

NOAA Fisheries Guidelines for Salmonid Stream Crossings in WA, OR and ID - 2022

NOAA FISHERIES

Guidelines for Salmonid Passage at Stream Crossings in Oregon, Washington, and Idaho

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Acronyms and Abbreviations

Symbol or Acronym	Term or Title
BOR	U.S. Bureau of Reclamation
ft^3/s	cubic feet per second
ESA	Endangered Species Act
FERC	Federal Energy Regulatory Commission
ft^3	cubic foot
ft/s	foot per second
MSA	Magnuson-Stevens Fishery Conservation and Management Act
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
O&M	operations and maintenance
USACE	U.S. Army Corps of Engineers
WCR	West Coast Region

1 Introduction

The guidance in this document applies to projects located in Washington, Oregon, and Idaho. Given significantly different hydrologic conditions, projects in California should refer to: Guidelines for Salmonid Passage at Stream Crossings in California (NMFS 2019). The content herein primarily addresses road crossings and grade control projects, where the bankfull width is 20 ft or less. Projects where the bankfull width is greater than 20 ft may still benefit from the information contained here, but due to scale effects associated with wider channels (Frissell and Nawa 1992), it may not be applicable.

The WCR has developed a flow chart for how to use their various fish passage guidance documents (Figure 1-1). Prior to designing a stream crossing facility, NMFS recommends the project proponent familiarize themselves with the “NOAA Fisheries WCR Guidance to Improve the Resilience of Fish Passage Facilities to Climate Change” (Improving Resilience) guidance document. The Improving Resilience document outlines how to incorporate projected future flows the facility may experience over the life of the project and should be the starting point for the design process.

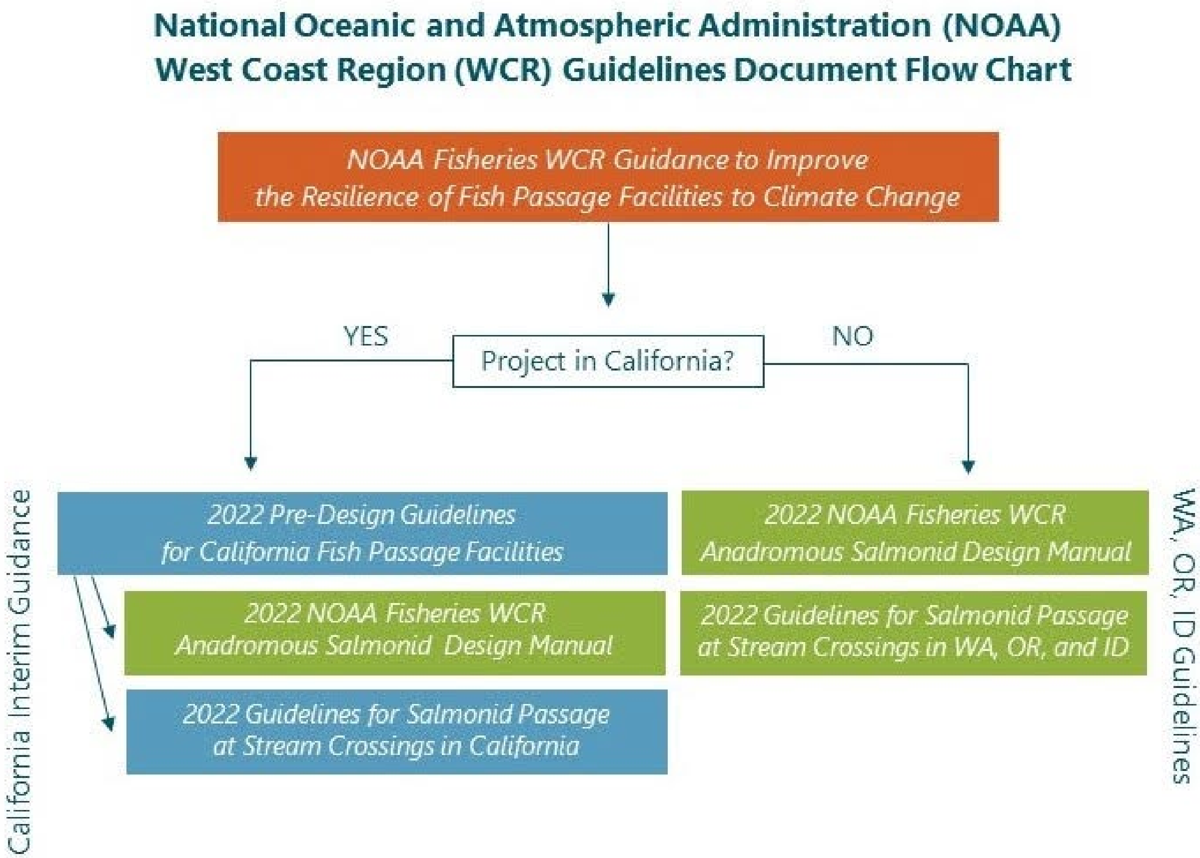


Figure 1-1. Flow Chart for Interaction of NMFS Design Guidance

The Environmental Service Branches provide technical and engineering assistance to National Oceanic and Atmospheric Administration's National Marine Fisheries Service (NMFS) West Coast Region (WCR) fisheries biologists. NMFS also plays a supportive and advisory role in the management of living marine resources in the areas under state jurisdiction. This document is intended to assist with improving conditions for salmonids that must migrate past barriers to complete their life cycle. Effective Fish passage requires the integration of numerous scientific and engineering disciplines including, but not limited to, fish behavior, ichthyomechanics, hydraulics, hydrology, fluvial geomorphology and engineering. Installing a fish passage structure does not constitute providing satisfactory fish passage unless all the above components are adequately factored into the design.

This document is intended to: 1) provide internal assistance to NMFS biologists in designing effective fish passage; 2) promote consistency across the WCR region; and 3) support the implementation of NMFS's statutory authorities related to the conservation and protection of marine resources.

The efficacy of any fish passage structure, device, facility, operation, or measure is highly dependent on local hydrology, target species and life stage, obstacle orientation relative to the stream, facility operation, and many other site-specific considerations. While the information provided herein will apply to many structures, it should be regarded as general guidance for the design, operation, and maintenance of fishways throughout the Pacific Northwest. The criteria described in this document are not universally applicable and should not replace site-specific recommendations.

This document provides general guidance and is not intended as an alternative to interactive consultation with NMFS biologists and engineers. Application of these criteria in the absence of consultation does not imply approval by NMFS. This document provides criteria and additional guidelines for the design and operation of facilities at barriers to fish migration and water intakes in Washington, Oregon, and Idaho. The facilities are designed to create safe passage routes for adult and juvenile salmonids in rivers and streams and through reservoirs, restore habitat connectivity within watersheds, and enhance salmonid population productivity. NMFS will use the criteria and guidelines to advise project applicants on the design of future fish passage projects and modifications to existing projects. The criteria are based on decades of experience developing, testing, operating fish passage systems and relies on the best available scientific information.

This document, *Guidelines for Salmonid Passage at Stream Crossings in Oregon, Washington, and Idaho* supersedes sections of the following document:

- Northwest Region's *Anadromous Salmonid Passage Facility Design*, dated July 2011

This document provides criteria and guidance for anadromous salmonids only. For additional guidance concerning non-salmonids, refer to applicable state and federal entities.

Throughout the chapters all criteria are italicized to be easily identifiable.

NMFS has separated these fish passage engineering guidelines into two volumes: *NOAA Fisheries West Coast Region Anadromous Salmonid Passage Design Manual* represents guidelines that are based on decades of research, monitoring, and NMFS' experience with these types of passage systems. NMFS considers material in *NOAA Fisheries West Coast Region Anadromous Salmonid Passage Design Manual* to be in a mature state and does not anticipate it will change significantly over time. This Stream Crossings document, *Guidelines for Salmonid Passage at Stream Crossings in Oregon, Washington, and Idaho* represents a growing body of work that NMFS expects will expand significantly in the future. Separating these guidelines into two volumes will allow NMFS to refine and expand *Guidelines for Salmonid Passage at Stream Crossings in Oregon, Washington, and Idaho* in the near future as new information becomes available, without having to reopen and modify the entire guidelines document. This volume includes Stream Crossings (Chapter 3) and Grade Control (Chapter 4)

The criteria and guidelines in this Volume address more emerging fields of fish passage engineering and stream restoration. The criteria and rationale provided will be revised as needed if new information suggests that updated criteria would further improve passage conditions for fish.

1.1 Statutory Background

NMFS is mandated by U.S. Congress to manage, conserve, and protect living marine resources within the U.S. Exclusive Economic Zone. NMFS is authorized to conduct these actions under the Federal Power Act (FPA; administered by the Federal Energy Regulatory Commission [FERC]), the Fish and Wildlife Coordination Act (administered by the U.S. Fish and Wildlife Service), the Endangered Species Act (ESA), and the Magnuson-Stevens Fishery Conservation and Management Act (MSA). This document provides criteria and technical assistance to project proponents on the design of fish passage facilities in order to provide safe, timely, and effective fish passage, consistent with NMFS responsibilities under the ESA, FPA, and MSA.

The requirement of safe, timely and effective passage derives from the unofficial but reliable definition of a fishway presented by Congress in a report related to the Energy Policy Act of 1992. The definition of "safe and timely passage" was expanded to include both passage structures and operations "necessary to ensure the effectiveness" of such structures. None of the terms "safe," "timely," or "effective" are further defined. However, in practice NMFS typically includes provisions which give these terms meaning. Regarding "safe" passage, NMFS requires licensees to design and operate their fishways so that they minimize the occurrence of injury or mortality experienced by fish while attempting to utilize the fishway. Regarding "timely" passage, a fishway prescription may include provisions for reducing the time in which a fish utilizing the fishway is subjected to stressful interactions, such as time spent in a trap or in transit, or a requirement for flows which will attract fish to a passage facility. Regarding "effective" passage, NMFS typically includes provisions requiring the operator to ensure that its facility succeeds in passing as close to 100% of the fish attempting to migrate through the system as possible.

