Chapter 4 Channels and Floodplains

4-1 Introduction

Channels and floodplains are runoff systems that include streams, rivers, ditches, and swales. Built extensions or modifications to these systems are included in this chapter.

Proper design requires sufficient hydraulic capacity to convey the flow of the design storm. All flow assessments require a hydrologic analysis with procedures and methodologies presented in Chapter 2. In the case of earth-lined channels or river channels, bank protection may also be required if the shear stress is high enough to cause erosion or scouring.

This chapter provides guidance for determining design velocity (Section 4-2) and critical depth (Section 4-4) for designing roadside ditches (Section 5-5), stormwater systems, swales, and roadway gutters. All other transportation hydraulic features require the use of a 2D hydraulic model; FHWA has developed a reference document for 2D hydraulic models, titled *Two-Dimensional Hydraulic Modeling for Highways in the River Environment* (FHWA 2019).

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.

Countermeasures for stream instability (Section 4-6) may be necessary for highly erosive, high-energy stream and river channels, to help stabilize the banks and/or channel bottom. The success of stabilization measures is dependent on the ability of the methods and materials used to withstand the hydraulic forces. For example, it is important to properly size the rock materials used for armoring; the methodology for sizing rock materials used in river stabilization is described in HEC-23, Volume 1 and Volume 2.

4-2 Uniform Flow Calculations

The determination of the flow characteristics for uniform flow conditions can be calculated based on the continuity equation (Equation 4-1). This equation states that the discharge (Q) is equivalent to the product of the channel velocity (V) and the area of flow (A).

$$Q = V\,A \tag{4-1}$$

where:

Q = discharge, cfs

V = velocity, ft/s

A = flow area, ft^2

While channel geometry can be estimated or surveyed, the flow velocity may not be as practical to manually or directly measure. When actual channel or flow velocity measurements are not available, the velocity can be calculated using the Manning's equation shown in Equation 4-2.

$$V = 1.486\left(R^{2/3}\right)\left(S^{1/2}\right)/n \tag{4-2}$$

where:

V = mean velocity of flow in feet per second

R = hydraulic radius in feet (R = area (A) of flow section / wetted perimeter (P) of flow in channel)

S = slope of the energy grade line (EGL)

n = Manning's roughness coefficient of the channel refer to Table 4-1.

The flow area of a channel can be determined by previous investigations, surveys, or studies, or can be estimated through measurements of the channel and corresponding flow conditions. Determinations of slope (S) can be directly measured in the field for typical uniform and non-uniform flow conditions; refer to Section 4-3 below for more guidance on measuring in the field. If one or more variables are unknown, the flow area or flow depth must be calculated by trial and error, as presented in HDS-4, or by using a computer hydraulic program, such as the FHWA Hydraulic Toolbox or StormShed. The hydraulic designer is also referred to HDS-4 for further information on channel flow rates and velocities.

4-3 Field Slope Measurements

The slope is calculated by dividing the vertical drop in the river channel by the horizontal distance measured along the channel centerline or along the thalweg, whichever applies for uniform flow or natural (non-uniform flow) channels, of a specific channel reach. Where slope (S) is needed to support Manning's equation calculations, it can be measured in the field for typical channel conditions. Calculated channel slope is often referred to as the "rise over run," whereby the "rise" in a channel is represented by the vertical change in channel elevation, and the run in a channel is the change in horizontal length between representative elevation points.

Both rise and run are measured along the lowest point of the channel. For channels that have assumed uniform geometries (i.e., same cross section and profile), which is typical of constructed gravity stormwater systems, roadside ditches and swales, roadway gutters, and can also include streams and conveyance channels, the lowest elevation point is typically along the middle of the bed of the channel, as shown in Figure 4-1 and Figure 4-2.

