Chapter 7 Water Crossings

7-1 Introduction

This chapter covers the design requirements for water crossings on state highways over fish-bearing waters, in addition to HEC-18, HEC-20, and HEC-23 Volume 1 and Volume 2. See Chapter 3 for the design of non-fish-bearing culverts, and HEC-18, HEC-20, and HEC-23 Volume 1 and Volume 2 for the design of bridges over non-fish-bearing waters, unless local requirements dictate otherwise. Most rivers and creeks in Washington State contain one or more species of fish during all or part of the year. This chapter has been updated to reflect the requirements for fish passage crossings on WSDOT highways from current WAC Hydraulic Code Rules; the current USACE, Seattle District, Nationwide Permit Regional Conditions; and the 2013 Federal Court Injunction for Fish Passage (Injunction). This chapter is specific to WSDOT projects. For non-WSDOT projects, it is up to the project owner to determine whether the guidance in this chapter is followed or other guidance is followed to obtain project permits and follow state law. WSDOT is actively monitoring completed fish passage projects and will update this chapter as new information becomes available. See Section 7-8 for more information.

All fish-bearing water crossings within Washington State must meet the requirements of WAC's Hydraulic Code Rules and the requirements of the *Hydraulics Manual*, unless a deviation is approved by the State Hydraulics Office. In Water Resource Inventory Areas (WRIAs) 1 through 23, the design must also meet the requirements of the Permanent Injunction Regarding Culvert Correction. This chapter uses WDFW's 2013 *Water Crossing Design Guidelines* (WCDG) as reference (WDFW 2013). Other published manuals and guidelines may be used with the approval of the State Hydraulics Office and permitting agencies.

New bridges and culverts in fish-bearing waters must be designed to meet current fish passage standards and WAC to ensure that they do not hinder fish use or migration. WAC requires a person to design water-crossing structures in fish-bearing streams to allow fish to move freely through them at all flows at which fish are expected to move. This is best accomplished by a multidisciplinary team, including engineers, biologists, and fluvial geomorphologists. Biologists are essential for understanding the habitat needs of the fish that use the site, whereas geomorphologists are essential for understanding the reach- and basin-scale stream processes that provide habitat and influence the crossing design.

WSDOT and WDFW have cooperated in a Fish Passage Barrier Removal Program since 1991. PEOs can check the WSDOT fish barrier database or contact the HQ Environmental Services Office Stream Restoration Program to determine whether the project has any fish barriers within its limits and whether the crossing will need to be included as part of the project. WDFW also maintains a database of fish barriers statewide. All water crossings over fish-bearing waters shall be designed by the State Hydraulics Office or by the Stream Team approved by the State Hydraulics Office (see Chapter 1).

Section 7-2 discusses requirements for assessing and documenting existing conditions to design a successful and fish-passable water crossing. Sections 7-3, 7-4 and 7-5 discuss the design process, considerations, criteria, and required scour analyses. Section 7-6 discusses the structure-free zone (SFZ). Section 7-7 provides guidance on temporary diversions, Section 7-8 describes the WSDOT monitoring process, Section 7-9 explains the performance management process, and Section 7-10 presents a discussion of additional resources. Section 7-11 provides the appendices.

This chapter uses the term “Stream Team” to denote work that either the State Hydraulics Office or the individual approved by the State Hydraulics Office performs and to separate that work from the work that the PEO would do in the rest of the *Hydraulics Manual*. At a minimum, the Stream Team consists of a stream design engineer, geomorphologist, and biologist who are leading or directly overseeing the work of other Stream Team staff. Minimum requirements for the stream design engineer include a Professional Engineering license in Washington and 2 years of design or construction experience in similar projects. The biologist shall be an aquatic or fisheries biologist with a minimum of 2 years of experience with similar projects, at least 1 year of which must be design experience and 1 year of construction experience. The geomorphologist must be a Licensed Geologist or Professional Engineer in Washington and have a minimum of 2 years of design and construction experience with similar projects. This chapter assumes that the stream designer or Stream Team has knowledge of WAC, WDFW’s 2013 WCDG, and hydrology and river hydraulics, and, as a result, does not cover every topic in thorough detail. This chapter outlines the process that the State Hydraulics Office follows in designing a stream crossing, and what is expected on WSDOT projects. These designs require a specialty report. Additional requirements about specialty reports are provided in Chapter 1. The template used by WSDOT can be found on WSDOT’s Hydraulics website along with training required to author a specialty report for a water crossing over fish-bearing waters. There is also a report checklist that outlines areas of focus during the specialty report review.

An FPSRD certificate number is required for all authors of any portion of a specialty report (including all members of the Stream Team). See Table 1-1 for a list of specialty reports and other requirements. An FPSRD certificate number is given to those who have viewed all of the training modules and successfully passed the comprehensive exam. Additional information, training resources, and the point of contact for this training can be found on the WSDOT Hydraulics Training web page. As WSDOT updates the FPSRD training modules a re-certification number is also required. Any updates to this training will be posted on the WSDOT Hydraulics Training web page.

A scour analysis is required for all WSDOT projects or WSDOT-managed infrastructure associated with scour or have a potential to be impacted by scour, such as water crossings, walls, roadway embankments, and other WSDOT infrastructure. A WSDOT *Scour Certification Record* number is required for all Stream Team members who are conducting scour calculations, lateral migration, scour analysis, and reviews as part of or supporting specialty reports. See Table 1-1 for a list of specialty reports and other requirements. A *Scour Certification Record* certificate number is given to those who have viewed all the WSDOT Scour Training Workshops and FHWA Bridge Scour Workshop Recordings; completed NHI Course 135046, *Stream Stability and Scour at Highway Bridges*, and NHI

Course 135048, *Countermeasures Design for Bridge Scour and Stream Instability*; and successfully passed the comprehensive exam. Additional information, training resources, and the point of contact for this training can be found on the WSDOT Hydraulics Training web page. As WSDOT updates the Scour Training modules a re-certification number is also required. Any updates to this training will be posted on the WSDOT Hydraulics Training web page.

The following training courses are required to obtain a scour certification:

- FHWA Bridge Scour Workshop Recordings
- NHI Course 135046, *Stream Stability and Scour at Highway Bridges*
- NHI Course 135048, *Countermeasures Design for Bridge Scour and Stream Instability*
- WSDOT 2023 Scour Training

Table 7-1 defines the design component of the stream channel that the individual members of the Stream Team, at a minimum, are responsible for in the design of fish-passable water crossings.

Table 7-1 Stream Team Responsibilities

Design Component	Stream Design Engineer	Geomorphologist	Biologist
Site assessment	✓	✓	✓
Watershed assessment	✓	✓	✓
Fish resources and habitat assessment			✓
Hydrology	✓		
Hydraulic analysis	✓		
Fish passage design	✓		✓
Streambed design	✓	✓	✓
Habitat features	✓	✓	✓
Scour analysis	✓	✓	

SRH-2D hydraulic modeling training is required for all WSDOT projects or WSDOT-managed infrastructure that requires hydraulic modeling as part of the hydraulic design process. Hydraulic modelers are required to obtain a training certificate from NHI for attending Course 135095, *Two-Dimensional Hydraulic Modeling of Rivers at Highway Encroachments*. Other equivalent SRH-2D hydraulic modeling training requires approval by the State Hydraulics Office.

7-2 Existing Conditions

The first step to designing a water crossing is understanding the behavior of the existing system and identifying a reference reach. There is no comprehensive set of biological and physical predictive equations for stream restoration design. Therefore, a reference reach approach is needed. This approach in channel design uses a reference reach, which exhibits channel and habitat properties that are not highly altered from natural, background conditions. By mimicking the reference reach, the design channel will approach (though not duplicate) natural, pre-crossing stream behavior and habitat. A thorough investigation of the site and adjacent stream reach, its history, and any known problems shall be performed prior to the field visit and confirmed during the field visit. Before or during the first field visit, the Stream Team shall complete the following:

- Determine whether the project is within a FEMA-mapped floodplain.
- Evaluate the watershed conditions/land cover (past, current, and future).
- Investigate the type of soils that are in the watershed and the underlying geology and consider how they might affect conditions and processes at the crossing.
- Look at historical aerial photographs and LiDAR for evidence of lateral migration of the channel, avulsion, debris flows, sediment pulses, LWM interactions, significant erosion, etc. Assess general watershed morphology and potential sediment sources using LiDAR, geologic maps, hazard maps, and other resources. Consider the location of the site within the context of watershed morphology and related processes.
- Discuss site history with the local agency and WSDOT area maintenance, specifically noting quantities of dredging, if available, scour repairs, and flooding.
- Review any available survey data and available historical as-builts.
- Confirm pre-field visit investigations and conclusions or document differences.
- Review any available watershed studies, watershed analyses, hydrology/drainage studies, reach assessments, sediment budget, transport investigations, etc.
- Review aerial photographs, topographic and survey maps, and previous watershed analyses for potential reference reach locations.
- Through site visits, the Stream Team will perform the following:
    - Determine the reference reach
    - Measure BFW
    - Determine sediment size using either a Wolman pebble count or a grab sample (as appropriate)
    - Investigate channel geometry
    - Note any channel-forming features
    - Note the presence and function of LWM
    - Note the presence and function of large cobbles or boulders

Multiple site visits are required, both before and after the survey has taken place, to ensure that all the necessary features are surveyed. The Stream Team will benefit by reviewing the survey request in the field with the survey crew. The information listed above shall be photographed or otherwise recorded for report documentation and design discussions. The Stream Team shall coordinate with the PEO for the attendance of the resource agencies and interested tribes during the reference reach selection and BFW determination.

7-2.1 Watershed and Land Cover

Understanding the past, current, and potential future conditions of a watershed is important for the long-term success of a project. For example, watershed conditions have an impact on sediment yield to the site.

Historical and current aerial photographs shall be examined to determine what type of land cover the watershed has now and how that has changed over time. GIS layers are also available for displaying and approximating the areal extent of land cover types. Verifying whether the system is in an urban setting, within an urban growth area, or in an actively managed forest will also help determine what the land cover could look like in the future and may increase the design flows expected during the design life and create the need for a larger structure. Understanding how the watershed has changed over time will help the Stream Team create a successful crossing. Clearcut timber harvest, land conversion to agriculture, road building, bank hardening, log jam removal, stream relocation, and channel dredging are examples of watershed- and reach-level alterations that are likely to have occurred prior to the earliest available aerial photography. It is thus important for the Stream Team to find imagery dating as far back as they can find and to consider the impacts to the stream. Imagery dating back to the 1950s is often obtainable and shall be used when available.

If a watershed has a high potential for future forest fires or has been recently affected by a forest fire, this shall be documented and taken into consideration when determining the final structure size.

7-2.2 Geology and Soils

The soil types in the drainage basin not only assist the Stream Team in understanding what is happening at the crossing but also can impact the calculated hydrology at the site location if a continuous-simulation method, such as MGSFlood, is used to determine design flood events.

The surrounding geology will have an impact on susceptibility to mass wasting, and lateral migration and may influence where a new crossing is placed. It may also influence sediment load and size distribution in the channel, as well as long-term degradation (LTD). Generalized soil types may be found in soil surveys produced by NRCS. Surficial geology maps are also useful in determining soil information.

The Stream Team shall coordinate with the project geotechnical engineer while the specialty report is being authored and update the report as more geotechnical information becomes available. The WSDOT *Design Manual*, Chapter 800, provides additional information on coordination expectations.

7-2.3 Fluvial Geomorphology

Fluvial geomorphology is an integral part of determining where the crossing shall be placed, how the stream or river should be aligned, and where the stream or river may end up in the future and is a primary determinant of the appropriate design of the channel. Because the reach- and watershed-scale geomorphology is not the same for every site, failure to include an in-depth reach assessment of a stream or river may result in an inappropriate crossing design, requiring performance management.

The channel shall be examined to determine if there are signs of lateral and vertical stability or instability, the potential for changes in the base level, and how the stream may be impacted in the future. Delineation of channel migration zones (CMZs) shall be investigated (and may be required by local jurisdictions). The potential for channel avulsion shall also be assessed. Primary topics for analysis to determine the natural, geomorphic characteristics of a stream to appropriately design a water crossing include channel geometry, channel processes, lateral migration, and vertical stability. The analyses are informed by desktop review and site visits; the entirety of this process is referred to as a reach assessment and is further described in this section.

7-2.3.1 Channel Geometry

Stream channel geometry is the combination of channel form in plan view, cross-section, and channel slope. Channel geometry is highly variable in undisturbed streams. In addition, streams have often been straightened or moved, simplifying channel geometry and resulting in shorter crossings that are perpendicular to the roadway. Roadway as-builts and old ROW plans are good sources for determining what the crossing looked like and may depict the stream alignment prior to roadway construction. Historical aerial photographs may give a good indication of the channel alignment over time, depending on tree cover. LiDAR, if available, is also a good resource to provide insight into general down-valley slopes and helps identify grade breaks beyond the limits of the survey. LiDAR can also identify relic channel features, such as side channels, previous channel flow pathways, scroll bars, avulsions, and alluvial fans.

Many WSDOT roads were built along alluvial fans or at the edge of stream and river valleys. As a result, it is not uncommon for the roadway prism to have been built at a slope break or transition zone within the stream reach. This often leads to a historical slope that is steeper than the adjacent reaches. Culvert crossings at roadways can serve as grade controls, which have been in place in some instances for many years and may have had an effect on the channel upstream and downstream of the crossing. Having a good understanding of sediment supply and general transport regime with and without the existing crossing within the system is important in determining the long-term potential for channel slope change over time.

The channel slope and changes in the channel slope shall be documented, both in the reference reach and near the culvert. These slopes shall be measured in the field or determined by survey data.

The channel shape, changes in vegetation, cross-section break lines, and other well-defined features shall be noted, as well as any low flow paths. It is important to verify that the survey matches what is in the field and represents the natural conditions in the hydraulic modeling.

7-2.3.2 Continuity of Channel Processes

WSDOT water crossings are designed using a reach-based approach to allow for continuity of channel processes such as the natural movement of water, sediment, wood, and aquatic organisms. This requires investigating the system as a whole, rather than focusing only on the channel corridor near the roadway. As part of the system evaluation, defining an appropriately sized channel corridor within a water crossing is essential for sustaining natural river function. A variety of techniques and tools are used to assess the continuity of natural channel processes. The Stream Team shall make sure to consider if the selected methodology fits or is appropriate and to make sure to include the surrounding constraints of the site. The Stream Team shall perform a meander belt assessment, and shall determine and document if a CMZ or other process is appropriate to include in the assessment. The combination of methods used for the final determination will be unique to each water crossing to account for site-specific variations and the data available. These assessments balance economic, social, and environmental values while also assisting WSDOT to understand future potential hazards posed by changes in a system due to natural channel processes, construction, or removal of infrastructure in the watershed and climate. Allowing continuity of channel processes also assists WSDOT with continuing to design sustainable, resilient, and reliable transportation networks for the traveling public.

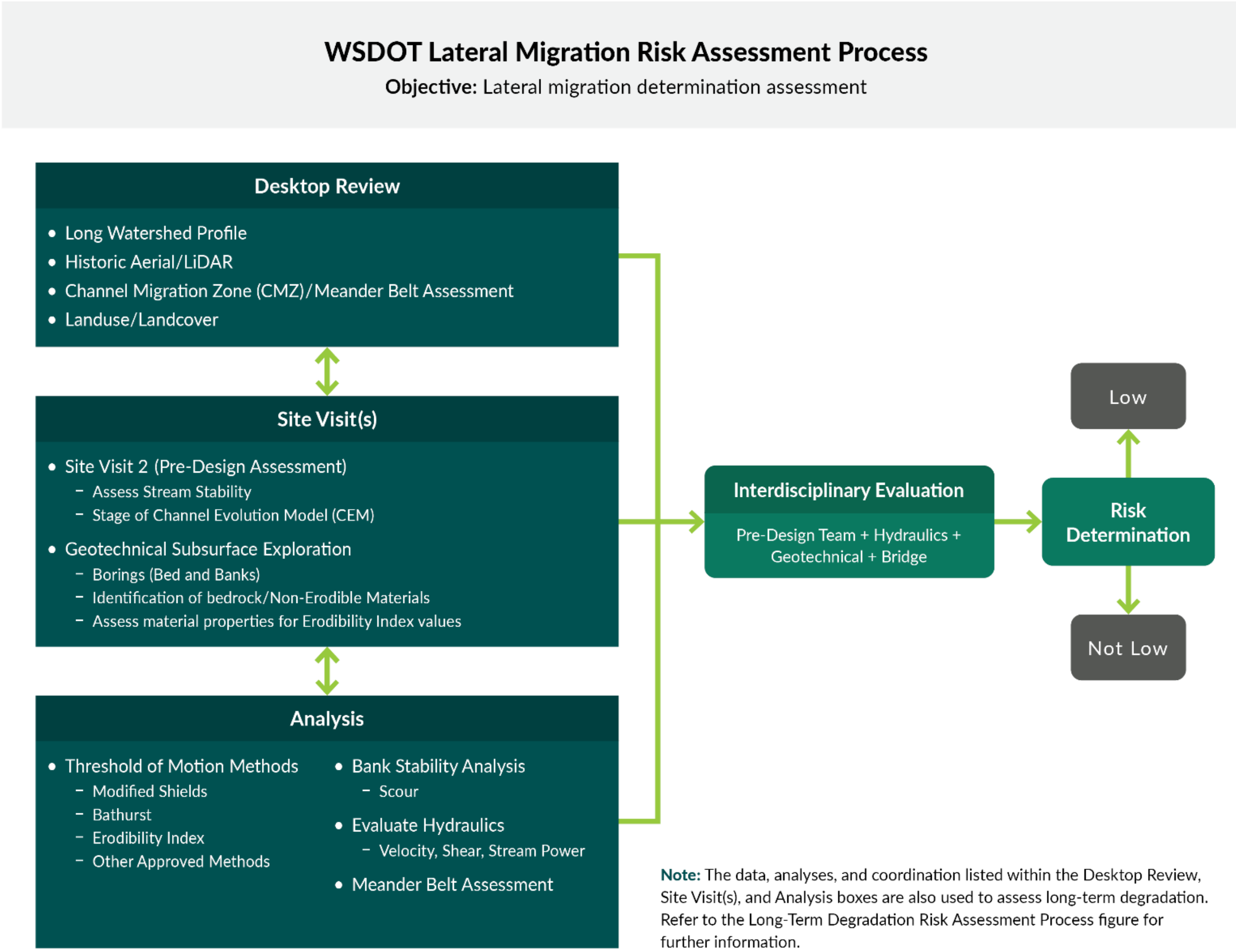
The following information is provided to assist project teams in considering continuity of channel processes in the design of water crossings. Future updates of this *Hydraulics Manual* will cover these topics in greater depth. Please check with the State Hydraulics Office for additional guidance.

1) As stated in Section 7-1, the Stream Team shall include an interdisciplinary team of hydrologists including a stream design engineer, geomorphologist, and biologist; the Stream Team shall also coordinate with the project geotechnical engineer. A desktop exercise shall be completed prior to a site reconnaissance (step 2) to determine available data, including existing reports, current and historical aerial imagery, LiDAR, existing topographic data, existing geologic information, and existing geotechnical investigations.
2) The Stream Team conducts a site reconnaissance to investigate the project reach, including documenting site-specific controls, constraints, and other information required in the specialty report.
3) The Stream Team selects the most appropriate methodologies to evaluate the continuity of natural channel processes of the stream system. Results of analyses/evaluation are documented in detail including assumptions and recommendations.
4) Meet with the State Hydraulics Office to discuss how various channel corridor widths based on the results of the analysis/evaluation may affect water crossing SFZ and general potential project impacts, and determine how to proceed. WSDOT applies professional judgment at step 4 with the information provided by the Stream Team in step 3.
5) Document the decisions that were made in step 4 in the specialty report.

7-2.3.3 Lateral Migration

The Stream Team shall assess lateral migration in the initial stages of design. All structure foundations shall be designed to account for the lateral migration expected to occur over the life of the structure. This does not require the full span of CMZs, but requires all structural elements to be designed considering the appropriate risk to lateral migration and for the structure to allow natural channel processes to the extent practicable. Lateral migration risk to water-crossing structures are classified as “low” or “not low.” Lateral migration risks shall be considered “not low” for all water crossings unless a detailed lateral migration risk assessment process is conducted and results in a determination that the risk for lateral migration to the structure is low and the determination is approved by the State Hydraulics Office. The process of determining lateral migration risk at water-crossing structures is illustrated below in Figure 7-1, including the necessary data, analysis, and coordination required. The determination is ultimately informed by data collection, site observations, and analysis, but most importantly by an interdisciplinary evaluation among the design, hydraulic, geotechnical, and bridge teams. The risk analysis shall consider risk during the expected project design life, which typically is 75 years. The flow chart is not meant to be exhaustive in analytical methods, data sources, or coordination across disciplines. Refer to the WSDOT *Design Manual*, Chapter 800, for additional information regarding interdisciplinary coordination.

Figure 7-1 WSDOT Lateral Migration Risk Assessment Process



Note: For water crossing design projects, the Hydraulics team is the Stream Team.

7-2.3.3.1 Desktop Review

Prior to the site visit, a desktop review of available information shall be conducted for the purpose of conducting a qualitative geomorphic assessment of channel stability. The desktop analysis is intended to review factors that influence channel stability and identify additional data that shall be collected during the ensuing site visit. Desktop review includes review of historical imagery and elevation data, a meander belt assessment, or CMZ delineation and review of land use/land cover in the watershed, each of which is described in the following paragraphs. A longitudinal profile shall also be developed to assist with overall analysis of channel stability; the profile can be used to help assess lateral migration in some cases, but pertains more to vertical stability analysis. Refer to Section 7-2.3.4.1 to read a description of longitudinal profile development.

7-2.3.3.1.1 Historical Aerial Photos and Elevation Data

Review of historical aerial photos and elevation data is the foundation of the desktop analysis and is used to quantify change over time to channel planform, profile, and watershed characteristics. The objective of reviewing the historical maps, elevation data, and aerial photographs is to understand channel migration within the current climatic regime. Reconstructing historical channel processes informs trends in future channel movement that may not be reflected in the historical record. Common sources for topographic elevation data and aerial photos include:

- Historical maps:
    - USGS Historical Topographic Maps (historical quad maps)
    - University of Washington River History (T sheets and survey plats)
    - BLM GLO Maps (survey plat maps, note these vary in quality)
    - As-builts or ROW maps
    - Others
- Elevation data:
    - Washington State Department of Natural Resources LiDAR Portal
    - Puget Sound LiDAR Consortium (PSLC)
    - U.S. Interagency Elevation Inventory
    - As-built data or survey from original construction
    - Others
- Aerial photos:
    - University of Washington River History (1930s-era aerial photos)
    - USGS Earth Explorer
    - USDA National Agriculture Imagery Program (NAIP)
    - Department of Ecology Coastal Atlas (obliques for shorelines)
    - Others

Review of aerial and elevation data for small streams with dense canopy cover can be challenging as the stream alignment is not readily identified from aerial photos. In this instance, information regarding lateral migration potential will be ascertained primarily from a detailed site visit, which is described in the following section.

7-2.3.3.1.2 Channel Migration Zone/Meander Belt

A meander belt and/or CMZ delineation shall be conducted to characterize how the channel planform has changed over time—specifically, identification of channel meanders and how they have spatially varied over time in the vicinity of the project (both upstream and downstream). This analysis typically involves review of historical maps, aerial photos, and elevation data and digitizing bank location and channel centerlines at multiple dates to identify change over time. Where a smaller stream drains into a larger river, the river may require a CMZ delineation because it acts as the local base-level control for the small stream. CMZ delineations shall be conducted using historical maps, elevation data, and aerial photographs that go as far back as possible, i.e., at least over the last 100 years depending on data availability. Detailed methodology is not described in this document. Additional information, can be found in, but is not limited to, the following publications:

- HEC-20 Chapter 6.3
- Washington State Department of Ecology: Channel Migration Toolbox (Ecology 2014)
- Washington State Department of Ecology Screening Tools for Identifying Migrating Stream Channels in Western Washington: Geospatial Data Layers and Visual Assessments (Ecology 2015)
- Washington State Department of Ecology: A Framework for Delineating Channel Migration Zones (Ecology 2003)
- NCHRP Report 533: Handbook for Predicting Stream Meander Migration (NCHRP 2004)
- HEC-16

7-2.3.3.1.3 Land Use/Land Cover

Aerial imagery shall also be reviewed to understand how the land use/land cover within the upstream watershed has changed or is expected to change. Land use/land cover is directly correlated to runoff rates as well as sediment supply, and large-scale changes can significantly impact both, ultimately impacting stream stability. For example, forest fires and silviculture can lead to increased peak flows and sediment supply as a direct result of loss of vegetation. Another common trend is associated with increased development/urbanization in a watershed, which will lead to increased peak flows and a decrease in sediment supply. Most streams and rivers in Washington that have experienced change because of anthropogenic influences likely started adjusting many decades ago with the arrival of the first European settlers. Therefore, it is important that the Stream Team understands that the record of available imagery may not reflect a stream or river's extent of adjustments, and the Stream Team shall strive to find aerial imagery dating back as far as possible (e.g., 1950s) and understand that those images may not represent a "natural" condition. In addition to review of aerial photos, land use/land cover information can be determined from the National Land Cover Database (NLCD), which provides digital land cover data beginning in 2001. The NLCD data sets include land cover and impervious surface as well as tools for conducting comparisons between data sets. See Section 7-2.1 for additional discussion.

