.004-0.063	Silt	82	30
<0.004	Clay	78	25

To calculate the weight of backfill above a log the embedded length of the log multiplied by the diameter of the log and the depth of backfill creates the volume of soil restraining the buried log. This volume is typically separated into two volumes one being submerged and the other being dry.

$$F_{soil} = \sum_i^n V_{soilsub_i} * \gamma'_{soil} + V_{soildry_i} * \gamma_{soil}$$ **Equation 8**

$$V_{soilsub_i} = L_{eb_i} d_{bole_i} h_{soilsub_i}$$ **Equation 9**

$V_{soilsubi}$ = volume of submerged soil above log i

L_{ebi} = embedded length of log i

d_{bolei} = bole diameter of log i

$h_{soilsubi}$ = height of submerged soil above log i

$$V_{soildry_i} = L_{eb_i} d_{bole_i} h_{soildry_i}$$ ***Equation 10***

$V_{soildryi}$ = volume of dry soil above log i

$h_{soildryi}$ = height of dry soil above log i

$$\gamma_{soil} = (99.2 + 18.6 * \log(d_{50}))$$ **Equation 11**

d_{50} = median grain size in millimeters

$$\gamma'_{soil} = \gamma_{sat} - \gamma_w$$ **Equation 12**

$$\gamma_{sat} = \frac{(SG_{rock} + e) * \gamma_w}{1 + e}$$ **Equation 13**

$$e = \frac{SG_{rock} * \gamma_w}{\gamma_{soil}} - 1$$ **Equation 14**

To increase the accuracy of this calculation, the volume of boulder ballast material above each piece of wood can be removed since it has already been accounted for in the boulder ballast force. These calculations include the assumption that the groundwater elevation is equal to the adjacent open water surface elevation.

Pile Skin Friction

If piles are installed, there is a vertical restraining force associated with the friction against the perimeter of the pile. These forces can aid in restraining overall buoyant forces if other LWM members are linked to the pile mechanically, but there is the potential for the buoyancy force of the piles to be larger than the skin friction, which would cause this force to be negative and would require additional embedment just to stabilize the pile. This type of condition would typically occur if the embedment depth was too shallow. The skin friction can be estimated for a group of piles by applying Equation 15.

$$F_{piles-v} = N_{piles} * \pi * d_{piles} * L_{piles}(k_s * \tan\frac{2}{3}\emptyset * \sigma' + \frac{d_{piles}}{4} * (\gamma_{wood} - \gamma_w))$$

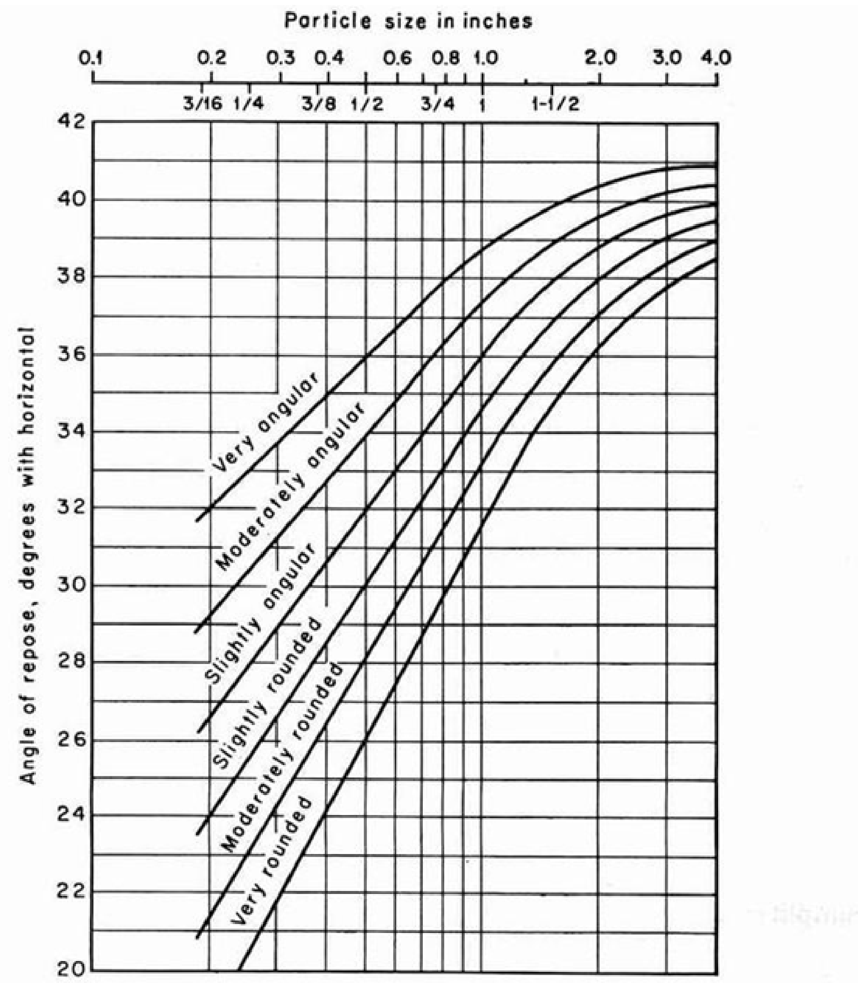
Equation 15

N_{piles} = number of piles
d_{piles} = diameter of piles
L_{piles} = embedded length of piles
k_s = coefficient of lateral earth pressure (0.5 to 1.5 depending on soil and density)
ϕ = internal angle of friction of soils

$$\sigma' = L_{piles} * (\gamma_{sat} - \gamma_w)$$

Equation 16

The internal angle of friction can be estimated from Table 5 or from Figure 11. The estimated skin friction forces are based on the assumption that piles are driven or vibrated into place. If piles are drilled or excavated, the associated coefficient of lateral earth pressures shall be approximately 50 percent and 25 percent of the driven value, respectively.



Angles of repose of noncohesive material. (*U.S. Bureau of Reclamation.*)

Figure 9. Internal angle of friction for noncohesive material (Reclamation 1952).

Total Buoyant Force

The buoyant force is the sum of all vertical forces associated with a LWM structure (Equation 17). If the buoyant force is negative, the structure is anticipated to float and be unstable. If the force is positive, the structure is anticipated to remain in place.

$$F_b = F_{LWMs} + F_{LWMd} + F_L + F_{boulder} + F_{soil} + F_{piles-v} \quad \textbf{\textit{Equation 17}}$$

Buoyancy Factor of Safety

The buoyancy factor of safety is the sum of all positive forces divided by the absolute value of the sum of all negative forces as seen in Equation 18. If FOS_b is not equal to or greater than

1.5 or higher such as the recommended values in Table 4, additional vertical restraint needs to be added in the form of anchors or additional ballast, backfill, piles, or dry wood. Adjustments to the design must continue and all vertical forces acting on the LWM structure must be recalculated until the buoyancy factor of safety is equal to or greater than the recommended minimum value of 1.5 (or higher depending upon risk such as those listed in Table 4).

$$FOS_b = \frac{F_{LWMd}+F_{boulders}+F_{soil}+F_{piles-v}}{|F_{LWMs}+F_L|}$$ **Equation 18**

FOS_b = buoyancy factor of safety

6.4.3 Resistance to Sliding

In addition to a LWM structure becoming buoyant and failing due to floatation, LWM structures are also susceptible to failure through sliding. Sliding of a LWM structure can occur because the downstream applied horizontal force is larger than the frictional and passive forces acting between the LWM and the channel bed and banks. Drag forces, and upstream hydrostatic pressures act on a structure and are countered by frictional forces, lateral resistance from vertical piles, downstream hydrostatic pressures, and passive forces from backfill or channel banks.

Drag Force

LWM structures are pushed downstream by the fluid drag forces acting upon the wood by the flowing water. Drag on a LWM structure is a function of the flow velocity and cross-sectional area subject to flow. The drag force can increase dramatically with increases in racking material that adheres to the head of structures, as well as ice that could rack on or otherwise increase the surface area of a structure exposed to flow. These various loading scenarios are described above and should be accounted for in the structural stability analysis of a LWM structure. The drag force is computed using Equation 19.

$$F_d = \frac{C_D * A_{LWM} * \gamma_w * U_c^2}{2 * g}$$ **Equation 19**

$F_d = drag\ force$

$C_d = drag\ coefficient$

A_{LWM} = *area of wetted debris based on the upstream water surface elevation projected normal to flow direction and the potential drift accumulation*

$\gamma_w = unit\ weight\ of\ water$

$U_c = velocity\ in\ contracted\ section$

$g = acceleration\ due\ to\ gravity$

Drag coefficients vary greatly from one structure to another depending on how they interact with flow, but typically range from 0.3 up to 1.5 (NRCS 2007a). A drag coefficient can be approximated by drag coefficient envelope curves based on obstructed area as seen in Figure 10 (Parola 2000). The obstruction ratio (B) is equal to the obstructed area divided by the total cross-sectional area (Equation 20). The study that was completed to develop Figure 10 also includes the influence of the contracted Froude number (Fr_c) as a variable in the drag coefficient (Equation 21). Equations 22, 23, 24, 25 and 26 show the valid ranges of B and Fr_c for each drag coefficient equation shown in Figure VI-5 (Parola 2000).