Figure 4-1 Field Slope Measurement of Uniform Flow Channels Plan View

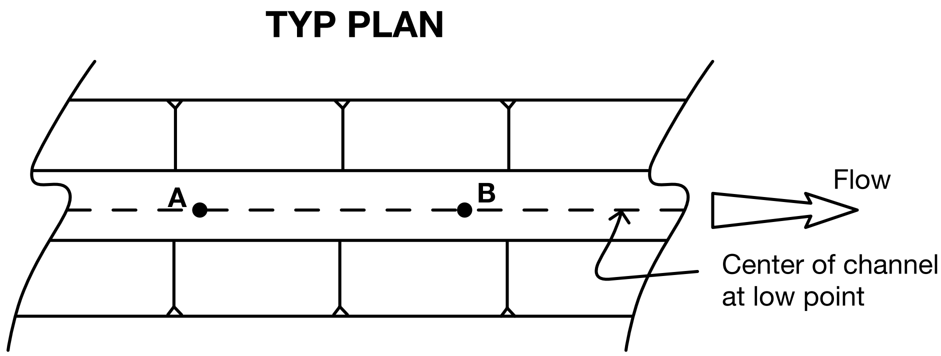
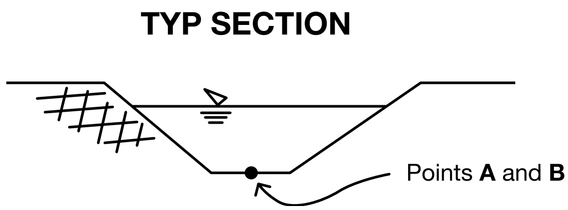


Figure 4-2 Field Slope Measurement of Uniform Flow Channels Section View



Where the channel has non-uniform geometries (i.e., changes gradient or channel dimensions), which is more typical of natural stream and river channels that have geomorphically governed characteristics (e.g., pools and riffles) but can also be constructed channels, the slope shall be measured for each similar channel reach, and the results shall be incorporated into the analysis so as to accurately represent the overall channel hydraulics. A reach is defined as a segment of the channel with similar hydraulic and geomorphic characteristics. In particular for natural channels, the gradient is typically measured along the thalweg, as shown in Figure 4-3 and Figure 4-4. The thalweg is the lowest channel elevation point for any given flow, typically located along the outside of bends, and then moves more to the center of the channel in straight reaches. The thalweg can change during peak flows.

Figure 4-3 Field Slope Measurement of Non-Uniform Flow Channels Plan View

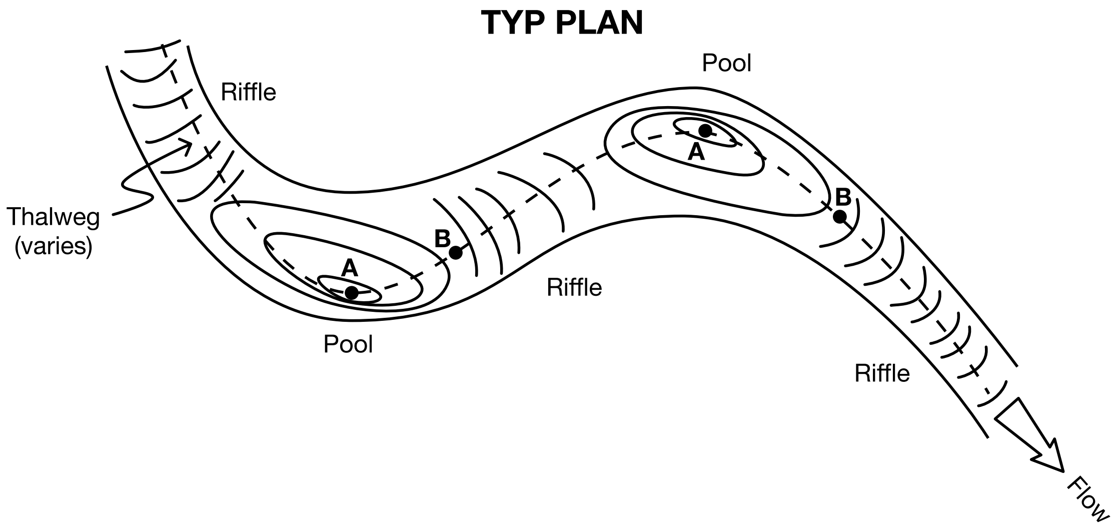
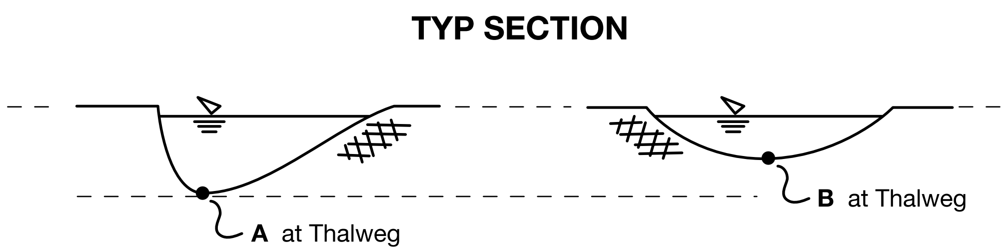