7-2.3.3.2 Site Visits

After the desktop review has been conducted, on-site investigations shall be conducted by both the Stream Team and geotechnical team. These on-site investigations are used to confirm, validate, or correct the assumptions established from the desktop review such as locations of control structures, any headcuts or knickpoints, etc. These visits may or may not be conducted at the same time. Early coordination among the teams is recommended if possible. The following paragraphs describe the data and observations that shall be collected in the field.

7-2.3.3.2.1 Stream Site Visit

A site visit by the Stream Team is necessary to identify fluvial and geomorphic factors that influence stream stability as well as information to support the design of the proposed structure, which includes BFW measurements and pebble counts to characterize the streambed material gradation. See Chapter 2.3 of HEC-20 for an additional summary of the geomorphic factors related to stream stability. The site visit shall be conducted both upstream and downstream of the crossing. This site visit is conducted during the PHD phase. During the site visit, the Stream Team shall make observations regarding bank stability, lateral stability, and vertical stability. Observations related to bank and lateral stability are the most applicable to determine the lateral migration risk; however, vertical stability shall not be discounted and also needs to be considered during design. Observations shall be recorded with site notes, sketches and photographs, and locations captured on a field map or with a Global Positioning System (GPS) unit. HEC-20 provides more specific data regarding collection and example field forms are included in Appendices B, C, and D.

A Channel Evolution Model (CEM) is a qualitative method that can be used to predict how alluvial channels respond to changes involving lowering base level, incision, and alterations to hydrology and sediment supply. Field observations can be used to determine the current stage of channel evolution and stability. Once the current channel evolution stage is identified, the CEM can be used to identify expected responses of the channel as it progresses toward a stable configuration through predictable stages. Channel responses may include incision, channel widening, and bank erosion before arriving at a stable configuration. An example of a CEM is the model developed by Cluer and Thorne (2013). Please also see Castro and Thorne (2019) and Powers et al. (2019) for additional CEMs. It shall be noted that CEMs are not appropriate for bedrock channels or recently engineered reaches.

7-2.3.3.2.2 Geotechnical Subsurface Exploration Site Visits

Geologic site reconnaissance shall be conducted by the geotechnical team to observe site conditions, including the extent and character of exposed soil units, and the condition of the roadway, bridge, channel banks, and embankment slopes. The exploration typically includes test borings conducted from the roadway and laboratory testing of selected samples retained from the test boring. Borings also identify if bedrock is present at the site and at what depths.

This information is typically summarized in a geotechnical scoping memorandum. The scoping memorandum also includes a summary of published geologic and soil data and a summary of historical borings in the project vicinity. Recommendations for hydraulic considerations, specifically regarding LTD, contraction scour, and local scour, are also included in the memorandum. It is critical that coordination between the geotechnical engineer and the stream designer or Stream Team is conducted early and ongoing through the design. The WSDOT *Design Manual*, Chapter 800, describes this coordination process. Pertinent parameters provided include a summary of HEC-18 Soil Type (Cohesive or Cohesionless), HEC-18 Erodibility Index (Low, Medium, High), and a median particle size (D_{50}) for the various stratigraphic units identified during the reconnaissance.

7-2.3.3.3 Analysis

Once the desktop review and site visits have been completed, detailed analysis can be performed using the collected information coupled with the results of hydraulic modeling. Analyses include the following:

- Threshold of motion
- Bank stability analysis
- Hydraulic analysis (modeling)
- CMZ/meander belt assessment

7-2.3.3.3.1 Threshold-of-Motion Analysis

A threshold-of-motion (incipient motion) analysis is used to determine if a sediment particle of interest will mobilize under specific hydraulic conditions. For example, this analysis could determine if a particle of interest is mobilized during a specific flood event. Alternatively, it could be used to determine what hydraulic forces would be required to mobilize a particle of interest. Common methods used include the unit discharge method (Bathurst 1987), which identifies a stable D_{84} particle size given a flood event of interest. This method is typically used for channels with gradients over 4 percent. For shallower slopes, the modified Shields approach (USDA 2008) is used to determine sediment mobility. WSDOT is currently working to incorporate another method of assessing the threshold of sediment transport and scour (the erodibility index) based on the work presented in HEC-18 and Annandale (2006). This work will be included in the next *Hydraulics Manual* update.

7-2.3.3.3.2 Bank Stability Assessment

A Bank Stability Assessment considers if the toe of the bank is susceptible to scour given the hydraulic conditions and geotechnical properties of the streambank material. Bank failure occurs when the bank height exceeds the critical bank height for geotechnical slope stability. This assessment is meant to be qualitative in nature, using the site observations, CEM stage, bank material properties, and local hydraulics present at the bank to make an informed judgment about bank stability. More detailed methods exist for quantifying bank stability, such as the Bank Stability and Toe Erosion Model (BSTEM) (Simon et al. 2009), or sediment transport modeling, but these would require approval from the State Hydraulics Office before being used for assessment of bank stability.

7-2.3.3.3.3 Evaluate Hydraulics

Pre- and post-project hydraulics shall be assessed and compared with the use of an SRH-2D hydraulic model. See Section 7-1 for further detail regarding WSDOT's hydraulic modeling requirements. Other modeling platforms or 1D modeling may be appropriate; however, they would require the approval of the State Hydraulics Office prior to being used. 2D modeling is required, as it provides more refined hydraulic results at locations of interest including flow and velocity distribution, WSELs and depths, shear stress, velocity magnitude, and direction.

Post-project hydraulics shall be reviewed for areas of high shear, stream power, and velocity, as these areas often are prone to erosion and scour. These hydraulic conditions are commonly located at the outside of bends. Often when a proposed project is replacing an undersized structure with a larger opening, the backwater upstream is eliminated, resulting in increases to shear and velocity upstream, and may mobilize material that had aggraded upstream because of the backwater.

An advantage of the 2D hydraulic model is the ability to predict flow patterns and velocity direction. Velocity vectors shall be reviewed at the proposed crossing and can be used to identify areas of contraction/expansion as well as determine the angle of attack on proposed structures. Velocity vectors entering channel meanders can be reviewed to provide an estimate of direction of potential lateral and down-channel migration paths.

7-2.3.3.3.4 Meander Belt

See 7-2.3.3.1 for discussion on meander belt assessment. Results of the hydraulic analysis can be used to confirm assumptions used in the amplitude assessment.

7-2.3.3.4 Interdisciplinary Evaluation

Once the desktop review, fieldwork, and analysis have been completed, an interdisciplinary evaluation shall be conducted that includes members of the predesign, geotechnical, hydraulic (or Stream Team), and bridge teams to present the results of the site visits and analysis and ultimately determine the lateral risk on a project basis per the guidelines in the WSDOT *Design Manual*, Chapter 800.

7-2.3.4 Vertical Stability

Vertical stability must be assessed in the initial stages of design, specifically a longitudinal profile analysis (Section 7-2.3.4.1) prior to the initial site visit. It is important to understand the history and processes affecting the stream's longitudinal profile (Section 7-2.3.4.1). Events such as forest clearing, loss of instream wood, dams, beaver removal, urbanization, changes in peak flows, and uplift, along with other factors can have and have had a major impact on the overall stability of streams in the Pacific Northwest. Processes taking place at different time scales (geologic versus human) and spatial scales (watershed versus reach versus site) could affect the project's success. Identifying and understanding causal factors and related stream adjustments are necessary when designing robust and resilient instream projects, and shall be part of any engineering design analysis (Skidmore et al. 2011).

The “goal” of a river is to move sediment, debris, and water at a minimal expense of energy. To this end, the stream will smooth the longitudinal (or simply “long”) profile as much as possible. The long profile shape (usually convex downward) reflects the adjustment of the river to (1) the climate of the watershed (current and past), which controls the amount of runoff; (2) the tectonic setting of the watershed, which controls its overall relief as well as changes in base level; and (3) the geology of the watershed, which controls sediment supply and the bedrock’s resistance to erosion.

Tectonic activity and climate are not static phenomena, and bedrock is spatially variable. In addition, it takes time for a river to complete the job of adjusting its profile to these independent variables. Because of this, longitudinal profiles are in constant readjustment or dynamic equilibrium, never quite catching up to the changes that affect them (Mount 1995). Under natural, background conditions, the longitudinal profile of a river is in slow, constant adjustment to watershed conditions. Profiles are convex downward in shape with a steep gradient at the head and a low gradient at the mouth. Variations in the shape of profiles reflect the response of the river to the overall tectonic, climatic, geologic, and base level conditions. Changes in these conditions can produce regional shifts in profiles involving widespread river aggradation or incision to reestablish the ideal shape.

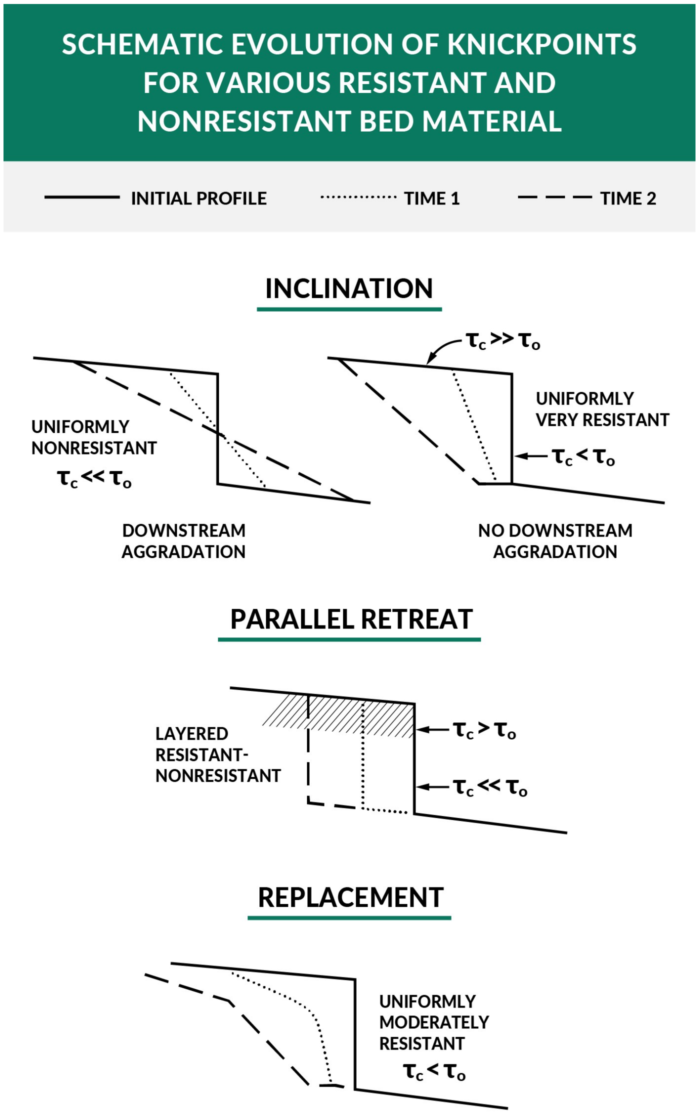
Rivers are constantly adjusting to local perturbations in their profile. Knickpoints are abrupt changes in stream gradient, and are often nearly vertical. However, they can also be less abrupt, and are sometimes call “knick zones.” In either case, the abrupt change is the stream’s response to a drop in a base level. The base level is a control on stream incision, and can be standing water—a wetland, lake, reservoir, or ocean—or it can be a resistant substrate. Downstream barriers or infrastructure shall not be considered a base-level control for the duration of the design life of a structure. In the case of the latter, bedrock is the ultimate base level control on the human time scale. On a larger time scale, bedrock is eroding, and depending on the strength of bedrock, incision can be relatively fast. Other types of substrate-related base level controls include log jams and boulder clusters. These types of base level controls are considered transitory, and can change during the human lifespan time scale.

Exactly how and how fast a knickpoint retreats in the upstream direction is highly specific to stream substrate and channel geometry (Gardner 1983). There are several styles of knickpoint retreat; these are illustrated in Figure 7-2. Parallel retreat can occur when a relatively resistant layer at the streambed surface is underlain by a weaker layer. The upper layer in this case gets undermined by the erosion of the weak layer, and collapses, allowing the process to begin all over again at a point upstream of the prior knickpoint location. Alternatively, if the substrate has a uniformly nonresistant material, the knickpoint can rapidly adjust profile by a combination of erosion upstream and deposition downstream. If material is uniformly resistant, the knickpoint is more persistent, with its slope decreasing gradually over time and almost no downstream aggradation. Slope replacement is another type of knickpoint evolution, in which the initial knickpoint changes by lowering in elevation but taking on a lower slope on the downstream side, and a steeper slope on the upstream side.

When assessing a stream for a new crossing, it is important to anticipate knickpoint migration and its implications for the new stream crossing. This may entail reconnaissance far downstream from the roadway. If necessary, survey may be needed to tie in a knickpoint that was observed. To understand the risk of knickpoints to a new crossing, the substrate must be examined and a knickpoint evolution model must be chosen based on professional judgment. If the knickpoint is relatively distant from the crossing, it may not pose a threat during the project design life. However, if there is evidence of rapid retreat of a knickpoint, even a distant knickpoint may pose a risk, particularly if the style of retreat is parallel.

Culverts that are replaced to provide fish passage often have served as grade control for 50 to 100 years. Removal and/or replacement of these grade control structures can set off a cascade of effects that negatively impact the habitat and passage that a project seeks to improve if the design does not account for the stability of the system. This instability can cause floodplain disconnection, loss of backwater and side channel habitat, increased levels of turbidity, and channel (and thus habitat) simplification. Evaluation of both the stage of stream evolution and a longitudinal profile analysis can help determine if morphologic grade control (Castro and Beavers 2016) is warranted, and if so, what type of structure is most geomorphically appropriate. Potential structures include placement of large wood and roughness elements, constructed riffles, step-pools, and cascades.

Figure 7-2 Styles of Knickpoint Evolution

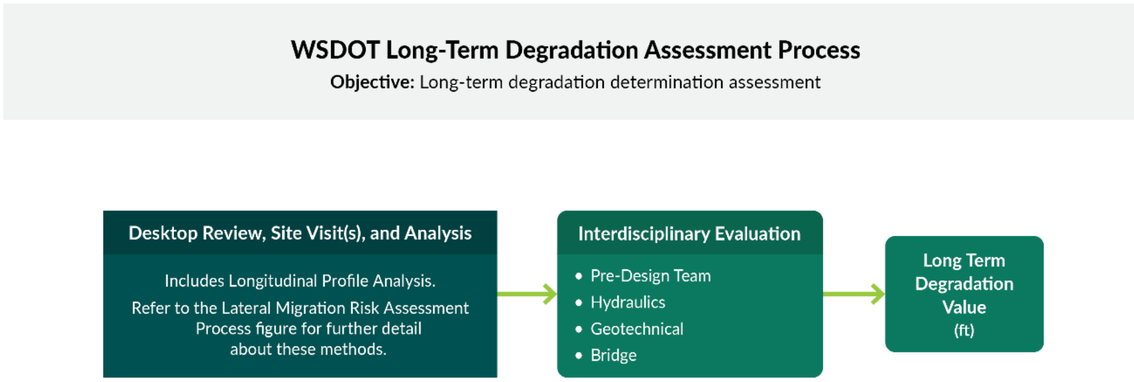


Adapted from Gardner 1983, where $\tau 0$ = bottom shear stress and τc = critical shear stress needed to initiate motion.

Vertical stream stability shall be evaluated and documented in the specialty report for all WSDOT road/stream crossings to determine if morphologic grade control is necessary, if additional freeboard due to aggradation risk is required, and to estimate the LTD component of total scour. Similar analyses performed to assess lateral migration are also used to assess vertical stability; refer to Figure 7-3 for the long-term degradation assessment process, and to Sections 7-2.3.3.1 through 7-2.3.3.4 for a discussion of the applicable assessments and interdisciplinary coordination among the design, hydraulic (Stream Team), geotechnical, and bridge teams. Refer to the WSDOT *Design Manual*, Chapter 800, for additional information regarding interdisciplinary coordination.

A longitudinal profile is the primary tool used to assess vertical stream stability.

Figure 7-3 WSDOT Long-Term Degradation Assessment Process



7-2.3.4.1 Longitudinal Profile Analysis

A longitudinal profile is the elevation profile of a stream drawn along the length of the thalweg. A profile is plotted with elevation on the vertical axis and stationing along the horizontal axis. Typically, horizontal stationing is relative to a known point, for example, the distance from the mouth of the stream or confluence. Elevation data for the profile can be obtained from detailed topographic survey or LiDAR data, or they can be collected during a site visit. If multiple elevation data sets are available, consider displaying all data on the profile. Knickpoints identified through either fieldwork or topographic analysis must be included in the longitudinal profile analysis. Downstream infrastructure, as well as downstream knickpoints that can affect the proposed crossing during the design life of the proposed crossing, are required to be assessed in the initial stages of design. Similarly, upstream infrastructure that could be affected by the replacement of the proposed crossing during the design life of the proposed crossing are also required to be assessed in the initial stages of design. Once created, the vertical profile shall be reviewed for identification of slope breaks and discontinuities, existing grade control structures, and any headcuts or knickpoints. It is also helpful to include and label any other structures in the profile (e.g., culverts, bridges, dams, weirs, or bedrock features). If data are available they are required to include subsurface information provided by the geotechnical engineer. See Section 7-2.3.3.2.2 for additional information. It is not uncommon for other existing crossings downstream of a project to act as grade control. The longitudinal profile is a tool used to assess overall channel stability, and in some cases is also used in desktop review to determine lateral migration potential; see Figure 7-1.

Additional guidance on procedure and considerations for vertical stability will be provided in later iterations of this *Hydraulics Manual*. The Stream Team shall contact the State Hydraulics Office at the beginning of a project to determine if supplemental guidance is available for vertical stability.

7-2.3.5 Existing Large Woody Material and Channel Complexity Features

LWM within the reference reach and near the crossing shall be documented, as well as the potential for future LWM recruitment. The channel type (Montgomery and Buffington

1993) and any key features such as LWM, boulders, and bedrock outcrops that are creating channel complexity or influencing channel alignment shall be noted as well as the capability of the system to move wood if future conditions provide a stream buffer that could recruit LWM. See Chapter 10 for additional information on how to document LWM in a reach assessment.

7-2.3.6 Sediment

Sediment size in the reference reach is determined through Wolman pebble counts or grab samples, depending on the size of the streambed material. If a grab sample is used, the sample size needs to be large enough to produce accurate results. Guidance on sample size is provided in scientific literature (e.g., Bunte and Abt 2001).

The sediment sampled shall be within the reference reach and a minimum of three samples is required. Note any large, naturally occurring material that is on site; it may not be appropriate to include the larger material in the gradation, but the material shall be noted within the design documentation. Depending on the stream regime, it may be appropriate to quantify all the larger material found on site. In some cases, large, unnatural material or large deposits not transported by the current flow regime may be shaping the current stream conditions including elements from previous or upstream streambank stabilization and scour protection efforts. While it may not be accurate to include this angular rock or other streambank-stabilizing material in the pebble counts, making note of it may be useful for understanding the reach conditions and what the stream is capable of mobilizing.

Understanding the sediment supply in the system is critical to being able to determine the correct size material to be placed back into the stream. If a system is sediment starved, it may be necessary to provide material that is coarser than the adjacent reaches to avoid channel incision. If a system has a healthy sediment supply, it may make sense to place material that is mobile and matches the sediment in the adjacent reach.

Where there is a natural streambed armor layer on the surface of the streambed, in addition to pebble counts, a sub-layer sample shall be used to capture the sediment size below the armored layer (see Section 7-3.8.3). For WSDOT projects, sampling below the ordinary high water level (OHWL) is allowed under General Hydraulic Project Approval. Work within the wetted perimeter may occur only during the periods authorized in the APP ID 21036 titled “Allowable Freshwater Work Times, May 2018.” Work outside of the wetted perimeter may occur year round. For more information see the APPS website.

Samples collected below the OHWL must be documented in the current Hydraulics Field Report.

7-2.4 *Hydrology*

If the hydrology at a site is estimated incorrectly, this can lead to underestimating or overestimating the required size for the structure’s span, incorrect scour elevations and depth estimates, incorrect channel shape, and incorrect LWM sizing and anchoring requirements.

Additional information about hydrology is provided in Chapter 2. Justification for the chosen methodology being the most appropriate is required for all projects, including if the USGS regression equation is used. In many instances, the USGS regression equation may be the best available information, but this shall be confirmed through modeling, site conditions, maintenance history, and engineering judgment. The standard error for the USGS regression equation is quite high in some areas and it may be necessary to adjust the flows based on these standard errors. Other methodologies, such as the basin transfer method or HSPF, may be more appropriate. In urban areas, hydrology models that include future buildout conditions may be available for use.

7-2.5 *Reference Reach*

The following process outlines several steps for locating the best reference reach possible while recognizing that many streams near roadway crossings are modified by human processes and thus are not perfect natural analogs. If a system is highly modified, contact the State Hydraulics Office for additional guidance. Figure 7-4 depicts a flow chart that describes the steps below that shall be completed by an interdisciplinary team consisting of a hydraulics engineer, geomorphologist, and biologist.

7-2.5.1 Step A: Examine Adjacent Reaches

Examine the reaches with project resource co-managers and stakeholders immediately upstream and downstream from the project reach and evaluate the following:

1. Does the average stream gradient change significantly between upstream and downstream?
2. Are there signs of significant erosion or deposition?
3. Is there variability of geology, e.g., knickpoints, hard pan, or bank failure?
4. Are there anthropogenic features or other water crossings that impact the crossing within the project reach?
5. Are there any sudden changes in sediment size distribution?

In evaluating the project reach for the above points, the Stream Team is trying to determine whether the morphological attributes (gradient, confinement, planform, shape, bed materials, etc.) of the reach reflect what would be expected in the vicinity of the site, and how/to what extent these attributes are modified by artificial features, constraints, or conditions.

Significant changes in gradient are an indication that sediment supply may be a concern, or that the crossing is in a transition zone, etc. Large amounts of deposition or erosion have an impact on the overall channel slope and shape that may not be sustainable in the long term. Constructed features within the channel and/or floodplain such as riprap, piers, foundations, levees, or mechanically altered channels could cause the reach to not reflect what the channel would look like under natural conditions. However, if the channel is mechanically altered, the channel shape shall be mimicked; in these instances, contact the State Hydraulics Office for additional guidance.

If the answer to any of the above questions is yes, proceed to Section 7-2.5.2. If the answers to all of the above questions are no, proceed to Section 7-2.5.3.

7-2.5.2 Step B: Similar Reference Reach

If the adjacent reach is not representative, an appropriate watershed reference reach will need to be located. Locate the watershed reference reach using the following steps:

1. Examine a topographic map at the 1:24,000 scale (or finer) for reaches farther upstream and downstream of the culvert reach with similar slope, watershed characteristics, and channel confinement.
2. When a new reach with similar slope, watershed characteristics, and channel confinement is identified, determine the size of the contributing watershed area. Is it similar (plus or minus 20 percent) to the contributing area above the project reach?

If the reach meets criteria in item 2 above, go to Section 7-2.5.3. If it does not, look to adjacent watersheds with similar aspect, elevation, levels of development, and geology and follow the procedures in Step A for the location identified.

Prior to starting the stream design, the Stream Team must receive approval of the reference reach selection from the State Hydraulics Office.