$$B = \frac{A_b}{A_b + A_c} \qquad \textbf{Equation 20}$$

B = obstruction ratio

A_b = cross-sectional flow area blocked by debris in the contracted section

A_c = area of contracted flow

$$Fr_c = \frac{V_c}{\sqrt{g * Y_c}} \qquad \textbf{Equation 21}$$

Fr_c = contracted flow Froude number

V_c = contracted flow velocity

Y_c = average flow depth in the flow contraction

$C_d = 1.8$	if $B<0.36$ and $Fr_c<0.4$	**Equation 22**
$C_d = 2.6 - 2.0 * Fr_c$	if $B<0.36$ and $0.4 <Fr_c <0.8$	**Equation 23**
$C_d = 1.0$	if $B<0.36$ and $Fr_c >0.8$	**Equation 24**
$C_d = 3.1 - 3.6 * B$	if $0.36 <B <0.77$ and $Fr_c <1.0$	**Equation 25**
$C_d = 1.4 - 1.4 * B$	if $B >0.77$ and $Fr_c <1.0$	**Equation 26**

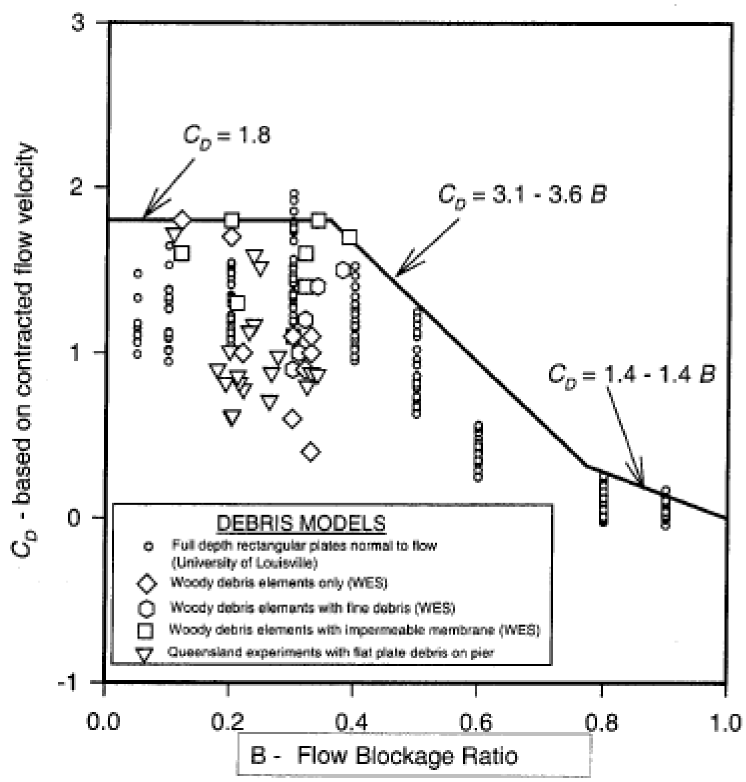


Figure 10. Variation in drag coefficient with blockage ratio (reprinted from Parola 2000).

As the LWM structure constricts the channel, the drag coefficient becomes lower and lower until the drag force becomes zero at a full constriction (channel-spanning blockage). At this point, all forces associated with the constriction have become hydrostatic. Some equations that estimate an applied drag coefficient, such as that seen in Equation 27, continue to increase as the constriction moves toward the full blockage of flow. These equations attempt to include hydrostatic forces, but have a higher variability and less accurate results as the constriction increases than if the drag force is separated from the hydrostatic forces as recommended in this document.

$$C_{d-applied} = \frac{C_d}{(1-B)^2}$$ C_d is typically estimated as 1.0 **Equation 27**

Hydrostatic Forces

Hydrostatic forces act on the upstream and downstream faces of a LWM structure. As a structure blocks a portion of the cross-sectional area of the channel, it forms a constriction. The channel can become so constricted that flow goes from subcritical flow through critical to supercritical flow and back to subcritical flow through a hydraulic jump. When this hydraulic jump formation occurs, the differences between the upstream and downstream hydrostatic forces can become significant and potentially risk stability of a LWM structure. At a full channel blockage the drag force goes to zero and the resultant force is completely hydrostatic.

This is a result of the velocity going to near zero above the structure as the flow goes above or around the structure. Hydraulic modeling is required to estimate the difference in water surface elevations upstream and downstream of a LWM structure in order to apply appropriate hydrostatic forces. If a one-dimensional model is used, cross-sections should be located immediately upstream of the influence of the structure, at the structure (upstream and downstream ends), and downstream of the hydraulic influence of the structure to accurately estimate the pertinent hydraulic conditions.

The hydrostatic force acting on the upstream side of the LWM structure is estimated based on Equation 28. The hydrostatic force acting on the downstream side of the LWM structure is estimated based on a similar equation (Equation 29). The hydrostatic force on the downstream end of the structure is negative, as it is acting in the upstream direction.

$$F_{hu} = \frac{1}{2} * \gamma_w * Y_u * A_u$$ **Equation 28**

Fh_u = hydrostatic force on the upstream side of a wood structure

Y_u = water depth on the upstream side of a wood structure

A_u = area projected normal to flow direction on the upstream side

$$F_{hd} = -\frac{1}{2} * \gamma_w * Y_d * A_d$$ **Equation 29**

Fh_d = hydrostatic force on the downstream side of a wood structure

Y_d = water depth on the downstream side of a wood structure

A_d = area projected normal to flow direction on the downstream side

Ice Loading

There are many equations that try to predict ice forces on bridge piers and superstructures that could be correlated to LWM, but ultimately, they require knowledge of the site and historical ice jam evidence to be able to apply equations to estimate potential forces accurately. For more information on ice forces and methodology on calculating these forces see *AASHTO LRFD Bridge Design Specifications* (AASHTO 2012). The designer of large wood structures should assess the potential for ice loading and design for it accordingly.

Impact Force

Other than potential debris loading and ice loading conditions the extra loading condition that should be assessed and potentially analyzed is the force associated with debris impacting a large wood structure. The impact force can be estimated by the impact force equation (Equation 30) as defined in ASCE (2006). Acceleration is defined as the change in velocity over the change in time. On debris impact loading it can be assumed that the debris is traveling at an initial velocity equal to the surface water velocity of the channel. Once it contacts the structure it comes to rest against the structure and its final velocity is zero. The time that it takes the debris to impact a structure is difficult to estimate and critical in the analysis as the force associated with the impact is inversely proportional to the reduction in time. The shorter the impact time the larger the force.

$$F_i = \frac{\pi w_{debris} * V_{channel} * C_i * C_o * C_d * C_b * R_{max}}{2 * g * \Delta t} \qquad \textbf{Equation 30}$$

F_i = *impact force*

w_{debris} = *weight of debris*

g = *acceleration constant due to gravity*

$V_{channel}$ = *water velocity in channel*

Δt = *time from initial velocity to zero velocity*

C_i = *coefficient of importance*

C_o = *coefficient of orientation = 0.8*

C_d = *coefficient of depth*

C_b = *coefficient of blockage*

R_{max} = *response ratio for impulsive loads = 0.8*

Table 6. Values of coefficient of importance based on risk.

Public Safety Risk Rating	Property Damage Risk Rating	Coefficient of Importance
High	High	1.0
High	Medium	0.9
High	Low	0.8
Low	High	0.7
Low	Medium	0.6
Low	Low	0.5

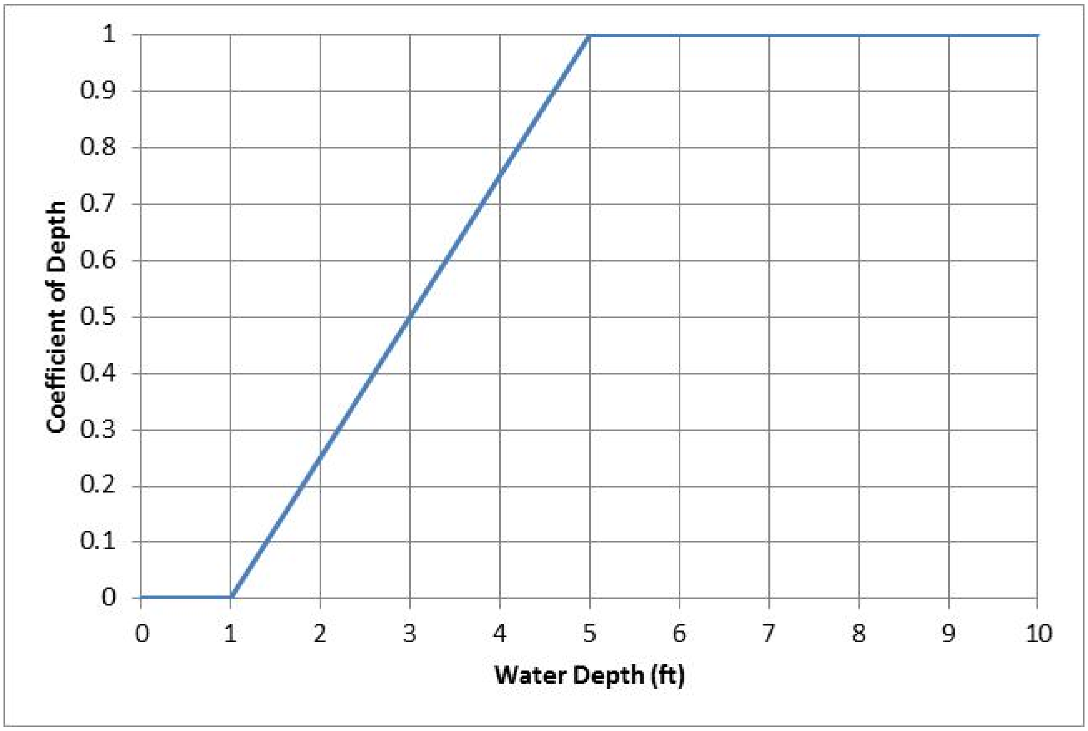


Figure 11. Coefficient of depth.