Figure 4-4 Field Slope Measurement of Non-Uniform Flow Channels Section View



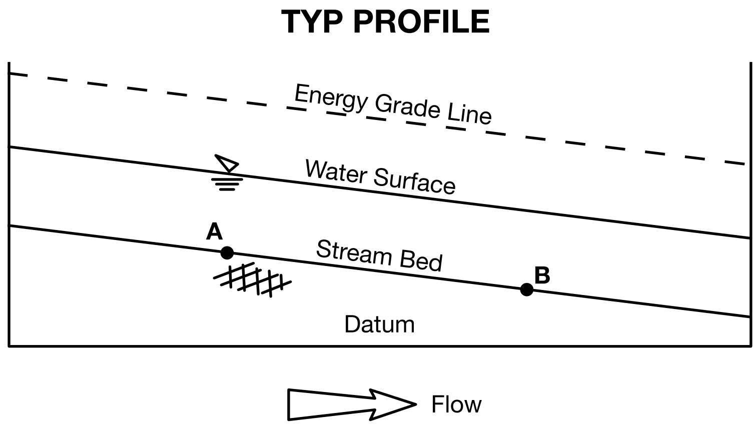
In both uniform and non-uniform channels, the engineer may need to apply discretion in how the gradient reaches are assessed and/or combined to best represent the channel hydraulic conditions, and where the thalweg is located.

4-3.1 *Uniform Flow Conditions: Gravity Stormwater Systems, Roadside Ditches and Swales, Roadway Gutters, Streams, and Conveyance Channels*

In constructed or natural channels with assumed uniform flow conditions (i.e., with corresponding uniform channel geometries and corresponding uniform flow depth, width, area, and velocity for the reach of interest) the channel bed gradient generally matches the top of flow gradient, as shown in Figure 4-5. Therefore, the vertical drop shall be measured at points along the bed elevation represented by points A and B in Figure 4-5. If the channel does not allow for practical or safe access to measure the channel bed (e.g., flows are too deep, or suspended sediment does not allow safe or practical visibility of bed conditions), then measure from the top of the water surface. The horizontal distance shall be measured between the two points where the bed or top of water points were located.

When discharge or flow is directed to cut slopes or fill slopes the designer shall include energy dissipaters along the drainage path to minimize erosion along the drainage path. The design shall follow Section 3-4.7.

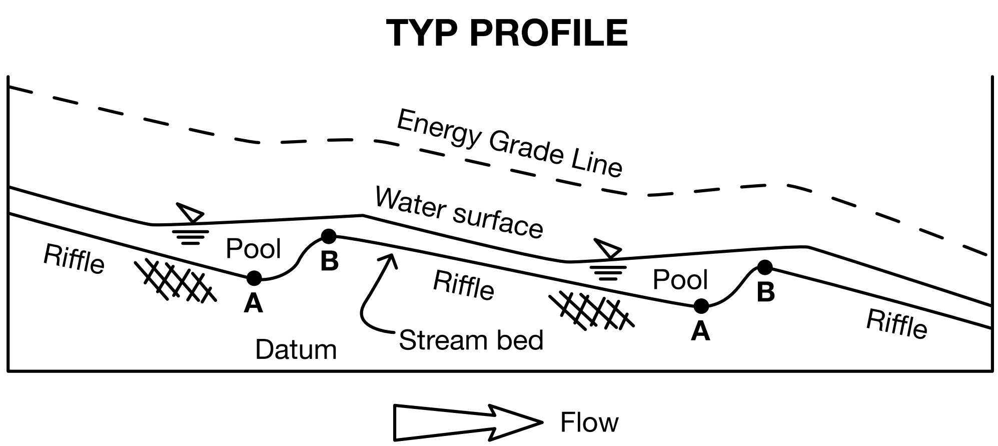
Figure 4-5 Field Slope Measurement of Uniform Flow Channels Profile View



4-3.2 *Non-Uniform Flow Conditions: Streams and Rivers*

In natural channels with assumed non-uniform flow conditions (i.e., changes in channel depth, width, area, and/or velocity corresponding to variations in channel geometries at geomorphically governed pools or riffles along the channel reach of interest), the channel bed gradient may be different from the water surface gradient at various points along the channel, as shown in Figure 4-6. For example, the bed elevation may drop in pools along the channel, resulting in slower velocity and deeper flows, and then rise in riffles along the channel, resulting in shallower and faster velocity flows.