7-2.5.3 Step C: Reference Reach Data Collection

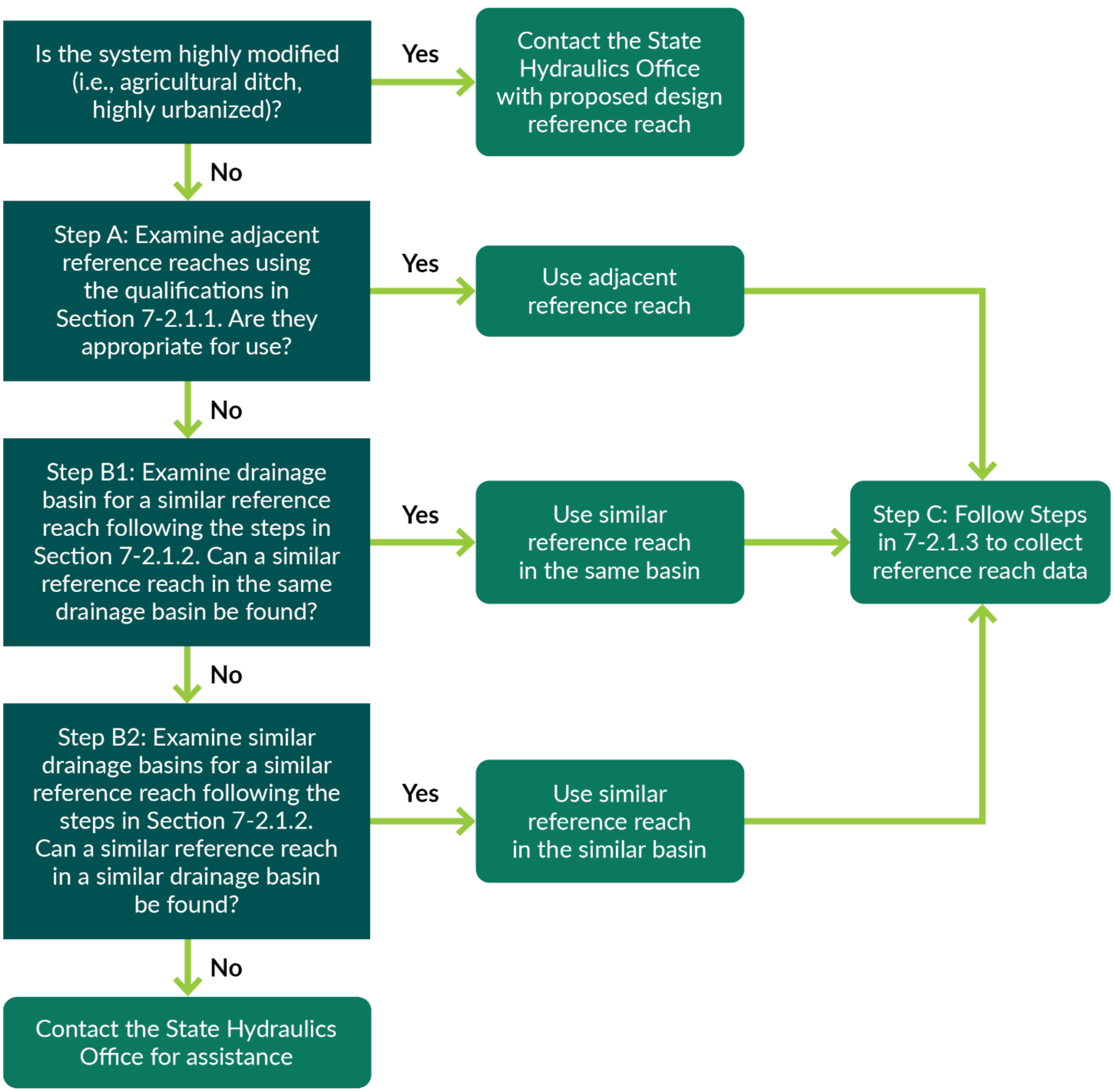
After locating an appropriate reference reach, collect data for the specialty report. At a minimum, collect the following information:

- Stage of channel evolution at the project reach (Cluer and Thorne [2013] evolution progression recommended)
- Water surface slope during non-flood event
- Channel sinuosity and radius of curvature
- Presence and residual depth of pools
- BFW in at least three representative locations; compare to those measured at project reach
- Pebble counts or grab samples in at least three locations on riffles or pool tailouts (Wolman 1954)
- Variability of sediment size throughout reach, i.e., armor layer, identification of largest size clasts
- Bank characteristics (i.e., height of banks, composition, cohesion, etc.)
- Note riparian zone vegetation, canopy density
- Note presence and function (or absence) of LWM, especially key pieces (see Chapter 10)
- Record geographic coordinates of reference reach
- Note anthropogenic impacts to the reach

7-2.5.4 Project Constraints

Constraints in the project reach such as adjacent properties or railroads may limit the channel geometry, particularly the slope. In this case what would otherwise be the logical reference reach may not be suitable. In these cases, the Stream Team looks for a design reference reach that has the approximate slope of the project reach dictated by constraints. The process for design reference reach determination is similar to the reference reach process, but filtered by the parameter that is constrained (most likely channel slope). This process is outlined in Appendix 7A. If it is determined that a constraint is present requiring a design reference reach, contact the State Hydraulics Office for concurrence requirements for the use of a design reference reach.

Figure 7-4 Reference Reach Determination



7-2.6 Bankfull Width

BFW is the most effective channel-forming flood event. Bankfull discharge is the flow at which the stream reaches BFW. Bankfull discharge occurs at a 1.2-year recurrence interval in western Washington and at a 1.5-year recurrence interval in eastern Washington (Castro and Jackson 2001). The bankfull discharge may be greater than the 2-year flood event for incised channels. Bankfull discharge may be exceeded multiple times within a given year. This may occur in a single flood event, or it might occur in different isolated flood events (Anderson et al. 2016).

An accurate BFW is critical. A minimum of three measurements shall be used when computing the average BFW. Measure widths that describe prevailing conditions at straight channel sections and outside the influence of any culvert, bridge, or other artificial or unique channel constriction (WAC 220-660-190). The Bankfull Width module of the FPSRD training provides guidance for measuring BFW for WSDOT water-crossing structures.

If there are significant differences between the measured and hydraulically modeled approximate BFW, further evaluation or justification will be required. The Stream Team shall verify that the channel hydrology is correct to the best of its knowledge, verify that the Manning’s n values are appropriate for the crossing, and use engineering judgment as appropriate to ensure that the hydraulic model is accurate, and any differences are explained. Sites that are not typical shall be discussed with the tribe(s) and WDFW to come to an early understanding of the channel behavior.

In cases where BFW cannot be measured, regression equations provided in Castro 2001 shall be used to determine bankfull discharge that shall then be modeled to determine an estimate for BFW to be used for structure sizing in confined systems. Proposed channel width in these cases shall follow the process described in Section 7-3.4.

WDFW and Castro 2001 have developed a regression equation used for estimating BFW, which shall be used only as a check to determine what a reasonable measurement is on streams within the limitations of that equation.

It is not always evident where the influence of an undersized structure ends. On a low-gradient system that has a high headwater at the crossing, the backwater during high flood events can extend upstream for hundreds of feet and result in an artificially wide BFW measurement. Once the existing-conditions model is created the bankfull measurement locations shall be checked to confirm that they are outside the influence of the existing structure. If the BFW measurements are determined to be within the influence of the structure, additional site visits are required for reevaluating BFW measurements.

7-3 Design

This section covers the Bridge Design and Stream Simulation Design methodologies (Section 7-3.1). Other methods may be appropriate but must be approved by the State Hydraulics Office prior to use (Section 7-5).

The design flood event for WSDOT projects are listed in Table 7-2 below.

Table 7-2 Flood Event for Hydraulic Design Elements

Design Element	Flood Event
Structure freeboard	Scour design flood [a,b]
Structure foundation [c]	Scour design flood and scour check flood [b,d,e,f]
Scour countermeasure depth [g]	Scour check flood [b,d,f]
Scour countermeasure stability [c]	Scour check flood [b,d,h]
Scour countermeasure freeboard	Scour design flood [b,d,i]
LWM stability	1% AEP (100-year) flood
Complex wood structures, flow deflectors, wood within a rock, and wood bank protection design	2080 100-year projected flood [b]
Velocity ratio	1% AEP (100-year) flood or the 2080 100-year projected flood [a,b]
Temporary bridges (freeboard and scour) [e, j]	4% AEP (25-year) flood [e]

Notes:

a. Discuss the impacts of structure size/impacts under climate predictions with State Hydraulics Office to determine how to proceed. PEO may need to be brought into discussion in case of low cover scenario. For tidally influenced areas, sea level rise shall also be taken into consideration. See Sections 7-3.5.4 and 7-3.5.5.
b. The 2080 100-year projected flood event shall be used for the design, unless the State Hydraulics Office has determined that the 2080 projected flood event is not practicable.
c. See the WSDOT *Bridge Design Manual* for more information on scour and how it pertains to structure foundations.
d. Collaborative discussion between Bridge and Structures Office, Geotechnical Office, State Hydraulics Office, and PEO to occur to determine risks and impacts and what is practicable.
e. For temporary bridges that will be in water for more than one season, use permanent structure design criteria.
f. Total scour shall be assessed for all flows up to the scour design flood and scour check flood events that results in worst-case total scour for each flood event.
g. Refers to location for toe of scour countermeasure.
h. Scour countermeasure stability shall be assessed for all flows up to the scour check flood that creates the greatest stresses on the countermeasure.
i. Scour countermeasures shall have 1 foot (minimum) of freeboard above the scour design flood. Scour countermeasures shall have 2 feet (minimum) of freeboard above the scour design flood when deep foundations have been designed to rely on the scour countermeasure.
j. For temporary bridges used only as work platforms or for construction equipment contact the State Hydraulics Office for additional guidance.

All the supporting calculations/information for the design process below shall be included in the specialty report.

7-3.1 *Determining Crossing Design Methodology for Documentation*

The three most used design methodologies by WSDOT from WDFW's 2013 WCDG are the Unconfined Bridge, Confined Bridge, and Stream Simulation methodologies. For all unconfined systems, the design methodology shall be described as Unconfined Bridge. For all confined systems over 20 feet, those expecting 1 foot or more of channel regrade, or slopes that are outside of the slope ratio, the methodology shall be described as Confined Bridge unless otherwise approved by the State Hydraulics Office. For all structures under 20 feet in width that do not fall into the categories described for Unconfined Bridge or Confined Bridge, the design methodology shall be Stream Simulation unless otherwise approved. If a different methodology was approved by the State Hydraulics Office, the design process shall be documented as the process that was approved. See Section 7-5 for some other available methods and Appendix 7B for a summary of the necessary stream crossing elements and associated guidelines for the methodologies.

7-3.2 Constraints

Constraints are infrastructure or land ownership issues that interfere with natural stream processes and need to be identified as soon as possible. Constraints can be constructed or natural and, when encountered, shall be discussed with resource agencies, tribes, and stakeholders early in the design process to prevent project delays in the future if not all parties agree on whether a constraint exists or may be resolvable within the scope of a project. There may be design constraints other than those covered in this section.

7-3.2.1 Infrastructure

Infrastructure can include adjacent culverts/bridges, pipelines, buildings, water intakes/diversions, groundwater wells, and roadways as well as other infrastructure types not listed here. Infrastructure that is a design constraint can be owned by WSDOT or by other parties.

Existing stormwater infrastructure is a key component to consider when determining stream gradient and grading impacts. Coordinate with the stormwater design engineer to verify that any changes in stream grade will not impact existing storm connections or ditches draining to the stream system. All stormwater discharges shall be placed above the 100-year WSEL.

7-3.2.2 Environmental Impacts

Environmental impacts shall be considered when completing a stream design. If meeting the design methodology causes a large environmental footprint (i.e., if a roadway that needs to be raised next to a wetland or stream grading would need to be extended for a great distance), discussions with WDFW and the tribes shall occur to determine the best design to move forward and whether mitigation (formal or informal) may be used in lieu of meeting requirements/recommendations. If impacts are temporary they may be more acceptable.

7-3.2.3 Grade Separation

Many culverts have been in place for a long time and the stream has adapted around them. Culverts may have been historically placed at a grade break in the channel that is dissimilar to the upstream and downstream reaches. The vertical stability and historical profile can often be assessed through use of a longitudinal profile; see Sections 7-2.3.4 and 7-2.3.4.1. If there is a large grade separation between the upstream reach and the downstream reach, it may be necessary to allow for a natural channel regrade, or to produce a steeper reach with an overcoarsened channel. As much information as possible shall be obtained about historical conditions and the cause of the grade break and discussions with WDFW and the tribes shall occur to determine the best solution for the project.

7-3.2.4 Cultural Resources

Impacts to cultural resources shall be considered when completing a stream design. If meeting the requirements and recommendations for the project would have an impact on cultural resources, WDFW and the tribes shall be consulted to determine the best way to proceed.

7-3.3 Channel Alignment

It is not always possible to cross a roadway at an ideal angle or avoid sharp bends leading into or out of a structure. The total length of a covered stream shall be considered and the maximum angle of a bridge structure to the centerline of a roadway per the *Bridge Design Manual*, if a bridge structure is used. While the State Hydraulics Office does not typically recommend a structure type or layout, it is important for the Stream Team to know what this constraint is and keep it in mind while designing the layout to make an efficient crossing.

Channel sinuosity and curve radii must match what would be expected in the reference reach, and a channel must not be artificially lengthened by increasing sinuosity beyond what would be expected to decrease slope. Meanders extended unnaturally to obtain length will not be stable. Conversely, channel sinuosity must not be unreasonably reduced or eliminated in the interest of shortening the structure span.

If a channel needs to be realigned, it must be done so in a way that does not increase the slope significantly or create an erosion risk. In the case of slope, WSDOT uses the stream simulation recommendation from WDFW's 2013 WCDG of a slope no steeper than 125 percent of the upstream reach (or downstream if it is determined that the downstream reach is more appropriate). In systems where the slope is low gradient (i.e., less than 1 percent), exceeding the slope limit while still meeting this criterion may be permissible but must be approved by the State Hydraulics Office. If it is not practicable to meet the slope constraint, approval by the State Hydraulics Office is required.

If a channel is being realigned and the existing crossing is not abandoned or removed and is to remain in place and open, the Stream Team and PEO shall coordinate with the HQ ESO Stream Restoration Program to make sure that the crossing is not considered a fish barrier after the project is completed.

If allowing for natural regrade is determined to be desirable, the Stream Team must evaluate the LTD, scour, potential equilibrium slopes, and whether a larger structure will be required as a result of the channel regrade. Lateral migration during the process of the regrade shall be considered and appropriate countermeasures must be implemented to protect banks from destabilization as a result of construction. Refer to Chapter 4 for additional guidance.

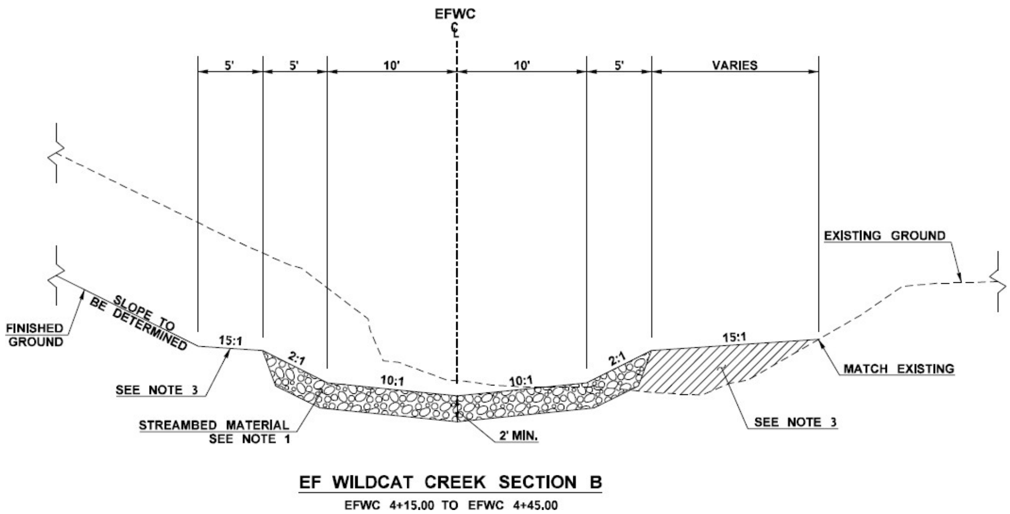
If regrade is determined not to be desirable, the reach must be designed to be stable. This may cause the project to be permitted as a fish passage improvement structure (see Section 7-5.2 and require long-term maintenance and monitoring. Additionally, extra consideration shall be given to bank integrity for these systems to help the water body dissipate energy. The Streambed Material Decision Tree found in Appendix 7A may help the Stream Team determine whether to allow for channel regrade.

7-3.4 Channel Cross Section

The channel cross section shall mimic that of the reference reach, while keeping construction methodologies in mind. If a system is highly modified (i.e., an agricultural ditch) and the grading for structure replacement is minimal, it may be appropriate to match the adjacent reach instead. For highly modified systems, contact the State Hydraulics Office for assistance.

Cross-section lengths shall be rounded to the nearest 0.1 foot. Slope shall be rounded to the nearest 0.5:1. Example plans and plan requirements are provided in WSDOT's *Plans Preparation Manual*. An example cross section is illustrated in Figure 7-5. Natural channel cross sections are usually asymmetrical. However, these can be problematic to construct. Therefore, a symmetrical cross section like the one shown in Figure 7-5 is acceptable, knowing that the stream will self-adjust. A low-flow channel that connects habitat features is typically added during construction that will further help adjust the channel shape to something that is more natural and help encourage fish passage immediately after construction prior to the larger flows that shape the channel. In larger systems the main channel can migrate within its floodplain and, therefore, the floodplain width can vary. It may be desirable to describe that with different design cross sections.

Figure 7-5 Final Design Cross Section



Flows within the channel cross section must mimic those in the reference reach. For example, if the active channel is overtopped at less than a 2-year flood event, the channel shall behave the same through the proposed graded reach.

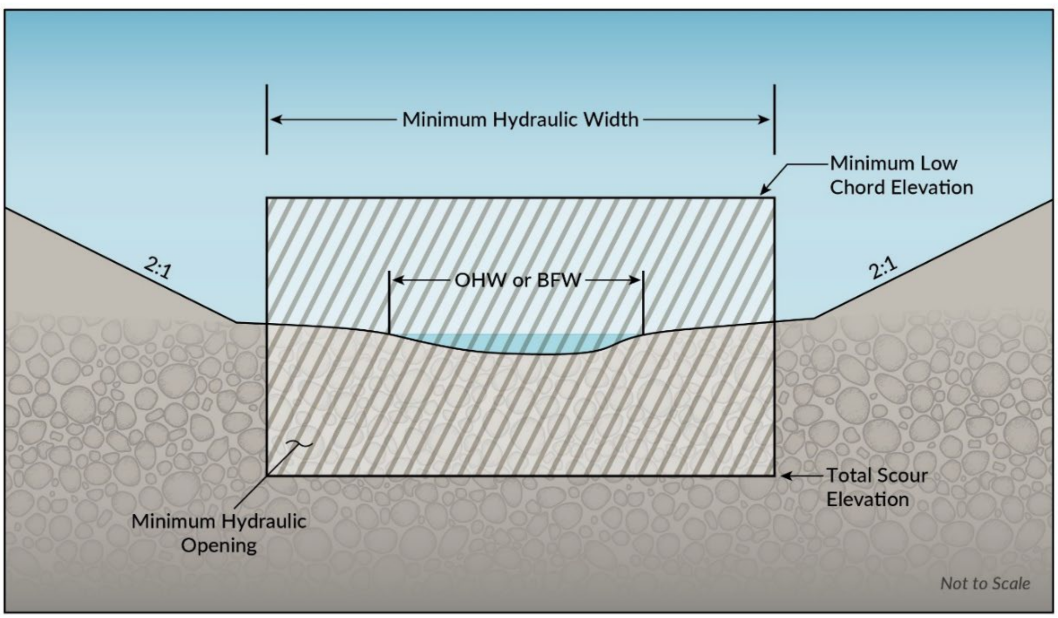
In crossings that serve a dual purpose for wildlife connectivity, consideration shall be given to whether the wildlife connectivity bench is to persist through the design life of the structure or a certain design event. If the wildlife connectivity bench is to remain stable, larger material or other means of bank stabilization may be necessary through the structure. The Stream Team shall coordinate with HQ ESO and the region to ensure that the proposed material will work with the wildlife for which that additional connectivity is provided.

7-3.5 *Hydraulic Opening*

For the purposes of this chapter, the minimum hydraulic width required by the specialty report and the hydraulic height defined by minimum low chord elevation and total scour elevation is defined as the minimum hydraulic opening (MHO). This section covers the hydraulic width portion of the definition. Freeboard and the maintenance clearance portion of the hydraulic height is covered in Section 7-3.6 and scour is covered in Section 7-4.1. The final SFZ determination made by the region in conjunction with the Bridge and Structures Office shall be, at minimum, the established MHO, but may be larger to include contextual needs (see Section 7-6). Any required scour countermeasure (Section 7-4.3) shall not encroach within the minimum hydraulic width and depth of scour. The depth of scour is determined as LTD + contraction scour at the scour check flood (minimum) or a minimum of 3 feet, whichever is greater, unless otherwise approved by the State Hydraulics Office and shall be set back horizontally far enough to establish planting as determined by the landscape architect. Coordination with a landscape architect is necessary to determine how far the countermeasure needs to be set back and maintain plant survivability. See the Plan Sheet Library for an illustration of the minimum structure width required by horizontal and vertical factors.

For preliminary plans, prior to the structure type being known, 2:1 cut slopes with a note that "grading limits to be based on final structure size, type and location" shall be shown unless it is known that the structure will be buried. This lets the reviewers know that the structure type is undetermined while showing the potential impact areas. Cross sections shall clearly depict where the minimum hydraulic width and MHO is, as shown in Figure 7-6.

Figure 7-6 Minimum Hydraulic Width and MHO



There are three methods for determining the minimum hydraulic width: (1) stream simulation, (2) confined bridge, and (3) unconfined bridge. However, the process used for confined bridge is the same as that used for stream simulation with the exception that the confined-bridge method includes an additional factor of safety (FOS). All methods are dependent on the floodplain utilization ratio (FUR), which determines how confined a stream is. A meander belt assessment shall be conducted for all crossings. This information shall be used by the State Hydraulics Office to determine if there needs to be an increase in the hydraulic width based on the channel's ability to naturally meander through the crossing.

The hydraulic width shall not be less than Equation 7-1 (2013 WCDG, Equation 3.2) or Equation 7-2, unless otherwise approved by the State Hydraulics Office.

$$W_{HYO} = 1.2 * W_{bf} + 2 \text{ feet} \quad (7\text{-}1)$$

$$W_{HYO} = 1.3 * W_{bf} \quad (7\text{-}2)$$

where
W_{HYO}= width of hydraulic opening
W_{bf}= BFW

The minimum hydraulic width is to be taken vertically through the entire structure. If a round or arch structure is used, additional width/height may be necessary to maintain the opening through the anticipated scour/required freeboard, as depicted in the SFZ Plans (see *Plan Sheet Library*).

7-3.5.1 Floodplain Utilization Ratio

The FUR needs to be calculated using existing conditions. The FUR is the width of the floodplain relative to the main channel. To determine the FUR for WSDOT designs, compare the flood-prone width (FPW) to the BFW. The FPW at a given location shall be divided by the BFW at the same location. The FPW and BFW must be measured in the same location along the stream alignment. If no measured FPW and BFW are available, then divide the modeled 100-year flood event width by the modeled 2-year flood event width at multiple representative locations. To determine what the FUR is through the upstream reach, the existing structure and roadway prism shall be removed from the model to remove any backwater from impacting FUR calculations.

A FUR larger than 3.0 is considered an unconfined system, while a FUR less than 3.0 is considered confined. If the system is unconfined, the unconfined bridge design method applies. If the system is confined, either the confined bridge design method or the stream simulation design method applies. More explanation of the FUR is provided in the 2013 WCDG. For areas that are tidally influenced, see Sections 7-3.5.4 and 7-5.3.

7-3.5.2 Unconfined Systems

An unconfined system has a FUR of greater than 3.0. In these situations, the velocity ratio, as defined by the WCDG, must be computed and shall be close to 1, which means that the ratio when rounded to the nearest tenth shall be 1.1 or less. In some low-velocity cases, a ratio of more than 1.1 may be allowable if the increase in velocity ratio does not result in bed coarsening, increased scour, significantly increased backwater, or negative biological/geomorphological effects. The State Hydraulics Office must approve in these instances. Design teams shall contact the Hydraulics Section in unconfined systems to determine the best path forward for modeling the proposed and natural conditions to determine the velocity ratio.

If an existing structure is being replaced by a new structure, a velocity ratio of more than 1.1 may be acceptable. In this case, the existing structure shall not have evidence of significant erosion, scour, or other performance issues. The State Hydraulics Office must approve in these instances.