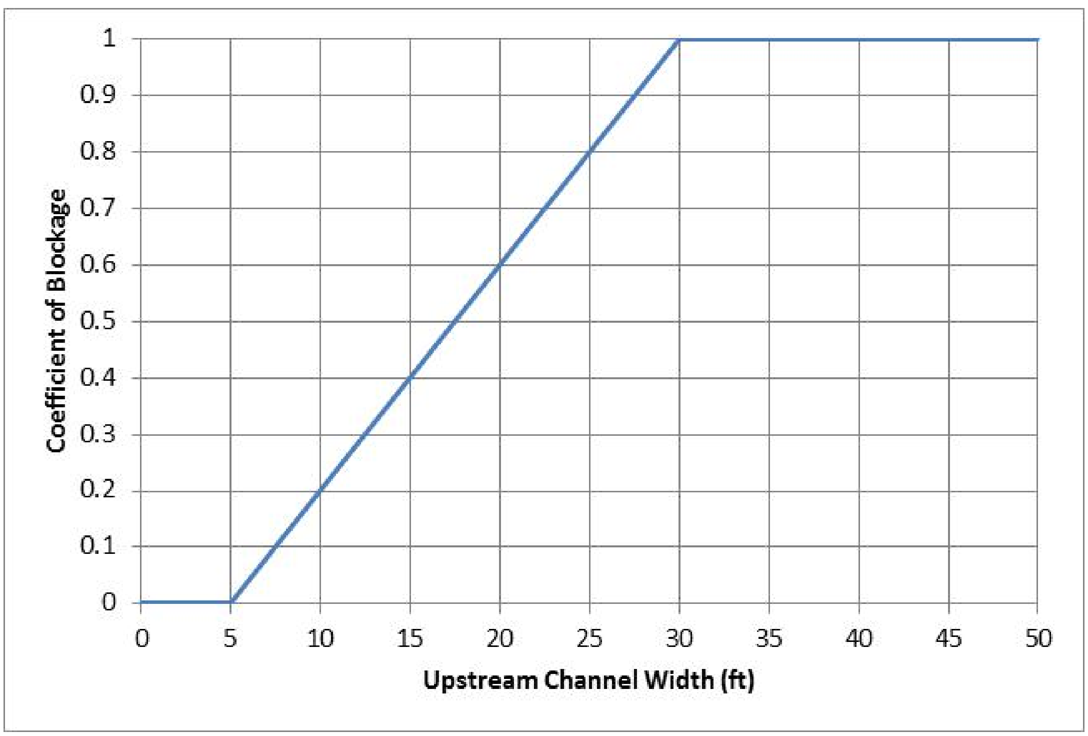


Figure 12. Coefficient of blockage.

The coefficient of importance was modified from the ASCE version for houses and structures by Reclamation to look at risk associated with LWM structure failure. The response ratio for impact loads assumes a natural dynamic frequency period of 0.14 seconds for the LWM structure, which is the minimum period measured in recent tests on one- to two-story wood-frame buildings, and provides the highest R_{max} ratio coefficient based on these recent tests (ASCE 2006). Recent research indicates impact from floodborne debris occurs over intervals of only 0.01 to 0.05 seconds (FEMA 2009). In accordance with *ASCE 7-05 Minimum Design Loads for Buildings and Other Structures* (2006), the recommendation is an impact interval of 0.03 seconds.

The designer is recommended to assess impact loading and if there is a high likelihood of debris impacting a structure, impact loading should be analyzed to ensure structural stability of LWM structures. Impact loading should be assessed for single debris logs per the design log length described in Section 6.3.3. The average diameter of the log should be estimated based on potential wood sources within one mile upstream of the proposed LWM site. It should be assumed that impact forces act at the water surface elevation and in a horizontal direction.

Friction Force

Frictional resistance is developed from interaction between the channel bed and the LWM structure. This force is the resultant vertical force (F_vF_b), from the vertical stability calculations in the previous section, multiplied by the coefficient of friction (μ_{bed}) and is therefore heavily reliant upon the vertical forces and ensuing buoyancy stability as seen in Equation 31. If the vertical force is negative, meaning that the LWM structure is floating, there is no frictional resistance force. The coefficient of friction in natural channels is assumed to be equal to the tangent of the internal angle of friction for the bed sediments. A range of angles of repose for a variety of non-cohesive material is shown above in Figure 9 as well as in Table 5.

$$F_f = -\mu_{bed} * (F_b - F_{piles-v}) \qquad \textbf{Equation 31}$$

F_f = force due to frictional resistance

F_b-$F_{piles\text{-}v}$ >0

$$\mu_{bed} = \tan \emptyset \qquad \textbf{Equation 32}$$

The restraining force from skin friction on the piles in a LWM structure is removed from the total vertical force in calculating the frictional force because the pile skin friction is a resistant force that is not located or acting on the channel bed.

Passive Forces

Passive forces act against drag forces when there is soil material behind the structure resisting the driving forces. This can act on both buried logs in the bank as well as a structure buried into the head of an island or mid-channel bar. Equation 33 estimates the passive force associated with a log buried perpendicular to flow.

$$F_{passive} = -0.5 * K_p * \sum_i^n \sigma_{v_i} * L_{em_i} * d_{log_i}$$ **Equation 33**

$$K_p = \frac{1+\sin\emptyset}{1-\sin\emptyset}$$ **Equation 34**

$$\sigma_{v_i} = D_{sub_i} * (\gamma_{sat} - \gamma_{water}) + D_{dry_i} * \gamma_{soil}$$ **Equation 35**

D_{subi} = depth of submerged soil above log i

D_{dryi} = depth of dry soil above log i

L_{emi} = embedded length of log i

d_{logi} = diameter of log i

In the estimation of passive forces, it is typically assumed that bank and backfill material are composed of homogeneous, isotropic soils; the groundwater elevation is typically equal to the water surface elevation within the channel; friction between the soil and log is ignored; and soils are typically granular and non-cohesive. Equations 33 through 35 represent the case where passive forces act along the length of a log perpendicular to flow. If the log is parallel to flow, the terms L_{emi} and d_{logi} would be replaced with the cut end area of the log (typically assumed to be a circle based on the DBH) resisting the acting forces.

Lateral Resistance from Piles

Lateral resistance from piles in a LWM structure has been typically based on work developed for the design of traffic signs susceptible to wind loads. The most common methodology for the typical noncohesive soils that comprise a channel bed is Brom's equation. Brom's equation assumes a maximum allowable deflection of the pile at the ground of 0.002 to 0.006 radians. A pile embedded 10 feet below the channel bed would have a theoretical maximum movement of approximately 0.7 inches at the channel bed given this methodology. This is based off the assumption that the pile is rotating about the pile tip. Brom's equation to estimate the lateral force from a group of piles is shown in Equation 36.

$$F_{piles-h} = -N_{piles} * \frac{L_{pile}^3 * \frac{1}{2} * \gamma_e * d_{pile} * K_p}{h_{load} + L_{pile}}$$ **Equation 36**

N_{piles} = number of piles

L_{pile} = length of pile embedded below potential scour depth

$$\gamma_e = \gamma_s - \gamma_w$$ *effective unit weight of soil* **Equation 37**

γ_s = dry unit weight of the soil

γ_w = unit weight of the soil
d_{pile} = diameter of the pile
h_{load} = height above the potential scour depth the load is applied

$$K_p = \frac{1+\sin\emptyset}{1-\sin\emptyset}$$ **Equation 38**

In an effort to be conservative in this analysis, the resultant forces from the other various lateral loads can be summed and used with the minimum design sliding factor of safety ($FOS_{sliding}$) to determine the required resistant force from the lateral piles (Equation 39). Then a minimum embedment depth (Equation 40) required can be estimated given a specified number of piles (N_{piles}) to achieve the desired stability. This solution is iterative and an initial guess value has to be used for the pile length in the right side of the equation to determine the next guess of the pile length. This numerical process typically requires little iteration before closing in on an appropriate solution. This analysis also assumes that the resultant force is located at half of the flow depth on the upstream side of the LWM structure to produce a conservative moment on the pile.

$$|F_{piles-h}| = FOS_{sliding-min} * (F_d + F_{hu} + F_i) + |F_{hd} + F_f + F_{passive}|$$

Equation 39

$FOS_{sliding-min}$ = minimum allowed factor of safety for sliding

$$L_{pile}^3 = \frac{|F_{piles-h}| * (L_{pile} + h_{load})}{N_{piles} * \gamma_e * d_{pile} * {}^{K_p}/_4}$$ **Equation 40**

It is important to look at the ultimate pile strength (shear and moment) versus the applied loads to ensure that the pile material is structurally sound and will not snap or shear off during the design event. This is often the limiting factor on piles and can result in more piles than originally estimated from the equations above.