Following these criteria will likely streamline processes, improve certainty, and improve the likelihood of success. NMFS also provides support and advice to states regarding the management of living marine resources in areas under state jurisdiction. This includes salmon (*Oncorhynchus spp.*) and steelhead (*O. mykiss*) due to their economic, cultural, recreational, and symbolic importance to society (NRC 1996).

NMFS pursues fish passage to contribute to its fishery management and ESA recovery goals. In reviewing, planning, designing, and implementing fish passage facilities, NMFS engineers will coordinate with NMFS biologists to make sure the particular target species, population numbers, migration timing and recovery goals are met.

1.2 Design Process

Resolving effects on salmonid migrations from barriers involves the integration of information on fish behavior and physiology, biomechanics, hydraulic and hydrologic conditions, and fluvial geomorphology. Simply installing a fish passage structure does not constitute providing satisfactory fish passage. A successful design requires that information on each of these components be factored into the design.

Instances can also occur where a fish passage facility may not be a feasible solution for correcting a passage impediment due to biological, societal, or economic constraints. In these situations, removal of the impediment or altering project operations may be a suitable surrogate in lieu of constructing fish passage facilities (Clay 1995).

This document addresses design features that may provide for the safe, timely, and effective passage of fish. It is the responsibility of the design engineer to ensure that other design requirements are met, such as the structural integrity of the facility and public safety.

When determining whether NMFS will promote or prescribe solutions for fish passage issues, NMFS will rely on a collaborative approach that considers the views of other fisheries resource agencies, Native American tribes, non-governmental organizations, citizen groups, and other governmental agencies. The approach strives to consider fish passage objectives developed by other parties (e.g., well-placed stakeholder groups) to support fisheries restoration and habitat enhancement actions identified in conservation plans.

This document provides specific fish passage facility design criteria and guidelines for actions within the Pacific Northwest pertaining to the various authorities of NMFS. In consultation with the project proponent, NMFS will apply the criteria and guidelines to major upgrades to existing facilities and the design of new fish passage facilities. Existing facilities that are not compliant with this document may have to be modified using the criteria identified herein if fish passage problems are observed at these facilities.

1.3 Temporary and Interim Passage

Where construction or modifications to artificial impediments (e.g., dams), natural impediments (rockslides, other natural issues) or upstream passage facilities are planned, upstream and downstream passage may be adversely impacted or interrupted. If possible, these activities should be scheduled for periods when migrating fish are not present, as specified in the in-water work period allowable for construction of facilities in streams. However, this may not always be possible or advisable. In these cases, an interim fish passage plan should be prepared and submitted to NMFS for review, in advance of work in the field.

In the interim plan, upstream and downstream fish passage should be provided for any adult or juvenile fish likely to be present in the action area during construction, unless passage did not exist before construction or where the stream reach is naturally dry at the time of construction. Methods for work area isolation and dewatering, as necessary, should be determined in consultation with NMFS.

Design criteria listed elsewhere in this document also apply to the interim passage plan. Where this is not possible, project owners should seek NMFS review of alternate interim fish passage design criteria, and a final interim passage plan. Coordination with NMFS ahead of time is advised to determine appropriate work windows and other recommended alternatives or both.

1.4 Experimental Technologies

Proponents of new, unproven fish passage designs (i.e., designs not meeting the criteria and guidelines contained in this document) should provide NMFS with the following prior to moving into the 30% design phase:

- A biological basis for the concept
- A demonstrated, favorable fish behavioral response in a laboratory setting
- An acceptable plan for evaluating the prototype installation
- An acceptable alternate fish passage design developed concurrently with the unproven fish passage design that satisfies the criteria listed herein, should the prototype not perform as anticipated nor adequately protect fish

The experimental technologies process is intended for new and innovative technologies that can be broadly applied, rather than for a fish passage design that applies to a single site. Appendix C (Experimental Technologies) provides additional information on the NMFS approval process for unproven fish passage technologies.

1.5 Section 7 Consultation under the Endangered Species Act

This fish passage manual can be useful during Endangered Species Act consultations. Incorporating the criteria within this document will help project proponents design projects that provide fish passage in a variety of situations. During the design process project developers can incorporate criteria within this document and work with NMFS engineers and biologists to ensure their projects meet these fish passage criteria. While this document provides substantial criteria related to fish passage, there are aspects of project design that are beyond the scope of this document. For instance, this manual does not identify or endorse specific construction best management practices. Project developers should coordinate with NMFS on project elements that fall outside the scope of this document.

This manual can also be used to achieve regulatory streamlining by aiding in the development of programmatic ESA and EFH consultations on activities involving fish passage. By incorporating these criteria into programmatic actions, action agencies and other stakeholders can help ensure their actions provide fish passage and appropriate conservation for protected resources, while streamlining the regulatory process.

1.6 Additional Information

Additional information on fish passage is available at the WCR website: http://www.westcoast.fisheries.noaa.gov/. Questions regarding this document and requests for assistance from NMFS fish passage specialists can be directed to the following offices:

NOAA Fisheries West Coast Region
Environmental Services Branch
1201 Northeast Lloyd Boulevard. Suite 1100
Portland. Oregon 97232

2 Definition of Terms

Anadromous – pertaining to a fish species that displays the life history pattern known as anadromy in which adults spawn in fresh water and juveniles migrate to sea to grow to their final size and then return to fresh water to spawn (Quinn 2005).

Applicant – a person or entity that proposes to design, modify, or construct, a fish passage facility at an existing or new barrier, water diversion, or water conveyance that NMFS will review under its authorities identified in Chapter 1.

Apron – a flat or slightly inclined slab of concrete below a flow control structure that provides erosion protection and produces hydraulic characteristics suitable for energy dissipation or, in some cases, fish exclusion.

Attraction flow – flow that emanates from a fishway entrance with sufficient velocity and quantity, and in the proper location and direction, to attract upstream migrants into the fishway entrance. Attraction flow consists of gravity flow from the fish ladder and any auxiliary water system flow added at points within the lower fish ladder.

Baffles – physical structures placed in the water flow path designed to dissipate energy or redirect flow to achieve more uniform flow conditions.

Bankfull flow – the bank height when a stream or river channel is inundated under a flow that occurs at the 1.2-year to 1.5-year average flood recurrence interval. Bankfull height may be estimated by morphological features in the channel such as: 1) a topographic break from a vertical bank to a flat floodplain or from a steep to a gentle slope; 2) a change in vegetation from bare ground to grass, moss to grass, grass to sage, grass to trees, or no trees to trees; 3) a textural change of depositional sediment; 4) the elevation below which no fine debris (e.g., needles, leaves, cones, seeds) occurs; and 5) a textural change of fine sediment deposits (matrix material) between cobbles or rocks.

Bedload – sand, silt, gravel, soil, and rock debris transported by moving water on or near the streambed.

Channel Migration Zone - Channel migration zones are areas in a floodplain where a stream or river channel can be expected to move naturally over time in response to gravity and topography. Water bodies such as rivers and streams gain or release energy as they flow, carrying away or spreading out sediments, building new areas, and supporting a variety of fish, wildlife, and vegetation. Rivers with room to migrate have the highest diversity of aquatic habitats.

Conceptual design – an initial design concept based on the site conditions and biological needs of the species intended for passage, also sometimes referred to as preliminary design or functional design. This is the first phase in the design process of a fish passage facility and is discussed in Chapter 3.

Fish ladder – the structural component of an upstream fish passage facility (or fishway) that allows fish to move over a barrier by dissipating the potential energy caused by the head differential that results from a barrier being placed in a waterway. The ladder dissipates energy using a series of discrete pools, a series of baffled chutes and resting pools, or uniformly with a single baffled chute placed between an entrance pool and an exit pool.

Fish passage season – the range of dates that characterize when juvenile or adult life stages of a species will arrive at a specific location during their downstream or upstream migration. The locations could include, for example, a dam or an existing or proposed fishway.

Fishway – the suite of facilities, structures, devices, measures, and project operations that constitute and are essential to the success of an upstream or downstream fish passage system. The suite provides a water passage route around or through an obstruction that is designed to dissipate the energy in such a manner that enables fish to ascend the obstruction without undue stress (Clay 1995).

Fishway exit – the component of an upstream fish passage facility where flow from the forebay of the dam or barrier enters the fishway, and where fish exit the ladder and enter the forebay upstream of the dam.

Fishway weir – the partition that divides two pools in a fishway and passes flow between adjacent pools.

Flood frequency – the probable frequency that a streamflow will recur based on historical flow records. For example, a 100-year flood event refers to a flood flow magnitude that is likely to occur on average once every 100 years or has a 1% chance of being exceeded in any given year. Although calculating possible flood recurrence is often based on historical records, there is no guarantee that a 100-year flood will occur within the 100-year period, or not occur several times within that period.

Floodplain – the area adjacent to a stream that is inundated during periods of flow that exceed the channel capacity the stream has established over time.

Flow control structure – a structure in a water conveyance designed to maintain flow in a predictable fashion.

Flow duration exceedance curve – the plot of the relationship between the magnitude of daily flow and the percentage of time during a specific period that flow is likely to be equaled or exceeded. Flow exceedance curves may use flow data from an entire year or part of a year. For example, the 1% annual exceedance flow is the flow level exceeded 1% of the time within the entire year (i.e., 3.6 days on average), whereas the 1% exceedance flow for the fish migration window is the flow level exceeded 1% of the time during the fish passage season for a particular species and location. Exceedance values are usually derived using daily average flow data.

Freeboard – the height of a structure that extends above the maximum water surface elevation.

Functional design – an initial design concept based on the site conditions and biological needs of the species intended for passage. This is also sometimes referred to as preliminary design or conceptual design. Also, see the definition for conceptual design in this chapter. The functional design commonly includes the general layout, interior dimensions, and specifications covering the hydraulic features of the fishway (Clay 1995).

Hydraulic drop – the difference in total head between an upstream water surface and a downstream water surface. It includes the sums of the elevation head, pressure head, and velocity head at the upstream and downstream water surface locations. For fishway entrances and fishway weirs, the differences in velocity head and pressure head are usually negligible, and only water surface elevation differences are considered when estimating hydraulic drop across the structure.

Invert – the lowest inside surface of a culvert or flume.

Plunging flow – flow over a weir that falls into a receiving pool where the water surface elevation of the receiving pool is lower than that of the weir crest elevation. Surface flow in the receiving pool is typically in the upstream direction, downstream from the point of entry into the receiving pool. Also, see the definition for streaming flow in this chapter.