When evaluating a crossing using the velocity ratio in the main channel, the floodplains shall also be considered. Floodplain velocity ratios do not need to be 1.1; rather, the velocities in the floodplains shall be similar to what is expected in the geomorphic context of the reach. Floodplain velocities shall not be accelerated to decrease main channel velocities. In some instances it is recognized that it may not be possible to mimic floodplain velocities through a structure because of a decrease in roughness (Manning's n) through the structure as compared to the adjacent floodplain; this shall be documented in the specialty report.

For preliminary design, the Stream Team is to assume vertical walls for the edge of structure while determining the MHO in the hydraulic model. Once the final structure size has been determined by others, the model shall be updated to reflect the updated structure. Additional width may be required in instances where lateral migration is a concern or to accommodate the meander belt; see Sections 7-4.2.

7-3.5.3 Confined Systems

For confined systems, the BFW plus an FOS shall be used. In the case of WSDOT crossings, minimum structure width shall not be less than the greater of Equation 7-1 or Equation 7-2 unless otherwise approved by the State Hydraulics Office. In many cases, this width is appropriate. In some cases, a wider structure may be more appropriate. The effects of LTD and aggradation shall be considered with regard to structure width.

Additional width is required if the following apply:

- The structure is creating an excessive backwater.
- The velocities through the structure differ greatly from the adjacent undisturbed reach.[1]
- Lateral migration of the channel is expected throughout the system.
- The stream has a natural sinuosity that can be replicated and justified (see Section 7-2.3.2).
- The structure is considered a long crossing (see Section 7-2.3.2).
- The Stream Team has reason to believe that additional width is needed. This shall be justified in the specialty report.

7-3.5.4 Tidally Influenced Systems

For tidally influenced systems follow at a minimum Appendix D from the 2013 WCDG and the guidance of this section. Tidally dominated crossings are crossings at locations where the flux varies with the tides and reverses direction during normal tidal events. Tidal datums

[1] In the case of a difference in velocities, if the structure size is not the cause of the velocity discrepancy, the cause shall be documented and efforts shall be made to reduce the difference if possible. An increase in structure size is not necessary if the difference in velocities is not tied to structure width unless other elements of the channel design leads to a change in structure width.

(except mean water level) are not computed beyond the head of tide (NOS CO-OPS 1 2000). The distance that the head of tide is located in a watercourse upstream from the coastline is dependent on the slope of the channel and the flow. Although the definition of the head of tide describes a point, it is really the zone of transition where the morphology of a watercourse changes from a fluvial to a tidal flow regime.

To design a fish passage structure on a watercourse that is tributary to the Salish Sea or the Pacific Ocean it is necessary to establish where the project is located with respect to sea level and the geomorphic processes that define the site. The structure must be appropriately sized and the channel through or under the structure must be appropriately shaped to facilitate passage. Because the "head of tide" may be miles upstream of the coastline, indicators can be used to locate the project on the continuum between the fluvial and tidal flow regimes.

7-3.5.4.1 Elevation

Determine mean higher high water (MHHW) using local tidal datums or using the NOAA VDatum tool. If the invert or any portion of any structure involved in the project is at a lower elevation than MHHW, then the project is located in the tidal zone. Washington Sea Grant, a collaborative organization of NOAA and the University of Washington, has developed extreme tide frequencies for Puget Sound and coastal Washington (unpublished data).

7-3.5.4.2 Indicators

The following field indicators that can be observed can then be used to help describe the project site:

- **Mud line:** A mud line demarks the elevation of transition between the frequently flooded zone and the uplands. In a tidal system the demarcation is normally bare soil or mud because of the twice daily inundation. This is different from an incised channel in a fluvial system, where the ordinary high water mark is characterized by reduced leaf litter and lack of woody vegetation. If a mud line is present, the location is likely in the zone below the "head of tide" and estuarine processes shall be considered in the crossing design.
- **Gravel bars:** Clean gravel bars are usually an indicator of fluvial processes. Gravels coated in fine sediments may be found in estuaries, especially in Puget Sound, where gravel beaches are common. Clean gravel bars would be found at the upstream limits of the "head of tide" zone. Projects in this area may be suitable for a stream simulation design.
- **Salt-intolerant vegetation:** Salt-intolerant vegetation would be found at the upstream limits of the "head of tide" zone. Hutchinson provides a comprehensive listing of the salt tolerance of vegetation associated with estuarine wetlands (Hutchinson 1988). Western hemlock, tall Oregon grape, yellow skunk cabbage, or pale yellow iris are common riparian species that are very sensitive to salt. If these species are observed at the project site, the site is probably fluvial. Projects in this

area may be suitable for a stream simulation design.

- **Reverse flow:** Flow upstream through the existing culvert would indicate that the site is located below the "head of tide." If possible, plan to visit the site during the flood tide during the daily higher high tide when the stream is at base flow. High stream flows following storm events may mask tidal flow. If reverse flow is observed, an estuarine solution shall be considered for the crossing design.
- **Salinity:** The salinity of the water can be measured with an electronic meter. The salinity of water in the ocean averages about 35 parts per thousand (ppt). The mixture of seawater and fresh water in estuaries is called brackish water and its salinity can range from 0.5 to 35 ppt. Fresh water has salinity of less than 0.5 ppt. The salinity of estuarine water can change from one day to the next depending on the tides, weather, or freshwater inflow. If the salinity is greater than 0.5 ppt, an estuarine solution shall be considered for the crossing design.

7-3.5.5 Climate Resilience

WSDOT uses climate science and tools to evaluate the influence that climate change has on projects throughout the state of Washington. This is done through the use of the best available science and working with the Climate Impacts Group and stakeholders' groups. Contact the State Hydraulics Office for guidance on incorporating climate resilience on projects.

The procedure as of the publication of this *Hydraulics Manual* is as follows:

1. Using the Climate-Adapted Culvert Design tool from WDFW, determine the percentage change in 100-year flood event. This tool can be accessed on WDFW's Designing climate-change-resilient culverts and bridges website.
2. The Stream Team uses the current 100-year design flow established from the hydrology evaluation process and applies the projected increase in 2080 to get the 2080 projected 100-year flow.
3. The Stream Team models the 2080 projected 100-year flow and evaluates whether the proposed hydraulic opening will see significant velocity increases through the crossing as compared to the adjacent reach. If the velocities are much higher, the Stream Team evaluates what size MHO is necessary to achieve similar velocities and discusses the results with the State Hydraulics Office to determine whether it is practicable to increase the structure size.
4. The Stream Team evaluates the 2080 projected 100-year WSEL and follows the guidelines outlined in Table 7-2. In situations where the system is tidally influenced, 2 additional feet shall be analyzed to account for sea level rise. Additional clearance shall be considered to account for sea level rise if applicable; refer to Projected Sea Level Rise for Washington State (Miller et al. 2018).
5. The Stream Team evaluates the 2080 projected 100-year scour elevation and follows the guidelines outlined in Table 7-2.

In steps 3, 4, and 5, the State Hydraulics Office may need to coordinate with the WSDOT Bridges and Structures Office, WSDOT Geotechnical Office, and PEO to determine what the effects of including climate change may be on the project, to ensure that all project impacts are quantified. See Table 7-1 above for more information.

Changes to this guidance will be provided in future revisions to the *Hydraulics Manual*. The Stream Team shall check with the State Hydraulics Office before beginning a WSDOT project to determine whether the process has changed. The process used for the project shall be included as an appendix in the specialty report.

Climate resilience shall also include the future risk of forest fire. If the watershed is located in an area that has a high potential for future forest fires, additional structure width and height may be warranted to accommodate this risk.

7-3.6 *Vertical Clearance*

The vertical clearance under a structure is made up of two components: the freeboard and the maintenance clearance. Vertical clearance is one component to the hydraulic height aspect of the MHO.

7-3.6.1 Freeboard

The design freeboard is the minimum dimension from the 100-year or 2080 100-year projected flood event (Table 7-2) WSEL to the minimum low chord that is necessary to pass all expected debris, water, and sediment expected over the life of a structure. The figures in the *Standard Plans* and *Plan Sheet Library* further illustrate the terms used here.

A minimum of 3 feet of freeboard above the 100-year or 2080 100-year projected flood event (Table 7-2) WSEL is required on all structures greater than 20 feet in span measured along the centerline of the roadway and on all bridge structures unless otherwise approved by the State Hydraulics Office. The Stream Team shall also confirm that local ordinance requirements are met and any necessary permit conditions are satisfied.

The 100-year or 2080 100-year projected flood event design freeboard required on all buried structures unless otherwise approved by the State Hydraulics Office are listed in Table 7-3.

Table 7-3 100-Year Design Freeboard Requirements on Buried Structures

Structure Bankfull Width	Required Freeboard
Less than 8-foot BFW	1 foot above 100-year or 2080 100-year projected flood event [a]
8- to 15-foot BFW	2 feet above 100-year or 2080 100-year projected flood event [a]
Greater than 15-foot BFW	3 feet above 100-year or 2080 100-year projected flood event [a]

a. The 2080 100-year projected flood event shall be used for the design, unless the State Hydraulics Office has determined that the 2080 100-year projected flood event is not practicable.

In areas that are tidally influenced, the impacts of 2 feet of sea level rise shall be evaluated for the project to determine if it shall be included in the freeboard requirements. For all projects, the Stream Team shall consider providing the clearances in Table 7-3 above the 100-year projected 2080 WSEL.

The required minimum design freeboard shall be maintained across the entire hydraulic width, as shown in the SFZ figures in the *Plan Sheet Library*. If aggradation is expected to occur, additional freeboard shall be given above the design freeboard equal to the anticipated aggradation.

Allowable exceptions are as follows. Fillets or arches may be inside the SFZ provided that all three of the following are true:

- The sum of all fillet areas (or arch encroachment areas) in a given cross section is less than 2 percent of the area calculated as the SFZ width multiplied by the SFZ height
- All fillet and arch encroachments are entirely above the elevation of the hydraulic design flood event plus the hydraulic design flood event freeboard within the limits of the hydraulic width

Four-sided buried structure allowable exceptions in addition to the above are as follows:

- The bottom fillets are allowed within the area that is 2 feet below total scour
- If total scour is calculated to be less than 1 foot, the bottom fillets shall be allowed to encroach only within the last 1 foot below total scour

If the design requirements listed above cannot be met, a hydraulic deviation approved by the State Hydraulic Engineer will be required. At a minimum, the Stream Team shall demonstrate the following:

- The proposed freeboard will pass all expected debris, water, and sediment through the system
- There is no history of repetitive maintenance at the existing crossing location
- Providing the required freeboard would cause adverse environmental impacts, impacts from changes to roadway geometry, or other unacceptable impacts
- Efforts have been made to maximize the freeboard to the extent practicable, including evaluating different structure types
- Documented acceptance of the proposed freeboard from WDFW and the Tribes

7-3.6.2 Maintenance Clearance

Maintenance clearance is the vertical dimension added to the height to allow for inspection, monitoring, and maintenance, and is measured from the highest ground elevation point on the floodplain bench within the hydraulic width. All structures are recommended to incorporate 6 feet of maintenance clearance.

Maintenance clearance is required for complexity features withing a water crossing as specified in Table 7-4.

Coordination with the PEO shall occur prior to proposing any habitat features that require additional maintenance clearance to determine if roadway geometrics would prohibit the incorporation of additional maintenance clearance. The roadway geometric impact may be unavoidable, depending on what is required for stream function. After the structure type, size, and location are determined and maintenance clearance is known, the Stream Team shall revisit the habitat elements listed in Table 7-4 to determine if any are appropriate given the updated geometric design.

Variance from the maintenance clearance requirements will require a Hydraulic Deviation approved by the State Hydraulics Office prior to implementation. More guidance on maintenance clearance can be found in the WSDOT *Design Manual*.

Table 7-4 Maintenance Clearance for Complexity Features

Item	Required Minimum Maintenance Clearance
Slash	Required design freeboard (see Section 7-3.6.1)
Small woody material (SWM)	6 feet
Mobile woody material (MWM)[a]	10 feet
Type one boulders	Discuss with State Hydraulics Office
Type two boulders	Discuss with State Hydraulics Office
Type three boulders	10 feet
Stable wood[b]	10 feet
Step pools	10 feet

a. Mobile wood may require scour countermeasures and may require an additional risk assessment; coordinate with State Hydraulics Office.
b. Stable wood will require scour countermeasures.

7-3.7 *Buried Structures*

Buried structures for WSDOT projects can follow either the bridge design or stream simulation design criteria. When a buried structure is used as the crossing structure, wing walls shall be used to minimize the overall length of the buried structure. Wing walls can also increase the efficiency of the crossing structure. Wing walls shall be designed in accordance with Section 8 of the *Bridge Design Manual*. Additional criteria are discussed below.

As discussed in Sections 7-2.3.2 and 7-2.3.3, a meander belt assessment shall be conducted for all crossings. If a structure length is more than 10 times its width, then the hydraulic width shall be increased to whichever is greater, a 30 percent increase, or incorporate the width necessary for the natural meander as determined through the meander belt assessment. A meander belt assessment and increased hydraulic width may also be warranted in crossings that are greater than 200 feet in length, for multiple crossings in a short length (interchange, divided highway, etc.), or in other situations for stream restoration as described in Section 7-2.3.2.

The WCDG and WAC require that all stream simulation culverts be countersunk a minimum of 30 percent and a maximum of 50 percent, but not less than 2 feet overall. Alternative depths of culvert fill may be acceptable with engineering justification that considers total scour. Scour analyses are considered acceptable engineering justification.

Four-sided buried structures shall be countersunk a minimum of 2 feet below total scour as defined in Section 7-4.1, regardless of span width. Round buried structures shall be countersunk a minimum of 2 feet below total scour at the scour design flood event throughout the horizontal limits of the minimum hydraulic width. If this requirement cannot be met, approval from the State Hydraulics Office is required. It is understood that four-sided structures are created in whole-foot increments because of construction practices, so if the countersink is slightly below 2 feet, contact the State Hydraulics Office to verify if additional depth is required.

The footings of three-sided buried structures shall be countersunk at minimum as described in Section 7-4.1.

In some cases, constructability is more straightforward if the structure is placed flat, but the Stream Team may recommend that the structure be placed at a different slope from that of the streambed. Buried structures may be placed at a different slope from the prevailing stream gradient so long as the minimum freeboard is met throughout the structure, the minimum required countersink is met throughout the structure, and justification is provided and approved by the State Hydraulics Office. In some cases, this may require a slightly taller structure. The reasoning for placing the culvert at a different slope shall be described in the specialty report.

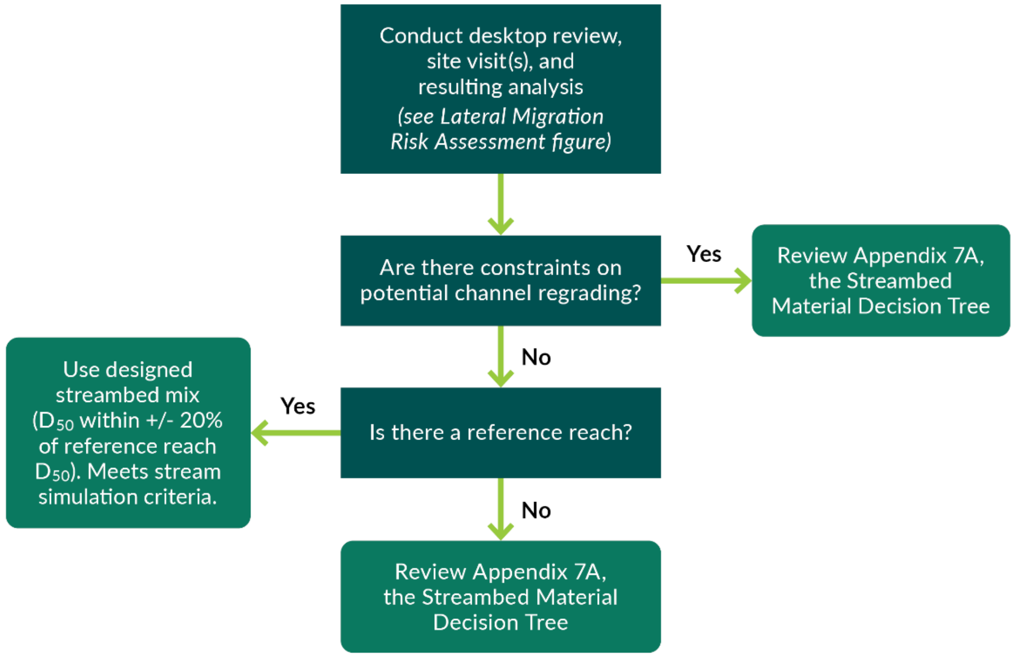
7-3.8 *Sediment Design*

WAC dictates allowable sediment sizes in a fish-bearing stream. Stream simulation design aims to mimic natural conditions to the extent possible, but sometimes stream conditions have been altered, reaches have been sediment starved, or adjacent infrastructure (constraints) do not allow for bed mobility into adjacent reaches.

After reviewing existing conditions as discussed in Section 7-2, use the flow chart found in Figure 7-7 to determine the appropriate streambed material design methodology depending on site-specific conditions. Apply the stream simulation requirement of a D_{50} that is within 20 percent of the reference reach unless constraints prevent this, or unless no reference reach is available. For these special cases, a Streambed Material Decision Tree to further assist the Stream Team in determining which methodology to use for streambed sediment sizing in these special cases is shown in Appendix 7A.

It may be appropriate to determine if other channel designs are applicable in certain situations; stream channels fall under the alluvial, threshold, or transition channel categories depending on their bed movement during a site-specific design flow event (NRCS 2007). After reviewing all streambed design methodologies within Appendix 7A, discuss with the State Hydraulics Office if an alluvial or threshold channel design could be appropriate.

Figure 7-7 Streambed Material Design Methodology



For assessing sediment mobility, WSDOT requires the Modified Critical Shear Stress Approach, as described in Appendix E from the 2008 United States Forest Service (USFS) Guidelines for all systems under 4 percent and the Unit-Discharge Bed Design as described by the 2013 WCDG for systems greater than 4 percent. A system is considered stable if the D_{84} is stable at the design flood event. If using WSDOT standard materials, it shall be noted that a minimum of 30 percent streambed sediment (9-03.11(1) is required to fill the voids in the various streambed cobbles mixes (9-03.11(4). Additional fines, typically using streambed sand (9-03.11(2) or native material), may be required to fully seal the bed.

7-3.8.1 No Constraints

As previously described, apply the stream simulation requirement of a D_{50} that is within 20 percent of the reference reach unless prevented by constraints. The design process for sediment sizing under these conditions is to match the reference reach material to the extent possible using the materials available from WSDOT's *Standard Specifications*.

Stability of the bed mix shall still be evaluated and documented in the specialty report.

7-3.8.2 Constraints

If constraints in the systems, as described in Section 7-3.2, could have an impact on the stream design, the risk of the stream not being stable will need to be evaluated.

In some cases, a bed design based on the pebble count from the existing reference reach will meet the requirements for stability. The existing pebble count will first need to be evaluated for stability, using the appropriate methodology from Section 7-3.8. If the D_{84} is not stable at the design flood event, then a risk assessment will need to be conducted to determine the next steps. The State Hydraulics Office and RHE shall be a part of the risk assessment process.

7-3.8.2.1 Risk Assessment

To complete a risk assessment for the site, the constraints must be identified and what the potential impact to those constraints would be if natural processes were to occur. If the constraints are private or public infrastructure not owned by WSDOT, the owners of the infrastructure shall be consulted. The Streambed Material Decision Tree in Appendix 7A can be helpful in determining the level of risk; however, the ultimate decision on constraints and risks to constraints is made by the project team.

If it is determined that the project is high risk and cannot be allowed to regrade, a roughened channel must be constructed. A roughened channel is designed to be completely non-deformable up to the design flood event. If a roughened channel is built, any habitat features must be installed at the time of construction, as they are unlikely to form themselves. A roughened channel will likely have additional permit requirements (and possibly long-term commitments) associated with it.

If a project is considered medium risk, an alternatives analysis needs to be conducted. The Stream Team needs to describe the constraint, describe the impact of meeting the requirements for sediment size, identify and evaluate any alternatives, and describe the preferred alternative. When describing the preferred alternative, the Stream Team must also describe how the preferred alternative reduces the risk to an acceptable level and what potential impact to fish life this alternative may have. In cases where coarser sediment is necessary on a medium-risk project, an overcoarsened channel with habitat complexity features may be constructed. This channel is subject to agreements between WSDOT and permitting agencies. An overcoarsened channel has a $D_{84,}$ which is stable at the design flood event.

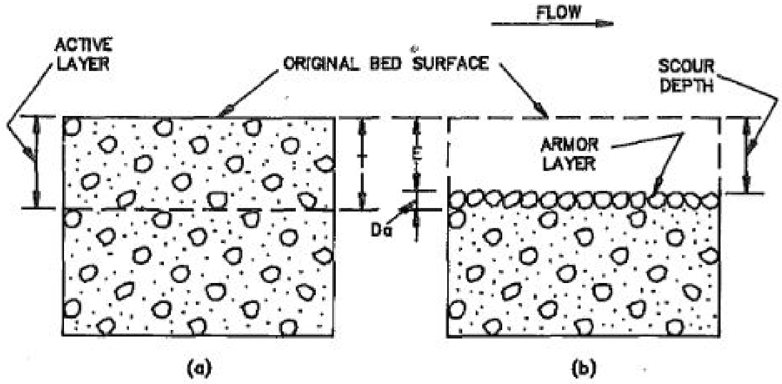
If a project is determined to be low risk, then the bed material shall match the pebble count in the reference reach and the process described in Section 7-3.8.1 applies.

7-3.8.3 Natural Streambed Armor Layer Design

The streambed material mix attempts to mimic the site-specific gradation of stream particles (sediment), normally prescribed via pebble count data, but also contains a large volume of fine-grained and highly mobile material with a desired outcome of bed sealing and relative bed stability. Streambed sediment can have as much as 20 percent by weight passing the No. 40 sieve, which is medium sand. In a gravel bed stream much of this finer material may be transported away from the active sediment layer during bed-forming discharges. This will be variable depending on sediment transported from upstream reaches. The bed will ultimately end at a state of dynamic equilibrium—a natural bed armor layer. The natural armor layer protects the integrity of the bed, adds stability, and renders the finer particles below it relatively immobile. However, a large volume of fine, highly mobile sediment must be “worked” by the stream to achieve this more stable state. The result is material transported downstream and likely lost within the reach. Figure 7-8 depicts formation of an armor layer.

Figure 7-8 Formation of an Armor Layer

(a) Well-Mixed Original Bed Material (b) Armor Layer with Underlying Bed Material



Source: Borah 1989.

To prevent this loss, an active layer that matches the reference reach pebble count, but with no fines below a calculated surface layer particle size, could be designed. If the Stream Team is in a system in which this may be appropriate and wants to pursue this design, approval from the State Hydraulics Office is required.

7-3.8.4 Construction Requirements

The final stream grading limits horizontally and vertically shall be discussed with the Geotechnical Office to identify the composition and suitability of the surrounding native material. If the underlying material is evaluated as scour-resistant, it may not need to be replaced. Additionally, if the surrounding material meets the project requirements for the designed streambed material gradation, the depth and extents of the excavation may be adjusted as directed by the engineer in the field.

The final streambed material shall be placed in lifts no thicker than 12 inches. Streambed material shall be placed to ensure that stream low flow rate is conveyed above each channel layer. The contractor shall apply water and 0.5 to 1.0 inch of streambed sand to each layer to facilitate filling the interstitial voids of the streambed materials. The voids are satisfactorily filled when water equivalent to the low flow rate of the stream does not go subsurface and there is no perceivable difference in the low flow rate from upstream of the project limits to the downstream of the project limits. Refer to the *Standard Specifications*, Section 8-30 Water Crossings, for additional information.

7-3.8.5 Step-Pool Design

Step-pool systems occur naturally, between 3 and 8 percent slopes, and occur through natural material sorting or are forced through LWM. Many Washington streams are within this gradient range and special consideration is required for their design.

If the system's reference reach is step-pool in nature or the Stream Team has other reason to believe that a step-pool system is most appropriate for the site, the Stream Team must coordinate with the State Hydraulics Office regarding the proposed design and for any additional guidance that has been developed. The design of a step-pool system may require stability features that are larger than typical habitat structures or sediment size, channel-spanning wood, higher than normally recommended drop heights, etc. Working closely with the State Hydraulics Office will also help expedite any deviations from this *Hydraulics Manual* that are necessary to ensure a successful step-pool design.

7-3.9 Channel Complexity

Channel complexities are obstructions within the stream channel that support channel shape, diverse habitat for fish, and streambed stability. These features are discussed within the context of the constructed environment, though they are based on natural features as much as possible. Channel complexity features include both wood and non-wood structures. See Chapter 10 for additional guidance on channel complexity using woody material (WM).