Sliding Factor of Safety

The sliding factor of safety is computed by dividing the resistance forces of downstream hydrostatic pressure, friction, lateral resistance from piles, and passive forces by the sum of drag forces and upstream hydrostatic forces as seen in Equation 41.

$$FOS_{sliding} = \frac{|F_{hd} + F_f + F_{piles-h} + F_{passive}|}{F_d + F_{hu} + F_i}$$ **Equation 41**

If $FOS_{sliding}$ is less than the recommended minimum FOS, additional resisting forces need to be created. Additional horizontal resistance can come in the form of additional piles, anchors, or ballast to increase the frictional resistance. Passive horizontal forces could include sediment and soil located on the reactive side of a structure as is typical on apex style LWD structure where the structure is located at the head (upstream) end of an island. The island would provide additional passive horizontal resistance to the drag force. The most common types of additional anchoring methods to resist drag forces include the addition of piles, extra ballast or backfill, and last is the addition of mechanical anchors if absolutely necessary.

6.4.4 Resistance to Rotation

Rotation of a LWM structure typically occurs where asymmetrical loading occurs and the structure is assumed to rotate around a point near the end of the structure. Rotation is typically associated with structures that are adjacent or buried into a bank. Apex type structures or structures placed in the middle of the channel are typically loaded in a fairly uniform manner and rotation is typically not a significant factor. The necessity to estimate the potential for asymmetrical loading on a mid-channel structure and the associated potential for rotation is left to the professional judgment of the responsible party completing the design. To estimate a structure's stability in relation to rotation it is necessary to calculate the moments associated with each force. The sum of the driving moments ($MD_{rotation}$) should ultimately be less than the sum of reacting moments ($MR_{rotation}$) to ensure stability. The driving force moment is shown in Equation 42. The resisting moment is shown in Equation 43 and the factor of safety of rotation is shown in Equation 45. The factor of safety of rotation should be equal to or greater than that recommended in Table 6.

$$MD_{rotation} = (F_i + F_d + F_{hu}) * (\frac{L_{sp}+L_{ebp}}{2})$$ **Equation 42**

L_{sp} = *length of wood structure from tip to point of rotation measured perpendicular to flow*

L_{ebp} = *embedded length of wood structure measured perpendicular to flow*

$$MR_{rotation} = \left| F_{hd} * \left(\frac{L_{sp} + L_{ebp}}{2}\right) + F_{passive} * \frac{L_{ebp}}{2} + F_f * \frac{L_{sp}}{2} + \sum_i^n F_{pile-h_i} * L_{ph_i} \right|$$

Equation 43

$$F_{pile-h_i} = \frac{F_{piles-h}}{N_{piles}}$$ **Equation 44**

L_{phi} = *distance from pile 'i' to the point of rotation measured perpendicular to flow*

$$FOS_{rotation} = \frac{MR_{rotation}}{MD_{rotation}}$$ **Equation 45**

6.4.5 Resistance to Overturning

Overturning could potentially occur on structures that are broad laterally, tall vertically, and narrow longitudinally (in the direction of flow) and interact with deep flow depths at the design discharge. However, it is very difficult to construct a LWD structure as described given that channels in the western United States tend to have width-to-depth ratios greater than 10 which tends to minimize structure heights compared to their longitudinal length. In this region, structures would typically fail by sliding prior to overturning. Overturning moments are calculated in a similar fashion to the rotation moments above. The necessity to estimate the potential of overturning is left to the professional judgment of the responsible party completing the design. The driving moment, resisting moment, and factor of safety of overturning are shown in Equations 46, 47, and 49 below, respectively.

$$MD_{overturn} = F_i * (Y_u + d_{bury}) + F_d * \left(\frac{Y_u}{2} + d_{bury}\right) + F_{hu} * \left(\frac{Y_u}{3} + du_{bury}\right) + |F_L| * L_s$$

Equation 46

du_{bury} = depth at the upstream side of the structure from channel bottom to point of rotation measured perpendicular to flow
Ls = length of structure measured parallel to flow

$$MR_{overturn} = |F_{hd}| * \left(\frac{Y_d}{2} + dd_{bury}\right) + |F_{passive}| * (dd_{bury}) + (F_b - F_L - F_{piles-v}) * \frac{L_s}{2} + \sum_i^n F_{pile-v_i} * Lpv_i$$

Equation 47

$$F_{pile-v_i} = \frac{F_{piles-v}}{N_{piles}}$$

Equation 48

L_{pvi} = distance from pile ‘i’ to the point of rotation measured parallel to flow

$$FOS_{overturn} = \frac{MR_{overturn}}{MD_{overturn}}$$

Equation 49

6.4.6 Resistance to Bed Scour

Scour of the bed adjacent to LWM structures can create instability in the foundation or backfill, causing partial or catastrophic failure of the LWM structure. Channel bed scour or degradation is often a primary casual factor in LWM structural failures (Herrera 2006). While pools provide valuable aquatic habitat, scour pools can undercut a LWM structure and ultimately threaten its structural integrity. It is recommended that high risk LWM structures be designed to a bottom depth that is deeper than anticipated scour depths to prevent undercutting and increase structural stability. Aquatic habitat benefit can often be achieved by allowing scour holes to undercut structures. Moderate to low risk structures can be designed to be undercut since the risk of failure is offset by the associated lowered risk to property damage and life, while potentially increasing aquatic habitat. It is also important to take into account the potential loss of backfill material if a structure is allowed to be undercut.

Total scour is the sum of all scour forms that could occur in one location, including long-term elevation change (scour), contraction scour, bend scour, bedform scour, and localized scour. In depth descriptions of all types of scour can be found in the *Hydraulic Engineering Circular* (HEC) No. 18 (FHA 2012a). To date most scour equations are developed as envelope equations making them inherently conservative. Scour equations have been developed for large hydraulic structures like bridge piers, abutments, etc. and require the level of risk associated with the envelope equations, but this might not be appropriate and/or practical for LWM structures. Engineering judgment should be used to develop the best estimate of scour associated with a LWM structure relative to the risk of structural failure.

Long-term Scour

Long-term aggradation or degradation is the vertical trend of a channel bed elevation resulting from some modification to the stream or watershed. If a dam is put in place, there will typically be aggradation above the dam and degradation below the dam as the channel adjusts to the blockage of sediment at the damsite. A few of the things that can affect long-term bed elevations are dams, reservoirs, land use changes, channelization, meander cutoffs, change in downstream control, and water diversions. A qualitative analysis can be completed by a geomorphologist to estimate long-term trends, determine if there is sediment transport, and use empirical formulae to better quantify vertical movement of the channel bed. Quantitative techniques are discussed in greater detail in HEC-20 (FHA 2012b).

Contraction Scour

Scour associated with a contraction in flow is typically caused by a constriction (e.g., bedrock wall), boulder clusters, LWM structures, or bridges and typically removes material across the whole width of the channel bed in the immediate vicinity of the constriction. Contraction scour typically occurs across the full width of the channel, but does not account for long-term degradation or localized scour immediately around the obstruction creating the contraction. This type of scour is highly dependent upon whether there is sediment transport (live-bed) or no sediment transport (clear-water) at the contraction. The Laursen equations have historically been well-used to accurately estimate contraction scour. A full description of this methodology is available in HEC-18 (FHA 2012a). Live-bed scour depths may be limited by the formation of an armor layer along the channel bed by large sediment particles. If armoring conditions occur, live-bed scour depths can be estimated by utilizing the smaller of the two depths calculated from the live-bed and clear-water scour equations (FHA 2012a).

Bend Scour

Bend scour is associated with the water accelerating around a bend and the helical flow occurring within the water column. There are numerous equations to estimate bend scour.

The typical variables include the top width of the channel, the radius of curvature of the bend, and sometimes the upstream flow depth. Common equations to estimate bend scour include the Thorne equation, Maynord equation, national engineering handbook equation, and the Zeller equation. The Maynord equation is utilized and recommended in HEC-20 (FHA 2012b).

Bedform Scour

Bedform scour is typically associated with dune and anti-dune formations within sand channels. The significant variables in estimating bedform scour include the sediment size range, flow velocity, hydraulic radius and flow depth. The *National Engineering Handbook* equation estimates the scour depth as half the amplitude of a dune bedform (NRCS 2007b).

Local Scour

Localized scour is scour isolated around the immediate vicinity of an obstruction or object within the channel and is caused by the acceleration of flow and resulting vortices created by the obstructions (FHA 2012a). Localized scour occurs in the immediate vicinity of a structure that has come into contact with the channel. Local scour around structures can include bridge abutments, piers, bedrock outcroppings, channel grade controls, and LWM structures. LWM structures can be placed along the edges of a channel, in the middle of a channel, or as a grade control across the channel width. Local scour is often estimated based off of envelope equations (worst-case scenarios) for hardened structures and are typically conservative. The use of these equations is not always practical for LWM structural design and engineering judgment should be used to determine equation use and applicability.