Figure 4-6 Field Slope Measurement of Non-Uniform Flow Channels Profile View



In these situations, it is important to measure bed elevations at similar geomorphic locations; otherwise, the resulting channel gradient may represent only localized flow conditions and could be artificially high or low when considering the reach flow conditions. For example, measuring the channel gradient at a pool and the next downstream riffle (see Figure 4-6, points A and B) could result in a localized flatter gradient, and similarly measuring from a riffle to the following downstream pool could result in a locally steeper gradient; neither of these situations accurately represents the reach flow conditions. Measurements shall ideally be taken from “riffle-to-riffle,” shown in Figure 4-6 as point B at the upstream end of the riffle to point B at the following downstream riffle.

4-3.3 *Energy Grade Line*

Note that in both uniform and non-uniform channel flow conditions, the most accurate representation of gradient for input into calculations is represented by the energy grade line (EGL). The EGL is generally represented as the sum of the flow depth and the velocity head. The concept of the EGL is presented here to recognize the basis for the standard of practice, and be able to reference back to more complex analyses, where needed; in practical terms the channel bed and/or water level is commonly used as a means for characterizing slope in calculations.

In uniform flow conditions the flow depth is generally constant and the resulting water surface is generally parallel to the bed elevation; therefore, the EGL is also typically parallel to the water surface, as shown in Figure 4-5 above. Simplified calculations using measured rise over run to estimate slope of the channel are therefore applicable.

In non-uniform flow conditions, where the depth of flow and gradient can vary corresponding to changes in channel geometry along the channel, the corresponding channel slope is better represented by the EGL, as shown in Figure 4-6. Non-uniform flow conditions are more difficult to accurately characterize with manual channel bed measurements and calculations. If no other options are available, then incorporate the methods described above for measuring channel slope, and the results shall be qualified accordingly.

Because non-uniform flow conditions are more complex, and the measurement of channel geometries (i.e., elevations, sections, gradients, etc.) often requires special equipment and expertise to complete bathymetric surveys to capture that information, the methods of calculating corresponding hydraulic results incorporate the EGL and require using complex analyses and/or hydraulic modeling software tools. Contact the RHE or State Hydraulics Office for more information regarding more complex analyses.

4-4 Critical Depth

Before finalizing a channel design, the hydraulic designer must verify that the normal depth of a channel is either greater than or less than the critical depth. If this cannot be achieved contact the RHE for additional guidance. Critical depth is the depth of water at critical flow, an unstable condition where the flow is turbulent and a slight change in the specific energy—the sum of the flow depth and velocity head—could cause a significant rise or fall in the depth of flow. Critical flow is also the dividing point between the subcritical flow regime (tranquil flow), where normal depth is greater than critical depth, and the supercritical flow regime (rapid flow), where normal depth is less than critical depth.

Critical flow tends to occur when passing through an excessive contraction, either vertical or horizontal, before the water is discharged into an area where the flow is not restricted. A characteristic of critical depth flow is often a series of surface undulations over a very short stretch of channel. The hydraulic designer should be aware of the following areas where critical flow could occur: culverts, bridges, and near the brink of an overfall.

A discussion of specific energy is beyond the scope of the *Hydraulics Manual*. The PEO shall refer to HDS-5 or HEC-14, for further information.

4-5 Manning's Roughness Coefficients (n)

Table 4-1 presents references for Manning's roughness coefficients.