Channel complexities are used to simulate natural characteristics in a stream. They are more important through water-crossing structures where vegetation and bank stability are absent or reduced. Simulating bank strength and naturally occurring channel complexity inside of a structure is difficult without soil cohesion and root strength.

It is important to consider the longevity of the channel complexity design: how it may change over time, its sustainability, and fish passability throughout the life of the crossing. The placement of complexity features can create a situation where the channel shape deteriorates over time, causing unintended aggradation or scour. When designing channel complexity features, the Stream Team shall protect the opposite bank from expected erosion using bioengineering and landscaping techniques unless bank protection is necessary for structural and roadway protection, in which case HEC-23, Volume 1 and Volume 2, measures would apply.

The following questions shall be considerations when designing channel complexity features:

- What is the design life of the structure?
- How could it change over time?
- Is it sustainable?
- Will it continue to serve its design functions after failure begins?
- Will it remain fish-passable throughout the design life of the crossing?
- How to incorporate slash? (see Chapter 10)

Channel complexities can be made up of coarser aggregate (cobbles and boulders) that is sized to be stable at the design flood events. Small woody material (SWM) (including slash) can be used in conjunction with coarse aggregate. Subsurface flow through channel complexities is a concern as voids in the coarser mixes allow low flows to penetrate below the stream profile. Layering the coarse aggregate and streambed fine sediment during placement and saturating the sediment between layers helps to seal the streambed. Streambed fine sediment bands have been installed upstream of complexity features to help seal the complexity features in situations where subsurface flow was a problem, post-construction.

WSDOT has used many types of channel complexity features, including single boulders, coarse bands, meander bars, and boulder clusters. To improve the success of complexity features, WSDOT has conducted research on meander bars to improve bank stability through water crossings. As additional research is conducted on other complexity features, further guidance will be provided in future revisions to the *Hydraulics Manual*. Confirm with the State Hydraulics office whether any new guidance has been released regarding complexity features since the last Hydraulics Manual revision.

7-3.9.1 Boulder Features

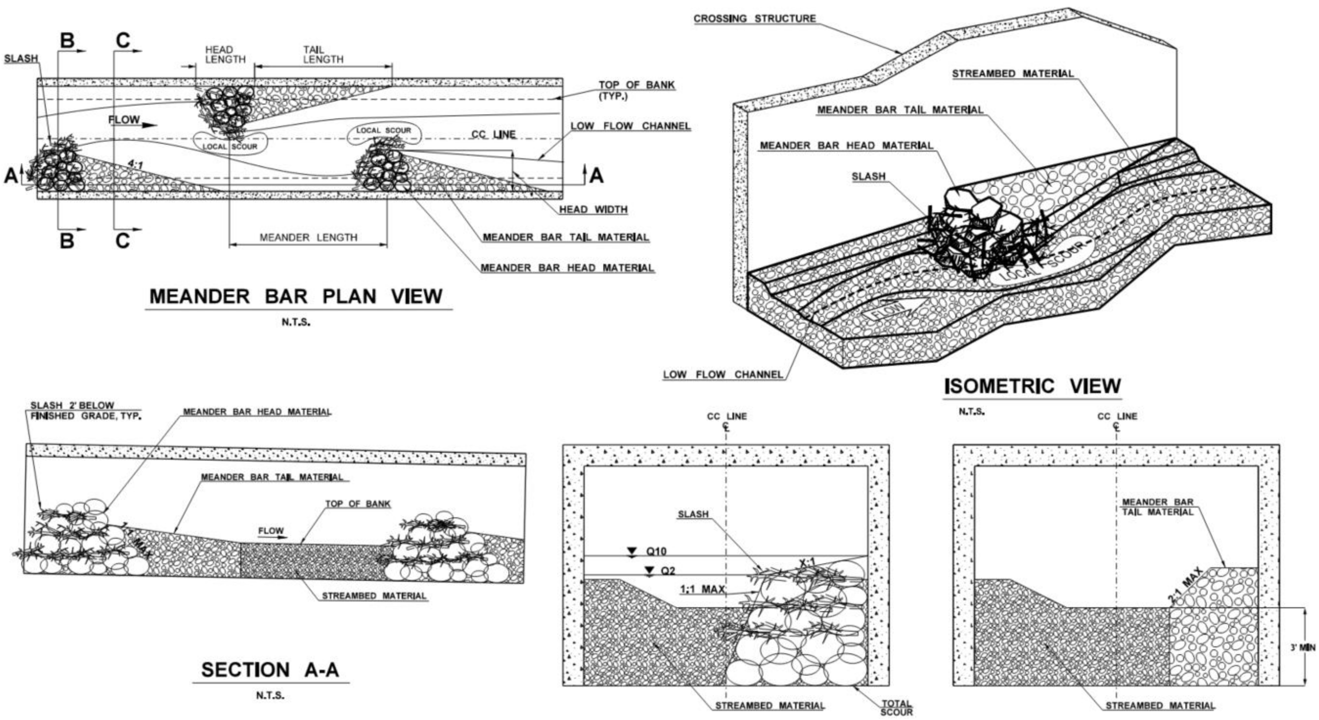
It may be necessary to have boulder features within water crossings to support channel complexity. In these cases, the Stream Team shall use engineering judgment to determine what this will look like and how it will tie in with other complexity features and the upstream and downstream planform.

If used, boulder features shall be spaced to simulate the expected sinuosity, and sized large enough to remain stable, be placed in a way that they promote localized scour/pool development, maintain high and low flow through the channel, do not create a low-flow barrier risk, and engage in the active channel. In addition to being stable during design flood events, consideration shall be given for the stream's location and whether vandalism could be an issue. If the location is in an area where there may be human activity, larger, heavier boulders may help keep the structures in place. Consider upsizing boulders when human contact is unavoidable; coordinate with the State Hydraulics Office and PEO to determine when upsizing may be appropriate. Boulder features are considered a channel complexity feature but with a hydraulic intention to direct flows away from a bank or structure where bank stability is critical.

7-3.9.2 Meander Bars

Meander bars were conceived of and designed to replicate the natural forcing elements of a stream channel (e.g., banks) that create sinuosity in western Washington streams within a water-crossing structure. Typically, meander bars shall not be used upstream or downstream of the water-crossing structure. Meander bars are forcing elements that drive scour during higher discharge events and are not intended to be mobile. Their primary purpose is to reduce structure wall entrainment, to provide thalweg maintenance, and to prevent a plane bed from forming. The U.S. Fish and Wildlife Service recommends similar features to maintain streambanks within structures (Hanson 2022). Proper design and installation of meander bars provides additional benefits such as reach-scale hydraulic diversity/complexity, pool scour, sediment sorting (important for spawning salmonids), high flow refugia for migrating aquatic organisms (e.g., fish), and channel roughness. WSDOT published research and a case study indicating that meander bars also function to rack and attenuate organic debris (e.g., small wood), further providing significant habitat benefits. Figure 7-9 presents an example of meander bar detail. See Section 7-8 for additional information regarding monitoring; updated monitoring protocol will be determined in the future to evaluate and adjust design criteria for future updates to the WSDOT *Hydraulics Manual*.

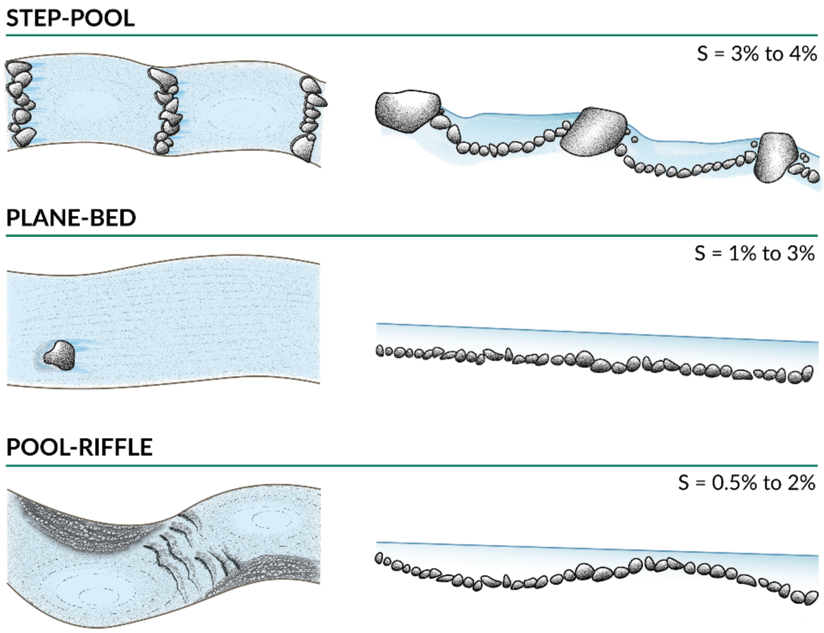
Figure 7-9 Meander Bar Detail



7-3.9.2.1 Design Considerations: Slope—1–3 Percent

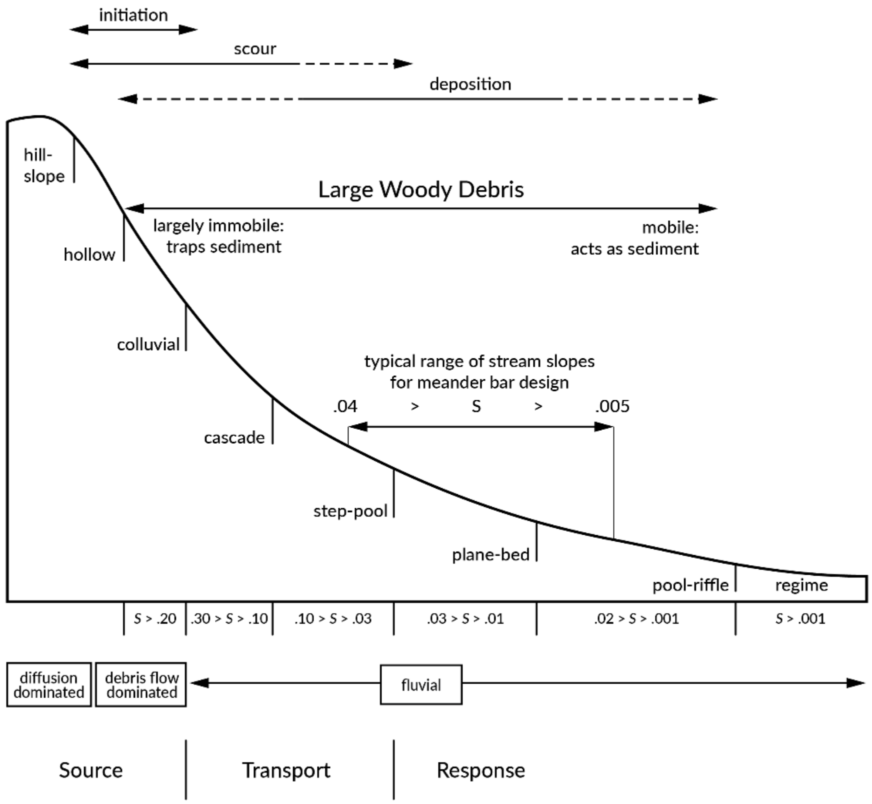
Meander bars shall be installed to simulate forcing elements typically found in riffle-pool systems or to re-form plane-bed streams into more productive, forced riffle-pool sequences (Figure 7-10). Montgomery-Buffington stream classification identifies a stream with a 1 to 3 percent gradient as a plane-bed response reach, unless there are forcing elements to create a riffle-pool system. Gradients less than 0.5 percent and between 3 and 4 percent could be acceptable depending on the stream characteristics (Figure 7-11). Meander bars shall not be used at gradients greater than 4 percent.

Figure 7-10 Typical Stream Morphologies Suitable for Meander Bar Application



Typical stream morphologies with slopes suitable for meander bar placement. Note: meander bars are typically placed in plane-bed and pool-riffle channels (adapted from Montgomery and Buffington 1997).

Figure 7-11 Range of Slopes Suitable for Meander Bar Application



Range of slopes suitable for meander bar placement (adapted from Montgomery and Buffington 1997).

7-3.9.2.2 Spacing

Meander bars shall be installed in an alternating pattern on the left and right banks of a channel and spaced to mimic natural sinuosity as seen in a reference reach at a similar gradient. If a natural sinuosity cannot be identified, hydraulic modeling may help inform appropriate spacing.

Lower-gradient streams require larger spacing between meander bars and additional consideration of complexity elements along the banks between the bars, while higher-gradient streams require closer spacing to generate natural sinuosity and mimic the observed pattern. Consideration of the banks between the meander bars shall be included. Variable spacing of meander bars may be appropriate and shall be considered.

7-3.9.2.2.1 Guidelines/Recommendations

The following are guidelines and recommendations for spacing of meander bars:

- Meander bars shall be installed on both sides of a structure, unless approved by the State Hydraulics Office.
- Meander bars are intended for application in crossings of sufficient length to contain

one, or more, river-meander wavelengths.

- Crossings shorter than one wavelength shall limit extending the meander bar design upstream and downstream of the crossing and the design shall consider using other complexity applications outside of the crossing structure such as wood features, when possible.
- Ideally, two or more bars will be placed within the structure for structures longer than 50 feet.
- The application of meander bars in crossings shorter than one wavelength requires approval of the State Hydraulics Office.

7-3.9.2.2.2 High Sediment Load Spacing

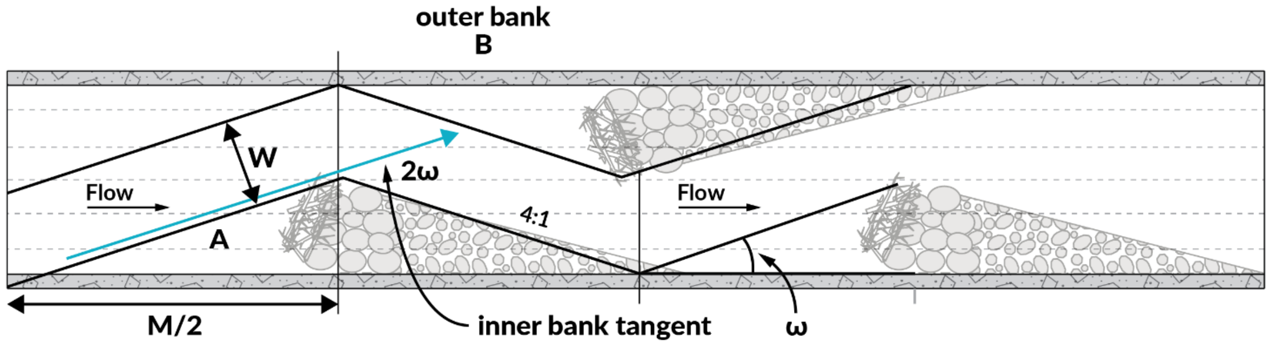
In the absence of natural meander forcing features, and if significant bedload sediment transport (sediment input is greater than 110 percent of sediment output) is anticipated through the crossing, the meander bars shall be designed to generate sediment deposition in consistent locations. The deposition of sediment in a consistently located gravel bar because of local hydraulic conditions is termed a forced bar. In the absence of local hydraulic controls on bar location, gravel bars can migrate downstream, a process termed free bars. Forced bars are recommended for crossings with high bedload transport rates to provide greater predictability of planform location and a lower rate of morphologic change (Figure 7-12 and Figure 7-13). Forced bars can be created by designing the meander bars to simulate a sufficiently high sinuosity.

Whiting and Dietrich (1993) define the threshold between forced bars and free bars. The authors place this threshold in a phase space with the ratio of the channel wavelength (M) to channel width (W) on the x-axis and the angle of the inner bank tangent (ω) on the y-axis (Figure 7-12 and Figure 7-13). The threshold of bar migration within this phase space is defined by Equation 7-3:

$$\frac{M}{W} = \frac{1}{\sin \omega \cos \omega} + 2 \qquad (7\text{-}3)$$

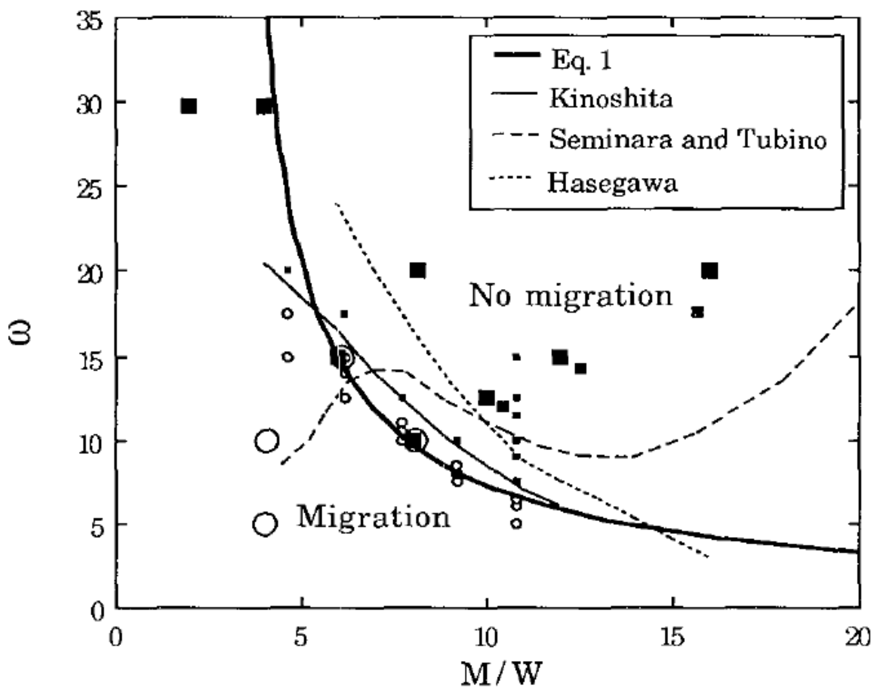
Note: In high sediment load conditions, the material behind the bar head may not be needed and requires coordination with the State Hydraulics Office.

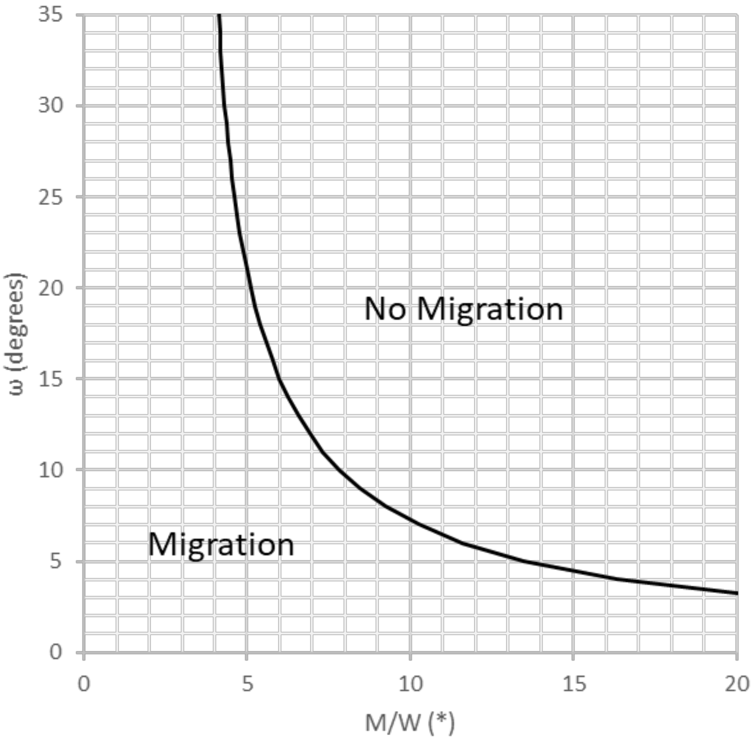
Figure 7-12 Meander Bar Spacing Detail



Source: Whiting and Dietrich (1993).

Figure 7-13 Forced Bar vs. Free Bar Threshold





Source: Whiting and Dietrich (1993).

7-3.9.2.3 Bar Height

Meander bars shall be designed to the full depth of the streambed and shall extend to the lesser of total scour or total excavation elevation if competent material exists.

The bar head shall be composed of stable large rock and be designed so that the top of the head is approximately at the 10-year flood event elevation measured at the structure wall and at the 2-year flood event elevation measured at the nose of the bar head, closest to the thalweg.

The bar tail shall be composed of a streambed cobble mix including boulders as necessary and be designed so that the top of the tail is approximately at the 10-year flood event elevation measured at the structure wall and tapers to the elevation of the streambed at the downstream end of the structure tail. Stable elements shall extend to a minimum of 3 feet or full design sediment thickness.

7-3.9.2.4 Additional Considerations

The following are additional considerations related meander bar design:

- Add a single boulder at the nose of the bar head, closest to the thalweg.
- Create a saddle between the meander bar and an additional boulder resulting in split flow at 2- to 5-year recurrence intervals. Coordinate with the State Hydraulics

Office for design considerations.

- Bar angle is an important component of design. Bars angled downstream will increase velocity and scour along the face. Bars angled upstream or perpendicular will create a pocket refugia upstream, keeping the thalweg more central, and will encourage deposition upstream of the bar head.
- Incorporation of SWM, slash, and/or boulders, if clearance allows, in the opposite bank of the meander bar head to reduce bank erosion and entrainment.

7-3.9.2.5 Channel Constriction

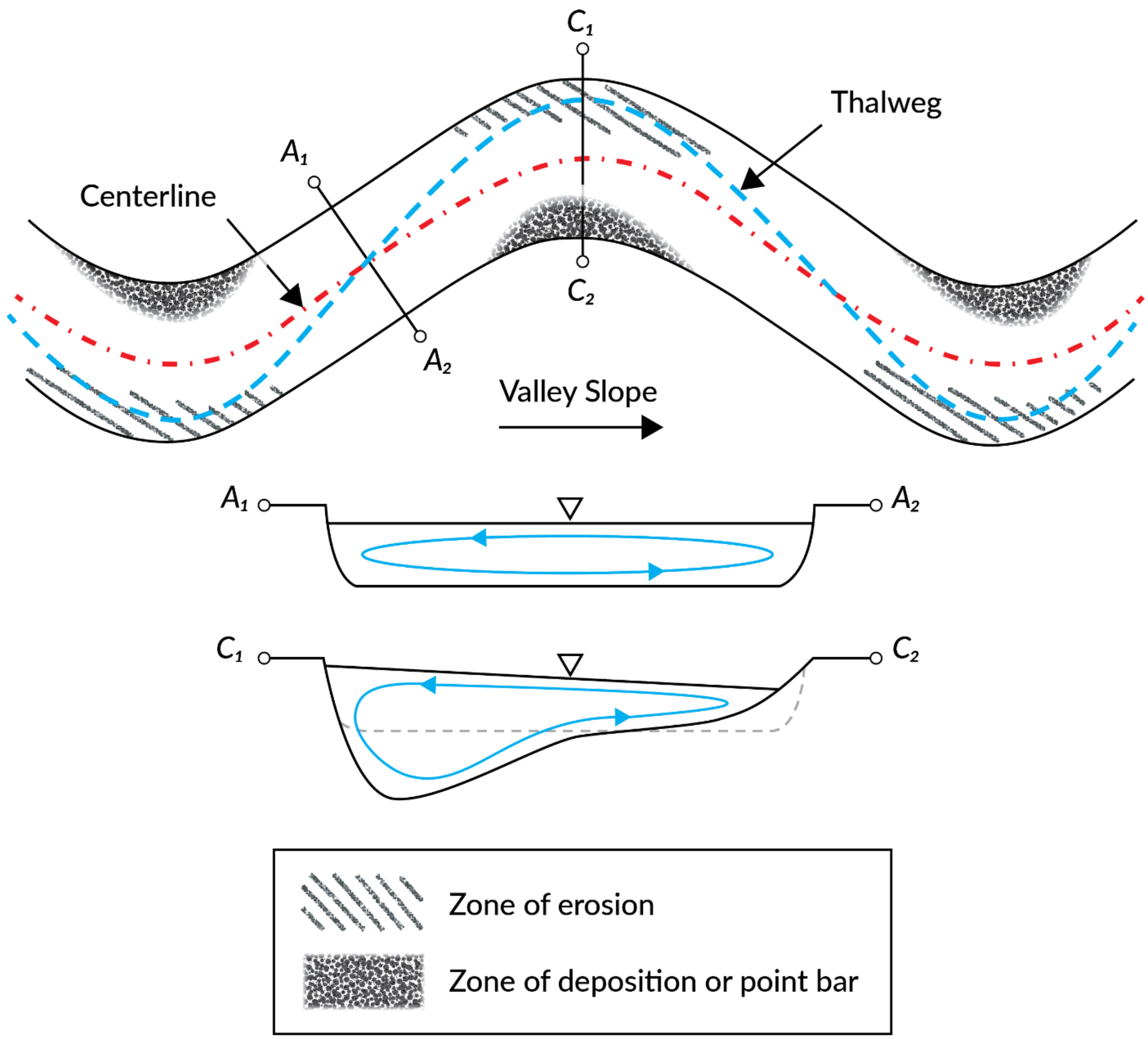
Meander bars shall occupy a minimum of 30 percent of the cross-sectional area of the channel to drive contraction scour, provide thalweg maintenance, and match the natural sinuosity of a reference reach. The meander bar shall constrict the channel width down to the minimum measured BFW. Larger structure widths require more obstruction width to perform the function needed and may require either the meander bar to extend farther into the channel and/or the use of slash and/or boulders in the opposite bank of the meander bar head to help maintain channel shape. Contraction scour shall be evaluated based on the width that is capable of moving sediment and documented in the specialty report.