LWM structures placed in the center of the channel act similar to bridge piers and have typically been modeled using the associated equations. USGS completed a study in 2004 on the evaluation of pier scour equations for coarse-bed streams and concluded that the Mueller equation described in earlier versions of the HEC-18 guidelines had the best correlation to measured scour depths for coarse bed streams (Chase and Holnbeck 2004). This scour equation included an armoring factor that has since been removed in the current edition of HEC-18 (FHA 2012a). It is recommended that this armoring factor be utilized in the calculation of scour at a mid-channel structure as described in the USGS report (Chase and Holnbeck 2004). The width of a LWM structure is typically greater than the flow depth and the latest version of HEC-18 includes a correction factor for wide mid-channel obstructions. These equations were developed based off of flume experiments and most mid-channel LWM structures do not typically fit within the tested parameters and will typically lead to over-prediction of scour depths.

Local lateral scour is associated with LWM structures that are placed in proximity or embedded into the channel banks. There are generally four equations that are used to estimate scour associated with this type of feature. The Kuhlne formula was developed to estimate scour for various spur dike geometries based on clear-water, steady-flow, movable-bed flume studies. The Karaki and Richardson equation estimate scour along an abutment or lateral structure where the transverse structure length projecting into the flow is small in comparison to flow depth. The Froehlich equation is a regression equation based on the analysis of 170 live-bed scour measurements in laboratory flumes. The Froehlich equation is recommended in HEC-18 for computation of scour along a bridge abutment; however, there is a built-in safety factor equal to the average flow depth that is used in design calculations (FHA 2012a). It is recommended that this safety factor be removed in the analysis of LWM structures since it tends to overestimate actual measured scour depths. If the LWM structure is buried below the potential scour depth, scour can be estimated by utilizing the scour equation against a vertical wall (FHA 2012b).

LWM structures that span the channel to act as a grade control typically induce scour immediately downstream of the structure as water flows over the tops of these structures, often in a jet angled down into the channel bed. The majority of equations used to estimate local scour of grade control structures were developed to compute the depth of scour downstream from dams (NRCS 2007b). Equations to estimate scour below a grade control structure have been developed by Reclamation, Mason and Arumugam, Laursen and Flick, and D'Agostino and Ferro. These equations can be utilized for vertical drops or sloping sills depending on the assumptions of each equation. All of these equations are described in detail in NRCS's *Technical Supplement 14B Scour Calculations* (NRCS 2007b).

6.4.7 Resistance to Bank Deformation (Erosion)

Bank erosion occurs when shear stresses remove the toe of a slope causing a failure of the bank and slumping of material, causing lateral migration of the bank through a series of hydrologic events. Banks erode and fail in three distinct ways: (1) rotational failures, (2) planar failures (with and without tension cracks), and (3) cantilever failures following undercutting. The recommended methodology to estimate bank erosion rates and evaluate stability on channels is through field analysis, historic imagery, and landowner interviews. Historical imagery is becoming more readily available and can provide a long-term visualization of lateral migration to estimate average rates of bank movement. There is a computer model available to evaluate stability and erosion of banks called the Bank Stability and Toe Erosion Model (BSTEM). BSTEM is a series of calculations developed in Microsoft Excel to estimate bank stability, failure modes, methods, and distances. BSTEM requires a significant amount of input data to determine erosional rates which often makes it not cost effective to implement for this type of work. BSTEM can be used to test the effects of hydraulic scour, water table height, vegetation, and stage-on stability; used iteratively with knowledge of the flow regime to predict widening rates; and used to test various mitigation strategies to control undercutting and mass failure (Simon et al. 2014).

6.5 Anchoring Methods

It is often necessary to provide some type of anchoring to a piece of LWM placed in a river to prevent it from floating, sliding, or rotating and migrating downstream during design flow events. These anchors essentially counterbalance buoyancy, drag and impact forces that are applied to the wood during a flow event. There are typically three methods of anchoring that have historically been used in wood placement within river channels. In order of preference for habitat formation these three methods include natural anchors, passive anchors, and active anchors.

Natural Anchors

Left to its own measures, wood becomes lodged and placed throughout a channel in a natural manner, with no type of anchor required to increase its stability. Wood movement and its associated effects are a natural part of productive riverine and ecosystem function. However, wood placed in this manner puts the full liability of risk associated with mobile wood in the river system on the designer and implementer. Natural anchoring methods include placing a log between two standing trees, bracing one or both ends of a log against a tree or bedrock outcrop, or positioning a log so that a portion of it rests on the bank above or outside the water extents during the design flow to resist acting forces (Photograph 1). This method works well in narrow streams and remote areas with large project land areas in a low-low risk environment only. The client or landowner must accept the risk associated with this type of placement and must be agreeable on the movement and loss of wood into the system as it naturally migrates downstream and into the floodplain.

Photograph 1. An example of a naturally anchored large LWM structure, flow is right to left.

Passive Anchors

Passive anchors use the weight, shape, and location of a structure and its associated fill components to resist movement from forces associated with the river (Saldi-Caromile et al. 2004). Examples of passive anchoring include the placement of boulder ballast, native soil or gravel over and on top of a structure, and pile supported structures. A LWM structure is considered passively anchored as long as it remains unattached to any exterior anchors (Saldi-Caromile et al. 2004). The placement of any type of passive anchors (especially boulders) should be with respect to the natural composition of the streambed and banks. Adding dozens of large boulders for ballast in a sand-bed stream may anchor a LWD structure, but it will also result in an unnatural pile of boulders in the stream long after the logs have deteriorated and washed away.

Embedding a structure into a bank or backfilling it with native gravel material to resist acting forces is the most preferred practice to stabilize a LWM structure (Photograph 2). During the backfill process, the contractor should be directed to compact the backfill material in lifts (8 inches or the largest diameter of rock in the native material, whichever is greater) to ensure proper compaction and backfilling in and around log members.

Photograph 2. Backfilling a LWM structure with native gravel material to increase stability.

Imported boulders placed on and within a LWM structure can provide additional stability due to the increased weight of competent rock. Imported boulders are also less likely to be eroded and/or transported downstream. Placement of imported boulders should be in a position to reduce the potential of them to vibrate and roll off a key member during design flows. A designer should think prior to specifying either angular or rounded boulders for ballast since angular rock might sit on key members better than rounded rock (Photograph 3).

Photograph 3. Boulder ballast material placed on top of a LWM structure.

A common practice is to utilize cabled rock as ballast material for increased stability for LWM structures. This method allows the cable to sit over the top of a log with a boulder on each side of the log holding the log in place. This reduces the potential for a boulder to move off of a log and increase its potential for failure. This method also theoretically doubles the size of available rocks. To create a cabled rock structure, two competent rocks are drilled and epoxied together with a steel cable linking them. More details about the methods to epoxy cable into rocks are described in published documents, including the *California Salmonid Stream Habitat Restoration Manual* (Flosi et al. 1998).

Pile-supported LWM structures are becoming more common as LWM design becomes more complex and structures are encroaching further into the main flow channel. Piles have historically consisted of everything from steel H-piles to structural timber piles. Natural timber piles are the most desirable pile for use in LWM structures. Depending on the substrate of the channel bed, piles have been driven by pneumatic hammers, drilled, vibrated, and excavated into place. The method for placing piles should be evaluated by the engineer based on anticipated soil conditions. In determining pile lengths as described, the potential scour depths should be estimated to ensure that the required structural length of the pile is below the potential scour elevation.

If piles are going to be driven or vibrated into place, penetration can be easier by creating a point on the tip of the wood pile. In some cases, these tips have been covered in a metal casing to prevent deformation or failure of the tip, but these additions have not greatly aided in ease of installation. Drilled piles need to occur in subgrades that have the ability to hold a vertical face so that the drilled hole does not collapse. This typically includes subgrades with some cohesion including silts, clays, and some sands. Vibrated piles have been installed on fairly coarse gravel sites, but success levels vary widely and depend on the level of consolidation in the native subgrade as well as the experience of the operator. In areas with coarse cobbles and boulders, or in glacial till, it is typically easiest and most economical to excavate down to the pile tip elevation and backfill around the piles (Photograph 4). During this process, the backfill material should be compacted effectively and in lifts.

Photograph 4. Excavated pile being backfilled.

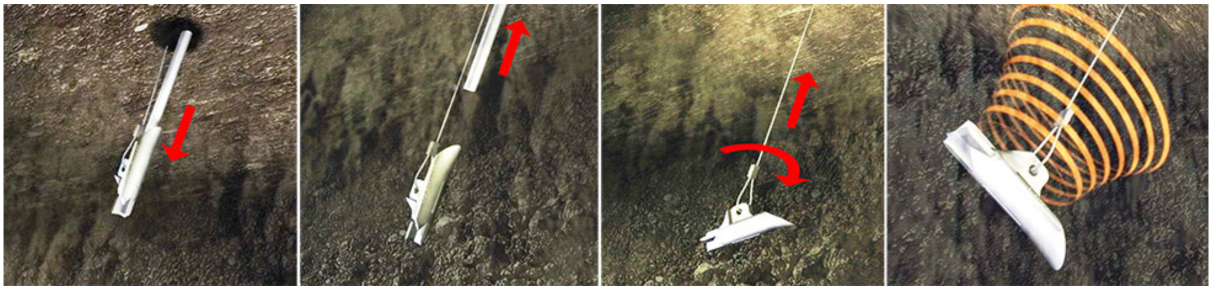
Another method of passive anchoring is to install gravity foundations for large wood structures. Gravity foundations include deep excavation into the subgrade and the development of a wood crib foundation that is linked together and backfilled with ballast and native backfill. The actual wood structure is then woven into this foundation to transfer loads acting on the structure to the foundation. If failure occurs, typically logs from the structure break free one at a time, while the foundation remains in-tact below grade. Gravity foundations allow for a greater volume of back fill material below the majority of the wood structure to aid in resisting those forces while reducing the visible backfill material on top of the structure. These types of foundations are excellent for structures that are designed to fully over-top during the design flow event (Photograph 5).