Preliminary design – an initial design concept based on the site conditions and biological needs of the species intended for passage. This is also sometimes referred to as a functional design or conceptual design. Also, see the definition for conceptual design in this chapter.

Redd – the nest a female salmonid excavates, deposits embryos into, and immediately buries with gravel substrate. Redds can be located in streams, rivers, or lake beaches. The locations selected vary with populations and species (Quinn 2005).

Scour – erosion of streambed material resulting in the temporary or permanent lowering of the streambed profile.

Soffit – the inside top of culvert or underside of a bridge.

Streaming flow – flow over a weir that falls into a receiving pool and where the water surface elevation of the receiving pool is above the weir crest elevation. In these situations, surface flow in the receiving pool is typically in the downstream direction and away from the point where flow enters the receiving pool.

Tailrace – the portion of the water channel below a dam that conveys turbine and spillway discharge downstream from the dam.

Tailwater – the body of water immediately downstream of a dam or other in-stream structure.

Thalweg – the streamflow path following the deepest parts (i.e., the lowest elevation) of a stream channel.

Upstream fish passage – fish passage relating to the upstream migration of adult and juvenile fish.

Upstream passage facility – a fishway system designed to pass fish upstream of a passage impediment, either by volitional passage (i.e., under their own swimming capability) or non-volitional passage (i.e., via a lift or transport vehicle).

Volitional passage – fish passage whereby fish transit a passage facility under their own swimming capability, using timing and behavior they choose, and under all naturally passable flows. Volitional passage means fish can enter, traverse, and exit a passage facility under their own power, instinct, and swimming capability. The fish pass through the facility without the aid of any apparatus, structure, or device (i.e., they are not trapped, mechanically lifted or pumped, or transported).

Weir – a low wall or dam built across the width of a river that pools water behind it while allowing water to flow steadily over the top of the structure.

3 Stream Crossings

3.1 Introduction

Chapter 3 contains criteria and guidelines for the design of stream crossings that provide upstream and downstream movement for all life stages of anadromous salmonids present at a site. These criteria and guidelines apply to bridges, culverts, and fords. For the purpose of fish passage, the distinction between a bridge, culvert, and low water crossing (also referred to as a ford) is less important than the effect the structure has on the form and function of the stream.

In addition to providing fish passage, any stream crossing design should maintain the ecological function of the stream, pass woody debris, pass flood flows and sediment, analyze the scour potential, and account for other species present at the site. The design team should collaborate with biologists and engineers familiar with the site to assess potential effects on species and life stages present and site geomorphology.

The criteria and guidelines presented in this chapter are general in nature. There may be cases where site constraints or unusual circumstances dictate a modification to one or more of these design elements. Conversely, where there is an opportunity to protect salmonids, additional site-specific criteria may be appropriate. Variances will be considered by NMFS on a project-specific basis. It is the responsibility of the applicant to formally request and provide compelling evidence in support of any modification of a guideline or criterion contained in this chapter. Requests must be submitted for approval early in the design process, well in advance of a proposed ESA consultation.

3.2 Preferred Alternatives for New, Replacement, or Retrofitted Stream Crossings

3.2.1 Description and purpose

Bridges, culverts, and fords have the potential to pass fish but some may facilitate better passage at a particular site. Based on the biological and ecological condition of an individual site, NMFS may require a specific road crossing design to restore or maintain critical fluvial processes and floodplain connectivity and morphology within the stream crossing-floodplain corridor.

3.2.2 Specific guidelines and criteria

NMFS prioritizes the following alternatives and types of structures in the order shown:

1. *No new crossing structure: realign the road to avoid crossing the stream.*
2. *Removal: Completely remove the crossing and restore the stream channel.*

3. *Bridge: Span the historically active floodplain or channel migration zone. This allows for long-term dynamic channel stability.*
4. *Stream Simulation Design: The following structures are prioritized in order of their ability to maintain stream simulation conditions over the life span of the project. methods:*
    a. *Bridge – Clear span*
    b. *Bridge – With mid-span piers*
    c. *Culvert*
        i. *Bottomless arch*
        ii. *Box culvert*
        iii. *Round pipe*
        iv. *Squash pipe*
    d. *Modified Stream Simulation Design – Requires NMFS approval.*
5. *Ford*
6. *Hydraulic design: This method may be accepted only when NMFS agrees that alternatives 1 through 5 (above) are unattainable or inappropriate. Hydraulic design styles include backwatered, embedded, baffled, and non-embedded culverts and culverts designed with a fishway.*

3.3 Stream Crossings in Spawning Areas

3.3.1 Description and purpose

The design team should work collaboratively with biologists familiar with the site to assess potential impacts on spawning, life stages requiring passage, and to assess bed stability. Bridges spanning the stream channel and floodplain provide better long-term dynamic channel stability, retention of existing spawning areas, maintenance of food (benthic invertebrate) production, and minimized risk of failure at spawning sites. Maintaining the stream bed at the natural grade and substrate material in as natural a condition as possible will reduce unnatural scour of spawning redds and promote population productivity through increased connectivity of the channel with the floodplain. These conditions can be facilitated better with bridge designs compared to culverts.

3.3.2 Specific criteria and guidelines

If a segment of stream channel where a crossing is proposed is in an active salmonid spawning area, then only Stream Simulation Design is recommended, and a bridge is the preferred structure for providing Stream Simulation.

It is important to maintain the bed at grade and substrate material in as natural a condition as possible. Bridges in particular, support population productivity by reducing scour of spawning redds through increased connectivity of the channel with the floodplain.

3.4 Crossing Alignment

Crossings which skew their alignment with the stream channel increase the probability of debris plugging (Furniss et al. 1998). A skewed crossing alignment may also affect scour and streambed instability through the crossing or large-scale loss of bed material exposing culvert bottoms or footings. Any of these outcomes can adversely affect upstream passage of adult and juvenile salmonids.

3.4.1 Specific criteria and guidelines

Stream crossing structures should be oriented to eliminate skew relative to the adjacent stream channel. Structures should be aligned to eliminate abrupt changes in flow direction upstream or downstream of the crossing.

Aligning the crossing structure so there are no abrupt changes in flow direction can often be accommodated by changing the road alignment, aligning a bridge's substructure components parallel to the stream flow, or by slightly elongating the culvert. Excessively elongating the culvert should be weighed against a better crossing alignment and modifying transition sections upstream and downstream of the crossing.

3.5 Culvert Length

3.5.1 Description and purpose

Culverts that are long compared to streambed width can reduce a stream's natural sinuosity and result in sediment transport problems even if the channel slope remains constant. Culvert length can also reduce the roughness, energy dissipation, channel planform, and promote unanticipated scour of the streambed through the culvert (Barnard et al. 2013). These impacts may lead to bed and bank instability through the culvert or large-scale loss of bed material exposing the culvert bottom or footings. Any of these outcomes can adversely affect upstream passage of adult and juvenile salmonids. Culvert length can also increase the risk of debris accumulation and plugging.

3.5.2 Specific criteria and guidelines

When the culvert length-to-span ratio is greater than 10 a bridge should be selected (Barnard et al. 2013). Stream crossings that are long compared to streambed width can reduce a stream's natural sinuosity and result in sediment transport problems even if the channel slope remains constant.

3.6 Flood Capacity

3.6.1 Description and purpose

Culvert failures in the Pacific Northwest occur primarily due to debris plugging, not insufficient hydraulic capacity (Furniss et al. 1998). Relative risk of culvert failure due to plugging is commonly assessed in the context of large wood. A deterministic presence or absence of large wood is the most often method of assessing this failure. Plugging risk is not a presence/absence determination and risk lies on a graded scale relative to site specific and watershed scale factors. Complicating assessing plugging risk is the fact that the plugging process can be initiated by relatively small pieces of wood and debris, not routinely identified as potentially troublesome (Flanagan 2004). Culvert failures due to plugging can lead to extensive damage of aquatic organism habitat which may persist over a long period of time (Love and Bates 2009). Culvert failures can also impair or impede fish passage. NMFS has provided risk pathway tables in the Improving Resilience document that may be of assistance for increases in debris plugging after fire events. Table 8 in that document covers risks that culverts may experience over a variety of facility element considerations.

3.6.2 Specific guidelines and criteria

All culverts should be designed to withstand the 100-year-recurrence peak flood flow without failure of the crossing. Stream crossings located in areas where there is significant risk of plugging by flood-borne debris should be designed to pass the 100-year peak flood with a minimum of 1 foot of freeboard (Barnard et al. 2013).

A number of culvert design manuals originating in the Pacific Northwest recommend culverts be designed to pass the 100-year flood (Barnard et al. 2013) (Love and Bates 2009) (Cafferata et al. 2017). This capacity should help reduce risk of crossing failure during flood flows.

3.7 Embedded Pipe Design Method

3.7.1 Description and purpose

Embedded Pipe Design Method represents a class of simplified culvert designs intended to size a culvert sufficiently wide, and embedded deep enough into the channel, to allow natural movement of bedload and formation of a stable streambed inside the culvert. Determination of the high and low fish passage design flows, water velocity, and water depth is not required for this method since the stream hydraulic characteristics within the culvert are intended to mimic the stream conditions upstream and downstream of the crossing. This design approach is predominantly for use in agricultural settings where irrigation canals or excavated channels contain fish and require crossing; and a landowner can perform the work of excavation and installation without the aid of surveying and engineering.

Embedded Pipe Methods cover several culvert designs originating in the Pacific Northwest, including: Active Channel method (NMFS 2001; CDFG 2002); No-Slope method (Barnard et al. 2013); Low Slope Stream Simulation Method (Love and Bates, (2009). These methods are similar in their design approach and differ predominately with the limitations on pipe length and slope of pipe installation. Price et al. (2010) concluded that as many as 45% of the designs using a No-Slope design approach failed to meet fish passage criteria based on post-construction evaluations. Most of the failure modes identified in Price et al. (2010) seem to be centered on conditions that arise from installing a pipe at 0% slope, regardless of channel gradient. To minimize failure of this method of culvert design, NMFS recommends installing Active Channel Method, No-Slope method, and Low Slope Stream Stimulation method pipes to the proposed average gradient of the project reach.