Table 4-1 References for Manning's Roughness Coefficients

Category of Surface	Surfaces Included	Source
Open channel and pipe	Closed conduits Pipes Pavement Gutter Man-made channels	HEC-22
River, stream, and culvert design for aquatic organism passage	Rigid channel Minor streams Floodplains Major streams Alluvial beds Sand beds Gravel beds Cohesive soils Composite roughness value	Aberle and Smart 2003 Barnes 1967 Bathurst 1985 Chow V.T. 1959 Griffiths 1981 Hey 1979 Jarrett 1984 Lee and Ferguson 2002 Limerinos 1970 Liu, X. et al. 2024 Rickenmann and Recking 2011 Yochum et al. 2012
Channel lining	Rigid channel Unlined channel Grass Gravel Riprap Gabion	HEC-15
Storm sewer conduit[a]	Concrete pipe Metal pipe Polyethylene pipe PVC pipe	HEC-22
Street and gutter	Concrete gutter Asphalt Concrete pavement	HEC-22
Maintained vegetation	Grass	HEC-15 Chow V.T. 1959

Notes:

a. For storm sewer pipes 24 inches or less in diameter, use n = 0.013.

4-6 Countermeasures for Stream Instability

Because of the abundance of watercourses in Washington State, and the legacy of highway placement along and across their corridors, stabilization of part of the river cross section or alignment is often necessary to protect transportation investments. New roadways and other infrastructure must be placed to minimize interaction with or effects on water bodies, avoiding them altogether if possible. This section discusses the options available for those cases where action must be taken and provides a subset of techniques and associated technical references to be used for those techniques. This is not a comprehensive guide, and as new techniques arise, all should be considered (in coordination with State Hydraulics Office for their cost-benefit in addressing interactions with water bodies. Countermeasures used for stream instability or bank protection have different design requirements from scour countermeasures used to protect a structure. Scour countermeasure design requirements for structures are provided in Section 7-4.3.

4-6.1 *Bank Protection*

Extensive guidance exists for numerous techniques for bank protection, from rock to revegetation. Many techniques recommended in Pacific Northwest rivers incorporate LWM; see Chapter 10 for guidance. Some of the most pertinent guidance documents are listed below:

- HEC-23, Volume 1 and Volume 2
- *Integrated Streambank Protection Guidelines* (ISPG) (WDFW 2002)
- *Bank Stabilization Design Guidelines* (Baird et al. 2015)
- WDFW's *Stream Habitat Restoration Guidelines* (Cramer 2012)

4-6.2 *Rock for Bank Protection*

Rock bank protection is a layer of rock placed to stabilize the bank and inhibit lateral erosion. Rock is deformable, compared to rigid channel linings such as concrete. Rigid channel linings generally shall not be used. If rigid linings are undermined, the entire rigid lining will be displaced increasing the chances of failure and leaving the bank unprotected. Rock encased in grout is also an example of a rigid channel lining.

There are disadvantages to using rock for bank protection. Replacing streambank vegetation with rock may create a relatively smooth surface, resulting in higher water velocities. This change may impact the channel downstream, and to some extent upstream, where the rock ends, creating a higher potential for erosion. Because of impacts to the adjacent channel, the hydraulic designer shall consider if using rock for bank protection would solve the problem or create a new problem. These aspects shall be considered when determining if rock is appropriate.

Rock bank protection is used primarily on the outside of curved channels or along straight channels when the streambank serves as the roadway embankment. Bank protection shall begin and end at a stable feature in the bank, if possible. Such features may be bedrock outcroppings or erosion-resistant materials, trees, vegetation, or other evidence of stability.

4-6.2.1 Rock Sizing for Bank Protection

For WSDOT projects, the rock material to be used will be quarry spalls or rock for erosion and scour protection (RESP) Class A, B, C, or D as defined in the *Standard Specifications*.

Once the hydraulic designer has completed a hydraulic analysis, the hydraulic designer shall consider the certainty of the velocity value used to size the rock along with the importance of the facility. For additional guidance and examples on rock sizing for bank protection design, see HEC-23, Volume 1 and Volume 2.