Photograph 5. Gravity foundation being installed on the Salmon River.

Active Anchors

The least desirable method of stabilizing LWM structures is the use of active anchors. Active anchors are constantly resisting against active forces and can be either rigid or flexible. Rigid forms of active anchors act as deadman anchors and also include logs that are anchored directly to bedrock or boulders.

Commercial deadman anchors include manta ray and duckbill type anchors (Photograph 6). Mechanical anchors are typically driven or screwed into the ground underneath the structure and then are activated by applying a specified tensile force onto the lanyard (cable) which tips a plate to resist the pulling force caused by buoyancy or drag. These anchors are capable of resisting up to 20 tons, depending on the soil characteristics of the site. These anchors rely upon the shear stress of the subsurface soil, and are typically not acceptable in unconsolidated gravel beds (Saldi-Caromile et al. 2004).



Photograph 6. Deployment sequence of a duckbill anchor; driving, extraction of driver, tensioning, and resisting forces.

Buried concrete blocks, logs, steel shapes, or boulders have historically been used in the construction of LWM structures, but their use has diminished greatly in recent years with a greater focus toward natural methods and means in LWM structure design and construction. However, in high risk cases where failure is unacceptable and all other options have been exhausted, a buried block can act as a deadman anchor and provide ample restraining force due to a larger bearing area than typical mechanical anchors. Concrete blocks can consist of precast ecology blocks to custom made anchors (Photograph 7). The buried anchor is typically connected to a log through the use of cables or chains. It is difficult to create sufficient tension in this type of anchoring system, as a result logs often can start moving slightly, causing the cable or chain to slice through the subsurface material and increasing potential erosion and possibly damaging the connection.

Photograph 7. Custom made concrete deadman anchor attached to chain and a key wood member to resist buoyant forces in a high risk location.

Flexible active anchors allow LWM structures or members to move with changes in flow or direction (Saldi-Caromile et al. 2004) and are used where a LWM structure is connected to a fixed anchor with some type of leash. Leashes are predominately made of steel rope, chain, or rope. These types of structures are used to provide habitat cover where the position of the structure is not critical. These structures have the potential to erode banks within their swing path and should be designed to stay off of the banks unless erosion is desirable. Structures utilizing flexible anchors should be connected in more than one location due to heavy dynamic loading and as such, flexible anchors should only be used as a last resort in backwater and other low energy environments (Saldi-Caromile et al. 2004).

6.6 Engineered Fasteners

It is often desirable to either connect two pieces of wood together or connect a log to an active anchor. This connection is typically done through tethers (rope, chain, cable) or pins (steel pins, bolts and nuts). By connecting multiple logs together, a structure could possibly act as one unit rather than a grouping of individual logs, which has the ability to increase the structural stability of a structure. However, increased structural resilience by the use of engineered fasteners must be balanced with recreational use. Recreational users expect natural hazards and designs that use natural materials (i.e. earthen fill or embedment) and designs that replicate natural features are most desirable (Colburn 2012). Therefore, the prioritized use of these methods is (1) no fasteners, (2) rope (3) pins, (4) chain (only in extreme cases), and (5) cable (only in extreme cases).

No Fasteners

A LWM structure with no fastening systems is the most desirable as it contains no foreign materials that are being introduced into the active floodplain. There are many benefits to having no fasteners, but the biggest benefit might be that a multiple log structure is not likely to fail catastrophically. If members are not connected, a failure will likely occur as a partial failure where one log at a time would typically be removed and/or transported downstream, mimicking the natural transport of wood in a stream. If the structure failed catastrophically, the LWM structure would break up into individual members. This reduces the chances of downstream effects (e.g., log structure wrapping up around a bridge pier) since individual logs will disperse and are less likely to hang up on features.

Rope

Attaching logs and piles together with a jute rope or other type of biodegradable rope (e.g., manila) provides a temporary attachment device to secure a LWM structure during its initial years (3-5 years). Once vegetation is well established above the LWM structure, vegetation is often what will persist into the future and increase long-term stability. Local environmental conditions will both influence rate of rope failure and rate of re-vegetation. Therefore, when using rope as an initial fastener, designers need to include robust re-vegetation plans for long-term LWM structure stability. Rope can provide a link to numerous key members of a LWM structure to increase its initial stability, while allowing it act more like a natural LWM structure in the future after the rope has deteriorated. Special attention should be taken during construction to apply adequate tension to the rope and to ensure that the tied knots are not going to allow the rope to loosen or slacken in the near future (Photograph 8 and Photograph 9).

Synthetic rope and straps can be utilized for securing logs to one another if the life span of the attachment needs to be extended from that of a more rapidly biodegradable fabric. All connections are typically weakest at connection points and knot redundancy should be applied at all connection points.

Photograph 8. Rope used as a fastener on a LWM structure.

Photograph 9. Rope used as a fastener on a LWM structure.

Pins

Pins tend to be a more rigid method of linking two or more key members of a LWM structure together. These pins could be made of wood, but are typically composed of some form of steel where the rigidity and shear strength are much stronger than wood. Pins can be free floating or can be locked in place to prevent two pieces of wood from moving away from each other. Locking pins in place can be done through various methods, depending on the type of pin used.

Wood Pins

A type of wood pin used in the past on small rivers is ELWd® where multiple small logs are connected to each other to theoretically act like a large piece of historic timber (http://www.elwdsystems.com/index.php). Wood pins, while natural, are not commonly used due to the loss of structural integrity of the logs being drilled out for the wood pins or the lack of strength in the wood pin itself as well as the labor cost associated with installation. Wood pins are typically locked in place through the use of wood or steel wedges that expand the ends of the pins to keep the attached wood in place (Photograph 10).

Photograph 10. Wood pins being installed to connect pieces of LWM.

Steel Pins

Steel pins are typically installed vertically through key members to structurally link logs together so that they act as one unit to aid in increasing stability. Steel pins are typically created from lengths of rebar. Steel pins rely solely on friction between the pieces of wood and the steel to keep the logs connected. If desirable, attaching a cable clamp at one or both ends or bending the protruding end over will reduce the chance of a pin pulling out of a piece of wood. Care in design and usage should be taken as steel bars used to pin LWM together may also be a hazard when exposed (WDFW 2004).

Steel pins are typically installed in two ways. The first is when the contractor predrills through the pieces of wood with a large auger bit. A steel pin is driven into the hole with a sledge hammer, pneumatic hammer, or other device. The second method is to plunge cut an “X” into the top log with a chain saw (cut a vertical slit through the diameter of a log) and maybe the bottom log. The steel pin is then driven into the “X” with the aid of an excavator pushing it into place with its bucket (Photograph 11). Some contractors sharpened one side of the steel pin to aid in driving through the wood (Photograph 12). This method appears to increase the ease of installation.

Photograph 11. An excavator pushing in a rebar steel pin into a LWM structure.

Photograph 12. Steel pin with sharpened end ready for installation into large wood members.

Threaded Steel Pins

Threaded steel rod pins can be installed both vertically and horizontally through key members and piles to structurally link log members to other members. This creates a structure that functions as one large unit as opposed to multiple individual logs acting independently. This type of pinning is considered more stable and permanent compared to steel rebar pinning due to the ability to lock the logs together with nuts.

To install threaded bar connections a pilot hole through the wood pieces is required. This often requires extended-shaft auger bits capable of drilling through stacked logs. For safety concerns, the contractor should be advised to use air drills instead of electrical drills to minimize the risk of electrical wires being submerged in standing water. Double nuts on each end of a threaded rod should be used to reduce the potential for loosening of nuts. All connections should always use large washers between the nut and wood. Depending on the design life of the rods and LWM structures, galvanized parts are commonly used on the exposed ends, or at a minimum, painted with rust inhibiting paint (Photograph 13 and Photograph 14).

Photograph 13. Close-up view of threaded steel rod with connected with a wide washer and nut after being sprayed with rust inhibiting paint.

Photograph 14. View of threaded steel rods used to connect logs to a wooden pile for a LWM structure.

Chain

Chain is more permanent than ropes and straps, but provides more insurance of stability at high-risk project sites. As with cable connections (see below), chain should only be used if necessary as it can present increased risks to infrastructure associated with logs rafting downstream with permanent connections. When utilized, logs are typically grooved around their circumference or drilled through the diameter to prevent the chain from moving up and down the log during the life span of the structural connection (Photograph 15 and Photograph 16).

Photograph 15. Large log grooved with chain installed around the bole.

Photograph 16. A pin connection of chain anchor around a large log with chain leading to a deadman anchor.