7-3.9.2.6 Bar Shape

The following are bar shapes:

- **Teardrop or modified crescent:** Meander bars are intended to provide some of the functions similar to point bars, which are found in natural, undisturbed systems (Figure 7-14). Meander bars are three-dimensional features with a crown (high point), deflecting head (upstream proximal end), and tapering tail (downstream distal end). Meander bars differ in function from point bars in that they drive scour along the margin of the proximal end, which reduces structure wall entrainment and provides thalweg maintenance. They also help with sediment sorting as energy dissipates toward the distal tail.
- **Half-dome without tail:** If it is determined that a tail is not required because of high sediment load within the system, the meander bar shall be designed with a half-dome shape consisting completely of head material with slash or SWM.

Figure 7-14 Typical Point Bar Formation in Meandering Streams



Source: Dey (2014). Meander bars are designed to imitate the functions of natural point bars.

7-3.9.2.7 Materials: Cobbles and Boulders Sized for Stability and Resilience

This section presents a discussion on bar materials, including bar head, bar tail, and other design.

7-3.9.2.7.1 Bar Head

Materials used in the design and construction of the meander bar head shall consist of large rounded rock designed to be 100 percent stable at the 100-year flood event. Although the smallest stable material shall be used, the size might need to be increased for meander bars to be stable for the long term. The material shall be sized to allow for minimal maintenance, which can be difficult within structures and provides resilient complexity. The stability analysis shall consider flow overtopping the rock (see 2012 WDFW *Stream Habitat Restoration Guidelines* pages T6-20 and T6-21 for an example) (Cramer 2012). The length of the head shall be a minimum of twice the D_{100} of the head material size at the top and will taper out at a 1:1 slope maximum. The head material shall be placed in lifts with well-graded stream material and fines to seal the bar head to prevent porosity. To prevent saltation of the head material and relocation of material by humans a minimum Type 2 Boulder is recommended. Consider upsizing boulders when human contact is unavoidable; coordinate with the State Hydraulics Office and PEO to determine when upsizing may be appropriate.

7-3.9.2.8 Bar Tail

If it is determined that a stable tail is needed for the meander bars, the D_{30} of the material in the tail of the structure shall be larger than the D_{84} of the observed streambed material and be stable at the 25-year flow event to dissipate overtopping energy. If this is larger than the material sized for the head, evaluate if the site is correct for meander bar installation. Fines shall also be incorporated into the bar tail to seal the bar tail to prevent porosity. In construction, the meander bars and tails shall be tested for subsurface flow similar to the streambed.

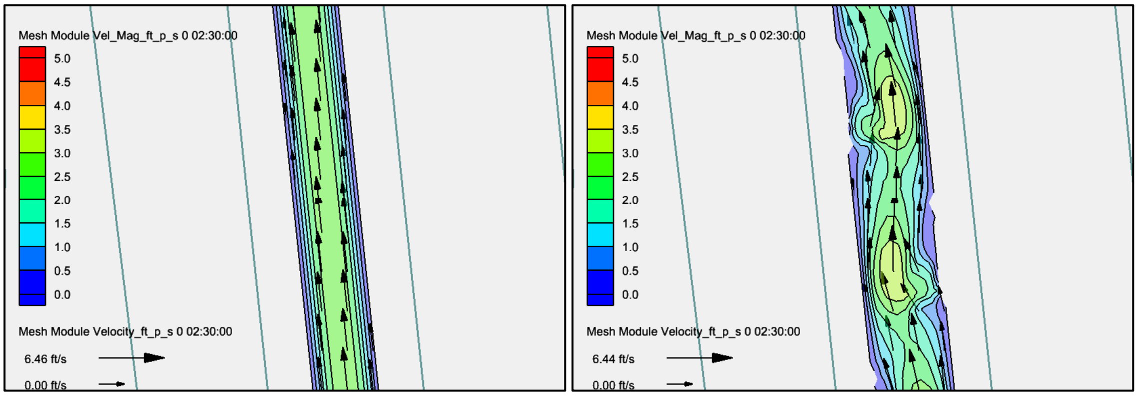
7-3.9.2.8.1 Slash and Small Woody Material

SWM (if clearance allows) or slash shall be placed in the head of bars to encourage racking increase stability and add habitat complexity to the stream. Between 30 and 50 percent by volume of SWM or slash shall be interwoven between the boulders forming the meander bar head and shall also wrap around the stream side to the beginning of the tail to engage with all flow conditions and encourage a scour pool. See Figure 7-9 for an example of meander bar slash implementation.

7-3.9.2.9 Hydraulic Modeling of Meander Bar Features

Meander bars can be modeled with composite roughness values during the conceptual phase of a stream design. However, there are times when it is necessary to include meander bars as part of the surface during preliminary phases of a design and documented accordingly. Meander bars shall be included as part of the streambed surface in the hydraulic model prior to the FHD. Figure 7-15 shows an example of a hydraulic model where the proposed surface was modified to include the meander bars. Contact the State Hydraulics Office for additional information on scour associated with complexity features.

Figure 7-15 Example Velocity Maps



Example modeled velocity maps for the McCormick crossing (left figure with composite roughness values in the model and right figure with meander bars included in the surface). This models the hydraulic diversity introduced by the meander bars.

7-3.9.3 Construction Requirements

Most channels take a few large flows before natural habitat elements form. In cases where a fish barrier is replaced, if these habitat elements are not formed during construction, the first migration of fish may be left with a long, straight channel that makes passage difficult. Leaving scour pools at the rootwads of LWM and other complexity elements at locations where a pool would naturally form is recommended as directed by the engineer in the field. A low-flow pilot channel is also required to be installed as directed by the engineer in the field, that connects the habitat complexity elements immediately after construction, unless otherwise approved by State Hydraulics Office. An example of a constructed meander bar is shown in Figure 7-16.

Figure 7-16 Example of a Constructed Meander Bar with Slash

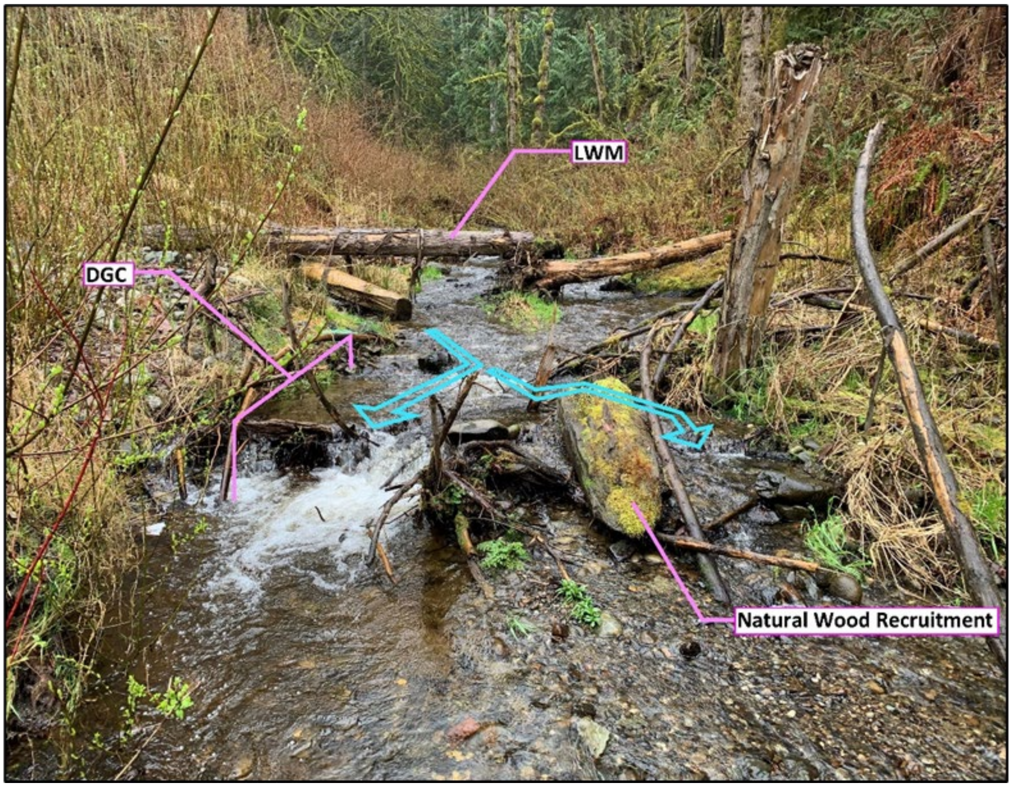
7-3.9.4 Deformable Grade Control

Complexity features of creeks—specifically lower-order, tributary systems—are often a product of messy, interlocking matrices of roots, branches, rocks, and sediment. A creek over time accrues diverse wood debris and incorporates it within its streambed, while the riparian vegetation grows and intwines itself into this mix (Bilby 1980; Bretschko 1990; Dolloff 2000). In addition to the application of LWM as forcing structures, an accumulation of smaller materials introduces local complexity and in series these structures support reach-scale processes (Shahverdian et al. 2019). The intent of deformable grade control (DGC) is to replicate a natural, cohesive matrix of debris and sediment, to construct features resilient and adaptive in nature that decrease the rate of stream degradation and restore stream processes and complexity.

The empirical hydraulic functions of DGCs change as the feature weathers. The following design considerations describe DGCs' adaptive hydraulic functions and how the deformability of a DGC is a product of design choices. Locally, a DGC promotes upstream floodplain connectivity and thus sediment retention, and as they degrade (Figure 7-17), they promote downstream pool formation and sediment sorting as seen in post-assisted log structures (PALSs) and beaver dam analogs (BDAs) (Shahverdian et al. 2019). On a reach scale, a series of DGC features provides vertical stability, ultimately counteracting headcuts, and regulating channel degradation (Fouty 2023; Shahverdian et al. 2019).

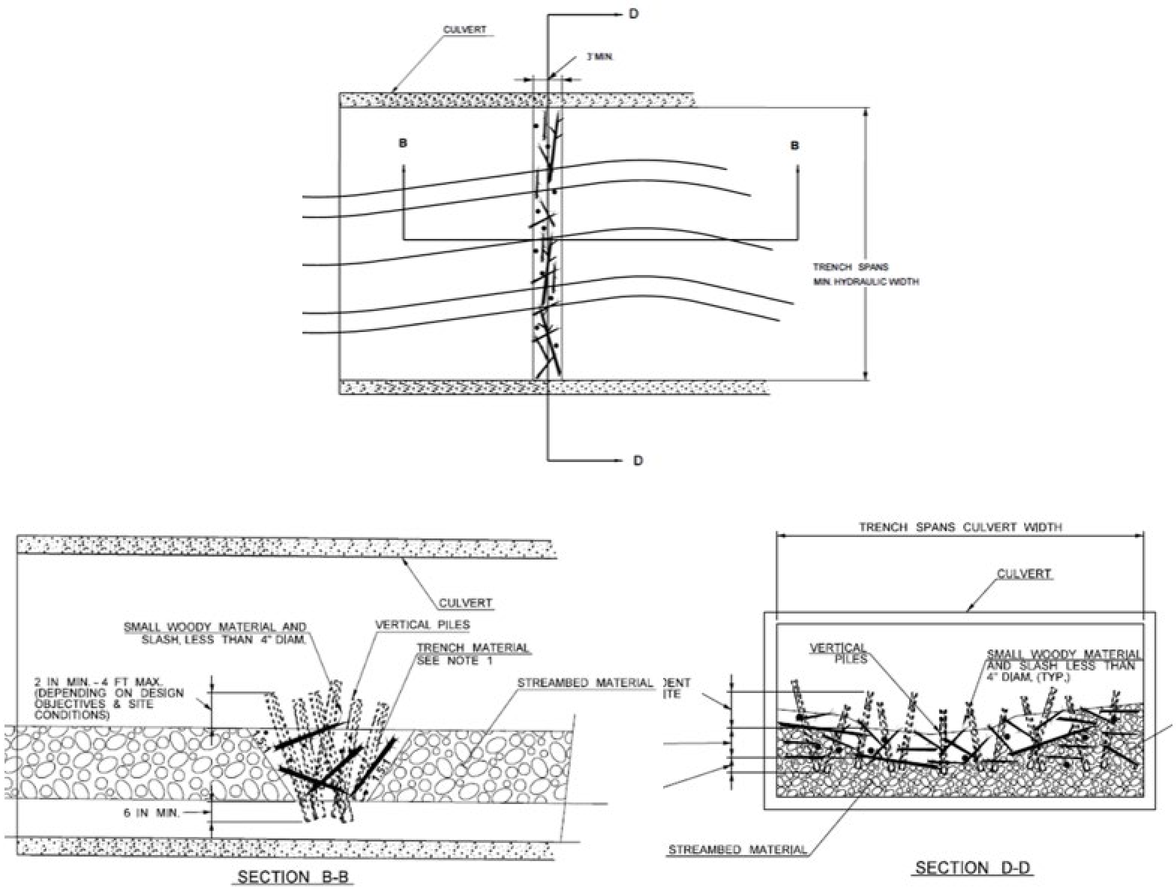
DGC, developed in partnership between WSDOT and the Tulalip Tribes, counteracts historical stream design methods and their legacy. In developed environments, streams were routed through undersized structures that fragmented riparian habitat, limited wood/sediment transport, were maintained to remove woody debris accumulation, and yet provided grade control. See Figure 7-18 for example details of the DGC. The exact sediment-to-wood ratio varies based on the design objectives and site conditions of the project, and the DGC shall be used in combination with other stream complexity features.

Figure 7-17 Example of Constructed DGC Feature, 2 Years after Construction



A headcut propagated through a downstream structure and was arrested at the photographed DGC. Consequently, the DGC deformed and created a forced step pool (stream's right) and simultaneously maintained a side flow path with no water surface drop (stream's left). This deformation demonstrates the ecological function of DGC and how weathered DGC provides fish passage for multiple species and life stages.

Figure 7-18 DGC Details



7-3.9.4.1 Design Considerations

DGC functions are fluid: initially, the channel roughness slows and deepens flow, accumulating more sediment and debris. The feature deforms as more overbank events occur and erosion and deposition patterns emerge. The weathered DGC may form a forced step pool, a slope transition, or alternate flow paths, promoting hydraulic diversity and heterogeneity in the gradient (Figure 7-17; Shahverdian et al. 2019). As noted, the deformability is a function of the site conditions (i.e., slope and reach characteristics) as well as the design choices (i.e., wood-to-sediment ratio; sediment and wood sizing; density, embedded depth, and exposure height of the vertical piles; and type of WM).

7-3.9.4.1.1 Slope

DGC shall be installed to mimic an accrued matrix of material found in response and transport reaches. Fouty (2023) tested DGC performance at 2 to 4 percent slopes and found that in systems over 2 percent DGC will deform, and that as the slope increases the rate and magnitude of feature deformation will consequently increase.

Montgomery-Buffington (1997) classifies a stream with a 2 to 4 percent gradient as a plane-bed, pool-riffle, or step-pool system. Gradients outside this range are acceptable depending on the design elements and design intent. Slopes greater than 4 percent will require additional consideration and the combined use of LWM, rock, and DGC. Contact the State Hydraulics Office for current guidance for high gradient systems.

7-3.9.4.1.2 Density and Location

Fouty (2023) tested the performance of an isolated DGC feature and concluded that a single DGC reduces upstream erosion and improves channel shape stability. A single DGC may be placed to provide localized function; i.e., channel roughness, targeted headcut arrest, or channel complexity with low impact and within tight construction limits.

If the intent of DGC is to promote reach-scale processes, DGCs shall be placed in series, and the recommended number and spacing is dependent on channel characteristics. Increasing the number of DGCs may result in extending the impacted reach length, increasing the stability of the grade controls, and intensifying the sediment retention. DGCs shall not be used in locations where these functions intensify risk to infrastructure or property. Consider the implications of site conditions (e.g., aggradation issues, beaver presence, limited structure clearance, and flooding) to evaluate if DGCs are acceptable.

7-3.9.4.1.3 Trench Dimensions

The following are design considerations for trench dimensions:

- **Within structure:** The trench dimensions are dependent on design objectives. Typically, the DGC shall span the minimum hydraulic width and reach the estimated depth of long-term degradation to a maximum of 6 feet. At a minimum, the trench shall have a depth of 3 feet, a 3-foot base, and a 1.5:1 side slope (see Figure 7-18).
- **Outside of structure:** Typically, the DGC shall span the estimated lateral migration of the channel and reach the estimated depth of long-term degradation to a maximum of 6 feet. At a minimum the trench shall have a depth of 3 feet, a 3-foot base, and a 1.5:1 side slope.

7-3.9.4.1.4 Trench Fill

The following are design considerations for trench fill:

- **Sediment sizing:** Fouty (2023) and WSDOT's constructed case studies recommend using the streambed material mix that is proposed for the project reach. Use of mixes that deviate from the general proposed gradation may be acceptable depending on the site conditions and design objective. Consider that the native and proposed sediment size and type does impact the stability of the DGC and will drive other design choices.
- **Wood-to-sediment ratio:** Fouty (2023) results suggest that at 2 to 4 percent slopes a trench fill consisting of 50 to 75 percent wood reduces sediment transport and optimizes channel shape stability. Consider how DGC influences sediment transport

and if there are implications to short- and long- term scour. If long-term scour is anticipated, consider how this shall be reflected in total scour.

- **Wood sizing:** According to Fouty (2023), a mixture of diameters provides reliable sediment retention and channel shape stability. The key finding from Fouty (2023) and supported by Shahveridan et al. (2019) is that a diverse distribution of wood diameter and length increases channel shape stability. The design shall allow these features to be complex and incorporate material available on site. The design may call out diameter and length ranges but does not need to specify precise mixes and rather could point to WSDOT's slash and SWM specifications. The vertical piles shall be 4 inches in diameter or smaller (i.e., SWM). Additional requirements for maintenance clearance may apply; see Table 7-4.

7-3.9.4.1.5 Wood Orientation/Positioning

The following are design considerations for wood orientation/positioning:

- **Vertical pile density:** Incorporating a higher density of vertical piles increases the stability of the DGC.
- **Vertical pile embedded depth:** Consider the site conditions and design objectives to determine appropriate embedded depth. The minimum pile depth is 6 inches below the trench excavation depth; driving the piles deeper will increase the stability of the DGC. The recommended minimum buried length is 2/3 of the pile length.
- **Woody material exposure:** Consider the site conditions and design objectives to determine appropriate exposure height. The vertical pile exposure height can vary from 2 inches to up to 4 feet; positioning the wood with higher exposure to flow provides higher channel roughness and racking potential while increasing the deformability of the feature.

7-3.9.4.1.6 Wood Type

The SWM and slash shall consist of a random assortment of branches, trees, brush, and treetops of the following native species: western red cedar (*Thuja plicata*), Douglas fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*) coniferous trees, or various hardwood trees. No more than 50 percent of hardwood species shall be used. The needles shall be left intact to the extent possible given the mechanics of handling slash. Slash shall not contain any material that causes turbidity. DGC features shall incorporate slash and SWM available on site.

7-3.9.4.2 Hydraulic Modeling of DGC Features

DGCs can be modeled with discrete sections with higher roughness to match the proposed DGC locations. Guidance on modeling DGCs is still in development; coordinate with the State Hydraulics Office for other current modeling methods.

7-3.9.4.3 Construction

Two common construction methods are outlined below. Other methods are acceptable if approved by the State Hydraulics Office:

- **Install DGC after streambed lifts are installed**: Construct streambed to final grade. Excavate trench per plan. Mix SWM, slash, and streambed material in specified ratios. Drive vertical SWM components into the trench. Care shall be taken to wash in streambed material including sand to seal as placement occurs.
- **Install DGC along with streambed lifts from subgrade**: Place SWM and slash as constructing streambed. Mix in streambed material at the ratio specified. This can be challenging to maintain vertical piles while constructing streambed lifts. Incorporate any streambed sand and water as required for adjacent streambed material installation sequencing.

7-3.10 *Landscaping/Planting*

The landscape architect will follow guidance for planting near streams located in WSDOT's *Roadside Manual* Chapter 830 for all projects located near streams. The Stream Team shall collaborate with the landscape architect to develop a restoration plan that includes the areas of bank stabilization countermeasures, habitat complexity, riparian restoration, and any planting that could be implemented prior to the first storm event post-construction to minimize erosion. The Stream Team will coordinate with the landscape architect regarding any plantings recommended for bank stability, and as discussed in Section 7-3.2.1, shall coordinate with the hydraulic designer doing the stormwater/drainage design for the project to ensure that the drainage works with the stream design and any outfalls properly drain to the stream without creating erosion and do not interfere with habitat features. The planting windows for WSDOT projects that do not install irrigation are October 1 to March 1 west of the Cascade Crest and October 1 to November 15 east of the Cascade Crest, per the WSDOT *Standard Specifications*). If planting needs to occur before the end of these windows for stability reasons, the contract will need to be updated to reflect the timeline.

7-4 Scour

This section covers scour analysis requirements for all WSDOT water crossings structures (bridges and culverts). Scour is evaluated throughout the project delivery process through early and often coordination with various specialty groups. Refer to the WSDOT *Design Manual*, Chapter 800, for additional information regarding interdisciplinary coordination.

7-4.1 *Total Scour*

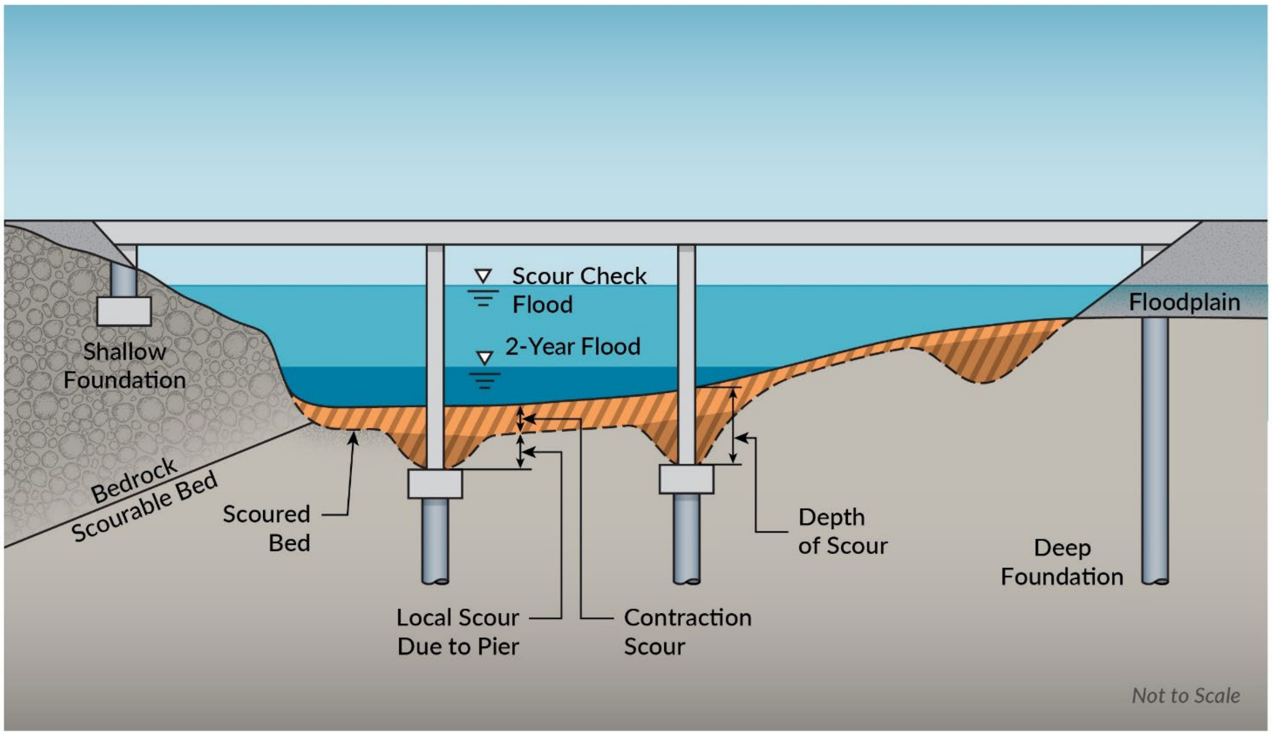
All water crossing structures (bridges and culverts) shall be designed for total scour, not just bridges. Total scour shall be assessed for all scenarios and flows up to the scour design flood and scour check flood events that results in worst-case total scour for each event. The hydraulic team or Stream Team shall follow appropriate method(s) depending on structure type, size, and location. A minimum of 3 feet of total scour is required to be assumed for all bridges and three-sided structures. Walls for all bridges and three-sided structures shall be designed for total scour and the length shall be based on the potential impacts of lateral migration as assessed by the hydraulic team or Stream Team. As defined by HEC-18, total scour is determined by the sum of various scour components—specifically, LTD, contraction scour, and local scour. Total scour must be computed using the D_{50} for both the proposed design mix and subsurface material provided by the Geotechnical Engineer when total scour is anticipated to be deeper than the depth of placed streambed material. Determination of whether the contracted section is in a clear-water or live-bed condition must use a representative grain size at the approach section for the material that would be transported from upstream into the water crossing. ***Coordinate with HQ Hydraulics, HQ Geotechnical, and HQ Bridge to ensure the provided depths of total scour are being correctly applied to determine the total scour elevations at each infrastructure component and are commensurate with the level of risk warranted for the crossing location.*** Methodologies and equations used for determining total scour shall follow HEC-18. Refer to the FHWA *Pier Scour Estimation for Tsunami at Bridges* (FHWA 2021) to design for the effect of tsunami events on pier scour for those bridges in locations within identified tsunami design zones (*Tsunami Design Zone Maps*).