3.7.2 Specific criteria and guidelines

The following subsections provide specific design criteria and guidelines for Embedded Pipe Design Method crossings.

3.7.2.1 Culvert width

The minimum culvert width should be equal to, or greater than, 1.5 times the bankfull width.

3.7.2.2 Culvert diameter

Minimum diameter should be 6 feet.

3.7.2.3 Maximum stream slope

Average stream slopes should be 3% or less.

3.7.2.4 Invert depth

Inlet and outlet inverts of the culvert should be set at a minimum of 3 feet below the streambed.

3.7.2.5 Embedment

The inlet and outlet invert should be buried into the streambed not less than 30% of the culvert height at the outlet and not more than 50% of the culvert height at the inlet.

3.7.2.6 Fill Materials

Fill materials should be composed of natural or simulated streambed material.

3.8 Streambed Simulation Design Method

The Stream Simulation Design method (Forest Service Stream-Simulation Working Group, 2008; Barnard et al., 2013) is intended to mimic the natural stream processes through a stream crossing and produce a design where fish passage, sediment transport, and flood and debris conveyance function as they would in a natural channel. Determining high and low fish passage design flows, water velocity, and water depth are not required for Stream Simulation Design because the stream hydraulic characteristics within the crossing are designed to mimic natural stream conditions upstream and downstream of the crossing. This method requires additional information on hydrology and geomorphology (e.g., the topography of the stream channel) and a higher level of engineering expertise compared to Embedded Pipe Design Methods.

3.8.1 Description and Purpose

3.8.2 Specific Criteria and Guidelines

The following subsections provide specific design criteria and guidelines for Stream Simulation Design crossings.

3.8.2.1 Crossing width

The minimum crossing span should be 1.5 times the bankfull width.

3.8.2.2 Streambed slope

The slope of the reconstructed streambed within the crossing should maintain an average slope of 1.0 to 1.25 times the natural average slope of the adjacent upstream and downstream reaches.

3.8.2.3 Culvert slope

When a culvert is used, the culvert slope should approximate the slope of the stream through the reach in which it is being placed.

3.8.2.4 Channel vertical clearance

The minimum vertical clearance between the crossing bed and the culvert or bridge deck soffit elevation should be no less than 6 feet to allow access for debris removal.

3.8.2.5 Embedment

Inverts, abutments, footings, or other foundations types should be designed for the total anticipated scour depth. Minimum embedment depth of inverts, footings, and abutments should be 3 feet. Pipe inverts (inlet and outlet) should be buried into the streambed not less than 30% and not more than 50% of the culvert height.

3.8.2.6 Fill materials

Fill materials should be composed of materials of similar size composition to natural bed materials that form the natural stream channels adjacent to the road crossing.

The designer should demonstrate to NMFS that the streambed of the crossing will be stable over time. This can be accomplished by assessing hydraulic conditions through the passage corridor over the range of fish passage design flow and whether a sufficient amount of bed material will be transported through the crossing to maintain the integrity of the streambed over time. NMFS may agree that incorporating large fill material into the design would maintain grade and provide resting areas for migratory fish.

3.8.2.7 Scour prism

Maintain the scour prism as a clear, unobstructed opening (i.e. free of any embankment fill, bed retention sills, scour countermeasure, or structural material). The horizontal dimension of the scour prism is defined as 1.5 times the bankfull width, and the vertical dimension is defined as the total scour depth elevation or the criteria embedment depth as described in 3.8.2.5, whichever is greater. Banklines incorporating irregular sized rock (Forest Service Stream-Simulation Working Group 2008), "course band" rock designs (Barnard et al. 2013), or similar; can be within the scour prism. Engineered material used to create stable bank-lines or simulated floodplains at the high design flow within the crossing are allowed.

The scour prism for a bottomless arch culvert and an elliptical culvert are illustrated in Figure 3-1. The scour prism is a cross-sectional area of the stream channel applied through the entire length of the road crossing design.

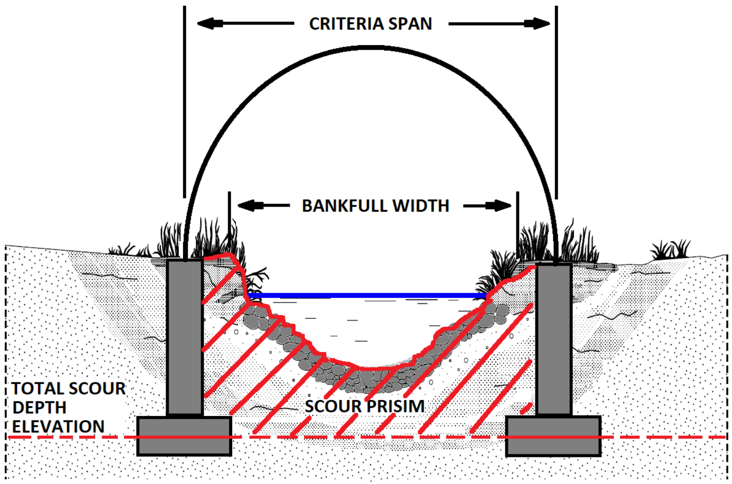
3.8.2.8 Bankline

Irregular banklines formed by lining rock of varying sizes along the culvert walls or by placing rock clusters at culvert walls, may improve channel complexity. Lack of channel complexity has been observed in stream simulation designs (Barnard et al. 2015) even though design methods are intended to mimic channel complexity of the reference reach. Creating banklines along the culvert walls may improve channel form complexity and habitat.

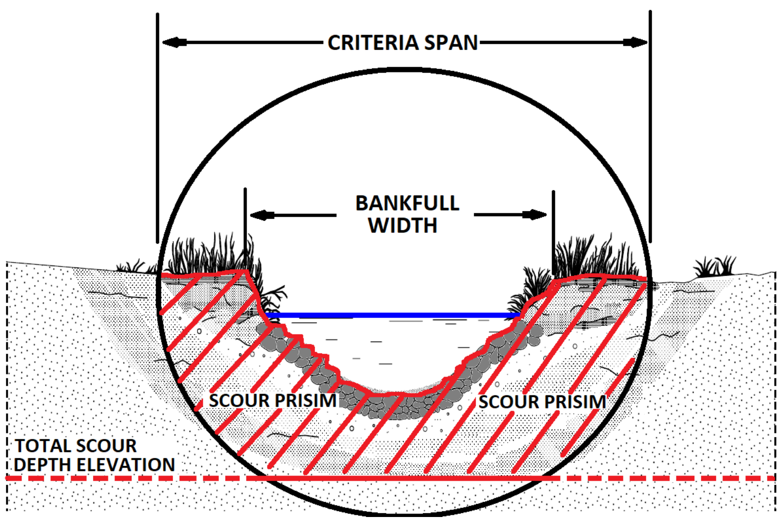
3.8.2.9 Simulated floodplain

Closed-bottom pipes less than 8 feet in diameter may pose challenges related to construction feasibility and long-term sustainability of a simulated floodplain. It is recommended that a simulated floodplain occupy no more than 30% of the criteria span.

Recommendations for the design of a simulated floodplain (i.e., bankfull bench) are still being developed. Forest Service Stream-Simulation Working Group (2008) states that sometimes a simulated floodplain can be constructed in a road crossing design but gives no detail on the design of such a structure. It has been shown via modeling (ESA Draft 2017) that there may be substantial benefits to the development of channel complexity and persistence of channel form and function through a road crossing when a pseudo floodplain is constructed. Barnard et al. (2015) observed a general lack of channel complexity in stream simulation designs even though mimicking the complexity and natural channel processes of the reference reach is a stated goal and intent of stream simulation design. Implementation of a simulated floodplain structure in road crossing designs may be critical to development and maintenance of long-term channel complexity and accompanying fluvial processes. Although no data supports any scale effects associated with construction of a simulated floodplain in closed pipes, it seems reasonable to be cautious of potential scale effects related to pipe size. Smaller pipes may reduce the potential benefits of constructing a simulated floodplain when compared to larger pipes. At some smaller pipe size simulated floodplains are not advisable. As the pipe diameter is reduced, pipe diameter and material sized to withstand a design flood may begin to converge on one another. This convergence may create channel stability issues or may functionally armor the crossing bed. Neither of these outcomes are desirable for fish passage.



(a) Scour prism in bottomless arch culvert (need modified image using “total” scour depth)



(b) Scour prism in elliptical culvert

Figure 3-1. Illustration of scour prism concept

3.9 Modifications to Stream Simulation Projects

Modification to stream simulation designs should be discussed with NMFS as part of the design process. Contact NMFS prior to consultation for project specific design input.

Stream simulation design was primarily developed for projects with a channel (1) that is alluvial, (2) possesses sediment transport characteristics which can replenish and maintain the simulated channel over the life expectancy of the road crossing, (3) can retain the average slope of the reference reach, and (4) the span of the crossing can incorporate the bankfull channel plus an appropriate degree of floodplain. On occasion geomorphic features such as the bankfull width cannot be confidently predicted by any means. This may occur at sites with:

- Moderately to heavily influenced by alluvial fans
- Backwater effects at confluences, estuaries, or impoundments
- Moderate to large natural breaks or discontinuities in stream channel slopes
- Channels with moderate to heavy bed or bank instability

Other conditions where stream simulation may not produce the intended results are identified by Barnard (2013) and Love and Bates (2009) and include the following:

- Projects exhibiting an extensive upstream wetland complex or pond
- Bedrock dominated systems or reaches
- Underfit channels: channel occupies a valley formed by glacial or fluvial processes far in excess of those present today
- Channelized or unnaturally confined systems or reaches
- Colluvial dominated systems or reaches
- Reference reach conditions predominately controlled by wood and debris
- Colluvial dominated systems or reaches

In these cases, modifying stream simulation design methods may be required. Design width of the crossing may need to exceed the stream simulation standard by some factor of safety, or a new width supported through hydraulic modeling. Boundary conditions for hydraulic models used to support modification of stream simulation design must adhere to the characteristics of stream simulation design outlined by Barnard (2013) below:

- Provide 100 year + flood conveyance with some freeboard
- Transport wood, debris, and sediment
- Similar sediment gradation and distribution as the reference reach
- Allow vertical adjustment of the streambed
- Provide bed mobility and stability
- Continuity of hydraulic conditions compared to the reference reach
- Mimic channel form, roughness, and gradient of reference reach
- Provide similar in-stream and margin habitat as the reference reach
- Ensure passage of fish and other aquatic organisms

3.10 Hydraulic Design Method

3.10.1 Description and Purpose

The Hydraulic Design Method is a design process that matches the hydraulic performance of a culvert with the swimming abilities of a target species and age class of fish. The Hydraulic Design method requires hydrologic data analysis; open channel flow hydraulic calculations; determinations of the high and low fish passage design flows, water velocity, and water depth; and information on the swimming ability and behavior of the target fish species and age classes.