Cable

Cable although commonly used for connections in the past should be avoided due to the risks associated with mass structural failure. If this occurs, a raft of wood that is linked together with cable can float down a river and has a much higher potential of racking on bridge piers and other infrastructure and causing property damage than individual logs floating down the river. Additionally, cable can pose significant public safety risks as they can form traps for recreational users and often have sharp ends (WDFW 2004). However, cable may be required when a LWM structure or location is considered a high-high risk and cable is the last option. Cable is available in galvanized and non-galvanized forms and is typically cut with guillotine-type cutters, skill saws, or hydraulic shears. Hydraulic shears provide the cleanest way to cut cable so that it can be routed through drilled holes in key wood members. Cable is typically connected with cable clamps which creates a weak point in the connection. The minimum number of clamps can range from 2 to 5 as the cable size increases from 3/8-inch diameter up to 1-inch diameter, respectively (Saldi-Caromile et al. 2004). Cables typically require the use of an excavator, winch or jack to create required tension on the cable prior to attaching clamps (Photograph 17 and Photograph 18). Care should be taken to minimize the use of cable, ensure that cable is taught around log members, and that ends are constructed to have minimal fray.

Photograph 17. LWM structure being connected with cable.

Photograph 18. LWM structure being connected with cable.

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APPENDIX A

Example Signature Page

Reclamation – Pacific Northwest Region

Large Woody Material Risk Assessment

Example Signature Page

Subbasin: ____

River: ____

Project: ____

Project Manager: __________________________________

Conceptual Design Completion

Risk Level ______________________________ Date: ____________________________

Required Team Member Concurrence: PE ___ FB___ FG___ HE___

Professional Engineer ______________________ Fish Biologist _________________________

F. Geomorphologist _______________________ Hydraulic Engineer ____________________

Sixty-Percent Design Completion

Risk Level ______________________________ Date: ____________________________

Required Team Member Concurrence: PE ___ FB___ FG___ HE___

Professional Engineer ______________________ Fish Biologist _________________________

F. Geomorphologist _______________________ Hydraulic Engineer ____________________

Final Design Completion

Risk Level ______________________________ Date: ____________________________

Required Team Member Concurrence: PE ___ FB___ FG___ HE___

Professional Engineer ______________________ Fish Biologist _________________________

F. Geomorphologist _______________________ Hydraulic Engineer ____________________

APPENDIX B

Washington State House Bill 1194
Fact Sheet – Washington State Recreation and Conservation Office

H-0166.2

HOUSE BILL 1194

State of Washington 63rd Legislature 2013 Regular Session

By Representatives Stanford, Warnick, Lytton, Goodman, Wilcox, Tharinger, Chandler, Blake, Nealey, Orcutt, Hansen, Kirby, Ryu, Fagan, and McCoy

Read first time 01/18/13. Referred to Committee on Judiciary.

AN ACT Relating to limiting liability for habitat projects; and reenacting and amending RCW 77.85.050.

BE IT ENACTED BY THE LEGISLATURE OF THE STATE OF WASHINGTON:

Sec. 1. RCW 77.85.050 and 2009 c 345 s 3 and 2009 c 333 s 25 are each reenacted and amended to read as follows:

(1)(a) Counties, cities, and tribal governments must jointly designate, by resolution or by letters of support, the area for which a habitat project list is to be developed and the lead entity that is to be responsible for submitting the habitat project list. No project included on a habitat project list shall be considered mandatory in nature and no private landowner may be forced or coerced into participation in any respect. The lead entity may be a county, city, conservation district, special district, tribal government, regional recovery organization, or other entity.

(b) The lead entity shall establish a committee that consists of representative interests of counties, cities, conservation districts, tribes, environmental groups, business interests, landowners, citizens, volunteer groups, regional fish enhancement groups, and other habitat interests. The purpose of the committee is to provide a citizen-based evaluation of the projects proposed to promote salmon habitat.

(c) The committee shall compile a list of habitat projects, establish priorities for individual projects, define the sequence for project implementation, and submit these activities as the habitat project list. The committee shall also identify potential federal, state, local, and private funding sources.

(2) The area covered by the habitat project list must be based, at a minimum, on a WRIA, combination of WRIAs, or any other area as agreed to by the counties, cities, and tribes in resolutions or in letters of support meeting the requirements of this subsection. Preference will be given to projects in an area that contain a salmon species that is listed or proposed for listing under the federal endangered species act.

(3) The lead entity shall submit the habitat project list to the salmon recovery funding board in accordance with procedures adopted by the board.

(4) The recreation and conservation office shall administer funding to support the functions of lead entities.

<u>(5) A landowner whose land is used for a habitat project that is included on a habitat project list may not be held civilly liable for any property damages resulting from the habitat project regardless of whether or not the project was funded by the salmon recovery funding board.</u>

--- END ---

Salmon Restoration Projects and Civil Liability for Landowners

WASHINGTON STATE Recreation and Conservation Office

FACT SHEET

About this Fact Sheet

The Recreation and Conservation Office is providing this fact sheet as a service to help educate our project sponsors and the public about our initial good faith view of how to apply the new law.

This fact sheet is not claimed to be without error or to provide a definitive official interpretation of the RCO.

If any question arises, we recommend you consult an attorney.

RCO will not be involved in determining whether a landowner and sponsor have complied with the conditions of the law.

Salmon Recovery Law

For more legislative context on the salmon recovery law, see House Bill 1194 at http://apps.leg.wa.gov/documents/billdocs/2013-14/Pdf/Bills/Session%20Laws/House/1194.SL.pdf

Contact

Recreation and Conservation Office
PO Box 40917
Olympia WA 98504 0917

Telephone: (360) 725 3937
TTY: (360) 902 1996

E mail:info@rco.wa.gov
Web: www.rco.wa.gov

Making it Easier to Do Salmon Restoration Projects

Landowners and government agencies were concerned about their ability to do habitat restoration projects in rivers and other waterways because of issues about their long-term liability for any property loss or public safety problems that may arise.

In 2013, a new state law exempting landowners from civil liability for property damages resulting from habitat projects on their land became effective. This new law amends the Revised Code of Washington (RCW) 77.85.050, which is the salmon recovery law.

The salmon recovery law was amended to include Section 5 as follows:

(5) A landowner whose land is used for a habitat project that is included on a habitat project list, and who has received notice from the project sponsor that the conditions of this section have been met, may not be held civilly liable for any property damages resulting from the habitat project regardless of whether or not the project was funded by the salmon recovery funding board. This subsection is subject to the following conditions:

(a) The project was designed by a licensed professional engineer (PE) or a licensed geologist (LG, LEG, or LHG) with experience in riverine restoration;

(b) The project is designed to withstand one hundred year floods;

(c) The project is not located within one-quarter mile of an established downstream boat launch;

(d) The project is designed to allow adequate response time for in-river boaters to safely evade in-stream structures; and

(e) If the project includes large wood placement, each individual root wad and each log larger than ten feet long and one foot in diameter must be visibly tagged with a unique numerical identifier that will withstand typical river conditions for at least three years.

Salmon Restoration Projects and Civil Liability for Landowners

FACT SHEET

Landowners

A landowner may be an individual, corporation, tribe, LLC, or governmental entity whose name is on the title or deed to the property. Landownership is complicated by the fact that many restoration projects occur over, or in, navigable bodies of water. These lands are often state-owned aquatic lands managed by the Washington Department of Natural Resources. If the project is on state-owned aquatic lands, the sponsor must work with the Washington Department of Natural Resources for authorization.

Habitat Projects Affected

The habitat project must either be funded by the Salmon Recovery Funding Board or be a habitat project identified on a habitat project list. As described in Revised Code of Washington 77.85.050(1)(b), a habitat project list is compiled by a committee established by the lead entity. Revised Code of Washington 77.85.050(1)(c) states that, "The committee shall compile a list of habitat projects, establish priorities for individual projects, define the sequence for project implementation, and submit these activities as the habitat project list. The committee shall also identify potential federal, state, local, and private funding sources."

The form of this list is determined by the individual lead entity and may include the lead entity's "Habitat Work Schedule (www.hws.ekosystem.us/)," or the lead entity's 3-year work plan, or other compiled list which meets the criteria of Revised Code of Washington 77.85.050.

Two landowner conditions must be met: 1) The landowner owns land that is used for a habitat project that is included on a habitat project list; and 2) The landowner has received notice from the project sponsor that the conditions of this section have been met.

Five Project Conditions

1. The project was designed by a licensed professional engineer (PE) or a licensed geologist (LG, LEG, or LHG) with experience in riverine restoration;
2. The project is designed to withstand 100-year floods;
3. The project is not located within one-quarter mile of an established downstream boat launch;
4. The project is designed to allow adequate response time for in-river boaters to safely evade in-stream structures; and
5. If the project includes large wood placement, each individual root wad and each log larger than 10 feet long and 1 foot in diameter must be visibly tagged with a unique numerical identifier that will withstand typical river conditions for at least three years.

Licensed Professional Engineer

It is the responsibility of the sponsor to complete his/her due diligence and determine if his/her selected licensed professional engineer has experience with riverine restoration.

Salmon Restoration Projects and Civil Liability for Landowners

FACT SHEET

100-Year Flood

It is the responsibility of the sponsor to work with his/her licensed professional engineer to design a project which can withstand 100-year floods.

In-River Boaters

It is the responsibility of the sponsor to work with his/her licensed professional engineer to design a project that allows adequate response time for in-river boaters to safely evade the in-stream structures.

Tagging Wood

Each individual root wad used in a project must be visibly tagged. Each log that is larger than 10 feet long and has a diameter of 12 inches or greater must be visibly tagged. At this time, no guidance exists as to the specifics on how logs should be measured to determine if the diameter of the log is over 12 inches, or if the log is longer than 10 feet. The Recreation and Conservation Office encourages the sponsor to be prudent and tag all logs which are longer than 10 feet and have a diameter of 12 inches or more at any point on the log. Each tag must include a unique numerical identifier and must be able to withstand typical river conditions for at least three years. It is up to the sponsor to conduct due diligence to determine if the selected tags fit this condition.