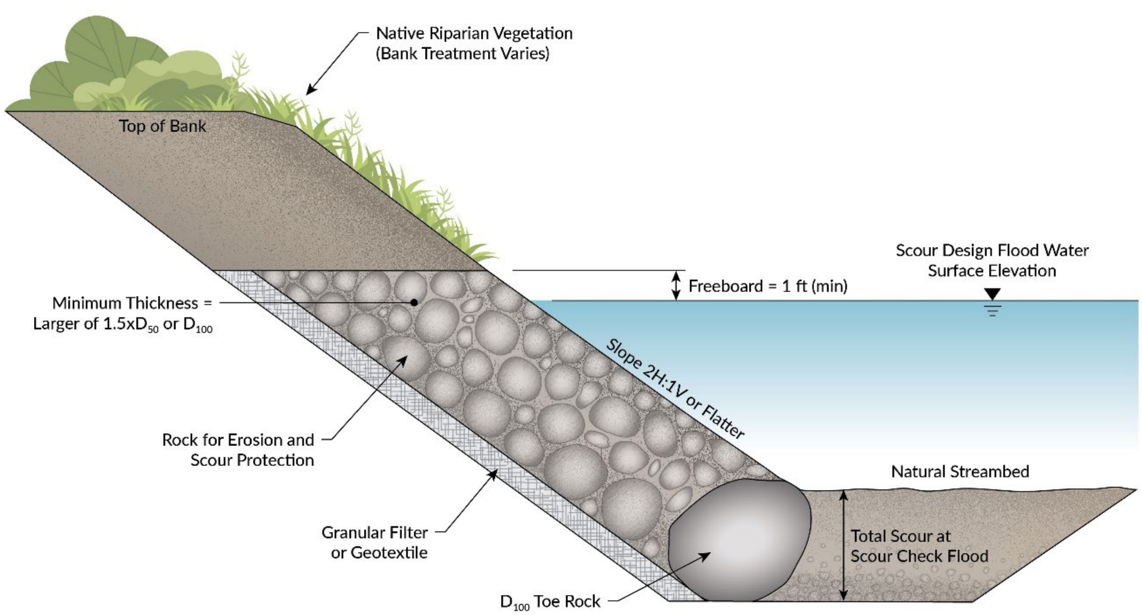
In some cases, on very high-velocity rivers or rivers that can transport large rocks downstream, even RESP Class D may not be adequate to control erosion and specially sized rock may need to be specified in the contract. The RHE, State Hydraulics Office, and HQ Materials Laboratory are available for assistance in writing a complete specification for special rock for erosion and scour protection.

4-6.2.2 Placement of Rock Bank Protection

Once the type of rock has been selected, the next step is to determine the appropriate installation. Several factors affect the placement of rock including the type of filter material best suited for the project site, the thickness of rock placement, and the depth to key rock to prevent undermining.

Figure 4-7 illustrates a typical cross section of a rock bank protection installation.

Figure 4-7 Typical Cross Section of Rock Bank Protection Installation



The filter material acts as a transition between the native soil and the rock, preventing the piping of fines through the voids of the rock structure while allowing relief of the hydrostatic pressure in the soil. Two types of filters are used: granular or geotextile. Filter materials are further described in the *Standard Specifications* and the *Geotechnical Design Manual*. If the existing banks are similar to the filter material of sands and gravel, no filter layer may be needed.

The proper selection of a filter material is critical to the stability of the original bank material in that it aids in preventing scour or sloughing. Prior to selecting a filter type, the hydraulic designer shall first consult with the RME or geotechnical engineer and the RHE to determine if there is a preference. In areas of highly erodible soil (fine, clay-like soils), the State Hydraulics Office shall be consulted, and an additional layer of sand may be required. For additional guidance selecting the appropriate filter material, see HEC-23, Volume 1 and Volume 2. Use of the FHWA Hydraulic Toolbox is required for design of filters.

The thickness of rock placed (Figure 4-7) depends on which type of rock was selected: quarry spalls or RESP Class A, B, C, or D. Additional guidance for determining minimum rock thickness can be found in HEC-23, Volume 1 and Volume 2. Care should be taken during construction to ensure that the range of rock sizes, within each group, is evenly distributed to keep the rock stable. Rock is required to be extended to 1 foot above the scour design flood WSEL as shown in Figure 4-7. However, if severe wave action is anticipated, it shall extend farther up the bank.

In some circumstances, the rock bank protection slope face may be steeper than 2:1. The hydraulics designer shall coordinate with the RME or geotechnical engineer for feasibility prior to implementing into the design.

The hydraulic designer and construction inspectors must recognize the importance of a proper toe or key at the bottom of any rock bank protection. The toe of the rock is placed below the channel bed to a depth equaling total scour at the scour check flood (Figure 4-7). If the estimated scour is minimal, the toe is placed at a depth equivalent to the thickness of the rock to help prevent undermining. The toe of the revetment needs to be clearly detailed in the project plans to ensure that the revetment's foundation is solid. Without a toe, the rock has no foundation and the installation is certain to fail. Added care should be taken on the outside of curves or sharp bends where scour is particularly severe. The toe of the bank protection may need to be placed deeper than in straight reaches.