In addition to the three scour components mentioned above, the potential for lateral migration (Section 7-4.2) must be assessed to evaluate total scour at water-crossing structures. WSDOT has also developed a scour review checklist to identify a list of elements examined during scour review; this checklist can be found on the WSDOT Hydraulics Training web page. Wall scour analysis is not appropriate for every water-crossing project, and shall be included only on a case-by-case basis depending on the characteristics of the stream and structure type. Coordinate with the State Hydraulics Office if it is determined that wall scour may be required at the crossing and consider applying principles from HEC-23 Volume 1.

7-4.2 *Lateral Migration for Water-Crossing Structures*

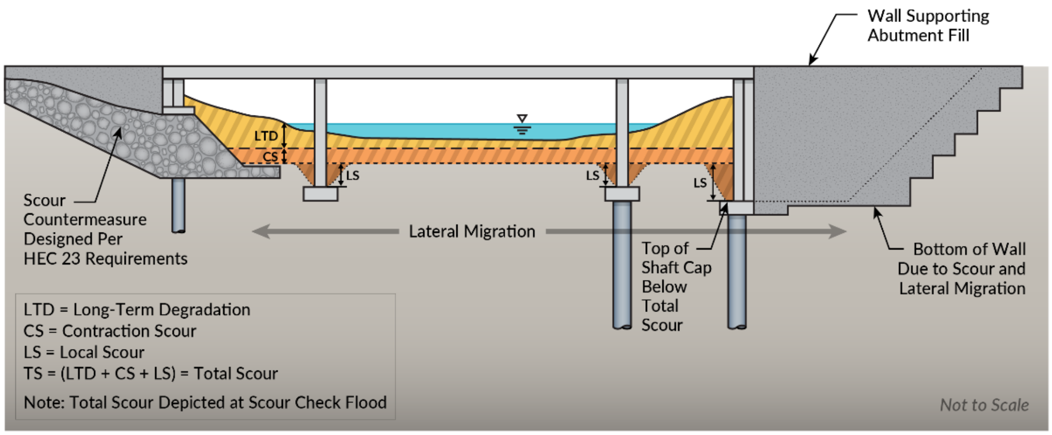
All structures shall be designed to account for the lateral channel migration expected to occur over the design life of the structure. See HEC-20 and Sections 7-2.3.2 and 7-2.3.3 for additional guidance on maintaining continuity of channel processes and assessing lateral migration and. If non-erodible soils are present such that no lateral migration is expected to occur over the design life of the structure, then LTD and contraction scour is a uniform offset from the existing channel section. Figure 7-19 illustrates various scour components for a channel that has been determined to be vertically and laterally stable. On the left side of Figure 7-19, based on geotechnical data, the channel bank and ground supporting the bridge foundation have been determined to be bedrock with low potential for erosion over the design life of the bridge. For these reasons, a shallow bridge foundation is acceptable because no scour is anticipated. Conversely, on the right side of Figure 7-19, a deep foundation is required because no bedrock or other non-erodible materials are present. The two intermediate piers are also deep foundations with shaft caps below anticipated total scour to minimize potential obstruction to the flow. The abutment scour occurring at the toe of the abutment on the right side of Figure 7-19 is above the channel thalweg because it is outside the main channel and there is no potential for lateral migration. For these reasons, the deep foundation needs to be designed only for abutment scour. Prior to using various scour equations, the hydraulic team or Stream Team needs to confirm what reference elevation a given scour equation uses. For example, some scour equations estimate scour as depth of flow after the scoured condition (e.g., measured from water surface to scoured bed), while others estimate scour as the vertical distance from the pre-scoured bed to scoured bed.

Figure 7-19 Total Scour Components without Potential of Lateral Migration



If lateral migration can occur over the design life of the structure, the hydraulic team or Stream Team shall document in the specialty report the risk of lateral migration at each pier and/or abutment and whether any scour countermeasures and potentially an increase in structure size (or SFZ) are recommended. The thalweg is the starting elevation for determining total scour for all infrastructure components that are within the extents of potential lateral migration. Figure 7-20 provides an example for a water crossing with deep foundations and abutments with potential of lateral migration. On the left side of Figure 7-20 a scour countermeasure designed meeting requirements, specifically the use of an apron below LTD and contraction scour at the scour check flood, is used to mitigate abutment scour. On the right side of Figure 7-20, no scour countermeasures are used, resulting in a greater depth of scour because of the requirement to account for abutment scour at the structure and wall foundations.

Figure 7-20 Total Scour Components with Potential of Lateral Migration



7-4.3 *Scour Countermeasures*

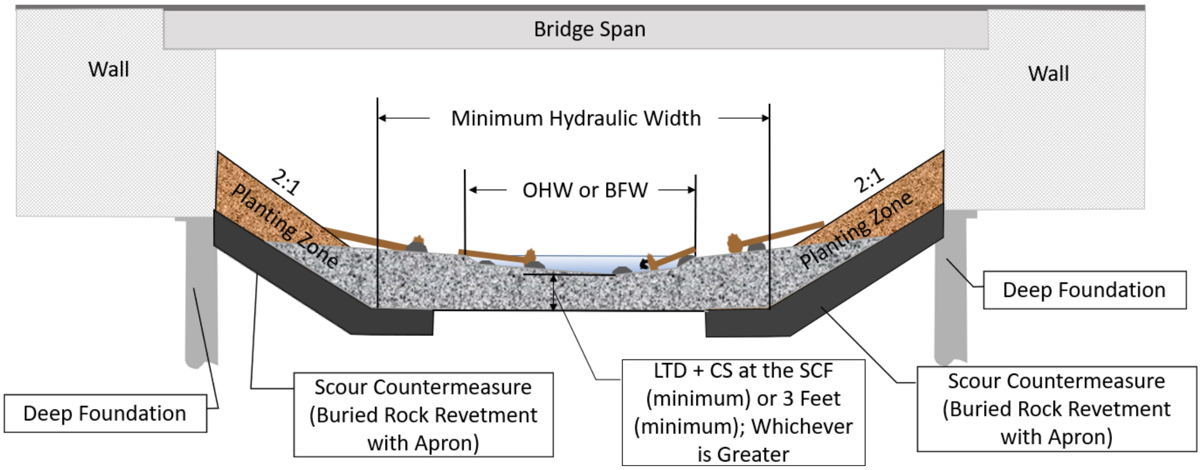
Scour countermeasures are used to protect the structure itself or to protect other elements of the roadway adjacent to a water body and have different design requirements from countermeasures used for stream instability or bank protection. Countermeasure design requirements for stream instability and bank protection are provided in Chapter 4. Scour countermeasures are required when stable wood is proposed and may be required when mobile wood or other large complexity features are proposed; refer to Section 7-3.6 and coordinate with the State Hydraulics Office. When a scour countermeasure is necessary, the specialty report shall document the risk to the infrastructure asset and rationale for the protection, any current evidence of erosion, and the countermeasure design standard. See HEC-23 Volume 1 and Volume 2 for additional guidance on the implementation of scour countermeasures.

For new structures, scour countermeasures shall not encroach within the minimum hydraulic width and depth of scour. The depth of scour is determined as LTD + contraction scour at the scour check flood (minimum) or a minimum of 3 feet, whichever is greater, unless approved by the State Hydraulics Office. The design of scour countermeasures first relies on an understanding and agreement of the asset they intend to protect and the required design standard for the asset. Elements of a water crossing that may need a scour countermeasure include but are not limited to the abutments, roadway approach walls, and the roadway embankment. Each of these elements can have varying levels of acceptable risk and thus different design standards. Scour countermeasure may be used to prevent scour at deep foundation abutments when recommended by the hydraulic team or Stream Team and the project shall require maintenance access per the Roadside Manual 830. When used with deep foundation, scour countermeasure rock class shall exceed the required design by one rock class. Figure 7-21 and Figure 7-22 provide conceptual sketches for where a scour countermeasure can be placed in relation to the minimum hydraulic width and depth of scour for a water crossing in a fish-bearing stream with and without abutment scour, respectively. The limits of scour countermeasure shall be determined based on the lateral migration determination process; see Sections 7-2.3.3 and 7-4.2. In the examples shown in

Figure 7-19 and Figure 7-20, the bridge is founded on deep foundations, which are designed to meet HEC-18 requirements and do not rely on the integrity of the scour countermeasure. The Stream Team shall also consider the effect of any placed habitat features and ensure that the opposite banks are properly stabilized and that the revetment will not become exposed because the stream migrates around, and interacts with, the habitat features.

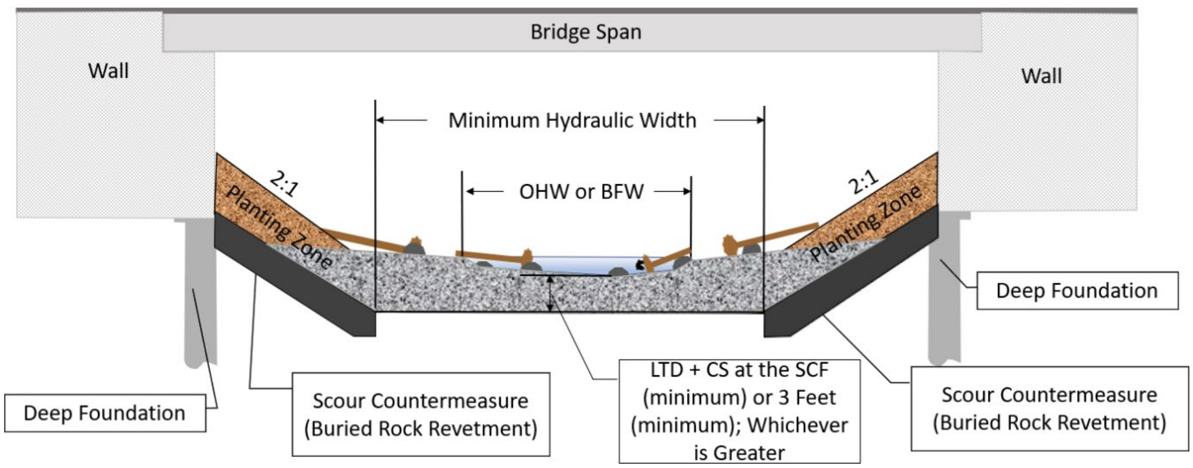
Also depicted in Figure 7-21 is a very important but often overlooked scour countermeasure feature for water crossings with abutment scour, the apron. Guidance for design of the apron can be found in HEC-23, Volume 1 and Volume 2 and the FHWA *TechBrief: Hydraulic Considerations for Shallow Abutment Foundations* (FHWA 2020). The example figures also contain curtain walls, which assist to retain the roadway embankment fill and were decided by the PEO, for this specific crossing, to rely on the integrity of the scour countermeasure for their design. Because of the site-specific nature of water crossings, the State Hydraulics Office shall be contacted to assist in coordinating with the appropriate subject matter experts to determine the design standards for the scour countermeasure and the level of protection they can assume to provide for a given asset. If scour countermeasures are included in the design, a maintenance access shall be included as part of the project to access the stream for future repairs as needed. The Stream Team shall coordinate with Maintenance to determine what is required for access.

Figure 7-21 Scour Countermeasure Design with Deep Foundation and Calculated Abutment Scour Greater than Zero



Coordinate with the project landscape architect regarding planting details.

Figure 7-22 Scour Countermeasure Design with Deep Foundation and Calculated Abutment Scour of Zero



Coordinate with the project landscape architect regarding planting details.

7-5 Other Design Methods

It is recognized that not all stream crossings will be able to meet stream simulation or either bridge design methodologies. As described in Section 7-3, other available design methodologies can be accepted on a case-by-case basis with the approval of the State Hydraulics Office. This section briefly describes some of the other methodologies available.

Some of these design methodologies may need to include project objectives with performance measures, inspection schedules, maintenance triggers, and a contingency plan shall the project fail to meet performance measures with permitting applications.

7-5.1 No-Slope Design

No-slope design recommendations can be found in the 2013 WCDG and WAC. The no-slope designs are performed on BFWs of less than 10 feet, low gradients (less than 3 percent), and short culvert lengths (less than 75 feet). This design methodology is not typically used on WSDOT water crossings and requires approval from the State Hydraulics Office.

7-5.2 Fish Passage Improvement Structures

Fish passage improvement structures are any structures that facilitate the passage of fish either through or around the fish barrier that do not necessarily mimic natural channel processes. Structures such as roughened channels, roughened rock ramps, structure retrofit designs, and hydraulic culvert designs are examples of fish passage improvement structures. Fish passage improvement structures require approval from the State Hydraulics Office. Additional information about roughened channels, roughened rock ramps, and structural retrofits is included below. Other fish passage improvement structures exist but are not covered here.

A fish passage improvement structure may be necessary to facilitate fish passage through an existing structure, allow for a transition between a newly constructed fish-passable structure and an upstream fishway, or as a means of grade control when deemed necessary. All fish passage improvement structures must meet WAC 220-660-200.

7-5.2.1 Roughened Channel Design Methodology

A roughened channel is a constructed channel with streambed material and configuration designed to be non-deformable up to the design flood event. A roughened channel can help dissipate energy from an adjacent fishway into a newly constructed channel or may be necessary to prevent a channel from degrading over time.

7-5.2.2 Roughened Rock Ramp Design Methodology

Roughened rock ramps are similar to roughened channels except a roughened rock ramp uses large boulders to dissipate energy.

7-5.2.3 Structure Retrofit Design Methodology

An existing structure that currently does not provide fish passage can be authorized to remain in place until the end of its useful life by retrofitting the culvert to make it fish passable. It must be demonstrated that the culvert will comply with WAC 220-660-200(11). It is unlikely that a structure retrofit will be allowed within WRIAs 1 through 23 because of the Injunction.

7-5.3 Tidal Crossing Structures

Tidal crossings are those water crossings on state highways in which the hydraulics are either influenced or dominated by tidal cycles that must be considered in the crossing design. Flow through structures at tidal sites are bi-directional and typically subject to a mixed semi-diurnal tidal cycle, unlike the one-way flow of riverine systems. Mixed semi-diurnal tides have two unequal high and low tides each tidal day (24 hours and 50 minutes).

At tidally influenced crossings it is necessary to assess the hydraulics through the tidal cycle as well as during events such as the tidal flood event and in conjunction with the design riverine flood event. Site assessments using topographic data compared with local tidal datums (refer to Section 7-3.5.4) can be used to evaluate the thalweg elevation relative to the local tidal datums. Sites with thalweg elevations at or below mean sea level are likely to be tidally influenced or dominated, depending upon the tidal prism. The tidal prism is the volume of water that is exchanged during a typical tidal cycle, excluding freshwater flow; the greater the tidal prism that is exchanged, the higher the design velocity. 2D modeling may be used to evaluate tidal hydraulics for tidally influence and tidally dominated crossings.

Crossings of embayments and lagoons with substantial tidal prisms would typically be tidally dominated for freeboard, scour, and stability. The location of a crossing at an embayment or lagoon must consider the effects of local waves and nearshore sediment transport on channel stability and meandering. Embayment and lagoon crossings may experience muted tide ranges because of local bathymetry of the typical shallow bays and estuaries where these crossings are located. Depending on the tidal prism, natural embayments and lagoons may have velocities that regularly exceed desirable fish passage velocities during peak ebb and flood tides. 2D modeling shall be applied to evaluate the typical range of velocities during typical spring and neap tides, in addition to flood event scenarios.

Crossings of coastal creeks are not typically associated with substantial tidal prisms and therefore are not typically tidally dominated. However, design freeboard, scour, and stability may be governed by either tidal or riverine processes depending upon local conditions. 2D modeling shall be applied to evaluate the typical range of water levels and velocities during typical spring and neap tides, in addition to flood event scenarios that combine both riverine and tidal events, to determine the governing processes for hydraulic design. Where tidal creek crossings occur at or near the shoreline, structure design shall incorporate study of coastal geomorphology on past, present, and future conditions.

River deltas are typically broad-low gradient areas that require long crossings to minimize impact to wetlands, essential fish habitat, flooding, and nearshore processes. Depending on river basin size, the sites may fluctuate between river and tidal dominance. 2D modeling shall be applied to evaluate the typical range of water levels and velocities during typical spring and neap tides in addition to flood event scenarios that combine both riverine and tidal events to determine the governing processes for hydraulic design.

Relative sea level rise (RSLR) data shall be acquired from NOAA or another appropriate source and validated using on-site observations. RSLR refers to sea level rise adjusted for changes in local land elevation due to either subsidence or glacial rebound. WSDOT recognizes that coastal terrain can be highly variable and that there may be no nearby tidal gage. In such instances, it is acceptable to use data from the nearest gage and adjust the data as necessary to obtain a tidal hydrograph that corresponds with field observations. Structure design must consider the RSLR in addition to the predicted 2080 100-year increase in riverine flow unless otherwise justified. A king tide event shall also be used in the hydraulic analysis unless otherwise justified.

It is not necessary to design a crossing that spans the full extent of the Tidal Design Event provided that there is a point of diminishing returns in terms of hydraulics in relation to structure size. 2D modeling shall be used to determine the point of diminishing returns.

Scour must be evaluated at tidal crossings; refer to HEC-25 for guidance on estimating scour at tidal structures.

Modeling guidance is provided in Section 4-8.

7-6 Structure-Free Zone

The SFZ is an imaginary prism of infinite length both upstream and downstream that is horizontally centered on the stream and represents the minimum boundary within which no part of the fish passage structure (footings, chamfers, etc.) shall be allowed (Plan Sheet Library).

The components of the SFZ that determine the boundaries are width, height, and length. The specialty report documents the MHO (width and height including freeboard, scour, and bed thickness), and length of the structure. However, there may be other reasons to increase the SFZ that are not hydraulic related, such as constructibility, maintenance access, wildlife connectivity, or cost, and the specialty report does not document justification for additional width or height outside of what is necessary to allow for stream processes.

7-6.1 *Complete Streets and Effect on Structure-Free Zone*

The inclusion of active transportation design elements or application of the Complete Streets program (see Section 1-5) could have an impact on the SFZ. It may be recommended to increase the hydraulic length of a water-crossing structure to accommodate pedestrians, bicyclists, or any other type of network connectivity supported by the program; discuss with the PEO whether an increase in hydraulic length is appropriate. If deemed appropriate, discuss with the PEO if a resulting increase in hydraulic width could be warranted.

7-7 Temporary Stream Diversions

Temporary stream diversions shall be designed following the methodology described in Chapter 3. Under most circumstances, determination of the design and configuration of temporary diversions for streams is left to the contractor. This allows the contractor to create the most efficient and innovative work plan. If the PEO wishes to design the temporary diversions, coordination with the State Hydraulics Office is required.

7-8 Monitoring

In September 2015, as part of the Culvert Injunction, state agencies and tribal nations agreed upon and finalized a set of Injunction Implementation Guidelines. Those guidelines are the basis of WSDOT's current fish passage monitoring plan. Some elements of the monitoring plan apply to all statewide fish passage projects, not just those within the case area. Some projects have monitoring requirements as part of a state or federal permit. The monitoring plan, based on the agreed-upon guidelines, provides protocols that can be applied to those special monitoring requirements and will ensure a consistent and efficient process.

The Fish Passage Monitoring Plan provides a protocol that can be broadly applied to ensure a consistent and efficient post-project monitoring process for all WSDOT fish passage projects. WSDOT's Fish Passage Monitoring Plan and the Injunction Implementation Guidelines are available by request from the State Hydraulics Office. Fish passage monitoring results are available for barriers corrected since 2013, and are available publicly online through WSDOT's interactive Fish Passage Webmap; click on a corrected barrier and select "more info" under the site attributes (reports available for barriers corrected since 2013).

There are four basic types of monitoring inspections:

- **Post-construction compliance inspection:** WSDOT evaluates all fish passage projects to ensure that they are constructed as designed and permitted. Sites are also evaluated for their ability to pass fish using WDFW barrier assessment methods.
- **Overwinter inspection:** WSDOT inspects sites corrected under the Injunction after the first full winter to evaluate the impact of high seasonal flows on fish passage at the new structure.
- **Long-term evaluations:** Sites are evaluated 5 and 10 years after construction to determine whether the project still provides fish passage and stream function. Monitoring protocols described for the Over-Winter inspection will be repeated to determine if the project still meets design expectations.
- **Additional monitoring:** Ad hoc evaluations can take place anytime between regular monitoring intervals at the discretion of the WSDOT monitoring biologist to reevaluate project performance based on responses recorded during a previous assessment.

The results of the monitoring efforts are summarized each year in the Fish Passage Annual Report, which can be found on the WSDOT Fish Passage Program website. WSDOT uses the information from the monitoring efforts to work alongside WDFW and tribes to improve upon the design and construction processes and will update this chapter as needed to reflect current practices and best available science.

7-8.1 *Streambed Camera Monitoring*

Since July 2021, WSDOT has included monitoring with cameras for selected fish passage sites. The purpose of monitoring with cameras is to collect live data during storm events to observe complexity features and evaluate how the streams are reacting/adjusting during various flow conditions, including winter storm events and during summer low flow periods. The data are used to validate the design technique and inform design changes to improve the overall function of stream features.

Pre-project streambed camera monitoring data that are available will be shared with the Stream Team. Contact the State Hydraulics Office for additional information on available data. The time-lapse photos/videos may inform design features including:

- Sediment observations (mobility, supply, erosion/scour, degradation/aggradation)
- LWM (transport, presence, racking)
- High flow events with associated high water marks (validate hydrology)
- Beaver activity
- Wildlife observations
- Low flow events/dry channel (in summer or not)
- Mobility of habitat features (wood, steps)
- Seasonal channel variation with roughness

Post-construction data, trends, and observations will be reviewed, distributed, and communicated to the State Hydraulics Office. Observations that could inform the design may include meander bars, step pools, and LWM. Any items of concern will be communicated and may trigger additional monitoring and potential adjustment to design criteria.

7-9 Performance Management

WSDOT is committed to managing fish passage sites to ensure continued fish passage and stream function. WSDOT's goal for performance management is to continuously improve policies, practices, and design guidance by learning from outcomes of post-project monitoring.