The drawback of using the Hydraulic Design method is that it only targets the physiology of specific fish species and lacks the sediment transport and geomorphic processes critical to restoring and maintaining a healthy ecosystem. There are also significant errors associated with estimating hydrologic parameters and fish swimming speeds that should be resolved by making conservative assumptions during the design process.

3.10.2 Specific Criteria and Guidelines

The following subsections provide specific design criteria and guidelines for the Hydraulic Design method.

3.10.2.1 High fish passage design flow

The high design flow should be average daily flow exceeded 1% of the time during the time fish are expected to be present at the site. If flow duration data or methods necessary to compute the data are not available, then 50% of the 2-year flood recurrence interval flow may be used as an alternative.

3.10.2.2 Low fish passage design flow

For passage of adults, if flow duration data are available or can be synthesized, the average daily flow exceeded 50% of the time adults are expected to be present or 3 ft^3/s, whichever is greater, should be used as the low fish passage design flow. For juveniles, the 95% annual exceedance flow or 1 ft^3/s, whichever is greater, should be used.

The low design flow for fish passage is used to determine the minimum depth of water within a culvert. Hydraulic controls may be required to maintain depth at low flows.

3.10.2.3 Minimum water depth

Minimum water depth at the low fish passage design flow should be:

- *1 foot for adult steelhead and chinook, coho, and sockeye salmon;*
- *0.75 foot for pink and chum salmon; and*
- *0.5 foot for all species of juvenile salmonids as measured in the centerline of the culvert.*
- *The minimum depth within the culvert barrel should be calculated at fish passage design low flow.*

3.10.2.4 Maximum hydraulic drop

Hydraulic drops at, or adjacent to, the inlet, inside the culvert, or at the outlet do not provide good fish passage and should not be included in design.

3.10.2.5 Minimum culvert width

The minimum culvert width is 6 feet.

3.10.2.6 Minimum vertical clearance

The minimum vertical clearance between the culvert bed and the inside soffit of the culvert should be 6 feet.

This clearance provides access for debris removal. Smaller vertical clearances may work if a sufficient inspection and maintenance plan is provided with the design that ensures the culvert will be free of debris during the fish passage season.

3.10.2.7 Embedment

The bottom of the culvert should be buried into the streambed a minimum of 20% of the height of the culvert below the elevation of the tailwater control point downstream of the culvert, or 1 foot, whichever is greater.

3.10.2.8 Maximum culvert slope

Maximum slope should not exceed 0.5%.

3.10.2.9 Fish passage design velocity

Maximum velocity at the high fish passage design flow should be 1 ft/s.

3.11 Hydraulic Retrofit

3.11.1 Description and purpose

Culverts and bridges that impede passage may be temporarily enhanced through retrofitting efforts. Retrofitting is not a long-term passage solution, but it may be authorized for projects where passage barriers will not be removed or replaced in the immediate future. Fish passage may be improved using gradient control methods, baffles or weirs, and in some cases fish ladders. However, these retrofit actions are temporary and are not viewed as fish passage solutions that lead to the recovery of ESA-listed species.

3.11.2 Specific criteria and guidelines

The following subsections provide specific design criteria and guidelines for the Hydraulic Design Method.

3.11.2.1 Hydraulic controls

A change in water surface elevation of up to 1 foot through a culvert is acceptable for retrofitting culverts designed to pass adult salmonids, provided water depth and velocity in the *culvert meet other hydraulic guidelines. A jump pool at the culvert outlet should be provided that is at least 1.5 times the jump height, or a minimum of 2 feet deep, whichever is deeper.*

Hydraulic controls in the channel upstream and downstream of a culvert can be used to maintain a continuous low flow path through a culvert and stream reach. They can be used to facilitate fish passage by establishing the following desirable conditions: control depth and water velocity within a culvert, concentrate low flows, provide resting pools upstream and downstream of a culvert, and prevent erosion of bed and banks.

3.11.2.2 Backwatering

Retrofit designs maximize backwatering of the crossing invert to the maximum extent possible. If baffles are installed, the downstream hydraulic control should backwater the first two baffles at the culvert outlet at the low fish passage design flow.

3.11.2.3 Baffles

Baffles, and similar internal weirs, should only be considered when all other retrofit alternatives are deemed infeasible. This is because many baffle designs are untested for anadromous salmonid passage, and baffles reduce the hydraulic capacity of culverts and have the potential to accumulate debris. NMFS may agree to baffled culverts on a site-specific basis if compelling evidence of successful passage at other sites using a similar design is provided and a suitable monitoring and maintenance plan developed and followed.

Baffles may provide incremental fish passage improvement in culverts with excess hydraulic capacity that cannot be made passable by other means. However, baffles may also increase clogging and debris accumulation within the culvert and require special design considerations specific to the baffle type. Culverts that are too long or too high in gradient require resting pools or other forms of velocity refuge spaced at increments along the culvert length. Baffles should only be installed after approval by NMFS on a site-specific basis, and typically are only approved if the baffles will be used on an interim basis until a permanent passage solution is implemented. In addition, if baffles are installed, a suitable inspection and maintenance plan should be provided. For example, the plan could call for the baffles to be inspected prior to each passage season and after any flood event greater than a 2-year exceedance flow and subsequent debris removal after the inspection, if needed. The baffle design configuration should demonstrate that it can provide successful fish passage over the range of fish passage design flows. If an inspection and maintenance plan is implemented and fish passage standards are met, NMFS may approve the use of baffles in a permanent installation.

Retrofitting culverts can involve the following baffle alternatives and structure types. NMFS prefers to retrofit culverts using baffles or internal weirs over fishways.

Fishways (Chapter 5 in *NOAA Fisheries West Coast Region Anadromous Salmonid Passage Design Manual 2022*) are generally not recommended for retrofitting culverts, but they may be useful in limited situations. Fishways require a specialized site-specific design for each installation, for which NMFS should be contacted prior to ESA consultation.

3.12 Additional Design Criteria for Road Crossings

3.12.1 Specific criteria and guidelines

The following subsections provide the additional design criteria for road crossings.

3.12.2 Trash Racks and Livestock Fences

Trash racks and livestock fences should not be installed near culvert inlets because debris accumulations on the structures may severely restrict fish passage and potentially may injure fish.

Where fencing cannot be avoided, it should be removed during adult salmon upstream migration periods. Otherwise, a minimum of 9 inches of clear spacing between pickets should be provided up to the high flow water surface. Timely clearing of debris is also important, even if flow is getting around the fencing. Cattle fences that rise with increasing flow are highly recommended.

Where trash racks cannot be avoided, the rack should only be installed above the water surface level indicated by bankfull flow. Clear spacing between the vertical components of the trash rack should be a minimum of 9 inches. If trash racks are used, a long-term maintenance plan should be provided along with the design describing how the timely clearing of debris will be addressed.

3.12.3 Lighting

Natural or artificial supplemental lighting should be provided in new and replacement culverts that are more than 150 feet in length. Where supplemental lighting is provided, the spacing between light sources should not exceed 75 feet.

NMFS should be contacted if a culvert greater than 150 feet in length is under consideration for lighting.

3.12.4 In-Stream Work Windows

NMFS has established in-stream work windows for each watershed that correspond to times of the year when salmonid presence is minimized. Work in the active stream channel should be performed within the work window. Temporary crossings placed in salmonid streams for water diversion during construction activities should meet all the guidelines in this document. However, if it can be shown that the location of a temporary crossing in the stream network is not a fish passage concern at the time of the project, then the construction activity only needs to minimize erosion, sediment delivery, and impacts to surrounding riparian vegetation.

NMFS and state resource agencies establish instream work windows for major watersheds.

3.12.5 Installation

Crossings should only be installed when a site is de-watered and for which sediment control and flow routing plans have been developed, reviewed, and are agreed to by NMFS. Upon completion of construction the work area and riparian corridor should be fully restored with a mix of native locally adapted riparian vegetation. Use of species that grow extensive root networks quickly should be emphasized. Sterile non-native hybrids may be used for erosion control in the short term if planted in conjunction with native species.

3.12.6 Construction Disturbances

Disturbances to the installation site during construction should be minimized and the construction activity should not adversely impact fish migration or spawning. If salmon are likely to be present fish clearing or salvage operations should be conducted by qualified personnel prior to construction. If the fish are listed as threatened or endangered under the federal or state ESA NMFS should be consulted prior to initiating salvage operations. During salvage care should be taken to ensure fish are not chased under banks or logs that will be removed or dislocated by construction and stranded fish should be returned to a suitable location in a nearby stream by a method that does not require handling of the fish and as specified in the ESA take permit, if applicable. Construction disturbance to the riparian area should be minimized and the activity should not adversely impact fish migration or spawning.

3.12.7 Pumps

If pumps are used to temporarily divert a stream to facilitate construction a compliant fish screen should be used to prevent entrainment or impingement of small fish (Section 8.7 in NOAA Fisheries West Coast Region Anadromous Salmonid Passage Design Manual 2022).

3.12.8 Wastewater

Wastewater associated with project activities should be disposed of upland in a location that will not drain directly into any stream channel.

3.12.9 Other Hydraulic Considerations

Water surface elevations in the stream reach should exhibit gradual flow transitions both upstream and downstream of the road crossing. Abrupt changes in water surface and velocity should be avoided with no hydraulic jumps, turbulence, or drawdown at the entrance. A continuous low flow channel should be maintained throughout the stream reach.