4-6.3 *Channel Stabilization*

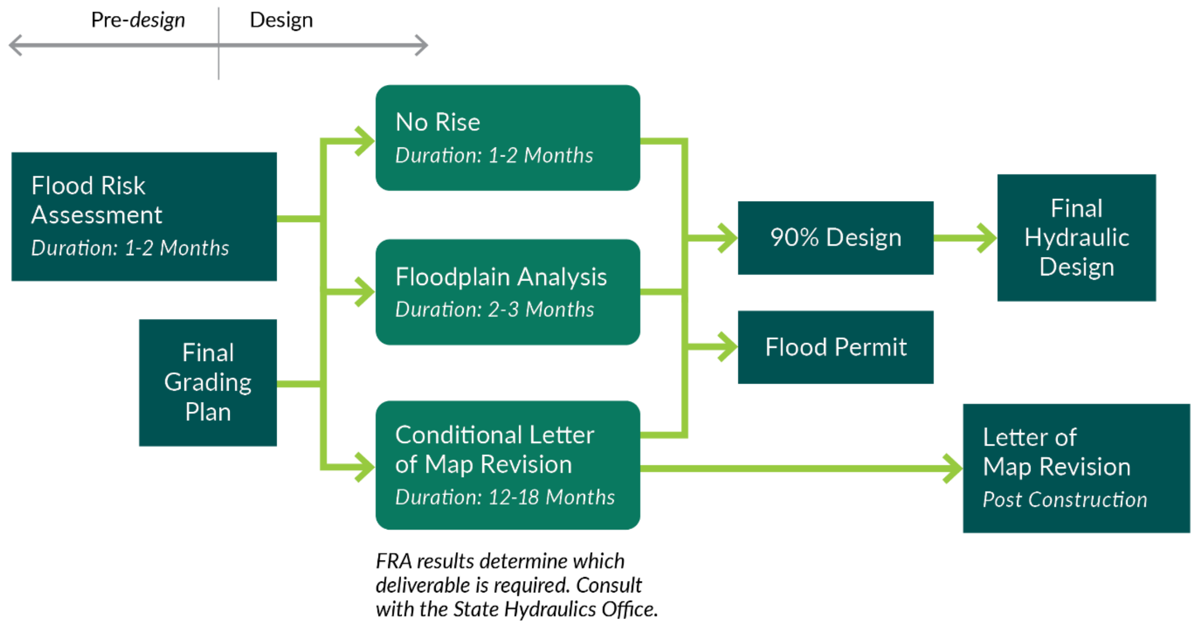
Channel stabilization, as opposed to bank stabilization, involves controlling and maintaining the channel cross section, alignment, and gradient, for some given length of the stream. There can be several reasons to stabilize a channel. At WSDOT, it is often to protect transportation infrastructure such as a culvert, bridge, or roadway embankment. These channel stabilization designs shall follow the guidance in HEC-23, Volume 1 and Volume 2. The major types of channel stabilization are concrete or rock linings, weirs, dams, and grade-control structures. Stabilization of roadside ditches and other constructed channels shall follow the guidance in HEC-15.

Notably, channel stabilization is a significant modification to natural processes, but is sometimes necessary for fish habitat or passage designs. It is not only technically challenging to design a maintenance-free, sustainable project of this nature, but it is also increasingly difficult to obtain the necessary environmental permits from the regulatory agencies. Therefore, such projects should be undertaken only when there are no other feasible options, and only in consultation with the State Hydraulics Office (see Chapter 7 and Chapter 10 for more details, as well as the ISPG (WDFW 2002).

4-7 Flood Risk Assessment

The Flood Risk Assessment (FRA) is a communication tool used to identify if there are potential risks of meeting FEMA, local jurisdiction, and public health and safety requirements in the preliminary stages of design. Specifically, the FRA identifies if there are potential risks (1) of meeting FEMA Code of Federal Regulations (CFR) requirements, (2) of meeting local jurisdiction code floodplain development requirements, and (3) to public health and safety in order for a project to be considered for permitting as a fish habitat enhancement project, as required per Revised Code of Washington (RCW) Section 77.55.181. The FRA also identifies subsequent deliverables (e.g., floodplain analysis, no-rise, Conditional Letter of Map Revision [CLOMR], etc.) that may be needed for the permitting process as shown in Figure 4-8. Each of these subsequent deliverables are covered in more detail in the following sections and are described on the FEMA website. This preliminary assessment should allow the PEO and other disciplines to know if the project may need a CLOMR, easement, ROW, temporary construction easement (TCE), etc. allowing the project schedule and budget to be modified, if needed, early in the project delivery process. These processes can be lengthy and add significant time to a project, so early coordination is critical. A Letter of Map Revision (LOMR) is completed after the project has been constructed. All stream projects, regardless whether they are in a FEMA special flood hazard area (SFHA), shall complete an FRA. The FRA template used by WSDOT and training can be found on WSDOT's Hydraulics website. For more information regarding the permitting process associated with floodplains, see the WSDOT *Environmental Manual*.

Figure 4-8 Potential Deliverables for Permitting Process



4-7.1 *No-Rise Analysis*

A no-rise analysis is required when the project is located in a FEMA-designated floodway, or when local codes have requirements above the FEMA minimum standards. A no-rise analysis provides the required justification and technical data to support a no-rise certificate to obtain a flood hazard permit from a local jurisdiction. This permit is submitted and approved locally, and does not require further permitting by FEMA.

4-7.2 *Floodplain Analysis*

If a project is not located in a FEMA-designated floodway, a floodplain analysis shall be conducted. Contact the State Hydraulics Office for more information about the complexity of the floodplain analysis required.

4-7.3 *Conditional Letter of Map Revision*

FEMA requires a CLOMR when a no-rise cannot be met or when there is a realignment or change to a floodway. Local communities may require a CLOMR for other work done in the floodplain. Contact the State Hydraulics Office for information about when a CLOMR is needed and for assistance in requesting effective FEMA models.

4-7.4 *Letter of Map Revision*

Once a project is constructed an as-built survey is required to verify the results from the CLOMR (if required) and to submit a Letter of Map Revision (LOMR) request to FEMA. Contact the State Hydraulics Office for information about when a LOMR is needed and for assistance in requesting effective FEMA models.

4-8 Hydraulic Analysis for Riverine and Coastal Areas

WSDOT requires the use of SRH-2D with steady-state boundary conditions unless otherwise approved by the State Hydraulics Office for all riverine and coastal area projects. Determine modeling extents and terrain spatial resolution necessary to support the basis of design and coordinate early with survey crew to collect these data. For a FEMA no-rise assessment, CLOMR, or LOMR, the model required by the local floodplain manager is acceptable for the analysis; however, an SRH-2D model is still required for design. Any project that uses SRH-2D modeling will require a specialty report with model outputs as outlined in the WSDOT specialty report templates. All hydraulic modeling files need to be provided to HQ Hydraulics by uploading to the ProjectWise project folder: the files shall include all input and output files; remove extraneous or working files/simulations; coverages and simulations shall be clearly named. As a basis for 2D hydraulic modeling principles, FHWA has developed a reference document for 2D hydraulic models called *2D Hydraulic Modeling for Highways in the River Environment* (FHWA 2019). WSDOT has put together a 2D hydraulic modeling checklist that is used during model audits to ensure that stream designers are meeting the requirements of the *Hydraulics Manual* as well as the FHWA manual; this checklist can be found on the WSDOT Hydraulics Training web page.

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.

4-8.1 *Intermediate Conditions*

In a situation where an existing feature affects the hydraulics at the focused modeling location (e.g., upstream or downstream culvert, bridge, or weir) and the possibility exists that the structure could be removed or altered within the lifetime of the proposed construction, hydraulic modeling shall be completed for both the condition that the existing structure stays in place and having it removed. The proposed project shall meet design requirements for both current and future conditions.

4-8.2 *Tidal Crossings*

Tidally dominated crossings are crossings at locations where the flux varies with the tides and reverses direction during normal tidal events. These sites shall be modeled as unsteady-state simulations using the tidal hydrograph described in Section 7-5.3 as the downstream boundary condition. Tidally influenced crossings are affected by tides, and are further described in Section 7-3.5.4. These may be modeled as steady- or unsteady-state simulations. The decision to model as steady or unsteady state is site-dependent and modeling as steady state must be approved by the State Hydraulics Office. If the system is modeled as a steady-state simulation, each flood event must be modeled with both high and low tide WSELs as the downstream boundary condition.