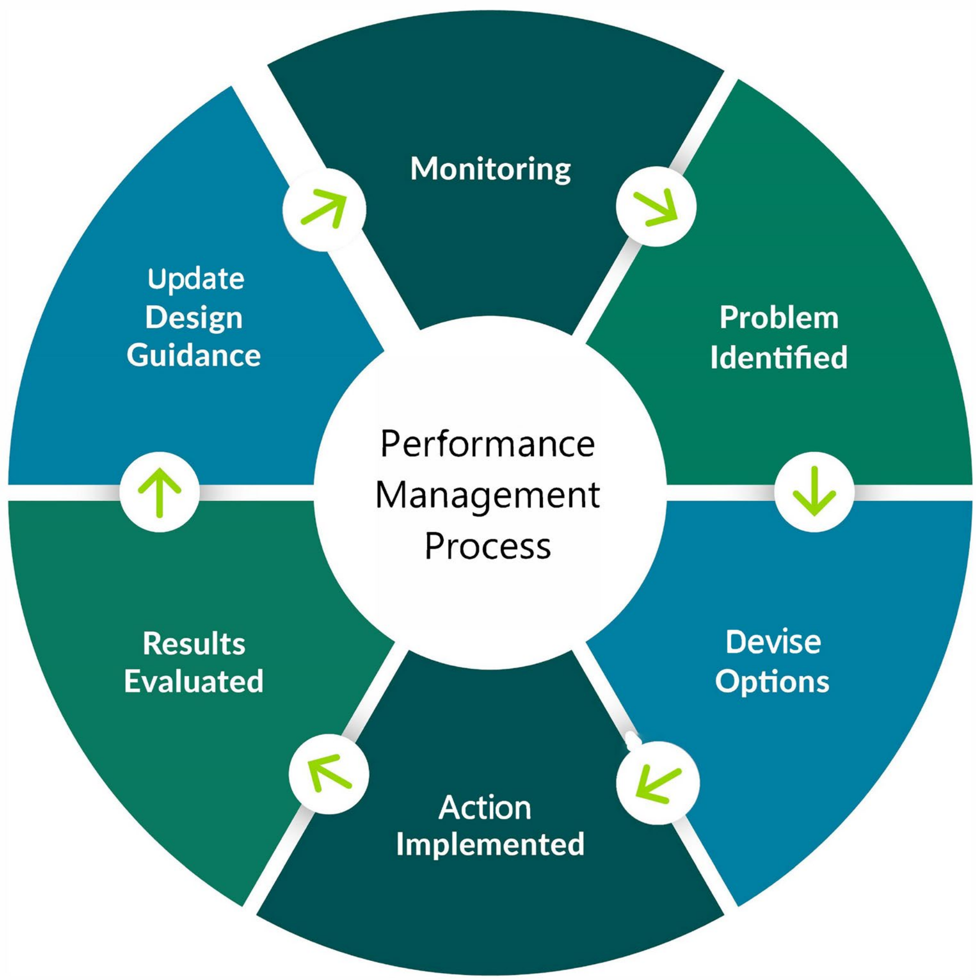
Monitoring is conducted by HQ Stream Restoration Program staff and reviewed by the Fish Passage Monitoring and Performance Coordinator. Any project trending toward becoming a barrier to fish passage or losing stream function receives an increase in the frequency of monitoring for a period to determine if an action is needed to correct the deficiency. If an observed deficiency is noted during the monitoring process as described above that hinders fish passage or stream function, the WSDOT performance management process is initiated (see Figure 7-23). WSDOT's performance management process is for repairs or modifications that are deemed necessary to maintain fish passage or stream function.

Once an action is proposed, the Fish Passage Monitoring and Performance Coordinator notifies the State Hydraulics Office and Regional Project Office of the status and refers it for further hydraulic evaluation. The State Hydraulics Office will either refer it back to Stream Restoration for continued monitoring or assign a status of action needed; if action is needed, the State Hydraulics Office will draft a technical memorandum documenting the design conditions, the existing conditions, and a concept for repair (not yet a barrier condition) or modification (barrier condition).

The State Hydraulics Office determines the appropriate repair or modification options and refines the technical memorandum into a Fish Passage Performance Management Recommendation document. The document is provided to the region for implementation.

Once a correction is designed, permitted, and implemented, the modification or repair is monitored for success and the design guidance is reviewed for potential updating. Contact the State Hydraulics Office for more information.

Figure 7-23 WSDOT's Performance Management Process



7-10 Additional Resources

The Stream Team may find the following manuals helpful for additional information:

- HEC-16: Highways in the River Environment: Roads, Rivers, and Floodplains (FHWA 2023b)
- HEC-17: Highways in the River Environment: Floodplains, Extreme Events, Risk, and Resilience
- HEC-18: Evaluating Scour at Bridges
- HEC-20: Stream Stability at Highway Structures Fourth Edition
- HEC-23: Bridge Scour and Stream Instability Countermeasures Experience,

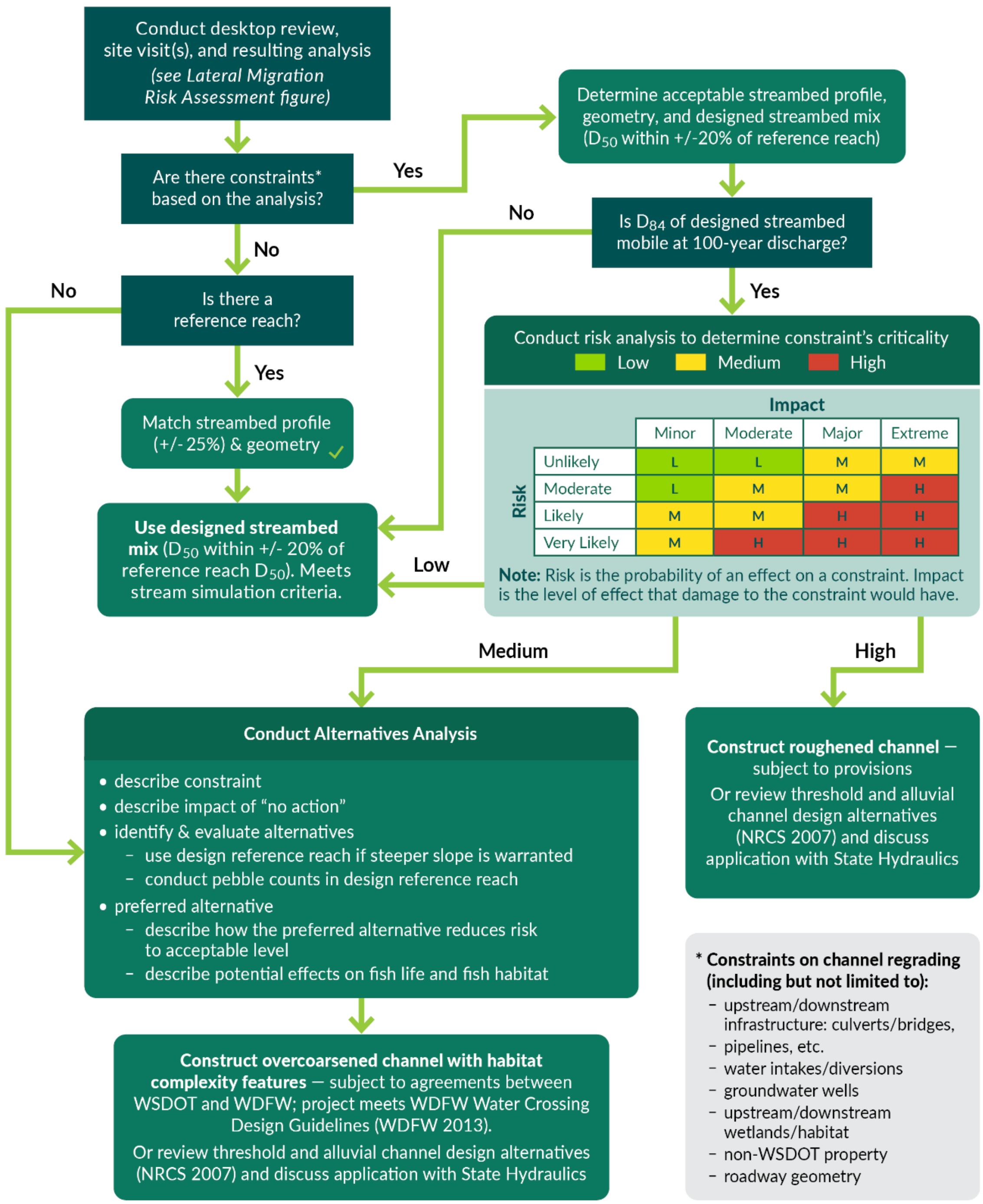
Selection, and Design Guidance Third Edition, Volume 1 and Volume 2

- HEC-25: Highways in the Coastal Environment
- *TechBrief: Hydraulic Considerations for Abutments on Deep Foundations and Bridge Embankment Protection* (FHWA 2023a)
- *TechBrief: Hydraulic Considerations for Shallow Abutment Foundations* (FHWA 2020)
- 2013 WDFW WCDG
- 2008 USFS Manual: Stream Simulation: An Ecological Approach to Providing Passage for Aquatic Organisms at Road-Stream Crossings
- WDFW ISPG
- WDFW *Stream Habitat Restoration Guidelines* (Cramer 2012)

7-11 Appendices

Appendix 7A Streambed Material Decision Tree
Appendix 7B Stream Simulation and Bridge Design Methodology Requirements

Appendix 7A Streambed Material Decision Tree



This document is intended to guide fish passage restoration design in cases where there are site constraints that are either too costly to resolve, or would take too long to resolve. In these cases, the regraded reach may be steeper than the initially identified reference reach. The reach assessment is an essential part of the process, but this document's scope is limited to the decisions that affect the design of streambed materials which may be larger than what would normally be indicated by stream simulation-based design.

Appendix 7B Design Methodology Requirements for Bridges and Stream Simulation Culverts

<table>
<tr><th>Stream crossing element</th><th>Goals</th><th>Stream Simulation Methodology</th><th>Bridge Design Methodology</th></tr>
<tr><td>Bankfull/bed width</td><td>Determine accurate bankfull width relative to site conditions. Design teams will reach agreement in the field where possible. If hydraulic modeling is necessary, meet after to discuss results.</td><td colspan="2">WAC: A person must measure at least 3 widths that describe prevailing conditions at straight channel sections and outside the influence of any culvert, bridge, or other artificial or unique channel constriction.

WDFW: Appendix C provides recommended methods to determine bankfull width.

WSDOT: Bankfull in highly modified (urban/agricultural) determined by hydraulic modeling, reference reach or comparative analysis. See WSDOT Hydraulics Manual, Chapter 7, Water Crossings.</td></tr>
<tr><td>Channel slope/gradient</td><td>The slope of the bed inside the culvert is within 25% of the slope of the upstream channel.</td><td colspan="2">WAC: The slope of the bed inside a stream-simulation culvert must not exceed the slope of the upstream channel by more than twenty-five percent.
If the channel is heavily degraded, the slope should be that of a stable channel that would fit within the geomorphic context of the reach.

WDFW: The slope of the bed inside a stream-simulation culvert must not exceed the slope of the upstream channel by more than 25%. $(S_{culvert}/S_{upstream}\ ch) < 1.25$
Slope ratios greater than 1.25 require a bridge or the application of the Hydraulic Design Option, specifically, the roughened channel option.

WSDOT: Slope ratio greater than 1.25 or more than 1' of uncontrolled regrade needs justification. In low-gradient systems, provide explanation if designed gradient is outside slope ratio. See WSDOT Hydraulics Manual, Chapter 7, Water Crossings.
In cases where placing the culvert at the same gradient as the stream would cause constructability issues, placing the culvert at a zero slope is acceptable as long as the necessary embedment depth and freeboard are met and the engineering justification is provided.</td></tr>
<tr><td>Countersink/scour</td><td>Bridge foundation / culvert bottom does not become exposed for life of structure and substrate size is similar to adjacent channel.</td><td>WAC: Must be countersunk a minimum of 30% and a maximum of 50% of the culvert rise, but not less than two feet. Alternative depths of culvert fill may be accepted with engineering justification.

WDFW: 30%–50%, not less than 2 feet unless justified by analysis.

WSDOT: WSDOT designs all water crossing structure foundations (bridges and culverts) to account for total scour at the scour design flood and scour check flood. A minimum of 3 feet of total scour is required to be assumed for all bridges and three-sided buried structures. See WSDOT Hydraulics Manual, Chapter 7, Water Crossings.</td><td>WAC: The bridge design must minimize the need for scour protection. Where mid-channel piers are necessary, design them so no additional scour protection is required.

WDFW: Follow AASHTO and FHWA guidelines. Prevent or limit local scour and coarsening of the stream substrate.

WSDOT: WSDOT designs all water crossing structure foundations (bridges and culverts) to account for total scour at the scour design flood and scour check flood. A minimum of 3 feet of total scour is required to be assumed for all bridges and three-sided buried structures. See WSDOT Hydraulics Manual, Chapter 7, Water Crossings.</td></tr>
<tr><td>Scour countermeasures</td><td>Minimize risk to the structure or elements of the roadways from scour by using scour countermeasures.</td><td>WSDOT: Stable wood within the structure requires scour countermeasures; mobile wood may require scour countermeasures. See WSDOT Hydraulics Manual, Chapter 7, Water Crossings.</td><td>WAC: The bridge design must minimize the need for scour protection. Where midchannel piers are necessary, design them so no additional scour protection is required. If scour protection is unavoidable, the design must minimize the scour protection to the amount needed to protect piers and abutments. The design must specify the size and placement of the scour protection so it withstands expected peak flows.

WDFW: Encroachments of abutments or embankment end slopes into the bankfull channel is unacceptable.
Riprap placed above Q100 elevation does not require mitigation for instream functions unless the bridge span is inadequate to allow meander migration or the rock significantly affects riparian vegetation.

WSDOT: Stable wood within the structure requires scour countermeasures; mobile wood may require scour countermeasures. See WSDOT Hydraulics Manual, Chapter 7, Water Crossings.</td></tr>
<tr><td>Channel geometry / cross section</td><td>Continuity of channel shape maintained throughout reach [channel complexity].</td><td>WAC: All water crossings must retain upstream and downstream connection in order to maintain expected channel processes.
If the channel is heavily degraded, the cross section must match expected stream measurements in order to limit main crossing channel velocity and scour to prevailing conditions.

WDFW: The natural channel cross section and the cross section constructed through the crossing should be the same (at least up to bank full) so that material that is moving in the natural channel will also pass through the constructed channel in the crossing.
Bed cross section should be similar to the adjacent stream cross section.

WSDOT: See WSDOT Hydraulics Manual, Chapter 7, Water Crossings.</td><td>WAC: Must design water crossing structures in fish-bearing streams to allow fish to move freely through them at all flows when fish are expected to move. All water crossings must retain upstream and downstream connection in order to maintain expected channel processes. These processes include the movement and distribution of wood and sediment and shifting channel patterns. Water crossings that are too small in relation to the stream can block or alter these processes, although some encroachment of the flood plain and channel migration zone will be approved when it can be shown that such encroachment has minimal impacts to fish life and habitat that supports fish life.

WDFW: The stream channel created or restored near the bridge should have a gradient and cross section similar to the existing morphology of the upstream and downstream adjacent channel.

WSDOT: See WSDOT Hydraulics Manual, Chapter 7, Water Crossings.</td></tr>
</table>

Stream crossing element	Goals	Stream Simulation Methodology	Bridge Design Methodology
Floodplain continuity	Constructed channel mimics adjacent floodplain habitat conditions and allows for floodplain connectivity.	WAC: Fish must be able to move freely at all flows when fish are expected to move. All water crossings must retain upstream and downstream channel processes. Floodplain encroachments may be approved if it can be shown that there are minimal impacts to fish life and habitat. WSDOT: See WSDOT Hydraulics Manual, Chapter 7, Water Crossings.	WAC: All water crossings must retain upstream and downstream connection in order to maintain expected channel processes. These processes include the movement and distribution of wood and sediment and shifting channel patterns. Some encroachment is allowed as long as proven to have minimal impacts to fish life and habitat [220-660-190(2)(a)]. A bridge over a watercourse with an active flood plain must be designed to prevent a significant increase in the main channel average velocity. The bridge is defined as the main bridge span(s) plus flood plain relief structures and approach road overtopping. This velocity must be determined at the 100-year flood event or the design flood event approved by the department. The significance threshold should be determined by considering bed coarsening, scour, backwater, flood plain flow, and related biological and geomorphological effects typically evaluated in a reach analysis. WDFW: Allow continued down-valley flow of water on the floodplain. The bridge/culvert design must comply with legislation governing development within floodplains. WSDOT: If the V2/V1 is less than 1.1, no additional justification needed. If V2/V1 is greater than 1.1, State Hydraulics Office approval is needed. See WSDOT Hydraulics Manual, Chapter 7, Water Crossings.
Freeboard	Crossing provides unimpeded passage of fish, 100-year flood event, LWM, and sediment.	**WDFW**: Culverts shall be installed to an approved design to maintain structural integrity to the 100-year flood event with consideration of the debris loading likely to be encountered. A list of suggested clearances is provided, though the values are not based on hydraulic modeling or empirical studies and therefore should be used with caution. -Small streams less than 8 ft BFW: clearance of 1 foot above the 100-year water surface -Medium streams from 8-15 ft BFW: clearance of 2 feet above the 100-year water surface -Large streams over 15 ft BFW: clearance of 3 feet above the 100-year water surface **WSDOT**: Same as listed above substituting the 100-year event with the 2080 100-year projected flood event. See WSDOT Hydraulics Manual, Chapter 7, Water Crossings.	**WAC**: The design must have at least three feet of clearance between the bottom of the bridge structure and the water surface at the 100-year flood event unless engineering justification shows a lower clearance will allow the free passage of anticipated debris. **WDFW**: Culverts shall be installed to an approved design to maintain structural integrity to the 100-year flood event with consideration of the debris loading likely to be encountered. A list of suggested clearances is provided, though the values are not based on hydraulic modeling or empirical studies and therefore should be used with caution. -Small streams less than 8 ft BFW: clearance of 1 foot above the 100-year water surface -Medium streams from 8-15 ft BFW: clearance of 2 feet above the 100-year water surface -Large streams over 15 ft BFW: clearance of 3 feet above the 100-year water surface **WSDOT**: A minimum of 3 feet of freeboard above the 100-year or 2080 100-year projected flood event is required on all structures greater than 20 feet in span measured along the centerline of the roadway and on all bridge structures. See WSDOT Hydraulics Manual, Chapter 7, Water Crossings. Additional justification possible when recommended freeboard is not achievable.
Substrate	Channel substrate mimics reference reach.	**WAC**: D50 must be +/- 20% of the D50 of the reference reach. The department may approve exceptions if the proposed alternative sediment is appropriate for the circumstances. **WDFW**: A reference reach approach to sizing sediment is preferred. Substrate should be designed to address bed stability at high flows and must be well-graded to prevent loss of significant surface flow. **WSDOT**: Streambed Material Decision Tree and WSDOT Hydraulics Manual, Chapter 7, Water Crossings.	**WAC**: The water crossing design must provide unimpeded passage for all species of adult and juvenile fishes. Passage is assumed when there are no barriers due to behavioral impediments, excessive water slope, drop or velocity, shallow flow, lack of surface flow, uncharacteristically coarse bed material, and other related conditions. **WDFW**: A reference reach approach to sizing sediment is preferred. Substrate should be designed to address bed stability at high flows and must be well-graded to prevent loss of significant surface flow. **WSDOT**: Streambed Material Decision Tree and WSDOT Hydraulics Manual, Chapter 7, Water Crossings.

Structure span	Crossing width (span) allows for geomorphic processes to occur including 100-year flood event; minimize the need for scour protection: maintain structural integrity for the duration of the design life; maintain water and sediment transport continuity.	**WAC:** Bed width inside a culvert may be calculated by using any published stream simulation design methodology approved by the department, or may be determined on a case-by-case basis with an approved alternative plan that includes project objectives. inspection, maintenance, and contingency components. **WDFW:** Typically culvert bed is 1.2*BFW+2 (in alluvial systems), note examples of exceptions for deviating. The structure span should span the calculated bed width. **WSDOT:** Starting point for sizing is 1.2*BFW+2 or 1.3*BFW (the larger of the two). A meander belt assessment shall be conducted for all crossings to determine if there are any changes to the minimum hydraulic width. If a structure length is more than 10 times its width, then the hydraulic width shall be increased to whichever is greater, a 30% increase or incorporate the width necessary for the natural meander as determined through the meander belt assessment. See WSDOT Hydraulics Manual, Chapter 7, Water Crossings.	**WAC:** The bridge must pass water, ice, large wood and associated woody material, and sediment likely to move under the bridge during the 100-year flood event or the design flood event approved by the department. The waterward face of all bridge elements must be landward of the Ordinary High Water Line (OHWL), except for mid-channel piers and protection required at the toe of embankment in confined channels. The span must be sized to prevent a significant increase in the main channel average velocity. The significance threshold should be determined by considering bed coarsening, scour, backwater, flood plain flow, and related biological and geomorphological effects. The span must account for channel migration during the bridge's lifespan. If there are levees or other infrastructure that constrains bridge design, WDFW may approve a shorter bridge span than would otherwise be required. **WDFW:** Existing bridges with a good performance rating can be replaced in kind. Confined channels, distance between bridge abutments should be bankfull width plus a safety factor. Unconfined channels with floodplain and overbank flow should be designed such that the velocity in the main channel under the bridge should be close to the prevailing velocity in the main channel of the river. **WSDOT:** Starting point for sizing is 1.2*BFW+2 or 1.3*BFW (the larger of the two). The confined bridge methodology may include an additional factor of safety. The unconfined bridge methodology requires the hydraulic opening to provide a velocity ratio of less than 1.1 (see “floodplain continuity” row). A meander belt assessment shall be conducted for all crossings to determine if there are any changes to the minimum hydraulic width. See WSDOT Hydraulics Manual, Chapter 7, Water Crossings.
Crossing length	Minimize confined length of channel and riparian impacts, increase width for long crossings. Skew also needs to be considered— crossing should use skew to avoid abrupt bends leading to the bridge/culvert inlet and from the bridge/culvert outlet.	**WDFW**: Culverts with a length-to-span ratio of greater than 10 are considered long and special consideration should be given to their design. Three alternatives for long culverts are proposed; the first two suggest increasing width and the third a change of crossing type. **WSDOT**: If a structure length is more than 10 times its width, then the hydraulic width shall be increased to whichever is greater, a 30% increase or incorporate the width necessary for the natural meander as determined through the meander belt assessment (see “culvert size” row).	**WSDOT**: See WSDOT Hydraulics Manual, Chapter 7, Water Crossings.
Floodplain utilization ratio (FUR)	Determine if a channel is confined (FUR < 3) or unconfined (FUR > 3). Look for frequent out of bank flows and/or high flows away from channel. Determine if unconfined bridge design criteria are adequate for the bridge or buried structure.	**WDFW**: FUR < 3 indicates a confined channel where a culvert is better suited. FUR is defined as the flood-prone width (FPW) divided by the bankfull width (BFW). **WSDOT**: When FUR > 3, use unconfined bridge method for minimum channel span. Measure FUR outside the influence of any crossing structures. See WSDOT Hydraulics Manual, Chapter 7, Water Crossings.	**WSDOT**: Measure FUR outside the influence of any crossing structures. See WSDOT Hydraulics Manual, Chapter 7, Water Crossings.
Streambank protection / stabilization	Minimize armoring (use of riprap or concrete) and use bio-engineering techniques where appropriate.	WAC: Any proposed bank hardening must include: (i) An analysis performed by a qualified professional assessing the level of risk to existing buildings, roads, or services being threatened by the erosion; (ii) Technical rationale specific to the project design, such as a reach and site assessment; (iii) Evidence of erosion and/or slope instability to warrant the work. Any bank hardening must protect fish life and habitat by using the least-impacting technically feasible alternative. The common alternatives below are in order from most to the least preferred: (i) No action-Natural channel processes to occur; (ii) Biotechnical techniques; (iii) Combination of biotechnical and structural techniques; and (iv) Structural techniques Streambank stabilization should be limited to the least amount needed to protect eroding banks. The project must be designed to withstand the maximum selected design flood event. Use natural materials whenever feasible, including large wood and vegetation; protect existing spawning and rearing habitat. WDFW: See Integrated Streambank Protection Guidelines (WDFW 2002) WSDOT: See WSDOT Hydraulics Manual Chapter 4, Open-Channel Flow.	

Hydrology / design flood events	Correlate to watershed conditions and land use, while avoiding over-engineered channels and banks. Develop design flood events that accurately reflect watershed conditions, including future conditions.	**WDFW**: See (Appendix G) Design Flows for Fish Passage **WSDOT**: Address potential effects of extreme events (e.g., 500-year); climate resilience should also be considered as current science suggests that both the magnitude and frequency of peak flows are expected to increase (WDFW 2016a). See WSDOT Hydraulics Manual, Chapter 2, Hydrology and Chapter 7, Water Crossings for design flood events and guidelines.

NOTES:
This table provides a brief summary of design criteria. It is recommended to read the full design criteria in each of the references to fully understand water crossing methodology and how the design criteria may apply to each water crossing site. In this table, the references denoted by bold and underlined characters are listed below.
WAC refers to the Washington Administrative Code 220-660-190 Water Crossing Structures or 220-660-130 Stream Bank Protection and Lake Shoreline Stabilization, published in 2015.
WDFW refers to the Water Crossing Design Guidelines, published in 2013.
WSDOT refers to the current WSDOT Hydraulics Manual.