3.12.10 Post-Construction Evaluation and Long-Term Maintenance and Assessment

A post-construction evaluation should be conducted to ensure the intended results of the design are accomplished and that mistakes are not repeated elsewhere. The post-construction evaluation consists of the following three elements:

1. *Verify the culvert is installed in accordance with proper design and construction procedures.*

2. Measure hydraulic conditions to ensure these guidelines are met.
3. Perform a biological assessment to confirm the hydraulic conditions are resulting in successful fish passage.

NMFS may assist in developing an evaluation plan to fit site-specific conditions and species. The goal of the evaluation plan is to generate feedback about techniques that are working well as well as those requiring future modification. The evaluations are not intended to cause extensive retrofits of a project unless the as-built installation does not conform to the design guidelines or an obvious fish passage problem persists. Over time, NMFS anticipates that the second and third elements of these evaluations will be abbreviated as clear trends in the data emerge.

All culverts should be inspected at least once annually over the life of the culvert to ensure proper functioning, any stream crossing failures or deficiencies discovered should be corrected promptly. A summary report of the inspection and corrections should be completed and submitted to the resource agencies. A less frequent reporting schedule may be agreed upon for proven stream crossings.

Any physical structure will continue to serve its intended use only if it is properly maintained. During the storm season timely inspection and removal of debris is necessary for culverts to continue to move water, fish, sediment, and debris.

4 Grade Control

In the context of this document's sole focus on fish passage designs, Grade Control are structures that control the grade and longitudinal profile of rivers, streams, and other engineered channels, which must also provide passage routes for fish. This chapter describes some of the design challenges and associated variables relevant to each type of Grade Control project and its ability to pass fish. It also seeks to provide insights into critical variables and potential solutions to some of the challenges they pose to fish passage.

In addition to providing fish passage, any Grade Control design should include consideration for maintaining the ecological function of the stream, passing woody debris, flood flows and sediment, scour potential, and other species present at the site. The design team should collaborate with biologists and engineers familiar with the site to assess potential effects on species and life stages present and site geomorphology.

The criteria and guidelines presented in this chapter are general in nature. There may be cases where site constraints or unusual circumstances dictate a modification to one or more of these design elements. Also, where there is an opportunity to protect salmonids, additional site-specific criteria may be appropriate. Deviations from this criteria will be considered by NMFS on a project-specific basis. It is the responsibility of the applicant to formally request and provide compelling evidence in support of any modification of a guideline or criterion contained in this chapter. Requests should be submitted for approval early in the design process, well in advance of a proposed ESA consultation.

4.1 Introduction

Grade Control structures in rivers and streams often span the entire channel. They can be used for road crossings; reach restoration after dam removal, improving habitat; and modifications to water diversion structures. They are designed to pass the stream's full hydrograph, sediment load, and debris through the structure. Often, the goal of design should be to reconnect the channel to its floodplain and simulate natural channel geomorphology, roughness, and vegetation objectives.

This chapter discusses four types of Grade Control:

- Constructed Channel
- Rigid weirs
- Boulder weirs
- Channel-spanning fish ladders

An extensive literature search was conducted to identify studies which could inform regulatory guidance on Grade Control as a fishway structure. However, very few studies were found which informed the topics covered in this chapter. This chapter covers design elements that NMFS feels are critical to the success of Grade Control projects used to pass fish, yet are not well represented within the current body of literature directly. Some material presented in this chapter is derived from NMFS experience, for which there are no direct references. This chapter should not be viewed or applied as a standalone set of instructions for engineering Grade Control for fish passage projects; such application is beyond the scope of this document. Rather, a user should consult one of the referenced design manuals and ensure specific design elements are consistent with the requirements of this chapter.

4.2 Specific Design Guidelines

Key considerations in the design and implementation of individual types of Grade Control projects are provided in Section 4.2.

4.2.1 Constructed Channels

Designers should select engineering methods for Constructed Channels that have a track record of success at a similar scale, and within similar geomorphic conditions, as the proposed design. Prior to selecting a Constructed Channel design approach for your project, contact NMFS to discuss how potential structure instability may affect ESA consultation of the project.

NMFS is using the term Constructed Channel to describe a large group of designs which go by different industry names. Constructed Channels cover structures termed as nature-like fishways, engineered riffles, roughened channel, and rock ramps, to name a few.

Constructed Channels are designed to mimic or simulate, to varying degrees, the hydraulic conditions by replicating the geomorphic form and complexity of natural channels. They may be used to facilitate the passage of a wide assemblage of fish and other aquatic species over a wide range of flows.

NMFS does not recommend strictly replicating local natural bed and bank material as the means of providing structure stability, especially in over steepened channels. Balancing the structural stability and geomorphic form of Constructed Channels is a complex engineering task. The goal is to ensure that the design provides adequate fish passage conditions, through hydraulic complexity and long-term stability of hydraulic conditions over the life of the project. It is critical for designers to select engineering methods that have a track record of success at the same scale—and within the same geomorphic conditions—as the proposed design. It has been observed that successful projects developed for small streams, do not always produce that same results at larger scales. The effect of scale on project success has been documented in different types of in-stream structures (Frissell and Nawa 1992).

A few points related to structure stability and project failure of Constructed Channels are worth discussion. Project failure is defined as the inability of the structure to meet the stated passage goals or expectations. Structure stability is defined as the ability of the structure to maintain its form over time. From a fish passage perspective, within the class of Constructed Channel designs, structure instability is not always associated with project failure. When other civil works are adjacent or associated with a Constructed Channel, such as a bridge apron, irrigation dam, culvert, or pipes (e.g., gas, sewer, or water) structure instability can be directly correlated (i.e., structure instability leads to project failure). In projects where there are no civil works within the hydraulic influence of the Constructed Channel, structure instability may not be directly correlated with project failure (i.e., structure instability has no adverse effect on passage conditions).

Additional information on Constructed Channels is available in the following publications: Newbury and Gaboury (1993), Mooney et al. (2007), Love and Bates (2009), Barnard et al. (2013), U.S. Bureau of Reclamation (BOR) and USACE (2015), BOR (2016), Castro and Beavers (2016), and Newbury (2016).

4.2.1.1 Design slope

NMFS recommends the design slope be restricted to no more than 4% greater than the average slope of the upstream and downstream reaches. For example, where the average slope of the upstream and downstream reach is 4%, the maximum design slope is 8% (4% + 4% = 8%). The design slope is the overall slope of the proposed section of the channel and not the discrete ramps, riffles or cascades segments within the project.

Design slopes more than 4% greater than the average slope of the project reach may experience structure instability. According to Castro and Beavers (2016), large discontinuities in slope may prevent desired hydraulic conditions of a Constructed Channel from being maintained throughout the life of the structure. These instabilities occur for a wide range of reasons. Improper installation of rock, inadequate rock size or distribution of rock sizes, lack of adequate hydraulic roughness, and insufficient energy dissipation throughout the structure, to name a few.

Structure instability can, although not always, cause fish passage to be blocked or delayed. Risk of creating a fish passage barrier is reduced as the slope of the Constructed Channel more closely resembles the project reach averaged slope. Calculating the average slope of both the upstream and downstream reaches should capture enough of the natural channel profile to provide a reliable baseline for calculating the natural slope of the project reach. Upstream and downstream surveys should capture a minimum length of channel equal to the length of the project. For example, if the project length is 100-feet, the survey should extend 100-feet upstream and 100-feet downstream of the project. Calculating the slopes of the natural channel should be done separately for the upstream and downstream reaches and considered individually, not as a composite value.

4.2.2 Rigid Weirs

Rigid weirs have the advantage of being able to remain in place over long periods while maintaining environmentally sensitive or specific hydraulic conditions. Rigid weirs, which are static, non-deformable structures, can be constructed from concrete, logs, or sheet pile material (Barnard et al. 2013). Due to corrosion and decomposition, rigid weirs made of wood and steel may fail over time.

4.2.2.1 Footing embedment

Designers should show that embedment of footings is placed deep enough to resist scour failure over the life span of the project by providing the hydraulic analysis performed to determine the placement depth.

Rigid weirs commonly fail when weir embedment is insufficient to resist scour. Weirs designed for larger systems with greater hydraulic energy may require additional embedment to maintain structural integrity of the design. Factors of safety applied to scour calculations should be identified with supporting justification.

4.2.2.2 Crest shape

Weir crests should be sloped across the width of the weir to produce a shallow "V" shaped crest that focuses flow toward the middle of the channel and away from banks. The side slope should be no steeper than 5H:1V.

The shape of the crest can aggravate upstream backwater effects and downstream scour of the bed and banks. Straight crested weir should be avoided as they increase the wetted width of the channel and induce erosion and scour of the banks. Weirs that are v-shaped, with sloped sides focus flow and reduce erosion and scour along the banks and margins of the channel. Side slopes exceeding 5H:1V may initiate excessive scour of the bed and banks. In relatively large channels, side slopes should be less than 5H:1V (Love and Bates 2009).

4.2.2.3 Concentrating low flows

In streams with base flows that routinely are less than 10 ft^3/s, weirs and notches should be sized to provide a concentrated, plunging flow of at least 1 ft^3/s.

Low-flow conditions require additional considerations when designing the geometry and function of a low-flow notch. To ensure adequate water depth at the lowest flows, the notch is sized and shaped to create a plunging flow regime at 1 ft^3/s. For projects where additional flow concentration is beneficial or required, the entire notch may be designed as a V-notch or the design could incorporate V-shaped geometry.

4.2.2.4 Weir spacing

Weir spacing may vary according to the erodibility of the bed and banks. As erosion and scour risk increase weirs are placed farther apart. Weir spacing is typically a function of the bankfull width. Common widths range between 0.5 and 2 times the bankfull width (Love and Bates 2009) (Barnard 2013). Weirs should be spaced a sufficient distance apart to maintain sediment presence along the upstream face of each individual weir. Spacing and associated project roughness should provide adequate resting and holding areas for migrating fish. Resting areas are designed as locations where the stream velocity is 2fps or less at the high fish passage flow.

Correct weir spacing is closely associated with site topography, channel and bed composition, and project passage goals. Please contact NMFS to discuss project specific weir spacing.

4.2.3 Boulder Weirs

Boulder weirs are low-elevation structures that span the entire width of a channel. They are designed to develop an abrupt drop in channel bed and water surface elevation and are used to stabilize stream grade, improve fish passage, and reduce erosion. Boulder weirs have been used to simulate natural, step-type drop structures in streams.

4.2.3.1 Design approach

Boulder weirs should be designed using guidance provided in Chapter 7 of BOR (2016). Boulder weirs are most appropriately used in systems with a step-pool morphology where the bed and banks of the stream channel are naturally armored. At a minimum, boulder weir designs require two rows of header rock and footer rock. Headers and footers are backfilled with scour-resistant rock along the upstream face of the headers and downstream face of the footers. The boulder weir structure as a whole should be constructed to be non-porous using material that is well graded which easily entrains the natural bedload transported in the channel.

Traditional boulder weir designs typically consist of two rows of rock: one header row and one footer row (Rosgen 1996). However, this design is highly prone to failure (Mooney et al. 2007) and is not recommended for use where sustaining specific streambed or water surface elevation is critical (Barnard et al. 2013). Drop heights mandated by hydraulic fish passage criteria more commonly govern this design approach than do natural geomorphic relationships. The traditional method of designing boulder weirs lacks sufficient consideration of geomorphic context.

The BOR (2016) boulder weir design approach was developed over the last decade and was informed through extensive monitoring of hundreds of project sites and hydraulic modeling.

The BOR design approach eliminates many of the failure modes routinely observed in traditional boulder weir designs.

4.2.4 Channel-Spanning Fish Ladders

Channel-spanning fish ladders are applications of more traditional fishway designs through which all streamflow and debris pass. Applications include retrofit designs, which are most commonly found at culverts and occasionally at bridges, control of large headcuts, and grade control associated with other channel instabilities. This class of grade control requires additional monitoring and maintenance challenges compared to traditional fish ladder applications. A channel spanning ladder may not be the appropriate fish passage approach in situations where large volumes of bed load or debris are transported through the project reach. The presence of sediment and debris may degrade the performance of the fishway for fish passage.

4.2.4.1 Fishway type

Due to the hydraulics of pool-and-chute designs they may perform better than other fish ladder types for channel spanning applications where passing bedload is and debris is required. Vertical-slot fishways, Ice Harbor-style fishways, Denils, and pool-and-weir designs are not recommended for channel-spanning applications due to the adverse effect entrained debris and sediment have on passage conditions.

Additional information regarding pool-and-chute fishway design can be found in Chapter 5 in *NOAA Fisheries West Coast Region Anadromous Salmonid Passage Design Manual 2022*.

4.2.4.2 Fishway width

Minimum fishway width for a channel-spanning technical fishway should be the bankfull width of the stream channel. NMFS should be contacted for project-specific recommendations.

Narrowing or widening the channel upstream of the fishway may cause adverse hydraulic effects in the fishway due to constriction and expansion. Either of these conditions should be avoided. Flow lines at the fishway exit should be as hydraulically smooth as possible.

4.2.4.3 Project gradient

Channel-spanning fish ladders are best suited for sites where project gradients exceed 5%.

Lower gradients increase the risk of sediment accumulating and impacting fish passage conditions and are better suited for Constructed Channels or rigid weirs, which do not depend on maintaining sediment-free pools to successfully pass fish.

4.2.4.4 Hydraulic criteria

All associated hydraulic criteria for fish ladder design contained in Chapter 5 in NOAA Fisheries West Coast Region Anadromous Salmonid Passage Design Manual 2022, should be met. NMFS should be contacted when modification of criteria is proposed.

4.3 General Design Guidelines

Key considerations in the design and implementation of all Grade Control structures required to pass fish are provided in Section 4.3.

4.3.1 Hydraulic Diversity

All Grade Control projects should be designed to mimic the hydraulic diversity found in natural channels.

Fish passage at a Grade Control structure is partially a function of hydraulic diversity. Grade Control structures that exhibit homogenous (i.e., uniform) hydraulics may limit passage compared to more hydraulically diverse structures. Smaller and weaker fish species may be able to pass in the shallower, lower velocity water found at the margins of a properly tapered Grade Control structure. Wilcox and Wohl (2007) found that due to three-dimensional flow patterns in step-pool channels approximately 35% of the flow in not oriented in the downstream direction, hence fish, especially smaller weaker individual, may use complex flow patterns found along hydraulically diverse banklines to assist their upstream migration. Figure 4-1 demonstrates how hydraulic diversity may be effectively incorporated into a Grade Control design using the following features:

- A rigid weir that incorporates large rock and wood to provide hydraulic diversity
- Concrete weirs that are spaced close together and function as sediment retaining structures while providing pool habitat at low flows
- Large roughness elements (i.e., large wood and rock elements) to provide the energy dissipation and velocity reduction necessary for passage at higher flows and retain and sort sediment in depositional zones throughout the structure

Figure 4-1. Example of hydraulic diversity in a Grade Control project

4.3.2 Geomorphic Assessment

All project designs should include appropriately scoped geomorphic assessments at the watershed scale, reach scale, and project site. The assessments should consider the geology, hydrology, morphology, sediment transport, vegetation, and potential for channel adjustment.

Conducting appropriate geomorphic assessments is the most critical aspect of designing successful Grade Control project. These assessments are used to determine a suitable design method and the scale and scope of its implementation. Each assessment should be commensurate with the relative risk of structural or biological failure of the project. Table 4-1 provides a sampling of geomorphic information and data collected for these assessments.

Table 4-1. Geomorphic Assessment

Category	Type of Data
Basic Characteristics	• Current and future climate conditions • Land use and development
Hydrology	• Ephemeral, intermittent, or perennial hydrology • Stream gage summary • Flood frequency analysis • Historical changes and potential future changes in streamflow • Peak flow response to land use changes.
Morphology	• Channel classification • Morphologic dimensions of planform, floodplain, and channel • Long profile • Channel migration zone • Bed and bank adjustment potential • Channel adjustment potential • Presence/absence of armor layers • Erosion/depositional features • Lateral and vertical channel floodplain and channel constraints • Channel evolution phase and trajectory • Dynamic equilibrium • Long profile stability • Historical channel changes/instability • Bank angle, height, layering, material size, sorting, cohesiveness, tension cracks, slumping, bare banks, and root exposure
Sediment Transport	• Sediment inputs/origins • Bed material: size, uniformity, packing, and sand fraction • Sediment transport characteristics • Sediment slug material and dimensions • Predicted sediment pulse characteristics
Vegetation	• Riparian composition and condition • Wood debris characteristics: maturity, species, collection points, form, and function

Geomorphic assessments should be properly scoped, focusing on the watershed and reach scales and project site under consideration. For instance, smaller, low-energy streams in confined and moderately confined channels possessing a highly armored bed and banks may not benefit from extensive geomorphic assessments. Whereas other projects may require more extensive assessments—regardless of stream size—because they release stored sediments, require connecting to floodplains, have incised channels, lack an armored bed and banks, possess highly migratory or response-driven channels, or are characterized as being unstable.

4.3.3 Fish Passage Design Flows

Design flows for grade control structures are determined using the process found in Chapter 4 of NOAA Fisheries West Coast Region Anadromous Salmonid Passage Design Manual 2022.

Designers should diligently investigate any and all flows that might destabilize the structure. The assumption that that 100-year flood event is the destabilizing flow may be false. Hydraulic jump or instabilities which may fail the structure can occur at flows substantially less than the 100-year flood event. Flows where hydraulic jumps and drops occur may produce more destabilizing forces than the 100-year flood event. Destabilizing hydraulic conditions can also become barriers to fish passage. Hydrologic and hydraulic analyses should be comprehensive enough to identify all potential critical flows essential to stability over its intended life span.

4.3.4 Structural Rock Placement and Spacing

The location, orientation, and spacing of the largest structural elements in a Grade Control project are critical to the structural stability and should be called out in exact detail in engineering and construction documents.

Intentionally placing structural rock, compared to dumping, may significantly improve its stability to resist hydraulic forces (Jafarnejad et al. 2014; Hiller et al. 2018a). This highlights the increased stability that Grade Control designs can achieve if structural rock locations, orientation, and spacing are calculated, specified, and implemented according to the design, compared to being randomly dumped or placed. Purposeful placement requires that greater detail and quality control procedures be identified in project specification documents

4.3.5 Particle Size Distribution of Engineered Streambed Material

Particle size distribution of engineered bed and bank material should be well-graded up to the D84 size class.

NMFS experience has shown that the particle size distribution is a critical component of Grade Control project stability and porosity. Failure to design a well-graded mix of engineered bed and bank material may lead to an unacceptable degree of structure deformation, which can result in a channel avulsion or flanking through the scour and displacement of larger structural rock.

4.3.6 Channel Form and Function

Designers should provide a detailed description of how the form and function of the Grade Control project will change over time. The description should explain the strategies that will be incorporated into the design and maintenance of the Grade Control project that can mitigate these changes over time, without adversely affecting fish passage or critical stream processes. This explanation should include the long-term effects that bed load movement and sediment transport will have on channel stability, porosity, and evolution at the project and reach scales.

Grade Control projects inevitably adjust over time, regardless of the design approach used. Some Grade Control projects are designed as threshold channels, where the movement of the boundary material is negligible during the design flow (NRCS 2007). Even when considerable factors of safety are used, significant bed and bank adjustment with Grade Control projects occurs after construction. NMFS recommends using design methods that increase the number of components within the design to enhance channel stability and form, rather than relying solely on conservative rock sizing to increase channel stability.

4.3.7 Channel Roughness

This criterion applies to Constructed Channels, Rigid Weirs, and Boulder Weirs. Designers should provide NMFS with detailed specifications showing how passage roughness will be physically represented in the design. Passage roughness consists of individual elements (such as rock or wood elements) that project into the water column 0.5 to 1.0 times the bankfull depth at the bankfull discharge. NMFS recommends an area of at least 30% of bankfull wetted channel be occupied by this size of roughness element.

Modeling requires the use of roughness values to estimate the effects of boundary roughness on water depth and velocity in channel design. NMFS has observed there can be large discrepancies between modeled roughness values and the actual roughness physical expressed in the design post-construction. These discrepancies are typical expressed as higher velocities, increased turbulence, unanticipated scour and erosion, and a fewer holding and resting areas than were expected. Individually and in aggregate these issues can adversely affect fish passage. It is expected that documentation of the methods, assumptions, and specifications used to detail and explain the roughness design process will result in fewer projects failing to meet passage requirements.

Channel roughness providing the bulk of fish passage benefits are best described and specified comparing the size of the elements to the depth of water at the high fish passage design flow. Large roughness elements will possess an exposed dimension above the thalweg that is analogous to the high fish passage design depth. Meaning once stable, the element should have a portion exposed to the air, or nearly exposed, at the high fish passage design flow. This relationship between water depth and roughness size is critical to providing the necessary energy dissipation and velocity reduction for fish to rest and move in higher gradient channels. Channels with low relative roughness (uniformly sized bed and bank material), are characterized as hydraulically smooth. Hydraulically smooth channels at high gradients provide little to no resting or holding areas for fish. Hydraulically smooth channels commonly fail to meet fish passage velocity criteria.

This criterion was developed based on the relationship between natural D84 and D90 class material and bankfull depth for streams in Washington State with slopes greater than 2% (Barnard et al. 2013). Barnard et al. measured stream discharge and bed roughness, observing that the rock providing the bulk of velocity reduction and hydraulic diversity were those elements which had a dimension analogous to the bankfull depth of the channel. Over a diverse range of project sizes, NMFS has also observed that velocity conditions are most often passable when somewhere in the range of 20%-40% of the project surface area is occupied by roughness elements extending significantly into the water column at the bankfull discharge.

4.3.8 Maximum average channel velocity

This criterion applies to Constructed Channels, Rigid Weirs, and Boulder Weirs. Maximum average channel velocity at the high fish passage flow should be no greater than 5 ft/s, *regardless of channel slope. The relationship between channel roughness and channel slope should be carefully engineered to ensure this criterion is not exceeded. Channel Spanning Fish Ladders maintain specific ladder velocity outlined in NOAA Fisheries West Coast Region Anadromous Salmonid Passage Design Manual.*

Barnard et al. (2013) indicates that at the 10% exceedance flow, high gradient streams in Washington State exhibit similar average channel velocities, regardless of channel slope, in the range of 4 ft/s. The velocity criterion in the section is presented to help designers express a more realistic relationship between channel slope and roughness in nature-like fishway designs. When channel slope and roughness have the proper relationship to maintain a 5 ft/s average channel velocity at the 5% exceedance flow, energy dissipation and turbulence are much more likely to be within the range observed in natural high gradient streams of similar slope and roughness. This criterion also simplifies and improves design and monitoring by providing a simple value to compare against hydraulic models and field measurements. An in-depth discussion on turbulence in higher gradient natural channels in contained in CH 6 of Barnard et al. (2013).

The origin of the 4ft/s criterion used the 10% exceedance flow to back calculate the energy dissipation factor (EDF) in high gradient natural channels in Washington (Barnard et al. 2013). When using a 5% exceedance flow it seems reasonable to increase the maximum average channel velocity to 5 ft/s. When using a 1% exceedance flow, it seems reasonable to use a maximum average channel velocity of 6 ft/s. These assumptions are supported by data from Castro and Jackson (2001) which indicates the average bankfull channel velocity in the Pacific Northwest can be well represented as an average of 6 ft/s. Work by Love and Lang (2014) reported that annual exceedance values associated with a discharge equal to 50% of the 2-year return interval ranged between 0.2% and 1.8%. Together these data indicate that annual exceedance flows between 10% and 1% exceedance are likely well represented by a range of average channel velocities between 4ft/s and 6ft/s.

4.3.9 Energy Dissipation

Energy dissipation structures or measures should be incorporated into the design at intervals that will ensure the average channel velocity remains no greater than 5 fps at the 5% exceedance flow, throughout the length of the project.

Channel roughness alone may not provide the energy dissipation needed to ensure velocity criteria are met. Energy dissipation pools may be needed to provide passage and improve structure stability and longevity. Pools can enhance fish passage by continuing to provide holding and resting areas for fish at flows higher than the fish passage design flow. Energy dissipation pools can also reduce destabilizing hydraulic forces acting on the structure. Bates (2009) recommend an energy dissipation pool for every 3 feet of vertical channel displacement. The minimum length of energy dissipation pools typically ranges between 1 to 1.5 times the bankfull width. Roughness element size appropriate for fish passage and energy dissipation is covered in section 4.3.7. NMFS will consider other pool geometries and pool frequency criterion if those methods can be supported by project specific or hydraulic modeling examples..

4.3.10 Bank Transitions

The natural channel and the fish passage design should exhibit gradual hydraulic transition of flow characteristics moving into (fish exit) and out of (fish entrance) the fishway. Designs should taper the upstream banks at the exit so there is a gradual hydraulic transition into the Grade Control project reach from the channel upstream. The transition area should also be armored so that the upstream channel does not outflank the fishway. The geomorphic assessment is critical in developing the scope and scale of flanking countermeasures.

Projects with significant channel confinement and skew have exhibited unintended and unmitigated scour, which has led to structural failure and passage barriers. These conditions may result in structural failure and development of a passage barrier. The presence of abutments, aprons, weirs, and other in-stream or adjacent structures that may affect near-field hydraulic drops and jumps should be modeled to determine an appropriate design approach for promoting smooth hydraulic transitions at the exit and entrance of the Grade Control project.

4.3.11 Slope Transitions

In situations where a channel-spanning fish ladder or rigid weirs are used, the three most upstream weirs (located at the fishway exit) should be set to gradually transition the slope of the water surface into the fishway exit. This is accomplished by limiting the vertical drop to no more than 3 to 4 inches between each.

Where discrete hydraulic drops are absent (i.e., riffles, cascades, or chutes) the upstream transition section begins at the uppermost end (exit) of the fishway. The length of the transition section extends upstream 1.5 times the bankfull width. The average slope of this section is half the design slope. For example, where the design slope is 4%, the average slope of the upstream transition section is 2%.

The purpose of this criteria is to promote a gradual hydraulic transition between the natural channel and the project reach. Abrupt changes in hydraulic conditions at these transition points has been observed to promote unintended scour which can result in development of a passage barrier. NMFS will consider other mitigation measures as meeting this criterion if those measures can be supported by project specific or hydraulic modeling examples.

4.3.12 Quality Control

Quality control methods for ensuring correct material, volume, condition, size, location, and distribution of rock and wood material used in Grade Control designs should be submitted with project plans and specifications to NMFS for review and comment.

NMFS has observed that the size, quantity, and quality of rock and wood material incorporated into Grade Control structures significantly affects the ability of the project to meet fish passage goals and criteria. A common observation when projects fail to achieve fish passage standards is that quality control during construction was not implemented, or the methods were poorly executed. This commonly results in a gap grade streambed or an inadequately engineered bed that is mobile at flows much less than designed for. The 12 inch minus fraction of rock has been seen to move with great mobility at flows much lower than anticipated when projects are gap graded between 12 inch and 24 inch class material. Quality control efforts should include ensuring the fraction of the engineered bed material between 18-24 inches are in the correct quantities and meet the specified size. This 18-24inch fraction of material seems to be critical to locking in the smaller fractions of the design particle distribution. Construction methods also play a role in project success. Project success also seems to be positively correlated to having an engineer on sight during installation of the project.

4.3.13 Washing and Sealing Bed and Banks

Engineered bed and bank material should be sealed during construction by washing, or flooding. NMFS engineers have observed that installing bed and bank material simultaneously with copious amounts of water seems to produce a better seal than periodically introducing water to the bed and banks at discrete points in the installation process. Sealing must prevent loss of surface flow in completed projects.

A sufficient flow of water through the Grade Control project should be provided to accumulate and compact fine sediments into any voids (i.e., flooding, washing). Sealing bed and bank material is critical for maintaining low-flow fish passage conditions; it should be conducted simultaneously with the bed and bank installation. Washing should be frequent, preferably continuous, throughout construction of the bed and banks.

Observation of Grade Control construction, and discussions with contractors installing Grade Control structures, indicates the term “jetting” has several connotations which introduce increased risk of a project bed failing to be sealed properly. Jetting seems to connotate that the force of water used which is the primary desirable water characteristic when sealing a bed. This can lead to the understanding that the project needs a high-pressure hose and less thought or concern about the amount of water a project will require. A high-pressure wash of engineered streambed material provides no guarantee the streambed will seal properly. Water velocity is not a substitute for water volume when sealing beds and banks properly. Turbid runoff should be treated to meet regional water quality standards before re-entering the channel downstream if necessary.

Periodic observations should be made to determine if bed and bank material is sealing properly during placement. Sections of channel that are not sealed should be brought into compliance by one or more of the following methods.

- Application of additional selected streambed gravel and washing
- Mechanical agitation using approved methods
- Removal and replacement of engineered bed and bank material

Projects that lose surface water as a result of an inadequately sealed bed run the risk of having to excavate significant portions of the project bed to properly seal the bed. Natural bed load transport of the stream and time may never fix conditions leading to subsurface water losses. Assuming the channel will repair itself is a faulty conclusion.

4.3.14 Maintenance and Monitoring

A NMFS-approved maintenance and monitoring plan is recommended. It should contain adaptive management triggers and measures that address how morphology and passage hydraulics will be monitored and modified if necessary. Monitoring should be conducted after the first bankfull event after construction. Additional monitoring should occur at the next 5-year flow event. If passage is achieved as designed at these first two events, future monitoring should occur following 10-year, 25-year, and 50-year events.

The following components should be included in the maintenance and monitoring plan:

- Fish Passage Assessment – Depending on project-specific considerations, monitoring may include an assessment of passage efficiency via NMFS-approved means of biological evaluation. This monitoring requirement is specific to each project and will be identified by NMFS on a project-specific basis.
- Channel Velocity – Channel velocity will be verified through monitoring. When average channel velocity exceeds velocity criteria, NMFS will evaluate the passage conditions of the fishway. Repairs or adaptive management actions, if warranted, will be identified by NMFS and carried out by the maintaining entity.

Due to the diversity of Grade Control designs and the variable nature of channel roughness, monitoring requirements are specific to each project and will be identified by NMFS on a project-specific basis. Repairs, if warranted, will be identified by NMFS and designed and carried out by the maintaining entity.

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