Recreation and Conservation Office and Salmon Recovery Funding Board Involvement

The Salmon Recovery Funding Board program is not directly affected by the revised statute, and the Recreation and Conservation Office will not develop a Washington Administrative Code related to the revision. *Manual 18, Salmon Recovery Grants* will be updated to include a reference to the revised statute for informational purposes, but the conditions of the statute will not be new requirements for application or project eligibility. As it is the responsibility of the sponsor to provide notice to the landowner that the conditions of the law have been met, the Recreation and Conservation Office and the Salmon Recovery Funding Board will not be involved in that process. The Recreation and Conservation Office and the Salmon Recovery Funding Board will continue to require a landowner agreement for all restoration projects, but the landowner agreement will not be revised to include the conditions of this law.

Stakeholder Input

The statute does not require stakeholder input. However, if the habitat project is funded by the Salmon Recovery Funding Board, the project may go through stakeholder review. The Salmon Recovery Funding Board outlines a detailed design process in Manual 18, Salmon Recovery Grants, Appendix D, which includes a design memo the sponsor prepares that consolidates and responds to stakeholder (landowners, co-managers, lead entity citizen and technical groups, Salmon Recovery Funding Board grant manager, etc.) comments and other considerations during the preliminary design review. See Manual 18, Salmon Recovery Grants, Appendix D (www.rco.wa.gov/documents/manuals&forms/Manual_18.pdf) for more information.

Who is Liable?

By complying with the conditions of this law the landowner (barring some change in law or constitutional issue or other legal complication) may not be held civilly liable for property damages that the project may have caused. Liability may fall on the project sponsor, engineers, designers, contractors, on-site construction inspectors, others, or no one (e.g., acts of nature or no negligence). It is the responsibility of the sponsors, engineers, inspectors, and other contractors to make their own decisions as to whether to hold insurance protecting them from liability related to their work.

APPENDIX C

Public Safety Risk Matrix
Property Damage Risk Matrix

Public Safety Risk Matrix

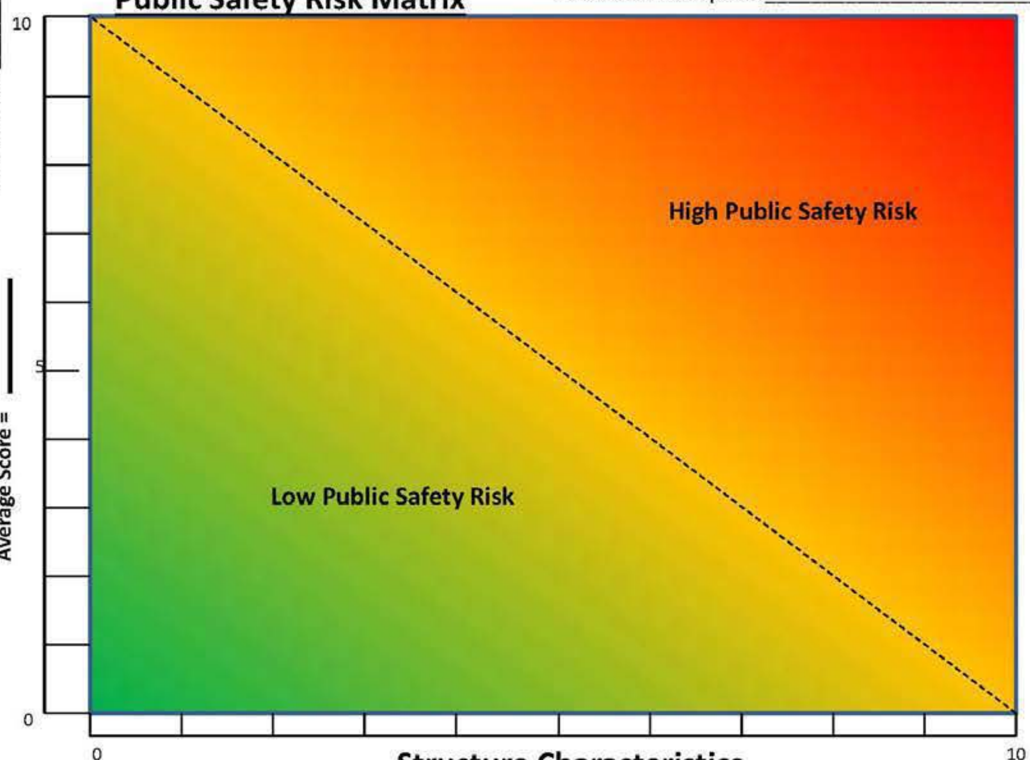
Structure Description:______________________________

Reach-user Characteristics

			Score
Low	Frequency of Use	High	____
Advanced	Skill Level	Beginner	____
Poor	Access	Good	____
Never	Child Presence	Often	____

Total Score = ____

Average Score = ____



Structure Characteristics

			Score
No	Active Channel?	Yes	____
No	Outside of bend?	Yes	____
Low	Strainer Potential	High	____
High	Egress Potential	Low	____
High	Sight Distance	Low	____
Low	Depth x Velocity	High	____

Average Score = ________

Total Score = ________

Project: ______________

Evaluator: ______________

Concurrence: ______________

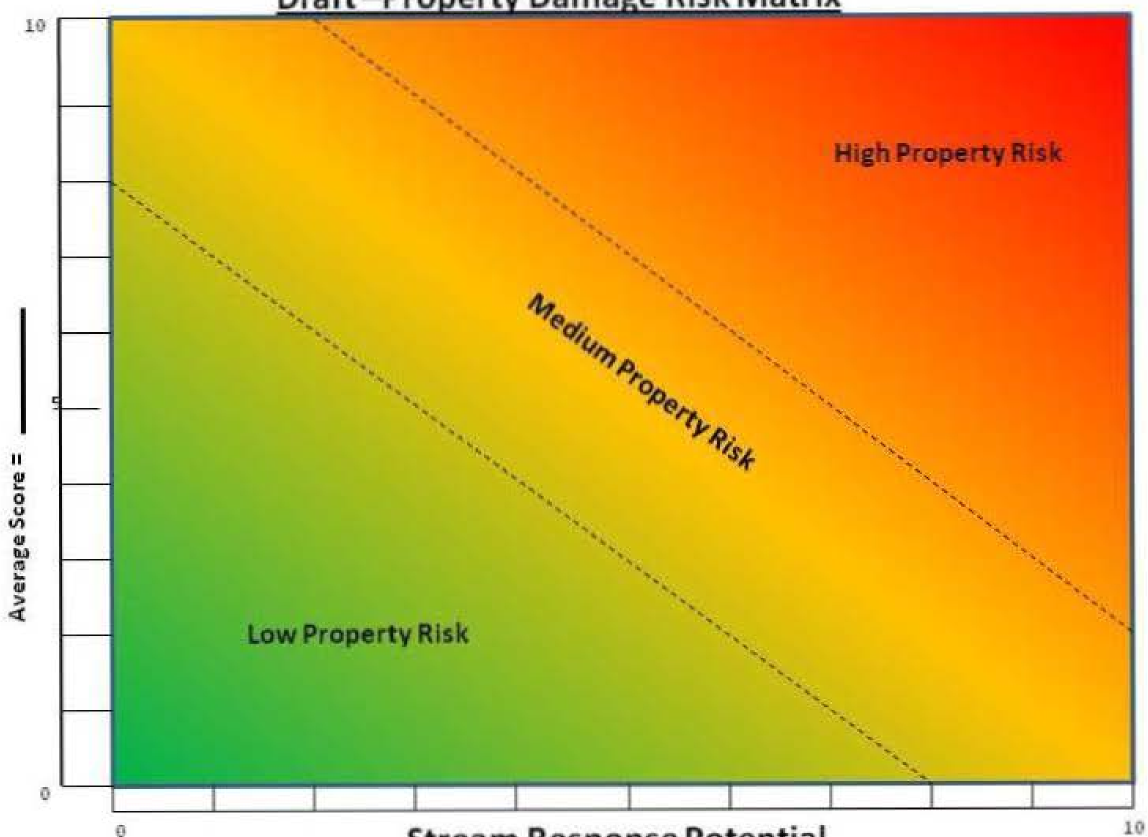
Date: ______________

Property/Project Characteristics

			Score
No Structures	In-channel Structures	Multiple	
No Buildings	Floodplain structures	Multiple	
National Forest	Land Use	Residential	

Total Score =

Draft –Property Damage Risk Matrix



Stream Response Potential

				Score
Stream Type:	Bedrock (source>10%)	Transport (3-10%)	Response (<3%)	
Riparian Corridor:	Continuous/Wide	Discontinuous/narrow	Urbanized/Levee confined	
Bed Scour:	Boulder/Clay bed	Gravel/Cobble	Sand/Silt	
Hydrologic Regime:	Spring-fed — Snowmelt	Rain — Rain-on-Snow	Thunderstorm	
Bank erosion:	Naturally non-erodable	Erosion resistant	Highly Erodable	

Average Score =

Total Score =

Project:

Evaluator:

Concurrence:

Date: