WHITE PAPER

Fish Passage

Prepared for

Washington Department of Fish and Wildlife

March 2008 (Working Draft – Do Not Cite)

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March 2008 (Working Draft – Do Not Cite)

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Executive Summary

The Revised Code of Washington (RCW) directs the Washington Department of Fish and Wildlife (WDFW) to "preserve, protect, perpetuate, and manage" the fish and wildlife species of the state as its paramount responsibility (RCW 77.04.012). Under RCW 77.55, any construction or work that uses, diverts, obstructs, or changes the natural bed or flow of state waters requires a Hydraulic Project Approval (HPA) issued by WDFW. The purpose of the HPA program is to ensure that hydraulic projects are completed in a manner that prevents damage to public fish and shellfish resources and their habitats. To ensure that the HPA program complies with the Endangered Species Act (ESA), WDFW is developing a programmatic multispecies Habitat Conservation Plan (HCP) to obtain an Incidental Take Permit (ITP) from the U.S. Fish and Wildlife Service (USFWS) and the National Oceanic and Atmospheric Administration (NOAA) Fisheries Service (also known as NOAA Fisheries), in accordance with Section 10 of the ESA. For WDFW, the objective is to ensure that activities conducted under an HPA avoid and/or minimize the incidental take of aquatic species potentially considered for coverage under the HCP (referred to in this white paper as "HCP species").

The HCP will address the impacts, potential for take, and mitigation measures for effects on HCP species from hydraulic projects that require HPAs. WDFW's intent is to build the scientific foundation for the effort to prepare an HCP for hydraulic projects that receive HPAs. To accomplish this, WDFW is compiling the best available scientific information related to the impacts, potential for incidental "take" of species that may be covered in the HCP (as defined in the ESA; see Section 9 of this white paper for a definition of "take"), and possible management directives and mitigation measures to avoid and/or minimize potential risk of take to the maximum extent practicable. Because the HPA authority covers all waters of the state, this white paper considers hydraulic project impacts in both freshwater and marine environments.

This white paper is one of a suite of white papers prepared to establish the scientific basis for the HCP and to assist WDFW decision-making on what specific HPA activities should be covered by the HCP. This particular white paper compiles and synthesizes existing scientific information on fish passage structures and operations, which for the purpose of this effort include culverts (removed, replaced, or retrofitted for fish passage), fish ladders and fishways, weirs (temporary or permanent structures explicitly intended to manage the movements of fish), roughened channels, and trap-and-haul operations. In addition, this white paper addresses the fish passage related effects of culverts with tide gates or flap gates. The broader ecological effects of these types of structures on the aquatic environment are discussed in the Flow Control Structures white paper (Herrera 2007b), but fish passage related effects are addressed here.

The objectives of this white paper are to:

- Compile and synthesize the best available scientific information related to the potential human impacts on HCP species, their habitats, and associated ecological processes resulting from the construction, operation, and maintenance of fish passage structures.

- Use this scientific information to estimate the circumstances, mechanisms, and risks of incidental take potentially or likely to result from the construction, operation, and maintenance of fish passage structures.

- Identify appropriate and practicable measures, including policy directives, conservation measures, and best management practices (BMPs), to avoid and/or minimize the risk of incidental take of HCP species.

The literature review conducted for this white paper identified six impact mechanisms that could potentially affect HCP species. These mechanisms of impact are both direct and indirect and can have temporary, short-term effects or permanent, long-term effects. The impact mechanisms analyzed in this white paper are:

- Construction and maintenance activities
- Water quality modifications
- Riparian vegetation modifications
- Aquatic vegetation modifications
- Hydraulic and geomorphic modifications
- Ecosystem fragmentation.

This white paper also includes a discussion of the potential direct and indirect impacts on the 52 HCP species and their habitats due to exposure to the six primary identified impact mechanisms. Following this discussion, an evaluation of potential for take of the 52 HCP species is included based on a separate analysis conducted using exposure-response matrices for each of the HCP species. This white paper also reviews data gaps and uncertainties, and estimates the risk of take. In addition, habitat protection, conservation, mitigation, and management strategies that could avoid, minimize, or mitigate the identified potential impacts are provided. Key elements of this white paper are:

- Identify the distribution of the 52 HCP species (i.e., whether they use fresh water, marine water, or both) and their habitat requirements.

- Identify the risk of take associated with each of these impact mechanisms based on the distribution information.

- Identify cumulative impacts.

- Identify data gaps.

- Identify habitat protection, conservation, and mitigation strategies.

1.0 Introduction

The Revised Code of Washington (RCW) directs the Washington Department of Fish and Wildlife (WDFW) to "preserve, protect, perpetuate, and manage" the fish and wildlife species of the state as its paramount responsibility (RCW 77.04.012). Under RCW 77.55, any construction or work that uses, diverts, obstructs, or changes the natural bed or flow of state waters requires a Hydraulic Project Approval (HPA) issued by WDFW. The purpose of the HPA program is to ensure that these activities are completed in a manner that prevents damage to public fish and shellfish resources and their habitats. To ensure that the HPA program complies with the Endangered Species Act (ESA), WDFW is developing a programmatic multispecies Habitat Conservation Plan (HCP) to obtain an Incidental Take Permit (ITP), in accordance with Section 10 of the ESA, from the U.S. Fish and Wildlife Service (USFWS) and the National Oceanic and Atmospheric Administration (NOAA) Fisheries Service (also known as NOAA Fisheries). For WDFW, the benefits of an HCP are to contribute to the long-term conservation of both listed and unlisted species through the minimization and mitigation of impacts on those species and their habitats, while ensuring that WDFW can legally proceed with the issuance of HPAs that might otherwise result in the incidental "take" of ESA-listed species (as defined in the ESA; see Section 9 of this white paper for a definition of "take").

The HCP will identify the impacts on those aquatic species considered for coverage under the HCP, the potential for take, and mitigation measures for hydraulic projects that require HPAs. This white paper is part of the effort to compile the best available scientific information to protect these species during the construction, maintenance, repair, and operation of fish passage structures and activities. To accomplish this, WDFW is identifying management directives and mitigation measures to avoid and/or minimize potential risk of take to the maximum extent practicable. Because the HPA authority covers all waters of the state, this white paper considers hydraulic project impacts in both freshwater and marine environments. This white paper is one of a suite of white papers being prepared to establish the scientific basis for the HCP and to assist WDFW decision-making regarding what specific HPA activities should be covered by the HCP and what minimization and mitigation measures can be implemented to address the potential effects of hydraulic projects.

This white paper addresses impacts and mitigation/minimization measures to be applied to the construction, maintenance, and operation of fish passage structures and activities. Species considered for coverage under the HCP (referred to in this white paper as "HCP species") are listed in Table 1-1. For the purpose of this white paper, some of the HCP species have been grouped where appropriate (and each group is separated by a gray-shaded row in Table 1-1).

1 **Table 1-1. The 52 HCP species addressed in this white paper.**

Common Name	Scientific Name	Status[a]	Habitat
Chinook salmon	*Oncorhynchus tshawytscha*	FE/FT/SC	Freshwater, Estuarine, Marine
Coho salmon	*Oncorhynchus kisutch*	FT/FSC	Freshwater, Estuarine, Marine
Chum salmon	*Oncorhynchus keta*	FT/SC	Freshwater, Estuarine, Marine
Pink salmon	*Oncorhynchus gorbuscha*	SPHS	Freshwater, Estuarine, Marine
Sockeye salmon	*Oncorhynchus nerka*	FE/FT/SC	Freshwater, Estuarine, Marine
Steelhead	*Oncorhynchus mykiss*	FE/FT/SC	Freshwater, Estuarine, Marine
Coastal cutthroat trout	*Oncorhynchus clarki clarki*	FSC	Freshwater, Estuarine, Marine
Redband trout	*Oncorhynchus mykiss*	FSC	Freshwater
Westslope cutthroat trout	*Oncorhynchus clarki lewisii*	FSC	Freshwater
Bull trout	*Salvelinus confluentus*	FT/SC	Freshwater, Estuarine
Dolly Varden	*Salvelinus malma*	FP	Freshwater, Estuarine
Pygmy whitefish	*Prosopiim coulteri*	FSC/SS	Freshwater
Olympic mudminnow	*Novumbra hubbsi*	SS	Freshwater
Lake chub	*Couesius plumbeus*	SC	Freshwater
Leopard dace	*Rhinichthys falcatus*	SC	Freshwater
Margined sculpin	*Cottus marginatus*	FSC/SS	Freshwater
Mountain sucker	*Catostomus platyrynchus*	SC	Freshwater
Umatilla dace	*Rhinichthys umatilla*	SC	Freshwater
Pacific lamprey	*Lampetra tridentata*	FSC	Freshwater, Estuarine, Marine
River lamprey	*Lampetra ayresi*	FSC/SC	Freshwater, Estuarine, Marine
Western brook lamprey	*Lampetra richardsoni*	FSC	Freshwater
Green sturgeon	*Acipenser medirostris*	SPHS/FSC/FT	Freshwater, Estuarine, Marine
White sturgeon	*Acipenser transmontanus*	SPHS	Freshwater, Estuarine, Marine
Eulachon	*Thaleichthys pacificus*	FC/SC	Freshwater, Estuarine, Marine
Longfin smelt	*Spirinchus thaleichthys*	SPHS	Freshwater, Estuarine, Marine
Pacific sand lance	*Ammodytes hexapterus*	SPHS	Marine & Estuarine
Surf smelt	*Hypomesus pretiosus*	SPHS	Marine & Estuarine
Pacific herring	*Clupea harengus pallasi*	FC/SC	Marine & Estuarine
Lingcod	*Ophiodon elongatus*	SPHS	Marine & Estuarine

Table 1-1 (continued). The 52 HCP species addressed in this white paper.

Common Name	Scientific Name	Status[a]	Habitat
Pacific cod	*Gadus macrocephalus*	FSC/SC	Marine (occ. Estuarine)
Pacific hake	*Merluccius productus*	FSC/SC	Marine & Estuarine
Walleye pollock	*Theragra chalcogramma*	FSC/SC	Marine (occ. Estuarine)
Black rockfish	*Sebastes melanops*	SC	Marine & Estuarine
Bocaccio rockfish	*Sebastes paucispinis*	SC	Marine & Estuarine
Brown rockfish	*Sebastes auriculatus*	SC	Marine & Estuarine
Canary rockfish	*Sebastes pinniger*	SC	Marine & Estuarine
China rockfish	*Sebastes nebulosis*	SC	Marine & Estuarine
Copper rockfish	*Sebastes caurinus*	FSC/SC	Marine & Estuarine
Greenstriped rockfish	*Sebastes elongates*	SC	Marine & Estuarine
Quillback rockfish	*Sebastes maliger*	FSC/SC	Marine & Estuarine
Redstripe rockfish	*Sebastes proriger*	SC	Marine & Estuarine
Tiger rockfish	*Sebastes nigrocinctus*	SC	Marine & Estuarine
Widow rockfish	*Sebastes entomelas*	SC	Marine & Estuarine
Yelloweye rockfish	*Sebastes ruberrimus*	SC	Marine & Estuarine
Yellowtail rockfish	*Sebastes flavidus*	SC	Marine & Estuarine
Olympia oyster	*Ostrea lurida*	SPHS	Marine & Estuarine
Northern abalone	*Haliotis kamtschatkana*	FSC/SC	Marine
Newcomb's littorine snail	*Algamorda subrotundata*	FSC/SC	Marine
Giant Columbia River limpet	*Fisherola nuttalli*	SC	Freshwater
Great Columbia River spire snail	*Fluminicola columbiana*	FSC/SC	Freshwater
California floater (mussel)	*Anodonta californiensis*	FSC/SC	Freshwater
Western ridged mussel	*Gonidea angulata*	None	Freshwater

Notes: For the purpose of this white paper, some of the HCP species have been grouped when appropriate (each group is separated by a gray-shaded row).

[a] Status:

FE=Federal Endangered
FP=Federal Proposed
FT = Federal Threatened
FC = Federal Candidate
FSC = Federal Species of Concern
SC = State Candidate
SS = State Sensitive
SPHS = State Priority Habitat Species

2.0 Objectives

The objectives of this white paper are to:

- Compile and synthesize the best available scientific information related to the potential human impacts on HCP species, their habitats, and associated ecological processes resulting from the creation, construction, maintenance, installation, repair, replacement, modification, and removal (hereafter collectively referred to as construction, maintenance, and/or operation) of fish passage structures.
- Use this scientific information to estimate the circumstances, mechanisms, and risks of incidental take potentially or likely resulting from the construction, maintenance, and/or operation of fish passage subactivity types.
- Identify appropriate and practicable measures, including policy directives, conservation measures, and best management practices (BMPs), to avoid and/or minimize the risks of incidental take of HCP species.

3.0 Methods

Information presented in this white paper is based primarily on the compilation and synthesis of the best available scientific information related to human impacts on HCP species, their habitats, and associated ecological processes. The methods used here included the acquisition of existing literature, followed by an analysis of impacts based on a review of the literature. The conceptual framework for assessing potential impacts is described in detail in Section 6, and below is a discussion of the literature acquisition and review process.

To acquire literature supporting the best available scientific information, an extensive search of the available literature was conducted using the Thomson Scientific Web of Science (Thomson Scientific Web of Science 2007), which has electronic access to more than 8,500 scientific journals encompassing all fields of environmental science. This yielded several hundred relevant publications, most published within the last 10 years. In addition, literature cited in previous white papers and conference proceedings from the last four Puget Sound–Georgia Basin Research Conferences was reviewed to identify relevant "gray literature" sources. The University of Washington School of Aquatic and Fisheries Sciences, Fisheries Research Institute Reports (UW-FRI) database was also searched (this database includes more than 500 reports pertaining to research conducted by Fisheries Research Institute personnel from its inception to the present). A thorough search of theses in the Summit system of libraries was performed to locate relevant student work. (Summit is a library catalog that combines information from Pacific Northwest academic libraries, including the Orbis and Cascade systems, into a single database available at URL = http://summit.orbiscascade.org/.) Finally, because this white paper was prepared by a diverse group of scientists from a wide range of backgrounds, many other primary resources (e.g., consultant reports and textbooks) were found in the personal collections of Herrera staff.

To obtain as much relevant species-specific information as possible, a literature review using the Thompson Scientific Web of Science was conducted to collect information related to the individual stressors for the 52 HCP species. A keyword search of the scientific name and/or common name for each species in Table 1-1 was conducted. For those species where the search returned more than 1,000 references, a few recent citations were selected for inclusion. Species in this category were the five salmon species (sockeye, chum, pink, coho, and Chinook), steelhead, and coastal cutthroat trout. For the remaining species, every reference in the search result was reviewed for the relevance of species-specific information to be included in this white paper. For several species, searches for scientific names and common names returned no references. These species included the margined sculpin, giant Columbia River limpet, great Columbia spire snail, western ridged mussel, river lamprey, longfin smelt, Newcomb's littorine snail, and many of the rockfish species.

To identify data gaps and evaluate the state of scientific knowledge applicable to the potential impacts of fish passage structures and/or operations on the HCP species and their habitats, the acquired literature was examined to assess the broader issue of how these species use aquatic habitats and how these subactivity types may alter habitat functions.

Existing literature reviews, peer-reviewed journal articles, books, theses/dissertations, and technical reports were reviewed for information specific to aquatic species and their interaction with each fish passage subactivity type. Through this process, a collection of information was assembled on the life history, habitat uses, and the potential impacts that these subactivity types pose to HCP species.

Reference material from each of the above databases was compiled in an Endnote personal reference database (i.e., Endnote version X). Reference types collected and entered into the database included journal articles, reports, web pages, conference proceedings, theses, statutes, books, and book sections. Each entry in the database included descriptive information, including author(s), year, title, volume, pages, and publisher. Whenever an electronic copy of the reference material was available, a link between the reference entry and a PDF copy of the reference material was included in the database. If an electronic (.PDF) copy of a reference was not available, a hardcopy of the material was kept on file. All reference materials cited in the literature review were either linked to the reference database or retained in an associated file as a hardcopy.

Endnote X is the industry standard software for organizing bibliographic information. It features a fully searchable and field-sortable database that can contain an unlimited number of references. Reference information is entered into the database either by direct import from online databases or by manually entering the reference information into reference type templates. Once all the references were entered, the database was used for organizational and archival purposes. The final database is included as an electronic appendix to this white paper (Appendix B).

4.0 Hydraulic Project Description

This white paper addresses the effects and related risk of take resulting from five fish passage related subactivity types authorized under the HPA program:

- Culverts (removed, replaced, or retrofitted for fish passage)
- Fish ladders/fishways
- Weirs (used solely to prevent, facilitate, or manage the passage of fish)
- Roughened channels (created to facilitate fish passage)
- Trap-and-haul facilities.

It is recognized that fish passage facilities are intended to improve fish passage and are actually mitigation measures for adverse effects associated with flow control structures. In addition, culverts are often replaced, modified, or removed for the purpose of improving the passage of other aquatic organisms. However, comparison to the existing baseline (i.e., the ecosystem as modified by some anthropogenic passage barrier) may not provide an adequate basis with which to assess the risk of take with a specific subactivity type. Accordingly, the baseline condition for assessing the effects of the fish passage facilities is considered to be the predeveloped state of the ecosystem (i.e., the natural stream channel with no dam, road crossing, or barrier). The culvert, fish ladder/fishway, and weir subactivity types are currently defined in the Hydraulic Code chapters of the Washington Administrative Code (WAC). The roughened channel and trap-and-haul subactivity types currently are not; however, elements of the WAC may be applicable to their regulation (see Section 4.2 [*Statutes and Rules Regulating Fish Passage Structures*] for further discussion).

A description of the different subactivity types and the elements of the existing Hydraulic Code applicable to permitting are provided in the following sections.

4.1 Characteristics, Applications, and Descriptions of Fish Passage Subactivity Types

The fish passage activity type describes projects that are intended to restore upstream and downstream fish access to habitats that have become isolated by human activities (e.g., placement of culverts, dams, and other artificial obstructions) or by natural obstructions (e.g., waterfalls, and changes in channel configuration imposed by landslides). As stated, this activity type addresses only the effects of those measures taken to provide fish passage at the obstruction, and not the effects of the structure or action that causes the obstruction itself.

4.1.1 Culverts

In the context of providing fish passage, the culvert subactivity type refers to the removal, replacement, and/or retrofitting of culverts that pose passage barriers. The effects of new culverts and the construction and operation of water crossings that necessitated the initial culvert placement are addressed in the Water Crossings white paper (Jones and Stokes 2006b) and are not discussed further here. For the purpose of this analysis, evaluation of the effects of culverts focuses specifically on the construction, operation, and maintenance-related effects of the culvert subactivity type, the effects of hydraulic and geomorphic modifications imposed by the structure, and the implications of efforts that fail to provide passage as intended. The baseline for this assessment is the natural stream, prior to the installation of the water crossing.

For the purpose of this white paper, the culvert subactivity type includes the removal, replacement, or retrofitting of culverts for the purpose of improving fish passage. This subactivity type can produce ecological effects during construction, maintenance, and operation, with variable effects depending on the type of action taken. The distinctions between removal/replacement/retrofitting are as follows:

- Removal – Complete removal of the culvert in conjunction with decommissioning of the roadway or flow control structure, or replacement of the culvert with a bridge.

- Replacement - Replacement of an existing culvert with a design that accommodates fish passage, using one of the approaches defined in current WDFW guidance (as described below).

- Retrofit – Modification of an existing culverts with baffles, internal weirs, or similar structural elements to enhance fish passage. Culverts may also be retrofitted for passage by using external weirs to backwater the structure, the effects of which are considered under the weir subactivity type (Section 4.1.4, *Weirs*).

The effects of the culvert subactivity type will vary depending on the nature of the project. For example, culvert removal or replacement will generally exert a broader degree of influence on aquatic habitat conditions than retrofitting an existing structure. The distinctions between culvert removal, culvert replacement, and retrofitting of existing structures; the resulting ecological effects of these actions; and the subsequent effects on HCP species are discussed in Section 7 (*Direct and Indirect Impacts*).

Culvert removal or replacement projects often require upstream and/or downstream habitat or channel modifications to account for changes in channel morphology that have occurred since the original structure was installed. These changes in channel morphology are typified by migrating headcuts that have been arrested by the structure, or by channel aggradation upstream of the structure that is likely to downcut when it is removed or replaced.

This type of change in channel form can occur for a variety of reasons. The culvert itself may induce upstream sediment deposition that changes the gradient profile upstream and downstream of the structure, or other hydromodifications or changes in watershed hydrology may induce changes in channel form that produce migrating headcuts that become arrested at the downstream end of the structure. Both of these conditions can produce fish passage barrier conditions that lead to the need to remove or replace the structure. In either circumstance, these geomorphic changes may produce a distinct change in gradient that is likely to become dynamic in the form of a migrating headcut when the existing structure is removed. Regardless of cause, culvert removal or replacement projects often involve channel or habitat modifications to control or moderate the channel response to the removal of the control point provided by the original structure. This may be desirable to avoid adverse effects on habitat conditions in upstream reaches.

The potential effects of geomorphic responses to culvert removal and replacement are described in this white paper, but the effects of related channel and/or habitat modifications used in conjunction with culvert replacement projects are not. The effects of these types of modifications are addressed in the Habitat Modifications and Channel Modifications white papers (Herrera 2007a, 2007c), respectively. Where appropriate, these effects are summarized in this document with reference to the relevant sections of the companion white papers for more detailed discussion.

Current WDFW guidance focuses on three culvert design options (Bates et al. 2003): the no-slope option, the hydraulic design option, and the stream-simulation option. The stream-simulation and no-slope options have emerged as the agency's preferred approach for providing fish passage for most new culverts and culvert replacement projects. The hydraulic design option is not favored for removal and replacement but is applicable where an existing culvert is being retrofitted to improve fish passage. The WAC (220-110-070) currently recognizes only the no-slope and the hydraulic design options.

Each of these design options is described in the following sections.

4.1.1.1 No-Slope Option

The no-slope design option is employed in low-gradient channel environments, which allows for the culvert barrel or box to be placed at a zero slope. No-slope designs incorporate culverts of sufficient dimensions to support the accumulation of bedload within the structure at a natural channel slope, allowing the channel to maintain some degree of natural function. In ideal circumstances, channel morphological features such as gravel bars and a thalweg will form inside the culvert.

The no-slope option can only be applied to culvert replacements and new culvert installations; it is not applicable in retrofit scenarios. It is expected to provide unhindered passage for a broad range of aquatic species and life-history stages, provided that design objectives are met. Specifically, fish passage is expected to be provided when the culvert supports accumulation consistent with the natural upstream and downstream channel gradient, promoting the formation of natural channel features within the structure.

A no-slope culvert is defined by the following characteristics:

- The culvert width is equal to or greater than the average channel bed width at the dimension where the culvert meets the streambed.
- The culvert is set at a flat gradient (i.e., zero slope).
- The downstream invert is countersunk below the channel bed by a minimum of 20 percent of the culvert diameter or rise.
- The upstream invert is countersunk by a maximum of 40 percent of the culvert diameter or rise.
- There is adequate flood capacity.

The no-slope design option is usually applicable in the following situations:

- New and replacement culvert installations in low-complexity settings
- Low to moderate natural channel gradient (generally <3 percent slope)
- Site conditions that permit culvert width of at least 1.25 times the natural channel width upstream of the structure
- Shorter length culverts
- Complex passage requirements for a range of species and life histories
- The likelihood of upstream headcutting can be avoided.

The upper limit for application of the no-slope option is defined by sites where the product of the channel slope and the culvert length (ft) does not exceed 20 percent of the culvert diameter or rise. The method can be applied with a certain degree of flexibility around these limits, provided the necessary hydraulic engineering expertise is available to account for the implications of constricting the upstream end of the culvert with the accreted bed or by installing a larger culvert. A typical no-slope option culvert configuration is shown in Figure 4-1.

4.1.1.2 Hydraulic Design Option

The hydraulic design option is used to design a culvert structure based on the swimming abilities of specific target fish species and age class. The hydraulic option can be applied to retrofits of existing culverts as well as to the design of new or replacement culverts, although the latter case is increasingly rare (as described below). Hydraulic design option culverts may employ features such as baffles, internal weirs, or other features that create the roughness necessary to promote fish passage.

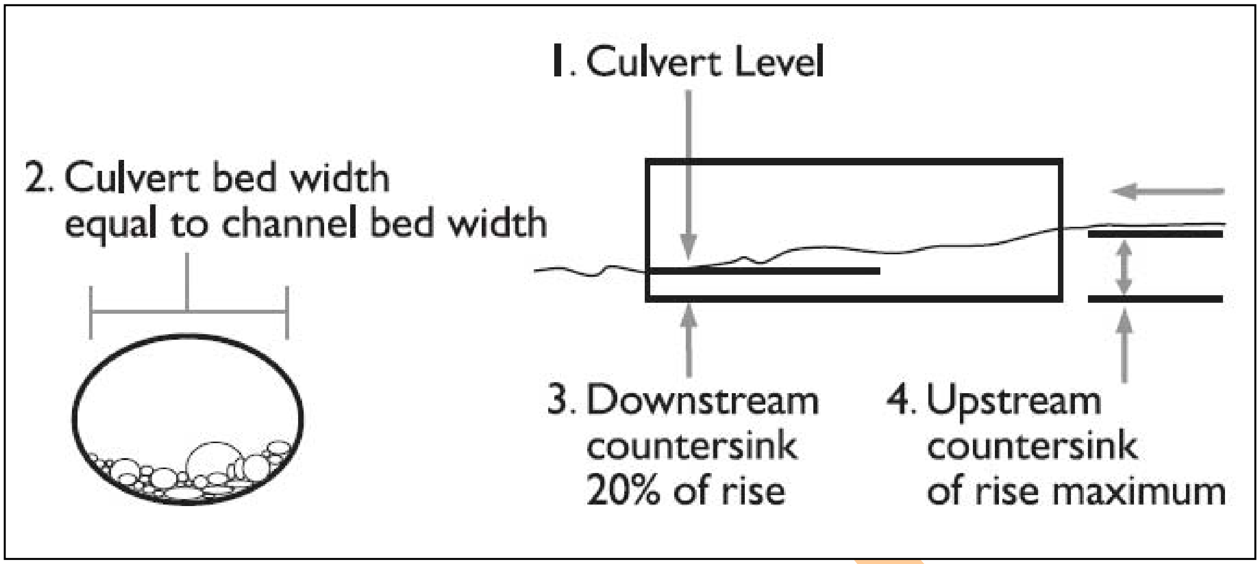


Figure 4-1. Profile and cross section for a typical no-slope culvert design (source: Bates et al. 2003).

Generally, the hydraulic design option may be employed in the following situations:

- New, replacement, and retrofit culvert installations
- Low to moderate culvert slope without baffles
- Moderate culvert slope with baffles (as retrofit)
- Target species have been identified for passage.

This design option requires a high degree of expertise in hydraulic engineering and hydrologic and geomorphic modeling capabilities, thorough understanding of the swimming performance and biological requirements of the target species, and site-specific survey information. Historically, this method was the standard approach used to design culverts for fish passage. It has become less favored, however, because of uncertaintly related to fish passage performance, a limited range of applicable settings, and a number of ecological limitations. Specifically, the passage requirements of many target species are poorly understood, which contributes to design uncertainty. Even when the passage requirements of target species are adequately addressed, the structure may fail to provide passage for nontarget species. This may lead to a range of unforeseen ecological consequences. Finally, this type of structure may not provide adequate transport of sediment and organic material, contributing to broader effects on ecosystem function and declining performance over time.

Because of these limitations, the hydraulic design option is most commonly used for temporary retrofits of existing barrier culverts in circumstances where replacement or removal is not practicable in the immediate future. A typical hydraulic design option culvert schematic is shown in Figure 4-2.

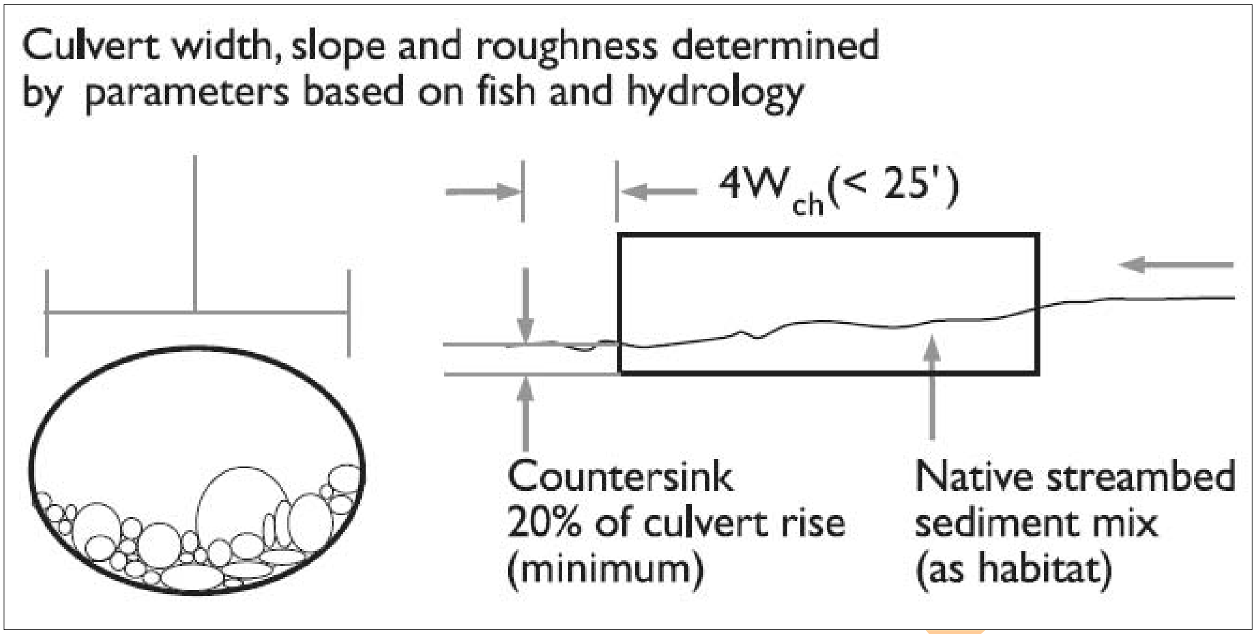


Figure 4-2. Profile and cross section for a typical hydraulic design option culvert, employing native sediment materials (source Bates et al. 2003).

4.1.1.3 Stream-Simulation Option

The stream-simulation option is similar to the no-slope option in that it attempts to mimic the natural streambed form to the greatest extent possible. Unlike the no-slope option, however, the culvert is installed at a slope matching or near the upstream channel gradient. This allows bed simulation to be employed over a broader range of gradients. Structure is placed at or near the natural channel slope and incorporates natural substrate features that mimic the streambed, provide for fish passage, and are transparent to the transport of sediment, wood, and organic debris.

Generally, the stream-simulation option is an appropriate method in the following circumstances (Bates et al. 2003):

- New and replacement-culvert installations
- Complex settings, including:
  - sites with moderate to high natural channel gradient and/or
  - sites requiring long culverts
  - narrow stream valleys
- Locations where passage is required for a broad range of aquatic species

- Systems where passage must be provided for species with poorly understood requirements
- Ecological connectivity (i.e., transparency to downstream transport of wood, sediment, and organic material) is required.

Culverts designed to simulate streambeds are sized wider than the channel width, and the bed inside the culvert is sloped at a similar or greater gradient than the upstream channel stream reach (i.e., no more than 125 percent of the upstream gradient). This type of culvert is filled with substrate material that emulates the natural channel, erodes and deforms similar to the natural channel, and is unlikely to change grade unless specifically designed to do so. This design method is intended to mimic a stream channel, allowing for minor adjustments in response to changes in upstream and downstream channel dynamics. The most basic stream simulation culvert is a bottomless culvert placed over a natural streambed. Here, the natural streambed remains in place. More complex designs may involve substrate intermixed with immobile bedform elements (e.g., boulders) to maintain bed conditions within the structure. Typical low-gradient and high-gradient stream-simulation schematics are shown in Figures 4-3 and 4-4.

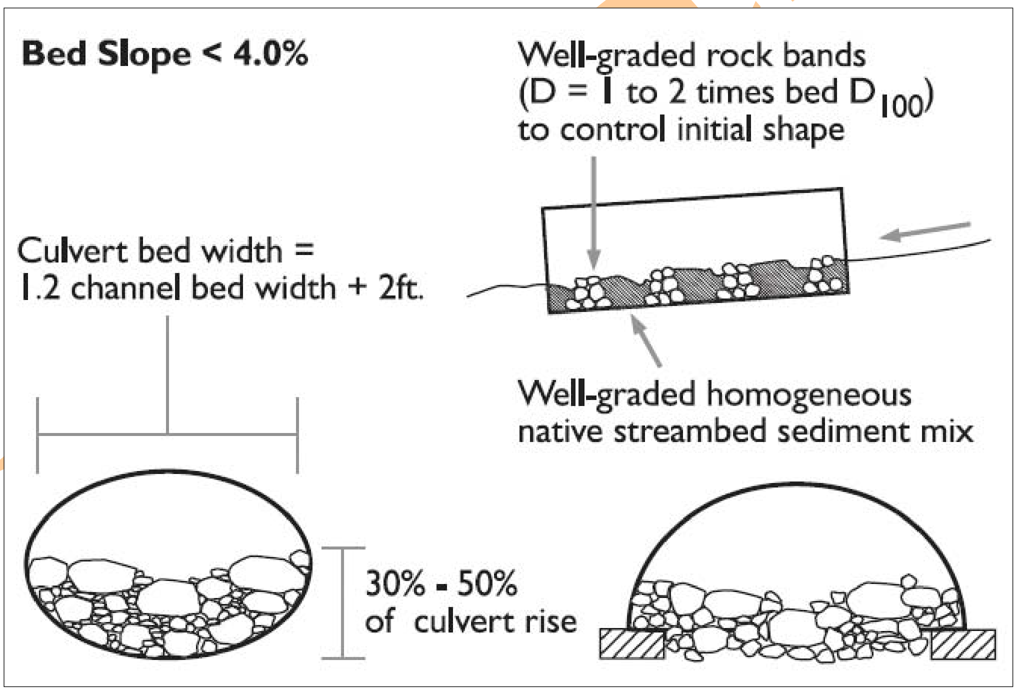


Figure 4-3. Profile and cross sections for typical stream simulation option culverts for low to moderate gradient settings (less than 4 percent slope) (source: Bates et al. 2003).

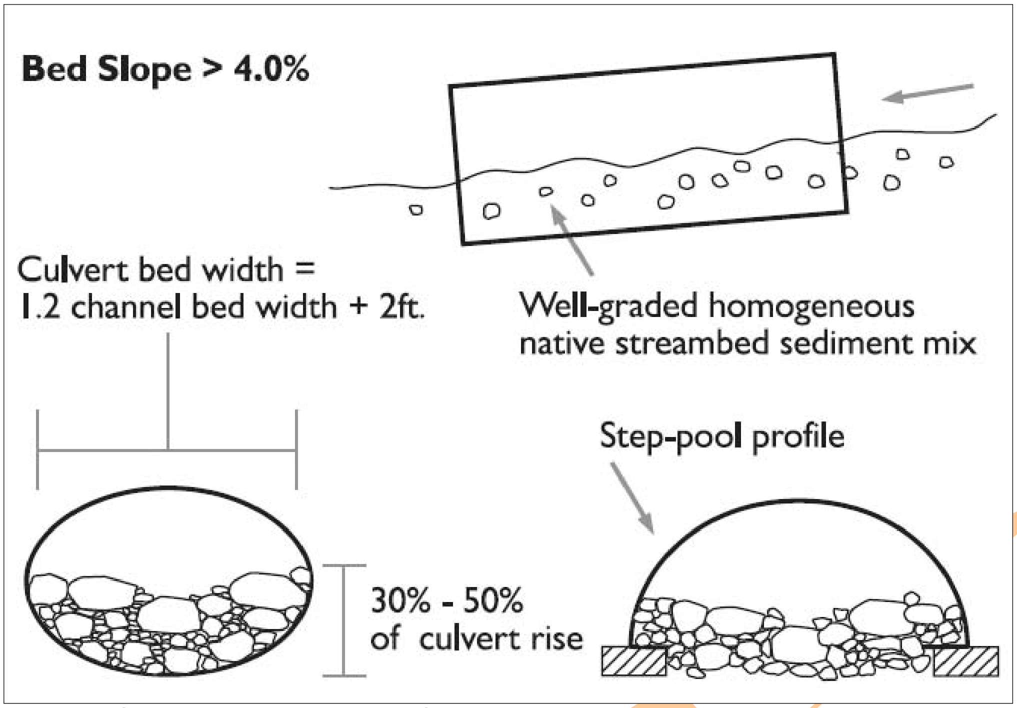


Figure 4-4. Profile and cross sections for typical stream simulation option culverts for higher gradient settings (< 4 percent slope) (source: Bates et al. 2003).

4.1.1.4 Gated Culverts

This white paper also considers effects on HCP species imposed by the replacement or retrofitting of gated culverts (i.e., tide gate or flap gated culverts). Gated culverts are culverts with a flap gate on one end that prevents the backflow of water through a channel modification, such as a dike or a levee. They are used to prevent inundation landward of the channel modification caused by high streamflows or tidal fluctuations, and are often employed in agricultural settings to aid in the draining and conversion of floodplains for human uses. Culverts of this type in tidally influenced environments are referred to as tide gates, which can affect both riverine and marine (i.e., estuarine) habitat types. In riverine environments, gated culverts that protect floodplain areas behind channel modifications from inundation by elevated streamflows are referred to as flap or flood gated culverts.

This type of culvert system is considered to be a flow control structure, the broader effects of which are addressed in the Flow Control Structures white paper under *Tide Gates* (Herrera 2007b). New tide gates and flap gated culverts can be designed to allow for some degree of fish passage, and existing structures can be retrofitted for this purpose. For example, self-regulating tide gates (SRTs) include a flap gate fitted with a float system that allows the gate to remain open to backflow for specified periods, thereby providing improved fish passage in exchange for permitting some inundation of upstream lands. Because the effects of gated culverts on fish passage were not considered in detail in the Flow Control Structures white paper, they are addressed here as a component of the ecosystem fragmentation analysis. Consistent with the analyses of other subactivity types presented herein, the environmental baseline for this assessment is the natural system in the absence of the tide gate or the channel modification it is associated with.

4.1.2 Fish Ladders/Fishways

Fish ladders and fishways are artificial structures that are used to provide passage through, over, and/or around artificial barriers (e.g., culverts, flumes, and/or dams) or natural barriers (e.g., waterfalls) (note: current WDWF policy does not allow for the creation of passage around natural barriers). These structures provide a graduated change in gradient with refuge areas that allow fish to navigate past the barrier. This white paper addresses only the effects of the construction, operation, and maintenance of this subactivity type. The effects of man-made structures (such as dams and weirs) and natural features (such as waterfalls) that necessitate the fish ladder or fishway are addressed separately in the Flow Control Structures white paper (Herrera 2007b). (Note: Waterfalls are mentioned here to accommodate special cases like the Sunset Falls trap-and-haul facility on the Skykomish River, which incorporates an intake structure; as stated, the effects of intakes are addressed in the Flow Control Structures white paper.)

Typically, fishways incorporate a sloping channel partitioned by internal weirs, baffles, or vanes with openings for fish to swim through. The sloping channels are designed to flatten hydraulic gradients and velocities to create conditions that target fish species can successfully navigate (Katopodis 1992). Examples of fishway designs include vertical slot, baffled, and weir type structures.

4.1.2.1 Vertical Slot Fishways

Vertical slot fishways incorporate a sloping channel partitioned by baffles spaced at regular intervals throughout the structure with passage through a vertical slot between the baffles. The hydraulic shadows behind the baffles provide refuge areas where organisms can rest before attempting to navigate the high-velocity flows in the slots between the baffles. A schematic of a typical vertical slot fishway design is shown in Figure 4-5.

A key advantage of this type of design is the ability to function over large variations in water levels. The design presents a number of disadvantages. This type of structure is limited to applications having slopes of 10 percent or less. The design also tends to produce uniform internal velocities between the baffles that may limit the passage of smaller or juvenile fish species. Finally, this design is also prone to sediment and debris accumulation, requiring routine maintenance.

4.1.2.2 Baffle Type Fishways

Baffle type fishways include a range of design types applied in a variety of settings. These include placement of baffles within existing culverts or other structures to address sheet flow (depth) and velocity barrier conditions, as well as structures designed to provide passage over man-made or natural vertical drop barriers. The Denil, Alaskan steep pass, and Lariner design variants are examples of the latter category. They incorporate a rectangular chute with a series of uniform, closely spaced baffles or vanes along the sides and bottom. Flow through this type of structure is turbulent with high energy dissipation, reducing the need for resting pools and similar features. A schematic of a typical baffle type fishway design is shown in Figure 4-6.

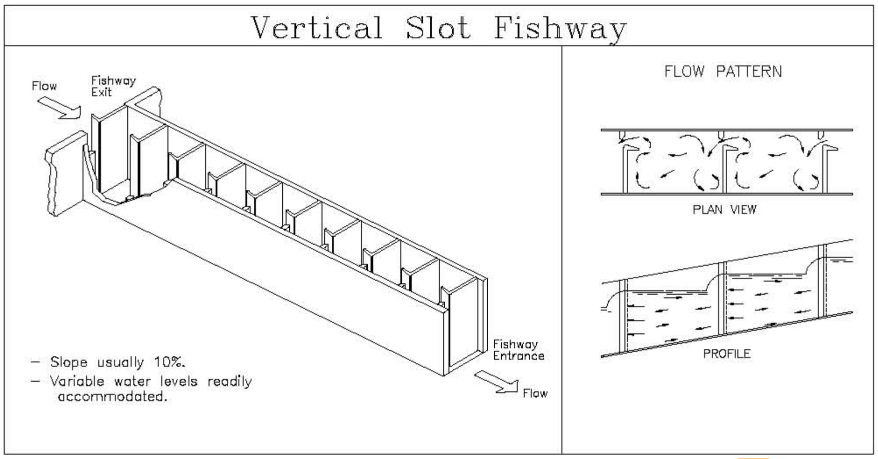


Figure 4-5. Typical vertical slot fishway (Source: Katopodis 1992).

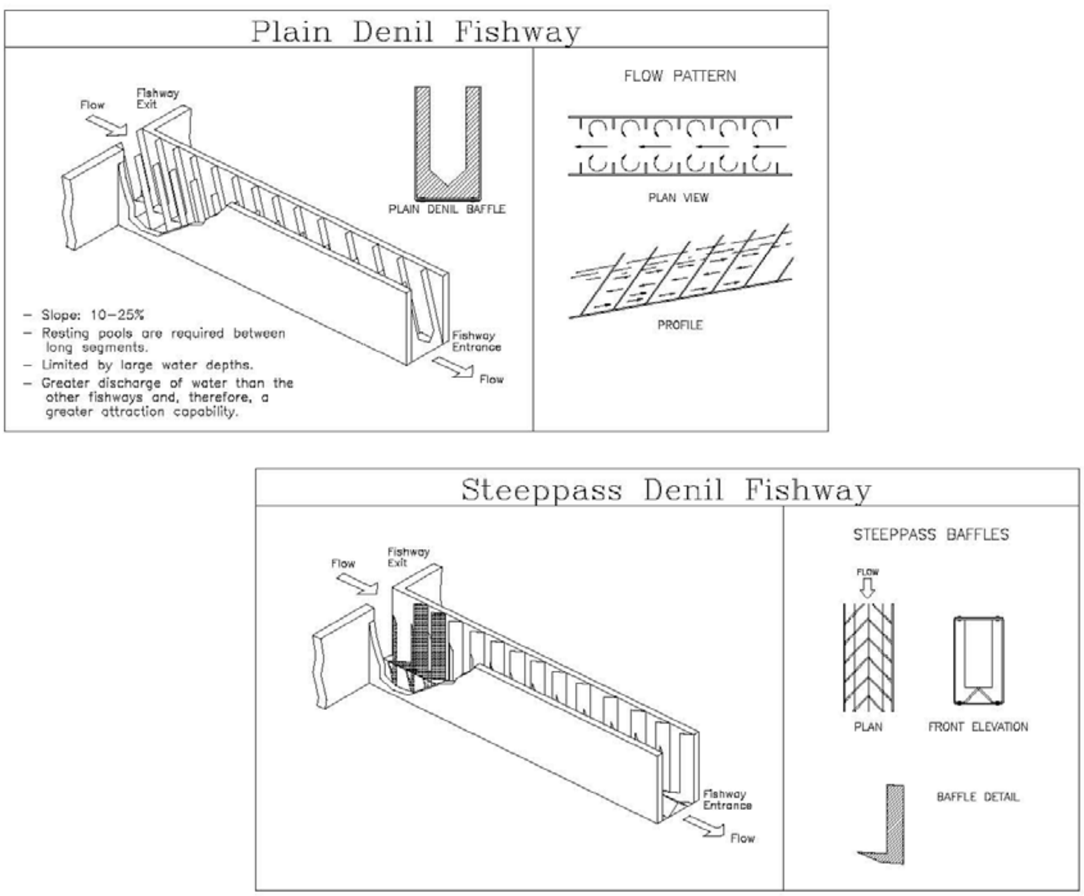


Figure 4-6. Typical baffle-type fishways (Source: Katopodis 1992).

The advantages provided by baffle type fishways vary depending on the environment in which they are employed. For example, barrier culverts are often retrofitted with baffles to create a fishway-like environment that improves passage conditions. However, this type of structure may not provide passage for the full range of species and life-history stages present under all relevant flow conditions. Moreover, retrofitted structures commonly require increased maintenance to maintain passage performance. As such, baffle retrofit projects are typically permitted only as an interim remedy until a long-term solution can be developed.

Alaskan steep pass fishways and similar designs are typically implemented in environments where artificial barriers such as dams and weirs present a vertical barrier to fish passage. This type of fishway can provide passage at gradients of up to 20 percent. Because they don't require resting pools, these compact designs can be implemented in settings where space is limited. Finally, the relatively high flow capacity provides good attraction flows and creates turbulent conditions inside the structures that discourage sediment accumulation.

A key disadvantage of Alaskan steep pass and similar baffle type fishways is that they may not provide passage for a broad range of species and life-history stages. Specifically, these structures create high flow velocities and turbulence that require fish to swim constantly. This may hinder passage of smaller or juvenile fish with weaker swimming performance. This shortcoming may be overcome by the inclusion of resting pools, but these features would negate the advantages of compact size and low maintenance. Baffles and vanes commonly employed in this type of structure are also prone to sediment debris accumulation that can interfere with passage performance. In some cases, baffles can accumulate large debris that can overload and damage the structure. This leads to maintenance requirements and structural failure risk that negate to some degree the general benefit of limited coarse sediment accumulation.

4.1.2.3 Weir Type Fishways

Weir type fishways consist of a rectangular chute with weir-separated pools of uniform length arranged in a stepped pattern. This creates create a long, sloping channel that gradually steps down the water level. This is the oldest type of fish ladder design. A schematic of a typical weir type fishway design is shown in Figure 4-7.

A weir type design requires fish to leap over the weir separating each step pool in the structure. However, an advantage of this type of structure is that the weirs can be configured with multiple notches and orifices to provide passage for fish of different sizes and life-history stages. The pools between weirs provide resting areas that enhance passage.

The weir type design presents several disadvantages. First this structure is limited to sites permitting design slopes no greater than 10 percent. Fishway function is sensitive to water level fluctuations, and performance varies depending on flow rates. Flow occlusion may lead to dewatering and fish stranding. The pools between the weirs are prone to sediment aggradation, meaning that maintenance requirements are more extensive than for other fishway designs. In addition, stoplogs commonly used as design elements in weir type fishways have a tendency to become dislodged, requiring adjustment or replacement.

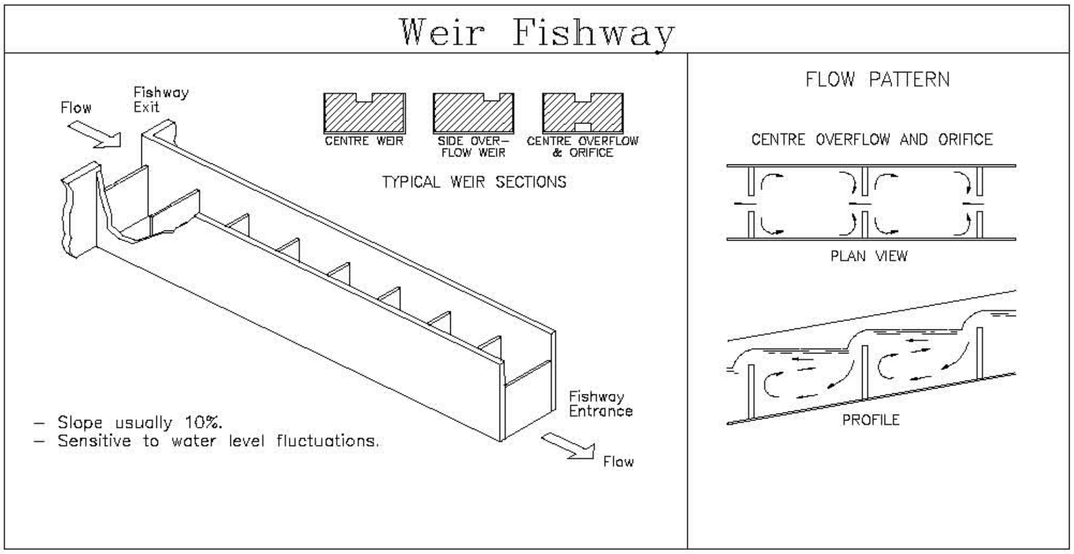


Figure 4-7. Typical weir-type fishway (Source: Katopodis 1992).

4.1.3 Roughened Channels

The roughened channel subactivity type describes intentional changes in channel configuration designed to facilitate the passage of adult and juvenile fish. Roughened channels may be used to provide passage around abrupt hydraulic drops (i.e., falls or cascades) or uniform channels with high-velocity flows lacking refuge areas. The roughened channel typically moderates gradient and provides sufficient hydraulic complexity to allow for fish to pass the natural or man-made obstruction. The effects of construction of roughened channels are similar to those imposed by channel creation and realignment, which are addressed in the Channel Modifications white paper (Herrera 2007c). The Fish Passage white paper focuses specifically on the hydraulic and geomorphic effects of roughened channels and the ecological effects of these structures resulting from changes in fish passage.

4.1.4 Weirs

Weirs constructed for fish passage management include both permanent and temporary structures. Temporary weirs are often installed to facilitate the counting of adult fish returning to spawning grounds. Permanent weirs are often used for similar purposes (e.g., hatchery weirs). The effects of construction of permanent weirs on the environment and the resulting risk of take for HCP species are evaluated in the Flow Control Structures white paper (Herrera 2007b). The Fish Passage white paper focuses specifically on the aspects of weirs that relate solely to passage. Fish passage weirs include structures installed in natural channels to enhance passage (e.g., a series of step pools formed by grade control structures composed of natural or man-made materials), as well structures designed to prevent fish passage to upstream areas consistent with specific management objectives. For example, barrier weirs are often installed at hatcheries to prevent the upstream passage of hatchery fish that might produce detrimental effects should they spawn in the wild. Barrier weirs are also used to prevent the invasion of non-native species into habitats where sensitive native species are present. Permanent weirs are also used to provide passage through barrier culverts. In such cases, a series of weirs may be used to provide access into the culverts isolated by outfall drops, or to backwater culverts that present velocity or depth barriers.

Fish passage weirs may also be construed to include grade control structures that are intended to improve instream habitat conditions with the added benefit of facilitating fish passage. These structures are typically constructed using large wood and are therefore considered to be large woody debris placement projects, the effects of which are discussed in the Habitat Modifications white paper (Herrera 2007a).

4.1.5 Trap and Haul

Trap-and-haul activities are specialized operations involving the capture of fish for transport around existing natural or man-made fish passage barriers. Trap-and-haul activities involving adult fish are often conducted at a dam, weir, or similar form of flow control structure that allows for the control of attraction flows used to direct fish into capture areas. Juvenile fish may be captured at similar structures, or may be captured using equipment and techniques (e.g., beach seining, rotary screw traps) that do not have a lasting physical effect on the environment.

The effects of construction and maintenance of dams, weirs, water intake and diversion systems, and similar flow control structures that are integrated with trap-and-haul activities have been evaluated in the Flow Control Structures white paper (Herrera 2007b), and are not addressed further here. Accordingly, this white paper focuses only on the effects of trap-and-haul operations on aquatic species and the environment (i.e., mortality, injury, and stress from capture; alteration of migratory behavior and dynamics; and the accidental introduction of biological and chemical contaminants).

4.2 Statutes and Rules Regulating Fish Passage Structures

RCW 77.55.011(7) defines a hydraulic project as "the construction or performance of work that will use, divert, obstruct, or change the natural flow or bed of any of the salt or freshwaters of the state." Fish passage activities have the potential to alter local hydrology and geomorphology and thus are defined as hydraulic projects. Fish passage enhancement is a broad activity type; consequently, many parts of the WAC are applicable to the subactivity types that fall into this category of activities.

The mechanisms of impact on HCP species associated with these projects include the long duration impacts associated with structure placement and operational activities, as well as the effects of construction activities that could result in short-term to longer term modifications of physical and biological processes. These include modifications to hydraulic and geomorphic characteristics, aquatic and riparian vegetation, changes in water quality that could result in direct and indirect effects on HCP species, and the effects of ecological fragmentation imposed by changes in habitat access for the range of species affected. They also include the effects of fish (and invertebrate) handling, relocation, and exclusion associated with such activities.

The WACs listed in Table 4-1 are applicable to the listed subactivity types: (note: * indicates that the activity may be related to the project subactivity type, but is not an implicit component of the activity).

Current WDFW design practices for culverts, fishways, weirs, roughened channels, and trap-and-haul facilities were used to define the subactivity types evaluated in this document (WDFW 2000; Bates et al. 2003; WAC 220-110-070). For the purpose of assessing impact mechanisms, resulting stressors, and biological responses to those stressors, the environmental baseline is the unaltered channel condition prior to the installation of the structure (i.e., the channel prior to culvert installation).

The effects of temperature and chemical barriers are not included in this white paper, except to the extent that these factors are influenced by the installation and operation of fish passage structures. The effects of fishways at hatcheries are also not included.

Table 4-1. Hydraulic Code section potentially applicable to the permitting of fish passage structures and/or activities.

Subactivity Type	Freshwater WACs	Marine WACs
Culverts	220-110-050 (FW banks)* 220-110-070 (water crossings) 220-110-080 (channel change) 220-110-120 (temp bypass)* 220-110-130 (dredging)* 220-110-140 (gravel removal)* 220-110-150 (LWD) 220-110-223 (lake banks)*	No specific existing WACs for fish passage structures in marine and estuarine environments; however, the following may apply: 220-110-250 (habitats of concern) 220-110-270 (common) 220-110-271 (prohibited work windows) 220-110-280 (non-SFRM bank) 220-110-285 (SFRM bank) 220-110-320 (dredging)
Fish ladders/ fishways	220-110-050 (FW banks)* 220-110-070 (water crossings)* 220-110-080 (channel change) 220-110-120 (temp bypass) 220-110-130 (dredging)* 220-110-140 (gravel removal)* 220-110-150 (LWD) 220-110-223 (lake banks)*	
Roughened channels	No specific existing WACs for roughened channels, however potentially applicable WACs for roughened channels are similar to those listed for fish ladders/fishways	
Weirs	220-110-050 (FW banks)* 220-110-080 (channel change) 220-110-120 (temp bypass) 220-110-130 (dredging)* 220-110-140 (gravel removal)* 220-110-150 (LWD) 220-110-223 (lake banks)*	
Trap and haul	No specific WACs for trap-and-haul activities, however WACs applicable to structures used to facilitate fish capture may be applicable, including: 220-110-050 (FW banks)* 220-110-070 (water crossings)* 220-110-080 (channel change) 220-110-120 (temp bypass) 220-110-150 (LWD) 220-110-090 (diversions) 220-110-223 (lake banks)*	

Note: * indicates that the activity may be related to the topics covered in this white paper, but it is not necessarily an implicit component of the activity as specified in the WAC.
FW = freshwater; LWD = large woody debris; SFRM = single-family residential marine.

5.0 Potentially Covered Species and Habitat Use

This white paper identifies what is known about the effects resulting from construction and operation of fish passage subactivity types on the environment and the resulting risk of take these effects pose for the 52 HCP species. To understand species-specific impacts, it is necessary to understand the geographic distribution, general life history, and habitat preferences of these species and how these characteristics relate to the subactivity type in question. This section provides a general summary of these characteristics, presented in Table 5-1, which lists the scientific name, Water Resource Inventory Area (WRIA) of occurrence, tidal reference area, and the reproductive patterns and habitat requirements of each of these HCP species.

Knowledge of species-specific habitat needs facilitates the risk of take assessment because the timing, frequency, duration, and magnitude of stressor exposure can be rated against the sensitivity of the species' life-history stages that rely on the affected habitat (see Section 9 [*Potential Risk of Take*] and the exposure-response matrices for each of these species as presented in Appendix A). Once the risk of take has been identified, this information facilitates identification of measures and guidance that can be used to avoid or minimize risk of take (see Section 11 [*Habitat Protection, Conservation, Mitigation, and Management Strategies*]).

Table 5-1. Range of occurrence of the HCP species and their habitat requirements.

Common Name	Scientific Name	Water Resource Inventory Area[a]	Tidal Reference Area[b]	Habitat Requirements and Reproduction Timing
Chinook salmon	*Oncorhynchus tshawytscha*	01–42, 44–50	All	**General Information (Habitats and Feeding/Life-history Types)** NOAA Fisheries recognizes eight ESUs of Chinook salmon in Washington: (1) Upper Columbia River spring-run; (2) Snake River spring/summer run; (3) Snake River fall-run; (4) Puget Sound; (5) lower Columbia River; (6) Washington coast; (7) Mid-Columbia River spring-run; and (8) Upper Columbia River summer/fall-run. Chinook salmon exhibit one of two life-history types, or races: the stream-type and the ocean-type. Stream-type Chinook tend to spend 1 (or less frequently 2) years in freshwater environments as juveniles prior to migrating to salt water as smolts. Stream-type Chinook are much more dependent on freshwater stream ecosystems than ocean-type Chinook. Stream-type Chinook do not extensively rear in estuarine and marine nearshore environments; rather, they head offshore and begin their seaward migrations. Ocean-type Chinook enter salt water at one of three phases: immediate fry migration soon after yolk is absorbed, fry migration 60–150 days after emergence, and fingerling migrants that migrate in the late summer or fall of their first year. Ocean-type Chinook are highly dependent on estuarine habitats to complete their life history. Chinook generally feed on invertebrates but become more piscivorous with age. **Reproduction/Life History** Chinook runs are designated on the basis of adult migration timing: • Spring-run Chinook: Tend to enter fresh water as immature fish, migrate far upriver, and finally spawn in the late summer and early autumn. • Fall-run Chinook: Enter fresh water at an advanced stage of maturity, move rapidly to their spawning areas on the mainstem or lower tributaries of the rivers, and spawn within a few days or weeks of freshwater entry. • Spring Chinook: Spawning occurs from mid-July to mid-December, and incubation lasts approximately 1.5–7 months, depending on temperature. Emergence follows, 6–8 months from fertilization. • Fall Chinook: Spawning occurs from late October to early December, with incubation occurring for 1–6 months. Emergence follows, approximately 6 months after fertilization. (Healey 1991; Myers et al. 1998; WDNR 2006a; Wydoski and Whitney 2003)

Table 5-1 (continued). Range of occurrence of the HCP species and their habitat requirements.

Common Name	Scientific Name	Water Resource Inventory Area[a]	Tidal Reference Area[b]	Habitat Requirements and Reproduction Timing
Coho salmon	*Oncorhynchus kisutch*	01–42, 44–48, 50	All	**General Information (Habitats and Feeding)** NOAA Fisheries recognizes four ESUs of coho salmon in Washington: (1) Lower Columbia River; (2) Southwest Washington; (3) Puget Sound and Strait of Georgia; and (4) Olympic Peninsula. This species is found in a broader diversity of habitats than any of the other native anadromous salmonids. Fry feed primarily on aquatic insects and prefer pools and undercut banks with woody debris; adults feed on herring and other forage fish. **Reproduction/Life History** Coho adults spawn from September to late January, generally in the upper watersheds in gravel free of heavy sedimentation. Developing young remain in gravel for up to 3 months after hatching. Fry emerge from early March to late July. Coho rear in fresh water for 12–18 months before moving downstream to the ocean in the spring. Coho spend between 1 and 2 years in the ocean before returning to spawn. (Groot and Margolis 1991; Murphy and Meehan 1991; WDNR 2005, 2006a; Wydoski and Whitney 2003)

Table 5-1 (continued). Range of occurrence of the HCP species and their habitat requirements.

Common Name	Scientific Name	Water Resource Inventory Area[a]	Tidal Reference Area[b]	Habitat Requirements and Reproduction Timing
Chum salmon	*Oncorhynchus keta*	01, 03–05, 07–29	All	**General Information (Habitats and Feeding)** NOAA Fisheries recognizes four ESUs of chum salmon in Washington: (1) Hood Canal summer run; (2) Columbia River; (3) Puget Sound/Strait of Georgia; and (4) Pacific Coast. Little is known about their ocean distribution; maturing individuals that return to Washington streams have primarily been found in the Gulf of Alaska. Chum migrate into rivers and streams of Washington coast, Hood Canal, Strait of Juan de Fuca, Puget Sound, and the Columbia River basin to spawn, but their range does not extend upstream above the Dalles Dam in the Columbia River. Fry feed on chironomid and mayfly larvae, as well as other aquatic insects, whereas juvenile fish in the estuary feed on copepods, tunicates, and euphausiids. **Reproduction/Life History** Chum salmon have three distinct run times: summer, fall and winter. Summer chum begin their upstream migration and spawn from mid-August through mid-October, with fry emergence ranging from the beginning of February through mid-April. Chum fry arrive in estuaries earlier than most salmon, and juvenile chum reside in estuaries longer than most other anadromous species. Chum salmon rear in the ocean for the majority of their adult lives. Fall chum adults enter the rivers from late October through November and spawn in November and December. Winter chum adults migrate upstream from December through January and spawn from January through February. Fall and winter chum fry emerge in March and April and quickly emigrate to the estuary. Chum salmon utilize the low-gradient (from 1–2 percent grade), sometimes tidally influenced lower reaches of streams for spawning. (Healey 1982; Johnson et al. 1997; Quinn 2005; Salo 1991; WDNR 2005, 2006a; Wydoski and Whitney 2003)

Table 5-1 (continued). Range of occurrence of the HCP species and their habitat requirements.

Common Name	Scientific Name	Water Resource Inventory Area[a]	Tidal Reference Area[b]	Habitat Requirements and Reproduction Timing
Pink salmon	*Oncorhynchus gorbuscha*	01, 03–05, 07, 09–11, 16–19, 21	1–13	**General Information (Habitats and Feeding)** NOAA Fisheries recognizes two ESUs of pink salmon in Washington, neither of which is listed: (1) Odd-year; and (2) Even-year. The most abundant species of salmon, with 13 stocks identified in Washington. They are the smallest of the Pacific salmon and mature and spawn on a 2-year cycle in Washington (primarily spawning during odd years). Adults are opportunistic feeders in marine habitat, foraging on a variety of forage fish, crustaceans, ichthyoplankton, and zooplankton. Juveniles primarily feed on small crustaceans such as euphausiids, amphipods, and cladocerans. **Reproduction/Life History** Pink salmon will spawn in rivers with substantial amounts of silt. Spawning occurs from August through October. Fry emerge from their redds in late February to early May, depending on water temperature, and migrate downstream to the estuary within 1 month. Juveniles remain in estuarine or nearshore waters for several months before moving offshore as they migrate to the Pacific Ocean, where they remain approximately 1 year until the next spawning cycle. (Hard et al. 1996; Heard 1991; WDNR 2005, 2006a)
Sockeye salmon	*Oncorhynchus nerka*	01, 03–05, 07–11, 16, 19–22, 25–33, 35–37, 40, 41, 44–50	5, 8, 14	**General Information (Habitats and Feeding/Life-history Types)** NOAA Fisheries recognizes seven ESUs of sockeye salmon in Washington: (1) Snake river; (2) Ozette Lake; (3) Baker river; (4) Okanogan River; (5) Quinault Lake; (6) Lake Pleasant; and (7) Lake Wenatchee. WDFW recognizes an additional sockeye salmon stock in the Big Bear Creek drainage of Lake Washington. Kokanee (landlocked sockeye) occur in many lakes, with the larger populations in Banks and Loon lakes in eastern Washington and Lake Whatcom and Lake Washington-Sammamish in western Washington. Juveniles feed on zooplankton, and adults primarily feed on fish, euphausiids, and copepods. **Reproduction/Life History** Spawn in shallow, gravelly habitat in rivers and lakes during August to October. Juvenile sockeye rear in lakes for 1–2 years before migrating to the ocean. Emergence occurs within 3–5 months. (Gustafson et al. 1997; Wydoski and Whitney 2003)

Table 5-1 (continued). Range of occurrence of the HCP species and their habitat requirements.

Common Name	Scientific Name	Water Resource Inventory Area[a]	Tidal Reference Area[b]	Habitat Requirements and Reproduction Timing
Steelhead	*Oncorhynchus mykiss*	01, 03–05, 07–12, 14, 15, 17–41, 44–50	All	**General Information (Habitats and Feeding)** NOAA Fisheries recognizes 15 Distinct Population Segments (DPSs) of steelhead, seven of which occur in Washington. During their ocean phase, steelhead are generally found within 10 and 25 miles of the shore; steelhead remain in the marine environment 2–4 years before returning to fresh water to spawn. Most steelhead spawn at least twice in their lifetimes. Escape cover, such as logs, undercut banks, and deep pools, is important for adult and young steelhead in the freshwater systems. The coastal west-side streams typically support more winter steelhead populations. **Reproduction** A summer spawning run enters fresh water in August and September, and a winter run occurs from December through February. Summer steelhead usually spawn farther upstream than winter populations and dominate inland areas such as the Columbia Basin. Spawning occurs from March to April for both winter and summer run steelhead. After hatching and emergence (approximately 3 months), juveniles establish territories, feeding on microscopic aquatic organisms and then larger organisms such as isopods, amphipods, and aquatic and terrestrial insects. Steelhead rear in fresh water for up to 4 years before migrating to sea. (Busby et al. 1996; McKinnell et al. 1997; WDNR 2006a; Wydoski and Whitney 2003)
Coastal cutthroat trout	*Oncorhynchus clarki clarki*	01–05, 07–30	All	**General Information (Habitats and Feeding/Life-history Types)** NOAA Fisheries has recognized three ESUs in Washington: (1) Puget Sound; (2) Olympic Peninsula; (3) Southwestern Washington/Columbia River. USFWS has assumed sole jurisdiction for this species. No coastal cutthroat trout DPSs are listed under the ESA in Washington. Coastal cutthroat trout exhibit varied life-history forms including: • Resident (stays in streams after rearing in their natal streams) – Resident coastal cutthroat trout utilize small headwater streams for all of their life stages. • Fluvial (migrates to larger rivers after rearing in their natal streams). • Adfluvial (migrates to lakes after rearing in their natal streams). • Anadromous (utilizes estuaries and nearshore habitat but has been caught offshore). Juveniles of all life forms feed primarily on aquatic invertebrates but are opportunistic feeders; adults tend to feed on smaller fish, amphibians, and crustaceans while foraging within the nearshore environment. **Reproduction/Life History** Coastal cutthroat trout are repeat spawners, and juveniles typically rear in the natal streams for up to 2 years. Spawning occurs from late December to February, with incubation lasting approximately 2–4 months. Emergence occurs after 4 months. (Johnson et al. 1999; Pauley et al. 1988; WDNR 2006a)

Table 5-1 (continued). Range of occurrence of the HCP species and their habitat requirements.

Common Name	Scientific Name	Water Resource Inventory Area[a]	Tidal Reference Area[b]	Habitat Requirements and Reproduction Timing
Redband trout	*Oncorhynchus mykiss gardnerii*	37–40, 45–49, 54–57	NA	**General Information (Habitats and Feeding)** Redband trout is a subspecies of rainbow trout found east of the Cascade Mountains, which prefer cool water that is less than 70°F (21°C), and occupy streams and lakes with high amounts of dissolved oxygen. Their food primarily consists of Daphnia and chironomids as well as fish eggs, fish, and insect larvae and pupae. **Reproduction/Life History** Spawn in streams with clean, small gravel from March through May. Incubation takes approximately 1–3 months, with emergence occurring between June and July. (USFS 2007)
Westslope cutthroat trout	*Oncorhynchus clarki lewisii*	37–39, 44–55, 58–62	NA	**General Information (Habitats and Feeding/Life-history Types)** Cutthroat trout tend to thrive in streams with extensive pool habitat and cover. The westslope is a subspecies of cutthroat trout with three possible life forms: • Adfluvial (migrates to lakes) • Fluvial (migrates to larger rivers) • Resident (stays in streams). The headwater tributaries used by resident cutthroat are typically cold, nutrient-poor waters that result in slow growth. Fluvial and adfluvial forms can exhibit more growth due to warmer water temperatures and nutrient availability. Fry feed on zooplankton, and fingerlings feed on aquatic insect larvae. Adults feed on terrestrial and aquatic insects. **Reproduction/Life History** Spawning: all three life forms spawn in small gravel substrates of tributary streams in the spring (March to July) when water temperature is about 50°F (10°C); incubation occurs during April to August, and emergence occurs from May through August. Fry spend 1–4 years in their natal stream before migrating to their ultimate habitat. (Liknes and Graham 1988; Shepard et al. 1984; Wydoski and Whitney 2003)

Table 5-1 (continued). Range of occurrence of the HCP species and their habitat requirements.

Common Name	Scientific Name	Water Resource Inventory Area[a]	Tidal Reference Area[b]	Habitat Requirements and Reproduction Timing
Bull trout	*Salvelinus confluentus*	01, 03–05, 07–23, 26, 27, 29–41, 44–55, 57–62	All	**General Information (Habitats and Feeding/Life-History Types)** Widely distributed in Washington; exhibit four life-history types: • Resident (stays in streams after rearing in their natal streams) • Fluvial (migrates to larger rivers after rearing in their natal streams) • Adfluvial (migrates to lakes after rearing in their natal streams) • Anadromous (bull trout in the nearshore ecosystem rely on estuarine wetlands and favor irregular shorelines with unconsolidated substrates). Young of the year occupy side channels, with juveniles in pools, runs, and riffles; adults occupy deep pools. Juvenile diet includes larval and adult aquatic insects; subadults and adults primarily feed on fish. **Reproduction/Life History** The migratory forms of bull trout, such as anadromous, adfluvial, and fluvial, move upstream by early fall to spawn in September and October (November at higher elevations). Although resident bull trout are already in stream habitats, they move upstream looking for suitable spawning habitat. They prefer clean, cold water (50°F [10°C]) for spawning. Colder water (36–39°F [2–4°C]) is required for incubation. Preferred spawning areas often include groundwater infiltration. Extended incubation periods (up to 220 days) make eggs and fry particularly susceptible to increases in fine sediments. Bull trout typically rear in natal streams for 2–4 years, although resident fish may remain in these streams for their entire lives; multiple life-history forms may occur in the same habitat environments. (Goetz et al. 2004; WDNR 2005, 2006a; Wydoski and Whitney 2003)

Table 5-1 (continued). Range of occurrence of the HCP species and their habitat requirements.

Common Name	Scientific Name	Water Resource Inventory Area[a]	Tidal Reference Area[b]	Habitat Requirements and Reproduction Timing
Dolly Varden	*Salvelinus malma*	01, 03, 05, 07, 17–22, 24	6–10, 14–17	**General Information (Habitats and Feeding/Life-History Types)** Species restricted to coastal areas and rivers that empty into them. Juveniles extensively use instream cover; while in the marine systems, they use beaches of sand and gravel. Prefer pool areas and cool temperatures. Feed opportunistically on aquatic insects, crustaceans, salmon eggs, and fish. Closely related to bull trout and exhibit the same life-history traits. Four life-history types occur: • Resident (stays in streams after rearing in their natal streams) • Fluvial (migrates to larger rivers after rearing in their natal streams) • Adfluvial (migrates to lakes after rearing in their natal streams) • Anadromous (migrates to marine waters after rearing in their natal streams). **Reproduction/Life History** Spawn and rear in streams from mid-September through November. Incubation lasts approximately 130 days. Juveniles can spend 2–4 years in their natal streams before migration to marine waters. (Leary and Allendorf 1997; WDNR 2005; Wydoski and Whitney 2003)
Pygmy whitefish	*Prosopium coulteri*	08, 19, 39, 47, 49, 53, 55, 58, 59, 62	NA	**General Information (Habitats and Feeding)** In Washington, pygmy whitefish occur at the extreme southern edge of their natural range; pygmy whitefish were once found in at least 15 Washington lakes but have a current distribution in only nine. They occur most often in deep, oligotrophic lakes with temperatures less than 50°F (10°C), where they feed on zooplankton, such as cladocerans, copepods, and midge larvae. **Reproduction/Life History** Pygmy whitefish spawn in streams or lakes from July through November. They prefer pools, shallow riffles, and pool tail-outs when spawning in streams. Lake spawning by pygmy whitefish occurs at night. Spawning occurs by scattering their eggs over coarse gravel. Incubation and emergence timing are unknown, but eggs are believed to hatch in the spring. (Hallock and Mongillo 1998; WDNR 2005, 2006a; Wydoski and Whitney 2003)

Table 5-1 (continued). Range of occurrence of the HCP species and their habitat requirements.

Common Name	Scientific Name	Water Resource Inventory Area[a]	Tidal Reference Area[b]	Habitat Requirements and Reproduction Timing
Olympic mudminnow	*Novumbra hubbsi*	08–24	NA	**General Information (Habitats and Feeding)** Occur in the southern and western lowlands of the Olympic Peninsula, the Chehalis River drainage, lower Deschutes River drainage, south Puget Sound lowlands west of the Nisqually River, and in King County. They are generally found in quiet water with mud substrate, preferring bogs and swamps with dense aquatic vegetation. Mudminnows feed on annelids, insects, and crustaceans. **Reproduction/Life History** Adults spawn from November through June (peaking in April and May). Females deposit eggs onto vegetation where fry remain firmly attached for approximately 1 week after hatching. Incubation lasts approximately 8-10 days. (Harris 1974; Mongillo and Hallock 1999; WDNR 2005, 2006a)
Lake chub	*Couesius plumbeus*	48, 61; other locations unknown	NA	**General Information (Habitats and Feeding)** Bottom dwellers inhabiting a variety of habitats in lakes and streams, but are known to prefer small, slow streams. In Washington, they are known only from the northeastern part of the state (small streams and lakes in Okanogan and Stevens counties). Juveniles feed on zooplankton and phytoplankton, whereas adults primarily feed on insects. **Reproduction/Life History** Lake chub move into shallow areas on rocky and gravelly substrates in tributary streams of lakes or lakeshores during the spring to spawn when water temperatures are between 55 and 65°F (13 and 18°C). The eggs are broadcast over large rocks and then settle into the smaller substrate, hatching after approximately 10 days. (WDNR 2005; Wydoski and Whitney 2003)
Leopard dace	*Rhinichthys falcatus*	25–31, 37–41, 44–50	NA	**General Information (Habitats and Feeding)** In Washington, leopard dace inhabit the bottoms of streams and small to mid-sized rivers, specifically the Columbia, Snake, Yakima, and Similkameen Rivers, with velocities less than 1.6 ft/sec (0.5 m/sec); prefer gravel and small cobble substrate covered by fine sediment with summer water temperatures ranging between 59 and 64°F (15 and 18°C). Juveniles feed primarily on aquatic insects; adult leopard dace consume terrestrial insects. **Reproduction/Life History** Breeding habitat for dace generally consists of the gravel or cobble bottoms of shallow riffles; leopard dace breed in slower, deeper waters than the other dace species. The spawning period for dace is from May through July. The eggs adhere to rocky substrates. Fry hatch approximately 6–10 days after fertilization, and juveniles spend 1–3 months rearing in shallow, slow water. (WDNR 2005, 2006a; Wydoski and Whitney 2003)

Table 5-1 (continued). Range of occurrence of the HCP species and their habitat requirements.

Common Name	Scientific Name	Water Resource Inventory Area[a]	Tidal Reference Area[b]	Habitat Requirements and Reproduction Timing
Margined sculpin	*Cottus marginatus*	32, 35	NA	**General Information (Habitats and Feeding)** Endemic to southeastern Washington (smaller tributary streams of the Walla Walla and Tucannon River drainages) where habitat is in deeper pools and slow-moving glides in headwater tributaries with silt and small gravel substrate. They prefer cool water less than 68°F (20°C) and avoid high-velocity areas. Food includes immature aquatic insects, invertebrates, small fish, and eggs. **Reproduction/Life History** Spawning occurs in May and June primarily under rocks, root wads, or logs. The female deposits a mass of adhesive eggs in the nest, which is guarded by the male. Incubation duration unknown. (Mongillo and Hallock 1998; WDNR 2005; Wydoski and Whitney 2003)
Mountain sucker	*Catostomus platyrynchus*	25–35, 37–41, 44–50	NA	**General Information (Habitats and Feeding)** Distribution restricted to Columbia River system. Found in clear, cold mountain streams less than 40 ft wide and in some lakes; prefer deep pools in summer with moderate current. Food consists of algae and diatoms. Juveniles prefer slower side channels or weedy backwaters. **Reproduction/Life History** Males reach sexual maturity in 2–3 years and females in 4 years. Spawning in June and July when water temperatures exceed 50°F (10°C). Spawning occurs in gravelly riffles of small streams when suckers move into those reaches to feed on algae. Spawning likely occurs at night when water temperatures are in a range of 51–66°F (10.5–19°C). Fertilized eggs fall into and adhere to the spaces between the gravel composite. Incubation period lasts approximatley 8-14 days. (Wydoski and Whitney 2003)
Umatilla dace	*Rhinichthys umatilla*	31, 36–41, 44–50, 59–61	NA	**General Information (Habitats and Feeding)** Umatilla dace are benthic fish found in relatively productive, low-elevation streams with clean substrates of rock, boulders, and cobbles in reaches where water velocity is less than 1.5 ft/sec (0.5 m/sec). Feeding is similar to that described for leopard dace. Juveniles occupy streams with cobble and rubble substrates, whereas adults occupy deeper water habitats. **Reproduction/Life History** Spawning behaviors are similar to those described for leopard dace, with spawning primarily occurring from early to mid-July. (WDNR 2005, 2006a; Wydoski and Whitney 2003)

Table 5-1 (continued). Range of occurrence of the HCP species and their habitat requirements.

Common Name	Scientific Name	Water Resource Inventory Area[a]	Tidal Reference Area[b]	Habitat Requirements and Reproduction Timing
Pacific lamprey	*Lampetra tridentata*	01, 03–05, 07–35, 37–40, 44–50	All	**General Information (Habitats and Feeding)** Found in most large coastal and Puget Sound rivers and Columbia, Snake, and Yakima river basins. The larvae are filter feeders, residing in mud substrates and feeding on algae and other organic matter for at least 5 years. **Reproduction/Life History** From July through October, maturing Pacific lamprey enter fresh water and gradually move upstream to spawn the following spring. The nest usually consists of a shallow depression built in gravel and rock substrates. Eggs hatch in 2–4 weeks, with newly hatched larvae remaining in the nest for 2–3 weeks before moving downstream as larvae (ammocoetes). Juveniles migrate to the Pacific Ocean 4–7 years after hatching and attach to fish in the ocean for 20–40 months before returning to rivers to spawn. (WDNR 2005; Wydoski and Whitney 2003)
River lamprey	*Lampetra ayresi*	01, 03, 05, 07–16, 20–40	1–9, 11–17	**General Information (Habitats and Feeding)** Detailed distribution records are not available for Washington, but they are known to inhabit coastal rivers, estuaries, and the Columbia River system. They have also been observed in Lake Washington and its tributaries. In the marine system, river lamprey inhabit nearshore areas. Adults are anadromous living in the marine system as parasites on fish. Adult river lamprey are believed to occupy deep portions of large river systems. The larvae feed on microscopic plants and animals. **Reproduction/Life History** Adults migrate back into fresh water in the fall. Spawning occurs in winter and spring. Eggs hatch in 2–3 weeks after spawning. Juveniles are believed to migrate from their natal rivers to the Pacific Ocean several years after hatching; adults spend 10–16 weeks between May and September in the ocean before migrating to fresh water. (WDNR 2005; Wydoski and Whitney 2003)

Table 5-1 (continued). Range of occurrence of the HCP species and their habitat requirements.

Common Name	Scientific Name	Water Resource Inventory Area[a]	Tidal Reference Area[b]	Habitat Requirements and Reproduction Timing
Western brook lamprey	*Lampetra richardsoni*	01, 03, 05, 07–14, 16, 20–40	NA	**General Information (Habitats and Feeding)** Found in small coastal and Puget Sound rivers and lower Columbia and Yakima river basins; spends entire life in fresh water. Adults are found in cool water (52–64°F [11–17.8°C]) on pebble/rocky substrate. Larvae (ammocoetes) are filter feeders, consuming primarily diatoms. Adults do not feed and die within a month of spawning. **Reproduction/Life History** Spawning generally occurs from April through July, with adults creating nests in coarse gravel at the head of riffles. Eggs hatch after about 10 days in water between 50 and 60°F (10 and 16°C). Within 30 days of hatching, ammocoetes emerge from the nests and move to the stream margin, where they burrow into silty substrates. Larvae remain in the stream bottom—apparently moving little—for approximately 4–6 years. (Wydoski and Whitney 2003)
Green sturgeon	*Acipenser medirostris*	22, 24, 28	All	**General Information (Habitats and Feeding)** NOAA Fisheries recognizes two DPSs of green sturgeon, both of which can be found in Washington. The southern DPS is listed as threatened and the northern DPS is a species of concern. Habits and life history not well known. Washington waters with green sturgeon populations include the Columbia River, Willapa Bay, and Grays Harbor, in addition to marine waters. They spend much of their life in marine nearshore waters and estuaries feeding on fishes and invertebrates. **Reproduction/Life History** Spawning generally occurs in spring in deep, fast-flowing sections of rivers. Spawning habitat includes cobble or boulder substrates. Green sturgeon move upstream during spring to spawn and downstream during fall and winter. Large eggs sink to bottom. (Adams et al. 2002; Emmett et al. 1991; Kynard et al. 2005; Nakamoto and Kisanuki 1995; Wydoski and Whitney 2003)

Table 5-1 (continued). Range of occurrence of the HCP species and their habitat requirements.

Common Name	Scientific Name	Water Resource Inventory Area[a]	Tidal Reference Area[b]	Habitat Requirements and Reproduction Timing
White sturgeon	*Acipenser transmontanus*	01, 03, 05–22, 24–37, 40–42, 44–61	All	**General Information (Habitats and Feeding)** Found in marine waters and major rivers in Washington, including the Columbia River, Snake River, Grays Harbor, Willapa Bay, Puget Sound, and Lake Washington. In marine environments, adults and subadults use estuarine and marine nearshore habitats, including some movement into intertidal flats to feed at high tide. Some landlocked populations exist behind dams on the Columbia River. Juveniles feed on mysid shrimp and amphipods; large fish feed on variety of crustaceans, annelid worms, mollusks, and fish. **Reproduction/Life History** Spawn in deep, fast-flowing sections of rivers (prefer swift [2.6–9.2 ft/sec (0.8–2.8 m/sec)] and deep [13–66 ft (4–20 m)] water) on bedrock, cobble, or boulder substrates. Spawning occurs from April through July, with incubation lasting approximately 7 days and emergence following in another 7 days. (Emmett et al. 1991; WDNR 2005; Wydoski and Whitney 2003)
Eulachon	*Thaleichthys pacificus*	01–29 (mouths of major rivers)	14–17	**General Information (Habitats and Feeding)** Eulachon occur from northern California to southwestern Alaska in offshore marine waters. They are plankton-feeders, eating crustaceans such as copepods and euphausiids; larvae and post larvae eat phytoplankton and copepods. They are an important prey species for fish, marine mammals, and birds. **Reproduction/Life History** Spawn in tidal portions of rivers in spring when water temperature is 40–50°F (4–10°C), generally from March through May; use a variety of substrates, but sand and gravel are most common. Eggs stick to substrate and incubation ranges from 20–40 days (dependent on temperature). Larvae drift downstream to salt water where juveniles rear in nearshore marine areas. (Howell et al. 2001; Langer et al. 1977; Lewis et al. 2002; WDFW 2001; WDNR 2005; Willson et al. 2006)

Table 5-1 (continued). Range of occurrence of the HCP species and their habitat requirements.

Common Name	Scientific Name	Water Resource Inventory Area[a]	Tidal Reference Area[b]	Habitat Requirements and Reproduction Timing
Longfin smelt	*Spirinchus thaleichthys*	01–03, 05–17, 22 and 24	1–9, 15–17	**General Information (Habitats and Feeding)** Marine species that spawns in streams not far from marine waters. They are anadromous, with some populations in Lake Washington that spawn in tributaries, including the Cedar River. Juveniles use nearshore habitats and a variety of substrates; juveniles feed on zooplankton. Adults feed on copepods and euphausiids. Most adults die after spawning. **Reproduction** Spawn in coastal rivers from October through December. Lake Washington populations spawn from January through April. Eggs hatch in approximately 40 days and the larvae drift downstream to salt water. (Gotthardt 2006; WDNR 2005; Wydoski and Whitney 2003)
Pacific sand lance	*Ammodytes hexapterus*	NA	All	**General Information (Habitats and Feeding)** Widespread in Puget Sound, Strait of Juan de Fuca, and coastal estuaries. Schooling plankton feeders. Adults feed during the day and burrow into the sand at night. **Reproduction/Life History** Spawn on sand and beaches with gravel up to 1-inch in diameter at tidal elevations of +4–5 ft (+1.5 meters) to approximately the mean higher high water (MHHW) line from November through February. Emergence occurs from January to April. Larvae and young rear in bays and nearshore areas. (Garrison and Miller 1982; Nightingale and Simenstad 2001; NRC 2001; Penttila 2000a; Penttila 2000b; WDFW 1997a)
Surf smelt	*Hypomesus pretiosus*	NA	All	**General Information (Habitats and Feeding)** Schooling plankton-feeding forage fish. They feed on a variety of zooplankton, planktonic crustaceans, and fish larvae. Adult surf smelt are pelagic but remain in nearshore habitats. Juveniles rear in nearshore areas, and adults form schools offshore; feed on planktonic organisms. Also an important forage fish. **Reproduction/Life History** Spawning occurs year-round in north Puget Sound, fall and winter in south Puget Sound, and summer along the coast. They spawn at the highest tides during high slack tide on coarse sand and pea gravel. Incubation is 2–5 weeks. Emergence varies with season: 27–56 days in winter, 11–16 days in summer. (Nightingale and Simenstad 2001; NRC 2001; Penttila 2000a; Penttila 2000b; WDFW 1997c)

Table 5-1 (continued). Range of occurrence of the HCP species and their habitat requirements.

Common Name	Scientific Name	Water Resource Inventory Area[a]	Tidal Reference Area[b]	Habitat Requirements and Reproduction Timing
Pacific herring	*Clupea harengus pallasi*	NA	1, 2, 4, 5, 8–13, 16, 17	**General Information (Habitats and Feeding)** Eighteen separate stocks in Puget Sound. Widely distributed throughout Puget Sound and coastal wetlands and estuaries. Pacific herring adults feed on small fish, copepods, decapod crab larvae, and euphausiids. Juveniles feed primarily on euphausiids, copepods, and small crustacean larvae. Are also an important forage fish. **Reproduction/Life History** Utilize intertidal and subtidal habitats (between 0 and -40 ft [0 and -12.2 m] mean lower low water [MLLW]) for spawning and juvenile rearing; spawning also occurs above MLLW. Spawning occurs from late January to early April. Eggs are adhered to eelgrass, kelp, seaweed, and sometimes on pilings. Eggs hatch after approximately 10 days. Larvae are pelagic. (Nightingale and Simenstad 2001; Penttila 2000a; Simenstad et al. 1979; WDFW 1997b)
Lingcod	*Ophiodon elongatus*	NA	All	**General Information (Habitats and Feeding)** The lingcod is a large top-level carnivore fish found throughout the West Coast of North America. Adult lingcod have a relatively small home range. Juveniles prefer sand habitats near the mouths of bays and estuaries, while adults prefer rocky substrates. Larvae and juveniles are generally found in upper 115 ft (35 m) of water. Adults prefer slopes of submerged banks with macrophytes and channels with swift currents. Larvae feed on copepods and amphipods; juveniles feed on small fishes; and adults on fish, squid, and octopi. **Reproduction/Life History** Spawn in shallow water and intertidal zone from January through late March. Egg masses adhere to rocks, and incubation is from February to June. Larvae spend 2 months in pelagic nearshore habitat. (Adams and Hardwick 1992; Emmett et al. 1991; Giorgi 1981; NMFS 1990; NRC 2001)

Table 5-1 (continued). Range of occurrence of the HCP species and their habitat requirements.

Common Name	Scientific Name	Water Resource Inventory Area[a]	Tidal Reference Area[b]	Habitat Requirements and Reproduction Timing
Pacific cod	*Gadus macrocephalus*	NA	All	**General Information (Habitats and Feeding)** Pacific cod are widely distributed in relatively shallow marine waters throughout the northern Pacific Ocean (Washington's inland marine waters are considered the southern limit of populations). Adults and large juveniles are found over clay, mud, and coarse gravel bottoms; juveniles use shallow vegetated habitats such as sand-eelgrass. Feed opportunistically on invertebrates (worms, crabs, shrimp) and fishes (sand lance, pollock, flatfishes). Larvae feed on copepods, amphipods, and mysids. **Reproduction/Life History** Broadcast spawners during late fall through early spring. Eggs sink and adhere to the substrate. Incubate for 1–4 weeks, and larvae spend several months in the water column. Juvenile cod metamorphose and settle to shallow vegetated habitats. (Albers and Anderson 1985; Bargmann 1980; Dunn and Matarese 1987; Garrison and Miller 1982; Hart 1973; Nightingale and Simenstad 2001; NMFS 1990; NRC 2001)
Pacific hake	*Merluccius productus*	NA	All	**General Information (Habitats and Feeding)** Pacific hake are schooling fish. The coastal stock of hake is migratory; Puget Sound stocks reside in estuaries and rarely migrate. Larvae feed on calanoid copepods; juveniles and small adults feed on euphasiids; adults eat amphipods, squid, herring, and smelt. **Reproduction/Life History** Puget Sound spawning occurs from March through May at mid-water depths of 50–350 ft (15–90 m); may spawn more than once per season. Eggs and larvae are pelagic. (Bailey 1982; McFarlane and Beamish 1986; NMFS 1990; NRC 2001; Quirollo 1992)
Walleye pollock	*Theragra chalcogramma*	NA	All	**General Information (Habitats and Feeding)** Widespread species in northern Pacific. Washington is the southern end of their habitat. Larvae and small juveniles are found at 200-ft (60-m) depth; juveniles use nearshore habitats of a variety of substrates. Juveniles feed on small crustaceans, adults feed on copepods, euphausiids, and young pollock. **Reproduction/Life History** Broadcast spawning occurs from February through April. Eggs are suspended at depths ranging from 330–1,320 ft (100–400 m). Pelagic larvae settle near the bottom and migrate to inshore, shallow habitats for their first year. (Bailey et al. 1999; Garrison and Miller 1982; Livingston 1991; Miller et al. 1976; NRC 2001)

Table 5-1 (continued). Range of occurrence of the HCP species and their habitat requirements.

Common Name	Scientific Name	Water Resource Inventory Area[a]	Tidal Reference Area[b]	Habitat Requirements and Reproduction Timing
Black rockfish	*Sebastes melanops*	NA	All	**General Information (Habitats and Feeding)** Adults prefer deep and shallow rock substrates in summer, deeper water in winter. Kelp and eelgrass are preferred habitat for juveniles that feed on nekton and zooplankton. Adults feed on amphipods, crabs, copepods, and small fish. **Reproduction/Life History** Spawning occurs from February through April; ovoviviparous incubation as with other rockfish species. Larvae are planktonic for 3–6 months, where they are dispersed by currents, advection, and upwelling. They begin to reappear as young-of-the-year fish in shallow, nearshore waters. (Kramer and O’Connell 1995; WDNR 2006a)
Bocaccio rockfish	*Sebastes paucispinis*	NA	All	**General Information (Habitats and Feeding)** Adults semidemersal in shallow water over rocks with algae, eelgrass, and floating kelp. Larvae feed on diatoms; juveniles feed on copepods and euphausiids. **Reproduction/Life History** Ovoviviparous spawning occurs year-round, with incubation lasting 40–50 days. Larvae and juveniles are pelagic. (Garrison and Miller 1982; Hart 1973; Kramer and O’Connell 1995; MBC Applied Environmental Sciences 1987; NRC 2001; Sumida and Moser 1984)
Brown rockfish	*Sebastes auriculatus*	NA	All	**General Information (Habitats and Feeding)** Utilize shallow-water bays with natural and artificial reefs and rock piles; estuaries used as nurseries; can tolerate water temperatures to at least 71°F (22°C); eat small fishes, crabs, and isopods. **Reproduction/Life History** Spawning occurs from March through June. Larvae are released from the female into the pelagic environment in May and June (ovoviviparous incubation). Larvae live in the upper zooplankton layer for up to 1 month before they metamorphose into pelagic juveniles. The pelagic juveniles spend 3–6 months in the water column as plankton. They then settle in shallow water nearshore, later migrating to deeper water. (Eschmeyer et al. 1983; Kramer and O’Connell 1995; Love et al. 1990; NRC 2001; Stein and Hassler 1989)

Table 5-1 (continued). Range of occurrence of the HCP species and their habitat requirements.

Common Name	Scientific Name	Water Resource Inventory Area[a]	Tidal Reference Area[b]	Habitat Requirements and Reproduction Timing
Canary rockfish	*Sebastes pinniger*	NA	All	**General Information (Habitats and Feeding)** Adults use sharp drop-offs and pinnacles with hard bottoms; often associated with kelp beds; feed on krill and occasionally on fish. Adults are mostly found at depths of 260–660 ft (80–200 meters) (with two recorded at 2,750 ft [838 meters]), tending to collect in groups around pinnacles and similar high-relief rock formations, especially where the current is strong. Young canary rockfish live in relatively shallow water, moving to deeper water as they mature. Juveniles feed on small crustacea such as krill larvae (and eggs), copepods, and amphipods, while adults eat krill and small fish. **Reproduction/Life History** Spawning is ovoviviparous and occurs from January through March. Larvae and juveniles are pelagic. (Boehlert 1980; Boehlert and Kappenman 1980; Boehlert et al. 1989; Hart 1973; Kramer and O'Connell 1995; Love et al. 1990; NRC 2001; Sampson 1996)
China rockfish	*Sebastes nebulosis*	NA	All	**General Information (Habitats and Feeding)** Occur inshore and on open coast in sheltered crevices. Feed on crustacea (brittle stars and crabs), octopi, and fish. Juveniles are pelagic, but the adults are sedentary associating with rocky reefs or cobble substrates. **Reproduction/Life History** Spawning occurs from January through July; ovoviviparous incubation as with other rockfish species. Individual China rockfish spawn once a year. Larvae settle out of the plankton between 1 and 2 months after release. (Eschmeyer et al. 1983; Kramer and O'Connell 1995; Love et al. 1990; NRC 2001; Rosenthal et al. 1988)
Copper rockfish	*Sebastes caurinus*	NA	All	**General Information (Habitats and Feeding)** Occur both inshore and on open coast; adults prefer rocky areas in shallower water than other rockfish species. Juveniles use shallow and nearshore macrophytes and eelgrass habitat; feed on crustaceans, fish, and mollusks. **Reproduction/Life History** Spawning occurs from March through May, with ovoviviparous incubation from April to June. Larvae are pelagic in deeper water before moving inshore. Newly spawned fish begin settling near the surface around large algae canopies or eelgrass, when available, or closer to the bottom when lacking canopies. (Eschmeyer et al. 1983; Haldorson and Richards 1986; Kramer and O'Connell 1995; Matthews 1990; NRC 2001; Stein and Hassler 1989)

Table 5-1 (continued). Range of occurrence of the HCP species and their habitat requirements.

Common Name	Scientific Name	Water Resource Inventory Area[a]	Tidal Reference Area[b]	Habitat Requirements and Reproduction Timing
Greenstriped rockfish	*Sebastes elongates*	NA	All	**General Information (Habitats and Feeding)** Adults found in benthic and mid-water columns. They live at between 330 and 825 ft (100 and 250 m). As they age, greenstriped rockfish move to deeper water. They are solitary and are often found resting on the seafloor and living among cobble, rubble, or mud. Adults feed on euphausiids, small fish, and squid. **Reproduction/Life History** From 10,000 to over 200,000 eggs are produced by the females each season by ovoviviparous spawning. Greenstriped rockfish release one brood of larvae in Washington. Larval release varies, occurring generally from January through July, depending on geographic location. (Eschmeyer et al. 1983; Kramer and O'Connell 1995; Love et al. 1990; NRC 2001)
Quillback rockfish	*Sebastes maliger*	NA	All	**General Information (Habitats and Feeding)** Shallow-water benthic species in inlets near shallow rock piles and reefs. Juveniles use eelgrass, sand, and kelp beds. Feed on amphipods, crabs, and copepods. **Reproduction/Life History** Ovoviviparous spawning from April through July, with larval release from May to July. (Kramer and O'Connell 1995; WDNR 2006a)
Redstripe rockfish	*Sebastes proriger*	NA	All	**General Information (Habitats and Feeding)** Adults found from 330- to 1,000-ft (100- to 300-m) depths, and young often found in estuaries in high- and low-relief rocky areas. Juveniles feed on copepods and euphausiids; adults eat anchovies, herring, and squid. **Reproduction/Life History** Spawning is ovoviviparous, occurring from January through March. Larvae and juveniles are pelagic. (Garrison and Miller 1982; Hart 1973; Kendall and Lenarz 1986; Kramer and O'Connell 1995; NRC 2001; Starr 1996)
Tiger rockfish	*Sebastes nigrocinctus*	NA	All	**General Information (Habitats and Feeding)** Semidemersal to demersal species occurring at depths ranging from shallows to 1,000 ft (305 m); larvae and juveniles occur near surface and range of depth; adults use rocky reefs, canyons, and headlands; generalized feeders on shrimp, crabs, and small fishes. **Reproduction/Life History** Ovoviviparous spawning peaks in May and June. Juveniles are pelagic. (Garrison and Miller 1982; Kramer and O'Connell 1995; Moulton 1977; NRC 2001; Rosenthal et al. 1988)

Table 5-1 (continued). Range of occurrence of the HCP species and their habitat requirements.

Common Name	Scientific Name	Water Resource Inventory Area[a]	Tidal Reference Area[b]	Habitat Requirements and Reproduction Timing
Widow rockfish	*Sebastes entomelas*	NA	All	**General Information (Habitats and Feeding)** Adults found from 330- to 1,000-ft (100- to 300-m) depths near rocky banks, ridges, and seamounts; adults feed on pelagic crustaceans, Pacific hake, and squid; juveniles feed on copepods and euphausiids. **Reproduction /Life History** Ovoviviparous spawning occurs from October through December. One brood of 95,000 to 1,113,000 eggs are produced by female widows per year. The season of larval release occurs earlier in the southern parts of their range than in the northern regions, likely January through April in Washington waters. (Eschmeyer et al. 1983; Kramer and O'Connell 1995; Laroche and Richardson 1981; NMFS 1990; NRC 2001; Reilly et al. 1992)
Yelloweye rockfish	*Sebastes ruberrimus*	NA	All	**General Information (Habitats and Feeding)** Adults are found from depths of 80–1,800 ft (24–550 m), near reefs and cobble bottom. Juveniles prefer shallow, broken-bottom habitat. Juveniles often hide in rock crevices; adults are demersal and solitary, tending to remain localized and not making extensive migrations. Adults feed on other rockfish species, sand lance, herring, shrimp, rock crabs, and snails. **Reproduction/Life History** Ovoviviparous spawning in late fall or early winter, with the larvae released from May to July. (Eschmeyer et al. 1983; Hart 1973; Kramer and O'Connell 1995; NRC 2001; Rosenthal et al. 1988)
Yellowtail rockfish	*Sebastes flavidus*	NA	All	**General Information (Habitats and Feeding)** Adults found from 165- to 1,000-ft (50- to 300-m) depths; adults semipelagic or pelagic over steep-sloping shores and rocky reefs. Juveniles occur in nearshore areas. Adults are opportunistic feeders on pelagic animals including hake, herring, smelt, squid, krill, and euphausiids. **Reproduction/Life History** Ovoviviparous spawning from October through December. Incubation is between January and March. Larvae and juveniles are pelagic swimmers. (Eschmeyer et al. 1983; Kramer and O'Connell 1995; Love et al. 1990; NRC 2001; O'Connell and Carlile 1993)

Table 5-1 (continued). Range of occurrence of the HCP species and their habitat requirements.

Common Name	Scientific Name	Water Resource Inventory Area[a]	Tidal Reference Area[b]	Habitat Requirements and Reproduction Timing
Olympia oyster	*Ostrea lurida*	NA	1–14, 17	**General Information (Habitats and Feeding)** Species found throughout the inland waters of Puget Sound, as well as in Willapa Bay and possibly Grays Harbor; also grown commercially in Puget Sound. They occupy nearshore ecosystem on mixed substrates with solid attachment surfaces and are found from 1 ft (0.3 m) above MLLW to 2 ft (0.6m) below MLLW. Intolerant of siltation. **Reproduction/Life History** Reproduce spring to fall when water temperatures are between 54 and 61°F (12.5 and 16°C) by broadcast spawning. After 8–12 days, larvae develop into free-swimming larvae. Larvae are free-swimming for 2–3 weeks before they settle onto hard substrate, such as oyster shells and rocks. (Baker 1995; Couch and Hassler 1990; West 1997)
Northern abalone	*Haliotis kamtschatkana*	NA	10	**General Information (Habitats and Feeding)** Also known as pinto abalone. Presence in Washington is limited to the Strait of Juan de Fuca and the San Juan Islands. Occupies bedrock and boulders from extreme low water to 100 ft (30 m) below MLLW; usually associated with kelp beds. The abalone is completely vegetarian and uses its radula to scrape pieces of algae from the surface of rocks. **Reproduction/Life History** Broadcast spawners that release pelagic gametes that develop into free-swimming larvae using cilia to propel themselves. After up to a week, the larvae settle to the bottom, shed their cilia, and start growing a shell to begin sedentary adult life on crustose coralline algae. (Gardner 1981; NMFS 2007a; WDNR 2006b; West 1997)
Newcomb's littorine snail	*Algamorda subrotundata*	NA	14–17	**General Information (Habitats and Feeding)** Found in Grays Harbor and Willapa Bay on Washington coast; current distribution uncertain. Algae feeder occupying narrow band in *Salicornia* salt marshes above MHHW and is not considered a true marine gastropod. **Reproduction/Life History** Broadcast spawning in salt marshes. Other reproductive information unknown. (Larsen et al. 1995)

Table 5-1 (continued). Range of occurrence of the HCP species and their habitat requirements.

Common Name	Scientific Name	Water Resource Inventory Area[a]	Tidal Reference Area[b]	Habitat Requirements and Reproduction Timing
Giant Columbia River limpet	*Fisherola nuttalli*	35, 36, 40, 45, 47–49	NA	**General Information (Habitats and Feeding)** Also known as the shortface lanx, it occupies fast-moving and well-oxygenated streams. It is found in the Hanford Reach segment of the Columbia River, Wenatchee, Deschutes (OR), Okanogan, Snake, and Methow rivers. Prefers shallow, rocky areas of cobble to boulder substrates and diatom-covered rocks, and feeds by grazing on algae attached to rocks. **Reproduction/Life History** Broadcast external fertilization. Reproduction timing is unknown. (Neitzel and Frest 1989; Neitzel and Frest 1990; Pacific Biodiversity Institute 2007)
Great Columbia River spire snail	*Fluminicola columbiana*	35, 45, 48, 49; other locations unknown	NA	**General Information (Habitats and Feeding)** Also known as the Columbia pebblesnail and ashy pebblesnail, its current range is restricted to rivers, streams, and creeks of the Columbia River basin. It requires clear, cold streams with highly oxygenated water and is generally found in shallow water (less than 5 inches [13 cm] deep) with permanent flow on cobble-boulder substrates. Spire snails live on and under rocks and vegetation in the slow to rapid currents of streams where they graze on algae and small crustaceans. **Reproduction/Life History** They are short-lived, usually reaching sexual maturity within a year, at which time they breed and die. Unknown reproduction timing. (Neitzel and Frest 1989; Neitzel and Frest 1990; Pacific Biodiversity Institute 2007)
California floater (mussel)	*Anodonta californiensis*	30, 36, 37, 40, 42, 47–49, 52–54, 58–61	NA	**General Information (Habitats and Feeding)** In Washington, it is known to occur in the Columbia and Okanogan rivers and several lakes. Freshwater filter feeder requiring clean, well-oxygenated water for survival that is declining throughout much of its historical range. California floater mussels are intolerant of habitats with shifting substrates, excessive water flow fluctuations, or seasonal hypoxia. **Reproduction/Life History** Spring spawning occurs after adults reach 6–12 years in age. Fertilization takes place within the brood chambers of the female mussel. Fertilized eggs develop into a parasitic stage called glochidia, which attach to species-specific host fish during metamorphosis. After reaching adequate size, juvenile mussels release from the host and attach to gravel and rocks. (Box et al. 2003; Frest and Johannes 1995; Larsen et al. 1995; Nedeau et al. 2005; Watters 1999; WDNR 2006b)

Table 5-1 (continued). Range of occurrence of the HCP species and their habitat requirements.

Common Name	Scientific Name	Water Resource Inventory Area[a]	Tidal Reference Area[b]	Habitat Requirements and Reproduction Timing
Western ridged mussel	*Gonidea angulata*	01, 03–05, 07–11, 13, 21–42, 44–55, 57–62	NA	**General Information (Habitats and Feeding)** Specific information on this species is generally lacking; reside on substrates ranging from firm mud with the presence of some sand, silt, or clay to coarse gravel in creeks, streams, and rivers. They require constant, well-oxygenated flow, and shallow water (<10 ft [3 m] depth). This species may tolerate seasonal turbidity but is absent from areas with continuous turbidity and is sensitive to water quality changes such as eutrophication or presence of heavy metals. **Reproduction/Life History** During breeding, males release sperm into the water and females must bring this into their shell for fertilization to occur. Larvae called glochidia are released by the female and attach to the gills of fish for 1–6 weeks; postlarval mussels hatch from cysts as free-living juveniles to settle and bury in the substrate. (COSEWIC 2003; WDNR 2006b)

Source: Modified from (Jones & Stokes 2006a).

[a] Water Resource Inventory Areas (WRIAs) are administration and planning boundaries for watershed areas, as established and managed by the Washington State Department of Ecology (Ecology). WRIA designations were formalized under WAC 173-500-040 and authorized under the Water Resources Act of 1971, Revised Code of Washington (RCW) 90.54. For WRIA boundary locations and related information, see URL = http://www.ecy.wa.gov/services/gis/maps/wria/wria.htm.

[b] Tidal Reference Areas as follows (from WAC 220-110-240): 1 = Shelton, 2 = Olympia, 3 = South Puget Sound, 4 = Tacoma, 5 = Seattle, 6 = Edmonds, 7 = Everett, 8 = Yokeko Point, 9 = Blaine, 10 = Port Townsend, 11 = Union, 12 = Seabeck, 13 = Bangor, 14 = Ocean Beaches, 15 = Westport, 16 = Aberdeen, 17 = Willapa Bay.

6.0 Conceptual Framework for Assessing Impacts

The fish passage activity type occurs throughout Washington State in both freshwater and marine/estuarine environments. The placement of fish passage structures and the uses associated with them will, to varying degrees, affect the controlling factors of the aquatic ecosystem in which they are located. In this white paper, an **impact** is defined as an unnatural disturbance to habitat-controlling factors such as light, stream energy, substrate, water quality parameters, littoral drift, or channel geomorphology. These controlling factors determine various aspects of the habitat structure (e.g., sand or cobble substrates, wide or shallow channels). For example, a culvert retrofitted for fish passage may increase fish migration into upstream areas. Fish migration may increase the delivery of marine-derived nutrients to the watershed (e.g., in the form of salmon carcasses), providing the ecological function of supporting food web productivity. Figure 6-1 illustrates the conceptual framework used in this white paper to identify impacts on HCP species and their habitats from fish passage structures and/or operations.

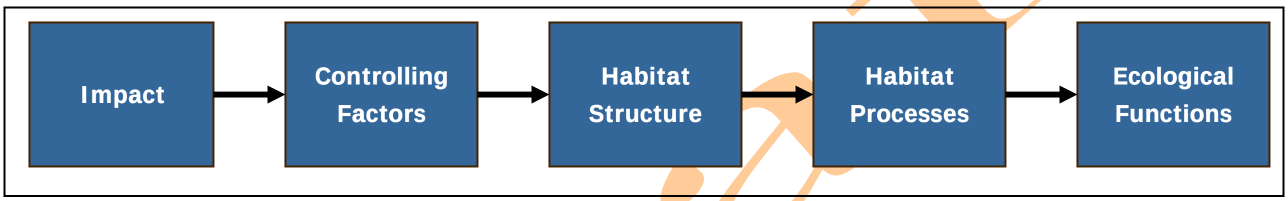


Figure 6-1. Conceptual framework for assessing impacts (Williams and Thom 2001).

Table 6-1 identifies the common **mechanisms of impact** that are known to be associated with the culvert, fish ladder/fishway, roughened channel, and weir subactivity types that are covered in this white paper. Trap-and-haul facilities are considered to be an operation permitted by an HPA that are associated with some other type of HPA-permitted structure (e.g., a weir or a dam). The physical effects on the environment of these types of structures are not addressed in detail in this white paper. These effects have been addressed in previous white papers (see Section 4.1.5 [*Trap and Haul*]), and are incorporated by reference as necessary. Trap-and-haul operations impose a distinct set of impact mechanisms, however, which are addressed in detail here. These impact mechanisms are identified separately in Table 6-1. This white paper presents what is known about the effects of these mechanisms on HCP species. By identifying the nature and extent of these impacts and the ecological stressors these impacts impose on HCP species, measures can be implemented to avoid and, if avoidance is not possible, to minimize harmful impacts on these species and the habitats that support their growth and survival.

The identification of impact mechanisms associated with HPA-authorized activities that affect habitat is based on a model described by Williams and Thom (2001). For analyzing risk of take potential and refining the impact analysis as it pertains directly to listed species or species that will be addressed in the HCP, the "exposure-response" model developed by USFWS was used (National Conservation Training Center 2004). Each of these models is discussed in more detail below.

Table 6-1. Impact mechanisms and submechanisms associated with fish passage subactivity types.

Subactivity Type(s)	Impact Mechanism	Submechanisms
Culverts; Fish ladders/fishways; Roughened channels; Weirs	Construction and Maintenance Activities	▪ Equipment operation and materials placement ▪ Elevated underwater noise and visual and physical disturbance ▪ Bank, channel, shoreline disturbance ▪ Dewatering and handling ▪ Dredging and fill
	Water Quality Modifications	▪ Altered temperature ▪ Elevated suspended sediments ▪ Altered dissolved oxygen ▪ Altered pH ▪ Introduction of toxic substances ▪ Altered nutrient cycling
	Riparian Vegetation Modifications	▪ Altered shading, solar exposure, and ambient air temperature regime ▪ Altered bank stability ▪ Altered allochthonous inputs ▪ Altered groundwater/surface water interactions ▪ Altered habitat complexity
	Aquatic Vegetation Modifications	▪ Altered autochthonous production ▪ Altered habitat complexity
	Hydraulic and Geomorphic Modifications	▪ Altered flow conditions ▪ Altered channel geometry ▪ Altered substrate composition and stability ▪ Altered groundwater/surface water interactions
	Ecosystem Fragmentation	▪ Altered longitudinal connectivity ▪ Altered aquatic/terrestrial connectivity ▪ Modified downstream transport of sediment, LWD, and organic material ▪ Modified upstream transport of allochthonous nutrients ▪ Passage barriers ▪ Altered groundwater/surface water interactions
Trap and haul	Operation	▪ Fish capture, transport, and release ▪ Introduction of toxic substances
	Ecosystem Fragmentation	▪ Alteration of migratory patterns ▪ Passage barriers ▪ Modified upstream transport of allochthonous nutrients

The Williams and Thom model provides the framework for analysis based on the literature search (as described in Section 3 [*Methods*]). The goals of this framework are to:

- Elucidate impacts associated with each HPA subactivity.
- Determine how those impacts manifest in effects on habitat and habitat functions utilized by the HCP species.
- Develop recommendations for impact avoidance, minimization, and mitigation measures that target the identified impacts.

The analysis process begins with an impact that, in this case, would consist of activities authorized under an HPA for a fish passage project. The impact will exert varying degrees of effect on controlling factors within the ecosystem (Williams and Thom 2001). Controlling factors are those physical processes or environmental conditions (e.g., flow conditions, sediment transport) that control local habitat structure (e.g., substrate or vegetation). Habitat structure is linked to habitat processes (e.g., shading or cover), which are linked to ecological functions (e.g., refuge and prey production). These linkages form the "**impact pathway**" in which alterations to the environment associated with HPA-authorized activities can lead to impacts on the ecological function of the habitat for HCP species. **Impact mechanisms** are the alterations to any of the conceptual framework components along the impact pathway that can result in an impact on ecological function(s) and therefore on HCP species.

For each HPA-authorized activity addressed in this white paper, several principal impact mechanisms were identified for each subactivity type, from a geomorphological, engineering, hydrologic, and biological perspective.

This impact analysis serves to identify the direct and indirect impacts that could potentially affect HCP species. To further refine the analysis in each white paper, the exposure-response model (National Conservation Training Center 2004) was incorporated into the impact analysis. The exposure-response model evaluates the likelihood that adverse effects may occur as a result of species exposure to one or more stressors. This model takes into account the life-history stage most likely to be exposed and thereby affected.

The exposure-response model was incorporated as a series of matrices, presented in Appendix A, with results synthesized in Section 7 (*Direct and Indirect Impacts*) and Section 9 (*Potential Risk of Take*) of this white paper. In these species-specific exposure-response matrices, each impact mechanism and submechanism was initially examined and evaluated to:

- Identify and characterize specific impacts or stressors (i.e., nature and magnitude)
- Evaluate the potential for exposure (potential for species to be exposed = stressor timing/duration/frequency, coincident with habitat use by the various life-history forms of the species in question)

- Identify the anticipated exposure response, based on the exposure parameters and life history specific sensitivity
- Identify measures that could reduce exposure
- Identify performance standards if appropriate
- Characterize the resulting effects of specific impacts on the various species.

With regard to exposure, standard language was used to indicate when an impact occurs, and for how long and how frequently the stressor or impact occurs. Definitions of the terms used in this exposure-response analysis are listed in Table 6-2.

Based on life-history information, an analysis of potential exposure was completed for each HCP species. This included an analysis of the direct and indirect impacts (associated with each of the impact mechanisms) on the different life-history stages of each species and the likely responses of each species to these stressors. Impact minimization measures to reduce or avoid submechanism impacts were also identified. A final conclusion regarding the overall effect of the submechanism/stressor on a species is also presented in Appendix A. Where information was available, the cumulative effects associated with the major impact mechanisms were also identified (see Section 8 [*Cumulative Effects*]).

The information generated by the exposure-response analysis is used to summarize the overall risk of take associated with the impact mechanisms produced by each subactivity type. The summary risk of take analysis is presented in Section 9, which presents the risk of take associated with each subactivity type using: (1) a narrative discussion of the risk of take associated with each subactivity type by the specific associated impact submechanism; and (2) risk of take assessment matrices that rate the risk of take resulting from each subactivity by impact mechanism and environment type. The risk of take ratings presented in the text and matrices in Section 9 are based on the rating criteria defined in Table 6-3.

Based on the identification of impacts and risk of take analysis, additional recommendations (e.g., conservation, management, protection, and BMPs) for minimizing or mitigating project impacts or risk of take were developed. (These are presented in Section 11 [*Habitat Protection, Conservation, Mitigation, and Management Strategies*].)

1 **Table 6-2. Definitions of terms used in the exposure-response analysis for this white paper.**

Exposure Parameter	Description	Exposure	Definition
When	The timing during which stressor exposure occurs (e.g., time of day, season, associated with operations or maintenance)	—	Defined flexibly as appropriate for each stressor
Duration	The length of time the receptor is expected to be exposed to the stressor	Permanent	Stressor is permanent (e.g., conversion of habitat to built environment)
		Long-term	Stressor will last for greater than 5 years to decades (e.g., time required for complete riparian recovery)
		Intermediate-term	Stressor will last from 6 months to approximately 5 years (e.g., time required for beach substrate to recover from construction equipment)
		Short-term	Stressor will last from days to approximately 6 months (e.g., time required for invertebrate community to recolonize following dewatering)
		Temporary	Stressor associated with transient action (e.g., pile driving noise)
Frequency	The regularity with which stressor exposure is expected to occur and/or the time interval between exposure	Continuous	Stressor is ongoing and occurs constantly (e.g., permanent modification of habitat suitability)
		Intermittent	Stressor occurs routinely on a daily basis
		Daily	Stressor occurs once per day for extended periods (e.g., daytime structural shading)
		Common	Stressor occurs routinely (i.e., at least once per week or several times per month)
		Seasonal	Stressor occurs for extended periods during specific seasons (e.g., temperature effects occurring predominantly in winter and summer)
		Annual	Stressor occurs for an extended period annually for a short period of time
		Interannual–decadal	Stressor occurs infrequently (e.g., pile driving associated with project construction and maintenance)

Table 6-3. Definitions of the terminology used for risk of take determinations in this white paper.

Risk of Take Code	Potential for Take	Definition
H	High	Stressor exposure is likely to occur with high likelihood of individual take in the form of direct mortality, injury, and/or direct or indirect effects on long-term survival, growth, and fitness potential due to long-term or permanent alteration of habitat capacity or characteristics. Likely to equate to a Likely to Adversely Affect (LTAA) finding.
M	Moderate	Stressor exposure is likely to occur causing take in the form of direct or indirect effects potentially leading to reductions in individual survival, growth, and fitness due to short-term to intermediate-term alteration of habitat characteristics. May equate to an LTAA or a Not Likely to Adversely Affect (NLTAA) finding depending on specific circumstances.
L	Low	Stressor exposure is likely to occur, causing take in the form of temporary disturbance and minor behavioral alteration. Likely to equate to an NLTAA finding.
I	Insignificant	Stressor exposure may potentially occur, but the likelihood is discountable and/or the effects of stressor exposure are insignificant. Likely to equate to an NLTAA finding.
N	No Risk	No risk of take ratings apply to species with no likelihood of stressor exposure because they do not occur in habitats that are suitable for the subactivity type in question, or the impact mechanisms caused by the subactivity type will not produce environmental stressors.
?	Unknown	Unknown risk of take ratings apply to cases where insufficient data are available to determine the probability of exposure or to assess stressor response.

LTAA = Likely to Adversely Affect.
NLTAA = Not Likely to Adversely Affect.

7.0 Direct and Indirect Impacts

This section identifies the range of ecological stressors caused by each impact mechanism, the exposure pathway, and species response to stressor exposure (i.e., the direct and indirect effects of the stressor). This discussion covers the state of knowledge about these issues as reflected in the best available science.

This section summarizes available information on each impact mechanism category and impact submechanism where available, and provides specific examples pertinent to the 52 HCP species addressed in this white paper. Note that specific information is not provided for each species. Instead, relevant information on species groupings or species with similar life-history characteristics is used to provide examples of the likely forms of direct and indirect effects that will result from stressor exposure. This section references the specific information provided for each species and species grouping in the exposure-response matrices in Appendix A. The matrices elaborate on the direct and indirect effects caused by stressor exposure and response.

This section is organized by subactivity type and impact mechanism. Note that for the purpose of this white paper, all fish passage type projects are considered to occur in riverine environments only. It is recognized that culverts and weir type passage projects may occur at the boundaries between riverine and lacustrine or marine habitat types, but consistent with the definitions of environment types applied in companion white papers on other types of HCP-permitted activities, the fish passage related effects of these structures are considered to occur within the riverine environment. The distinctions between the direct and indirect effects of these subactivity types in these three environmental settings are addressed in this text, supported by the assessment of impact mechanism related stressor exposure and response for the 52 HCP species as explicitly discussed in the exposure-response matrices. The matrices, presented in Appendix A, explicitly address the differences in effects on each species and species grouping by habitat type.

Most of the impact mechanisms imposed by each of these subactivity types are similar in terms of their extent and their potential direct and indirect effects. For this reason, this effects analysis incorporates a common discussion of the effects of each impact mechanism and submechanism on HCP species (see Section 7.6 [*Ecological Effects of Common Impact Mechanisms and Stressors*]). The effects of each subactivity type are summarized based on their relative magnitude in comparison to the description of common effects. Where the effects of a specific impact submechanism are sufficiently unique, additional discussion of these effects is provided at the subactivity level as appropriate.

7.1 Culverts

Culverts that impose barriers to fish passage are broadly recognized as having a significant effect on fish as well as on invertebrate populations. Barrier culverts are ubiquitous and their effects are pervasive, restricting access to a cumulatively significant amount of aquatic habitat that would otherwise be suitable for a range of species. Addressing passage barriers at culverts to restore access to fragmented habitat is recognized as a priority issue in salmon habitat restoration strategy (Roni et al. 2002).

As discussed in Section 4.1 (*Characteristics, Applications, and Descriptions of Fish Passage Subactivity Types*), fish passage problems at culverts can be addressed by: removing the structure entirely (e.g., replacing it with a bridge or removing the roadway); replacing it with a culvert design that provides improved passage (e.g., a structure designed using the stream-simulation option); or by retrofitting an existing structure (e.g., placing internal weirs and baffles inside a concrete box culvert to reduce flow velocity).

While each of these approaches involves a similar range of impact mechanisms, the extent and intensity of ecological stressors produced will vary, as will the subsequent effects on HCP species. For the purpose of assessing the potential effects, it is necessary to distinguish where each of these methods produces impact mechanisms and ecological stressors of different timing, frequency, or intensity. This information is then used to evaluate the likely extent of effects on HCP species.

7.1.1 Impact Mechanisms

Impact mechanisms associated with the culvert subactivity type include:

- Construction and maintenance
- Water quality modifications
- Riparian vegetation modifications
- Aquatic vegetation modifications
- Hydraulic and geomorphic modifications
- Ecosystem fragmentation.

The submechanisms associated with each of these impact mechanisms are identified in the following sections. As noted, many of the impact submechanisms, ecological stressors, and their effects associated with removing/replacing/retrofitting culverts for fish passage are similar to those caused by other fish passage subactivity types. Therefore, where appropriate, the reader is directed to the discussion of common ecological stressors and their effects provided in Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors*). Impact mechanisms with potential effects that are unique to this subactivity type are described in detail below.

7.1.1.1 Construction and Maintenance

Impact submechanisms and stressors associated with construction and maintenance of culverts removed, replaced, or retrofitted for fish passage are in many ways expected to be similar to those caused by initial construction. These effects have been discussed in detail in the Water Crossings white paper (Jones and Stokes 2006b). As noted, however, the range of effects associated with each of these methods is expected to vary; therefore, additional discussion is warranted here.

Construction and maintenance of culverts for fish passage purposes are expected to impose a number of impact submechanisms, including noise, visual, and physical disturbance; stressors associated with dredging and fill and dewatering and handling; and water quality effects. These impact submechanisms are expected to be similar to those imposed by all fish passage subactivity types (with the exception of trap-and-haul programs as explained later in this document). Therefore the discussion of common impact mechanisms and stressor response provided in Section 7.6.1.1 (*Construction and Maintenance*) is incorporated by reference as appropriate.

Construction and maintenance associated with the culvert subactivity type will involve the following impact submechanisms:

- Equipment operation and materials placement: producing elevated underwater noise, visual, and physical disturbance (see Section 7.6.1.1.1 [*Equipment Operation and Materials Placement*]).

- Dewatering and handling: associated with creation of exclusion areas and capture and relocation of fish and invertebrates (see Section 7.6.1.1.2 [*Dewatering and Handling]*).

- Dredging and fill: associated with removal of the old structure and placement of new materials (see Section 7.6.1.1.3 [*Dredging and Fill*]).

Because the intensity of stressors and the response-related effects on HCP species are likely to vary depending on the approach used to address the passage problem, the relative magnitude of the impact mechanisms produced by each approach is discussed further below.

Culvert removal involves the removal of the structure in its entirety and, in many cases, the recontouring of the stream channel and the adjacent floodplain. These activities are expected to occur within the footprint of the road prism or flow control structure that the culvert is associated with. Culvert removal is expected to involve relatively extensive construction-related effects. Therefore, this method is expected to produce stressors and resulting ecological effects on the higher end of the range discussed in the sections referenced.

It is important to note as well that culvert removal or replacement often involves channel and/or habitat modifications to maintain or restore appropriate channel gradient. These activities involve extensive construction in and along the active channel that extends well beyond the footprint of the structure. The construction-related effects of these activities have been addressed in the Habitat Modifications and Channel Modifications white papers (Herrera 2007a, 2007c, respectively).

Once this construction activity is completed, it is expected that subsequent maintenance requirements will be minimal, as the stream is allowed to respond to natural processes. In addition, because any maintenance actions that would take place involve channel or habitat modification (rather than modification of a structure), this maintenance would no longer be considered a component of the culvert subactivity type.

Culvert replacement involves the removal of the existing structure and replacement with a new culvert structure. Like culvert removal, these activities are expected to take place within the footprint of the existing structure and the associated road prism or channel modification. Culvert replacement is expected to produce impact submechanisms and related stressors of similar magnitude to culvert removal. Therefore, the magnitude of stressors and resulting effects are expected to be at the higher end of the ranges discussed in the sections referenced above.

Unlike culvert removal, culvert replacement includes the potential for at least some level of ongoing maintenance to keep the structure functioning as intended. These activities and their related impact submechanisms would be expected to occur at frequencies ranging from interannual to decadal. In general, culvert maintenance is expected to require less-extensive work than initial construction, so the intensity and duration of the related stressors would be expected to be similarly reduced.

For the purpose of this assessment, retrofitting of culverts involves work conducted essentially within the existing structure, such as the placement of baffles or internal weirs. Construction-related effects are expected to take place within the footprint of the original structure, as well as some distance upstream or downstream as necessary to complete the retrofit. For example, many retrofits are accomplished by backwatering the structure using downstream weirs or grade control structures. Such cases might involve the isolation and dewatering of the structure using a flow bypass, and securing vanes, baffles, or similar structural elements inside the body of the culvert. Some dredging of accumulated sediments may be required, and this activity may extend a short distance upstream or downstream of the structure. The effects of in-channel construction activities associated with weirs for backwatering are expected to be similar to those discussed in Section 7.4 (*Weirs*) of this white paper and in the Habitat Modifications white paper (Herrera 2007a). The effects of other forms of construction-related channel modifications are expected to be similar to those described in the Channel Modifications white paper (Herrera 2007c).

The need for maintenance is a recognized issue with retrofitted culverts. This type of structure tends to accumulate sediment, which increasingly limits the effectiveness of fish passage. Routine (e.g., annual) maintenance, typically in the form of dewatering, suction dredging of accumulated sediments, and/or debris removal, will likely be required to maintain fish passage.

7.1.1.2 Water Quality Modifications

There are several water quality related impact submechanisms that may occur as a result of removing, replacing, or retrofitting a culvert for fish passage. As with construction and maintenance, many of these impact submechanisms are similar across fish passage subactivity types. Therefore, the discussion of common impact mechanisms and stressor response provided in Section 7.6.1.2 (*Water Quality Modifications)* is incorporated by reference as appropriate. See the discussion of ecological stressors and related effects on HCP species in the referenced subsections for each of the water quality stressors referenced below.

- Elevated suspended sediments: May occur over periods ranging from temporary sediment pulses associated with construction and maintenance, to intermediate-term chronic seasonal elevation associated with altered hydraulic and geomorphic and riparian conditions (see Section 7.6.1.2.2 [*Elevated Suspended Sediments*]).

- Altered dissolved oxygen: May occur on a short-term basis as a result of changes in nutrient cycling from increased biochemical oxygen demand, particularly if distinct road-impounded wetlands are dewatered and nutrient-rich pore water is released (see Section 7.6.1.2.3 [*Altered Dissolved Oxygen*]).

- Altered pH: Short-term episodes may occur during construction and maintenance as a result of in-water concrete curing or discharge of concrete leakage to surface waters (see Section 7.6.1.2.4 [*Altered pH*]).

- Introduction of toxic substances: Temporary episodes may occur as a result of accidental spills during construction and maintenance (see Section 7.6.1.2.5 [*Introduction of Toxic Substances*]).

- Altered nutrient cycling: Intermediate-term episodes may occur as a result of dewatering of distinct road-impounded wetlands during removal or replacement of existing structures (see Section 7.6.1.2.6 [*Altered Nutrient Cycling*]).

The type and extent of water quality modifications associated with the culvert subactivity type are expected to vary depending on the approach taken. Therefore, some additional discussion of the distinctions between the stressors produced by the three approaches to improving fish passage (i.e., removing, replacing, or retrofitting) is warranted.

In general, more extensive water quality effects are expected to be associated with the initial construction-related effects of culvert removal and replacement. This is due to the fact that the associated earthwork, in-channel work, and materials placement requirements are more extensive. While culvert retrofits will have less extensive initial construction-related impacts, water quality modifications are expected to occur on a more frequent basis because the maintenance requirements for retrofitted structures are more extensive.

Virtually every culvert project will result in some release of suspended sediments, and any in-water construction project involving mechanized equipment poses some risk of release of toxic substances. In contrast, other stressors such as altered dissolved oxygen (DO), altered pH, and altered nutrient cycling are only expected to occur in specific circumstances. Altered pH is likely to occur only in culvert replacement or retrofitting projects involving concrete poured and cured on site. Culvert removals are unlikely to cause this effect because they typically will not involve pouring of new concrete.

In contrast, culvert removal or replacement is more likely to lead to altered nutrient cycling and changes in DO levels, because these methods may in certain circumstances involve the dewatering of distinct road-impounded wetlands. Distinct road-impounded wetlands are created by road beds and culverts that interfere with the hydraulic and geomorphic continuity of the stream system and create a new habitat type (Barnard 2002). This type of habitat feature can sequester a large amount of sediments and organic material. Removal or replacement projects that release this sequestered material can cause nutrient and DO effects in downstream reaches (see Section 7.1.1.5 [*Hydraulic and Geomorphic Modifications*] for further discussion).

Culvert retrofits are unlikely to cause these stressors because the configuration and conveyance characteristics of the structure remain similar. Even where distinct road-impounded wetlands are present, retrofits are unlikely to cause the extensive hydraulic and geomorphic effects associated with altered nutrient cycling and DO conditions.

7.1.1.3 Riparian Vegetation Modifications

In general, most culvert removal, replacement, or retrofitting projects are expected to be conducted within the footprint of the existing structure and the related road prism or channel modification. As such, extensive disturbance of riparian vegetation can typically be avoided. However, riparian modification may be necessary for certain removal or replacement projects, or may occur as a result of broader hydraulic and geomorphic changes imposed by these methods. Impact submechanisms associated with this subactivity type include the following:

- Alteration of shade, solar exposure, and ambient temperature regime: Caused by alteration of vegetation canopy cover and insulating effect of boundary layer condition created by riparian forest.
- Altered bank stability: Caused by degradation of riparian vegetation, loss of vegetative cover as well as root cohesion, and reduced resistance to erosive forces.
- Altered allochthonous inputs: Caused by reduced inputs of leaf litter, woody debris, and terrestrial insects and other biota associated with riparian vegetation.
- Altered groundwater/surface water interactions: Due to the influence of altered riparian vegetation on hyporheic zone function.
- Altered habitat complexity: Due to loss of large woody debris (LWD) recruitment sources and reduced bank stability leading to simplification of complex bank habitat.

The effects of riparian modifications on temperature conditions and nutrient and pollutant loading and resulting effects on HCP species are common water quality modification effects that occur to varying degrees across all subactivity types. These effects are discussed in Section 7.6.1.2 (*Water Quality Modifications).* The ecological stressors imposed by the remaining impact submechanisms are also similar; however, these stressors and their effects on HCP species are discussed in Section 7.6.1.3 (*Riparian Vegetation Modifications).*

When considering the effects of culverts on HCP species using the common effects discussion, it is important to recognize that the extent to which this subactivity type is likely to affect riparian vegetation is limited in most cases. Therefore, the potential for effects on HCP species from this impact mechanism must be considered in this context.

Culvert retrofit projects are likely to have little or no effect on riparian vegetation, as construction and maintenance work will be implemented from the existing roadway and will take place within the footprint of the existing structure. Removal and replacement projects may have more broad-reaching effects on riparian vegetation. In many cases, the work can be implemented from the existing road prism or channel modification, requiring little riparian disturbance. However, in some cases culvert removal or replacement may cause hydraulic and geomorphic modifications that affect riparian conditions in both upstream and downstream reaches more broadly. This is particularly likely to be true in situations where road-impounded wetlands are created as a result of backwater conditions. Draining of these impoundments may alter the relationship between the stream and riparian vegetation as the channel adjusts to the new gradient condition (see Section 7.1.1.5 [*Hydraulic and Geomorphic Modifications*] for further discussion).

7.1.1.4 Aquatic Vegetation Modifications

Culvert removal and replacement have the potential to modify aquatic vegetation through short-term construction-related effects, and more broadly through hydraulic and geomorphic modifications that induce changes in habitat suitability for the vegetation community. The following impact submechanisms may occur as a result of aquatic vegetation modifications associated with culvert fish passage projects:

- Altered autochthonous production: Alteration of nutrient cycling and conversion of dissolved organic material into biomass available for grazers, affecting food web productivity (see Section 7.6.1.6 [*Ecosystem Fragmentation*]).

- Altered habitat complexity: Through changes or reduction in three dimensional structure, refuge and edge habitat, and foraging opportunities (see Section 7.6.2.1 [*Altered Habitat Complexity*]).

The potential for this subactivity type to result in aquatic vegetation modifications is generally more limited in comparison to other types of HPA-permitted activity types. This is due to the fact that the footprint of the existing structure has already imposed its effects on the vegetation community. Therefore, any work within the footprint of an existing structure will not displace or affect vegetation. Some extended effects are possible, however, if removal or replacement results in hydraulic and geomorphic modifications that change habitat suitability (see Section 7.1.1.5 [*Hydraulic and Geomorphic Modifications*] for further discussion). The effects of aquatic vegetation modification on HCP species are discussed in Section 7.6.1.4 (*Aquatic Vegetation Modifications*).

Retrofitting of culverts is not expected to have any appreciable effect on aquatic vegetation. Construction and maintenance activities will take place within the footprint of the existing structure, which is not expected to support aquatic vegetation of any habitat significance.

7.1.1.5 Hydraulic and Geomorphic Modifications

While generally considered beneficial from an ecological perspective, addressing fish passage barriers at culverts may lead to hydraulic and geomorphic modifications that impose ecological stressors on HCP species. The improper matching of culverts to local hydraulic and geomorphic conditions can result in a variety of channel responses, some of which create barriers to fish passage (e.g., outfall drops caused by localized scour), and others that modify habitat conditions (e.g., the creation of road-impounded wetlands).

While generally considered beneficial from a broader ecological perspective, the removal or replacement of barrier culverts may require associated channel or habitat modifications. These modifications are necessary to avoid hydraulic and geomorphic responses that cause undesirable effects on stream habitat conditions. In contrast, these responses may be allowed to occur based on an educated understanding of the likely results. Many legacy culverts in Washington State have altered the process of channel migration and evolution, as well as the transport of sediment and woody debris, particularly in cases where barrier conditions are created. Alterations of these physical processes are commonly associated with changes in channel gradient and morphology upstream and downstream of the culvert. Culvert removal or replacement with stream simulation either partially or fully eliminates this restriction, requiring the channel to adjust to a new equilibrium condition. Because current culvert replacement guidance emphasizes designs that attempt to maintain these processes to the greatest extent possible (e.g., stream simulation), replacement is likely to cause similar effects. The intent of the stream-simulation approach is to provide a culvert configuration that allows for natural channel processes to operate to the greatest extent possible.

One important concern results when culverts are not designed appropriately for their hydraulic and geomorphic context. In such cases, the culvert may fail to meet the dual objectives of providing fish passage while adequately conveying flood flows, or may interact with the environment in a way that creates undesirable conditions. For example, culverts that produce high exit velocities may scour the channel at the outlet, leading to an enlarging outfall drop that creates a fish passage barrier over time. Similarly, culvert designs that fail to address sediment transport requirements may aggrade over time, creating a barrier condition and reducing the hydraulic capacity of the structure, leading to flooding. For example, road prisms have commonly been placed at the edge of river valleys, perpendicular to stream channels draining onto the valley floor. Channels in these settings are naturally depositional, requiring the channel to migrate in response. Culvert designs that fail to recognize these characteristics are likely to aggrade and fail over time. Culvert replacement projects should therefore incorporate sediment transport processes into the design, and maintenance should be incorporated as necessary to accommodate design limitations.

Because this particular form of hydraulic and geomorphic modification is somewhat unique within the fish passage activity type, a specific discussion of the impact submechanisms, related stressors, and resulting effects on HCP species is provided here. It is important to note, however, that this discussion is specific to these special cases, and not all culvert removal or replacement will cause effects of this nature. Other more general forms of hydraulic and geomorphic modifications are discussed in Section 7.6.1.5 (*Hydraulic and Geomorphic Modifications*).

Hydraulic and geomorphic modification impact submechanisms discussed in this section include:

- Altered flow conditions
- Altered channel geometry
- Altered substrate composition and stability.

Because perturbations leading to these submechanisms of impact and the ecological responses to the same perturbations are interrelated, the discussion of the potential effects on HCP species is integrated.

For the purpose of this white paper, headcut migration is assumed to be a potential result of culvert removal or replacement. While this type of impact can be avoided in many cases by employing appropriate channel modifications, these measures are not always practicable or desirable due to cost, concerns about private property access, and the fact that instream structures interfere with natural geomorphic recovery after the culvert is removed. Therefore, the potential for these types of impacts to occur must be acknowledged.

Channel and habitat modifications such as channel regrading, substrate augmentation, and grade control structures used to halt headcut migration and maintain gradient continuity are commonly associated with culvert removal and replacement. However, for the purpose of this white paper, they are not considered a component of this subactivity type. Depending on the type of structure used, it may be considered a channel modification or habitat modification. Designs that incorporate grade control structures composed of natural materials (e.g., LWD) that mimic the function of logjams and other natural features in channel environments would be considered habitat modification. Designs that rely on structural approaches using non-native materials (e.g., large, angular boulder or concrete weirs) would be considered channel modifications. The effects of these types of projects on the aquatic environment and on HCP species are discussed in the Habitat Modifications and Channel Modifications white papers (Herrera 2007a, 2007c, respectively).

Retrofitting of culverts is not expected to cause significant hydraulic and geomorphic effects in most cases, as this option will maintain the existing structure and not significantly perturb the current channel geometry. However, the placement of internal weirs or baffles is likely to decrease flow capacity, which may impose backwater effects upstream of the structure, leading to potential sediment aggradation, bar formation, and changes to flood elevations. (These perturbations can also promote debris accumulation, increasing the risk of structural failure.) Depending on the amount of material captured, the natural sediment transport rate, and the maintenance frequency and methods used, this could result in effects on substrate composition in downstream reaches.

7.1.1.5.1 Hydraulic and Geomorphic Impact Submechanisms

The intent of culvert removal is to restore and reconnect the natural hydraulic and geomorphic processes, reducing or eliminating ecosystem fragmentation. Current culvert replacement guidance favors approaches that at least partially restore these processes (e.g., the stream-simulation and no-slope approaches). These approaches are generally expected to produce a net benefit, particularly when the existing structure is a complete barrier to fish passage. In certain cases, however, removal of the culvert or replacement with a structure that reconnects natural geomorphic processes can lead to broader hydraulic and geomorphic consequences. Specifically, culvert removal or replacement can reinitiate headcuts that have been arrested by the existing structure, allowing these headcuts to continue to migrate upstream. Headcuts are most often caused by downstream perturbations and include changes to processes related to hydrology and hydraulics, interruption of sediment transport, hardened bank stabilization or confinement modifications, or the lack of large woody debris that contributes to channel stability. In many cases, arrested headcuts are the cause of outfall drop formation at the mouth of the culvert that leads to a barrier condition. The outfall drop can become quite large in some cases, creating a large change in gradient across the structure. Culvert removal or replacement will likely reinitiate the arrested headcut and cause channel incision, bank instability, and bedload mobility, with a number of detrimental changes in habitat conditions in upstream reaches. Based on experience in Washington State, the potential for headcut migration is a factor that must be considered in 50 percent or more of culvert removal or replacement projects (Bates 2007).

Bed scour occurs at culvert outfalls, initially the result of high flow velocities exiting the structure, and then by the impinging jet produced downstream of a sudden drop in channel elevation (Jia et al. 2001). As the water jet penetrates the pool and reaches its bottom, the jet divides into two jets parallel to the bed and in opposite (upstream and downstream) directions (Flores-Cervantes et al. 2006). In homogeneous soils, upstream migration of the scour hole occurs as the upstream jet scours the headcut face, and as the downstream jet removes this sediment and sediment delivered from upstream. Flores-Cervantes et al. (2006) showed that plunge pool erosion varies with the headcut height, flow rate into the pool, and soil properties. The formation of a scour pool at a culvert outfall sets up the condition for headcut or knickpoint propagation upstream if the culvert is removed.

In general, headcut migration will occur when erosion of the headcut face by the upstream jet is faster than the erosion of the bed at the top of the headcut (Flores-Cervantes et al. 2006), and when there is sufficient transport capacity downstream to remove the eroded sediment from the plunge pool (Jia et al. 2001). The distance a headcut propagates upstream will depend on how these conditions change with headcut migration and whether the headcut encounters resistant materials.

Channel incision during headcut propagation decreases the channel gradient and destabilizes the banks (Kondolf et al. 2002; Sandecki 1989). Bank erosion can increase the local supply of fine sediment and result in channel instability (Sear 1995), leading to increased bedload mobility and ongoing water quality effects in the form of sedimentation. Channel incision can also result in the loss of floodplain and channel complexity through the fragmentation of off-channel habitats, and can adversely affect riparian vegetation (Kondolf et al. 2002). This is of particular concern when channel incision exposes underlying bedrock. Incision to bedrock can significantly reduce the productivity and quality of aquatic habitat for a range of fish species, particularly salmonids dependent on alluvial bedded systems for spawning habitat and forage (Kauffman et al. 1993). Moreover, depending on the underlying geology, bedrock exposure can accelerate weathering and erosion in lower gradient systems (Stock et al. 2005), leading to the ecosystem fragmentation effects described above.

A related issue of concern is the potential for culvert removal or replacement to dewater or otherwise alter road-impounded wetlands, leading to hydraulic and geomorphic changes and potentially a shift to wetland type habitat. Similar to the issues described above for headcuts, removal or replacement of the culvert can lead to reestablishment of natural geomorphic processes, with a range of effects on instream habitat conditions. The potential dewatering of road-impounded wetlands is a factor for consideration in a relatively low number of cases, estimated to be less than 5 percent of all culvert projects (Bates 2007). The cases where potentially significant hydraulic and geomorphic effects are likely to occur represent a small component of this total (Barnard 2002). These effects are nonetheless potentially significant and are therefore discussed here.

The quality of wetland habitats produced by road-impounded wetlands can vary (Barnard 2002). In most cases, these wetlands are of marginal habitat value, and the importance of restoring natural stream processes is overriding. In rare circumstances, however, high-value habitats may have developed that are occupied by species of interest. In cases where a significant change in hydraulic gradient is induced by the barrier, deposition of fine substrates will occur upstream of the culvert, and the interception of these sediments will cause some degree of sediment coarsening in downstream reaches. Because road-impounded wetlands can raise surface water levels, they may inundate adjacent floodplains more often, creating wetland conditions (Hammerson 1994). Larger impoundments with increased floodplain connectivity are also likely to accumulate organic material, increasing the size of the sediment wedge behind the barrier.

Erosional processes following culvert removal or replacement where backwater effects and sediment deposition has occurred are expected to be similar to those following the removal of low-head man-made dams. Doyle et al. (2002) and Doyle et al. (2003) demonstrated that channel evolution after small dam removal follows the classic model of incision and widening that is induced by base-level lowering. Accumulated sediments will erode rapidly and be transported to lower gradient, downstream reaches where aggradation is likely to occur. Water depths and flow conditions within the former impoundment will change, and the wetted perimeter will decrease. Bank stability within the former impoundment will decline until the channel adjusts and vegetation becomes established (Bednarek 2001; Doyle et al. 2002, 2003; Pollock et al. 2003). Bank failure will, in turn, induce channel-widening and bed-aggradation processes that lead to an eventual dynamic equilibrium in the longitudinal profile of the channel (Schumm et al. 1984).

Downstream channel geometry will be only temporarily affected by the removal of small impoundments (Pollock et al. 2004). Deposited sediment will be transported to downstream low-energy environments (e.g., pools, channel margins) but will likely be entrained and exported farther downstream in subsequent flooding events. Upstream channel geometry will change more dramatically. The main channel in the upstream reach responds by narrowing. Channel narrowing may limit access to shallow water habitat and decrease the surface area exposed to solar radiation (Margolis, Raesly et al. 2001).

These perturbations and the related ecological stressors they impose will range in severity depending on the size of the road-impounded wetland, the volume and characteristics of impounded sediments, and the equilibrium gradient of the restored channel. In some cases, these effects may be relatively minor. For example, a study of the effects of removal of two small dams in Wisconsin found insignificant sediment export, attributed to the small impoundment size and relatively high thalweg velocities that limited sediment accumulation prior to removal (Orr et al. 2006).

Several forms of water quality modifications may occur as a result of channel response to headcut-induced erosion. An immediate and potentially lasting effect is elevated suspended sediments caused by channel bed and bank erosion. Although research has indicated widely varying results (Bash et al. 2001), the scientific consensus is that elevated suspended sediment concentrations can be detrimental to fish and invertebrates when the stressor exceeds the natural range of turbidity typical for the system, or when sensitive life-history stages are exposed during periods when the stressor exposure would not typically occur (Bash et al. 2001; Newcombe and Jensen 1996). Suspended solids may affect aquatic species by altering their physiology, behavior, or habitat. The direct and indirect impacts of suspended solids on fish and invertebrates are addressed in Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors*).

Another ramification of impoundment dewatering is the potential for a spike in nutrient export with resulting water quality effects both within the former impoundment area and downstream. For example, impoundments behind beaver dams have been shown to accumulate phosphorus-associated sediments, and the resulting biological activity produces ammonium-rich pore water in the substrate (Margolis, Castro et al. 2001). Bed scour and sediment mobilization associated with barrier removal may liberate trapped nutrient-rich pore water, exporting these nutrients downstream in large pulses. These types of effects have been observed following the removal of low-head man-made dams (Ahearn and Dahlgren 2005; Orr et al. 2006). This suggests that scouring of accumulated sediments from road-impounded wetlands following culvert removal or replacement could induce similar effects. These nutrient releases could be beneficial for aquatic biota in oligotrophic headwater reaches, but detrimental in nutrient-impacted lowland areas. These water quality related stressors are expected to be short term to intermediate term in duration, depending on the size of the impoundment, the quantity of sediments eroded, and the time required for the channel to reach a new equilibrium state. For more information on the impacts of nutrient-enrichment in productive waters see Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors*).

7.1.1.6 Ecosystem Fragmentation

Culverts can induce ecosystem fragmentation through a number of pathways. Principally, ecosystem fragmentation occurs through the following: effects on fish passage; the interruption of natural channel migration processes and channel configuration; altered transport of sediments, organic material, and large woody debris; and in some cases the creation of new habitat types that are inconsistent with the natural channel form.

Culvert retrofits are intended specifically to improve fish passage, thereby addressing one component of ecosystem fragmentation. However, retrofitting typically will not reduce the fragmentation of ecological processes induced by the structure, and may exacerbate certain problems. For example, placement of internal weirs and baffles will decrease the hydraulic capacity of the culvert, which can create backwater effects upstream of the structure and lead to sediment deposition. This can interrupt sediment transport processes, leading to some degree of sediment starvation downstream of the structure.

From the perspective of existing conditions, improving fish passage at culverts must generally be viewed as having beneficial effects on ecosystem fragmentation. However, this analysis explicitly considers the effects of the culvert subactivity type against the natural stream baseline. From this perspective, only culvert removal projects have little to no potential to produce adverse ecosystem fragmentation effects. It is important to note, however, that if the culvert is replaced by a bridge, that structure may incorporate riprap, concrete abutments, or other elements that affect ecosystem functions. These potential effects are addressed in the Stream Crossings white paper (Jones and Stokes 2006b).

Even the most carefully designed culvert replacement or retrofitting project can produce some forms of ecosystem fragmentation. Ecosystem fragmentation effects may occur through the following impact submechanisms:

- Passage barriers: The culvert may not provide full fish passage, unintentionally imposing specific types of barriers; headcut migration may cause changes in channel morphology that impede passage, or fish passage may decrease over time due to design limitations or improper maintenance.

- Modified downstream transport of sediment, LWD, and organic material: The structure may not allow for the unrestricted downstream transport of woody debris and organic material, affecting habitat complexity and food web productivity in downstream reaches. (Generally, this effect is associated with retrofitted culverts, as stream simulation is intended to provide these functions.)

- Lateral and longitudinal habitat fragmentation: This can be caused by headcut liberation and channel incision in upstream reaches.

These common impact submechanisms and resulting effects on HCP species are discussed in detail in Section 7.6.1.6 (*Ecosystem Fragmentation)* under Section 7.6 *(Ecological Effects of Common Impact Mechanisms and Stressors).*

In addition to effects on aquatic species, roads and flow control structures also have the potential to fragment foraging, migratory, and dispersal corridors used by nontarget aquatic, semi-aquatic, and terrestrial species. Researchers in the United States and Europe are currently investigating the utility of different culvert designs to provide migratory corridors for terrestrial species (Bates et al. 2008). It is conceivable that ecosystem fragmentation effects imposed by culverts on terrestrial species could result in indirect effects on HCP species. However, insufficient research has been conducted on this subject to assess the nature and extent of any indirect effects that may occur.

7.1.2 Summary of Effects on HCP Species

The removal, replacement, or retrofitting of culverts for fish passage is generally expected to produce net benefits for HCP species by improving ecological connectivity. In specific cases, however, culvert removals or replacements may result in unintentional or unavoidable effects that are detrimental to some species over short-term to intermediate-term periods. For example, specific subactivities may cause dewatering of impoundment type habitats upstream of barrier culverts, leading to short-term to intermediate-term effects on habitat suitability as the channel adjusts to a new equilibrium condition. Alternatively, replacement or retrofit projects may result in unintentional ecosystem fragmentation in the form of partial barriers to fish passage or effects on ecosystem processes.

Culvert construction and maintenance involve several impact submechanisms with the potential to cause direct mortality, injury, altered survival, growth and fitness, harassment, and/or behavioral alterations for HCP species. Specifically, equipment operation and materials placement, dewatering and handling, and dredge and fill are all actions with the potential to cause direct and indirect effects. See Section 7.6.1.1 (*Construction and Maintenance)* under Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors)* for more detailed discussion of the potential effects of specific impact submechanisms and stressors on HCP species.

Culvert construction and maintenance also have the potential to cause changes in water quality conditions. Water quality perturbations are typically temporary to short term in duration, but certain effects may be more lasting (i.e., intermediate term) in nature. Specifically, construction and maintenance activities can cause multiple temporary to short-term perturbations including elevated suspended sediments, introduction of toxic substances, and altered pH conditions. These stressors would be expected to abate rapidly once the activity producing the stressor is completed. In contrast, hydraulic and geomorphic modifications can lead to intermediate- to long-term effects on water quality, nutrient cycling, and pollutant loading. Depending on their severity, short-term stressors have the potential to cause effects ranging from injury and direct mortality to behavioral avoidance and other minor changes. Longer term changes in water quality conditions are not likely to be directly fatal but may change habitat suitability to the extent that survival, growth, and fitness of HCP species are affected (positively or negatively). See Section 7.6.1.2 (*Water Quality Modifications)* for more detailed discussion of the potential effects of specific impact submechanisms and stressors on HCP species.

With regard to riparian and aquatic vegetation modifications, the effects of this subactivity type are expected to be relatively minor. As discussed in Sections 7.1.1.3 (*Riparian Vegetation Modifications*) and 7.1.1.4 (*Aquatic Vegetation Modifications*), the extent of these impact mechanisms is expected to be relatively limited. This subactivity type will occur predominantly within the footprint of the existing infrastructure accessed from the existing stream crossing, requiring little additional habitat disturbance (in the case of retrofits, effects on vegetation are considered to be entirely avoidable in most cases). Therefore, effects on HCP species would similarly be limited and minor. Exceptions to this general statement may occur, however, in situations where culvert removal or replacement results in significant geomorphic disturbance upstream and downstream of the structure (see Section 7.1.1.5 [*Hydraulic and Geomorphic Modifications*]). In such cases, the effects on riparian and aquatic vegetation may be more extensive. For the purpose of this white paper, this worst-case scenario is applied.

Hydraulic and geomorphic modifications associated with culvert removal and replacement may cause a range of ecological stressors affecting habitat suitability. In general, these stressors are associated with the channel returning to a more natural equilibrium condition in conjunction with the rehabilitation of natural fluvial processes, and are expected to be long term in nature. In rare cases, hydraulic and geomorphic responses to culvert removal or replacement projects may affect habitats used by species of interest. This is most likely to occur when arrested headcuts are liberated by culvert removal or replacement, leading to headcut migration through upstream habitats.

Headcut migration is a concern from the standpoint of both lateral and longitudinal habitat fragmentation. Channel downcutting associated with headcut migration can cause a range of habitat-related effects. For example, lowering of surface water elevations can disconnect side channel and off-channel habitats, as well as reduce the frequency and extent of floodplain inundation. Headcut migration can also lead to habitat simplification, reducing the diversity of channel habitat types along a longitudinal gradient. These forms of fragmentation can substantially reduce the extent and productivity of aquatic habitats. A detailed discussion of the causes of lateral and longitudinal habitat fragmentation, ecological responses, and resulting effects on HCP species is provided in the Channel Modifications white paper (Herrera 2007c).

Culvert removal or replacement can also cause relatively unique forms of habitat disturbance. In certain cases, replacement or removal can eliminate or alter distinct wetlands formed by road-impounded wetlands. For example, the Olympic mudminnow is restricted to slack-water habitats in slow-moving streams, ponds, and wetlands with several centimeters of soft sediment substrate (Mongillo and Hallock 1999). Culvert removal could alter flow, channel geometry, and substrate conditions, reverting the impounded reach to a coarse-grained, free flowing condition (Naiman et al. 1988). This would eliminate habitat for this species. In such special circumstances, it may be desirable to design a culvert replacement that maintains the impoundment habitat.

Likewise, this subactivity type may impose unintended effects on fish passage relative to natural conditions, with detrimental effects on HCP species. Effects on fish passage can have significant implications for survival, growth, and fitness at juvenile and subadult life-history stages, as well as on adult spawning productivity. From a long-term perspective, these collective effects can have broader implications for population viability. These effects are discussed in detail in Section 7.6.1.6 (*Ecosystem Fragmentation*).

Culvert retrofits are more prone to produce fish passage related stressors than culvert replacement. Retrofitting a culvert for passage purposes requires knowledge of the swimming performance and passage requirements of the full range of HCP species likely to attempt to navigate the structure. It may be challenging to produce a design that provides for the needs of all species of interest, meaning that some degree of ecosystem fragmentation may occur. Moreover, retrofitted culverts typically require regular maintenance to maintain function. When they are improperly maintained, fish passage performance is likely to decline significantly.

Replacement culverts are generally less likely to produce ecosystem fragmentation effects because current design guidance favors approaches that mimic natural stream hydraulics. In certain circumstances, however, these structures may also produce barriers to fish passage. For example, improperly maintained culverts may become blocked by debris, leading to barrier conditions.

7.2 Fish Ladders/Fishways

Fish ladders and fishways (hereafter referred to as fishways) are structures intended to provide fish passage through, over, and/or around natural or man-made barriers. Most commonly, these structures are incorporated into dams, weirs, or other large man-made structures, but may also be employed to provide passage around natural obstructions such as waterfalls or high-velocity channels. Although current WDWF policy does not allow for the creation of passage around natural barriers, this type of project may occur in certain circumstances. For example, the fishways constructed at Hells Gate and other locations in the Fraser River Canyon in British Columbia, Canada, were developed to provide fish passage around a quasi-natural barrier. In this case, the naturally high flow velocity conditions in the channel were made impassible by human-caused rockslides that altered hydraulic conditions sufficiently to create a nearly complete barrier to passage of sockeye salmon and other anadromous species. While possible, this type of fish ladder/fishway project would occur only in special circumstances and is therefore not considered further here.

Fishway construction and operation present the potential for ecological stressors imposed by a number of different impact mechanisms. These include the initial effects of constructing the structure, the long-term effects of the presence of the structure on ecological processes and functions, and the potential for ecosystem fragmentation effects of increasing magnitude over time if the structure is poorly conceived for the site or improperly maintained.

The impact mechanisms associated with fishway construction and operation, and effects on HCP species are summarized in the following sections. It is important to note here that for the purpose of this white paper, the scope of this evaluation is limited to the effects of fishway operation and maintenance, and not the effects of man-made structures (e.g., dams and weirs) that are bypassed. The effects of these structures on the environment are addressed in detail in the Flow Control Structures white paper (Herrera 2007b). Because the impact mechanisms and related stressors considered are in common with those imposed by other fish passage subactivity types, this discussion incorporates by reference the information presented in Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors)* as appropriate.

7.2.1 Impact Mechanisms

Impact mechanisms associated with fish ladders and fishways include the following:

- Construction and maintenance
- Water quality modifications
- Riparian vegetation modifications
- Aquatic vegetation modifications
- Hydraulic and geomorphic modifications
- Ecosystem fragmentation.

Each of these impact mechanisms is associated with a range of more specific submechanisms that can cause stressors having potential effects on HCP species. These submechanisms, related ecological stressors, and their relative magnitude in comparison to those imposed by other fish passage subactivity types are described in the following sections. Where appropriate, the reader is directed to the discussion of ecological stressors and their effects provided in Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors*). Impact mechanisms with potential effects that are unique to this subactivity type are described in detail below.

7.2.1.1 Construction and Maintenance

The effects of construction and maintenance of fish ladders and fishways are expected to be generally similar to those caused by the placement of other types of hard structures in flowing water systems. Specifically, placement of fishways is expected to impose a number of construction-related impact submechanisms, including noise, visual and physical disturbance, stressors associated with dredging and fill and dewatering and handling, and construction-related water quality effects. These construction and maintenance-related impact submechanisms are expected to be common across all fish passage subactivity types (with the exception of trap-and-haul operations). Therefore, the discussion of common impact mechanisms and stressor response provided in Section 7.6.1.1 (*Construction and Maintenance)* is incorporated by reference as appropriate. See the discussion of ecological stressors and related effects on HCP species in the referenced subsections for each of the impact submechanisms referenced below.

- Elevated underwater noise and visual and physical disturbance: Caused by equipment operation and materials placement (see Section 7.6.1.1.1 [*Equipment Operation and Materials Placement*]).

- Dewatering and handling: Associated with creation of exclusion areas and capture and relocation of fish and invertebrates (see Section 7.6.1.1.2 [*Dewatering and Handling*]).

- Dredging and fill: Associated with placement of a new structure and routine maintenance required to address aggradation or debris accumulation (see Section 7.6.1.1.3 [*Dredging and Fill*]).

7.2.1.2 Water Quality Modifications

Several water quality related impact submechanisms may occur as a result of fishway creation. Similar to construction and maintenance, many of these impact submechanisms are similar across fish passage subactivity types. Therefore, the discussion of common impact mechanisms and stressor response provided in Section 7.6.1.2 (*Water Quality Modifications*) is incorporated by reference as appropriate. See the discussion of ecological stressors and related effects on HCP species in the referenced subsections for each of the impact submechanisms referenced below.

- Elevated suspended sediments: May occur over periods ranging from temporary sediment pulses associated with construction and maintenance, to intermediate-term chronic seasonal elevation associated with altered hydraulic and geomorphic and riparian conditions (see Section 7.6.1.2.2 [*Elevated Suspended Sediments*]).

- Altered pH: Short-term episodes may occur during construction and maintenance as a result of in-water concrete curing or discharge of concrete leakage to surface waters (see Section 7.6.1.2.4 [*Altered pH*]).

- Introduction of toxic substances: Temporary episodes may occur as a result of accidental spills during construction and maintenance (see Section 7.6.1.2.5 [*Introduction of Toxic Substances*]).

7.2.1.3 Riparian Vegetation Modifications

Fishways are often constructed along one bank of the affected stream system and thereby have the potential to affect riparian vegetation. These structures are commonly associated with existing weirs or dams, they may be integrated into this infrastructure, and the incremental effects of the fishway on riparian vegetation are negligible in comparison. In some cases, fishways may be required in locations where some modification of riparian vegetation is required. The potential effects of this subactivity type from riparian vegetation modification are considered in this context.

Potential impact submechanisms associated with fishways include the following:

- Alteration of shade, solar exposure, and ambient temperature regime: Caused by alteration of vegetation canopy cover and insulating effect of boundary layer condition created by riparian forest.

- Altered bank stability: Caused by degradation of riparian vegetation, loss of vegetative cover and/or root cohesion, and reduced resistance to erosive forces.

- Altered allochthonous inputs: Caused by reduced inputs of leaf litter, woody debris, and terrestrial insects and other biota associated with riparian vegetation.

- Altered groundwater/surface water interactions: Due to the influence of altered riparian vegetation on hyporheic zone functions.

- Altered habitat complexity: Due to loss of LWD recruitment sources and reduced bank stability leading to simplification of complex riparian habitat.

The effects of riparian modifications on temperature and other water quality effects are discussed in Section 7.6.1.2 (*Water Quality Modifications)* under Section 7.6 *(Ecological Effects of Common Impact Mechanisms and Stressors)*. The ecological stressors imposed by the remaining impact submechanisms and their effects on HCP species are discussed in Section 7.6.1.3 (*Riparian Vegetation Modifications*).

7.2.1.4 Aquatic Vegetation Modifications

The fishway subactivity type has the potential to modify aquatic vegetation through short-term construction-related effects, and more broadly through hydraulic and geomorphic modifications that induce changes in habitat suitability for the vegetation community. The following impact submechanisms may occur as a result of aquatic vegetation modifications associated with fishways:

- Altered autochthonous production: Alteration of nutrient cycling and conversion of dissolved organic material into biomass available for grazers, affecting food web productivity.

- Altered habitat complexity: Through changes or reduction in three-dimensional structure, refuge and edge habitat, and foraging opportunities.

The effects of stressors imposed by these submechanisms are discussed in Section 7.6.1.4 (*Aquatic Vegetation Modifications*) under Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors)*. The following context should be considered, however, when using this information to interpret the likely magnitude of effects on HCP species.

The potential for the fishway subactivity type projects to result in aquatic vegetation modification is generally more limited in comparison to other types of HPA-permitted activity types. This is due to the fact that the in-water footprint of fishway structures is typically small and, in the case of passage around man-made barriers, the fishway is integrated into the barrier structure, and the incremental effect on aquatic vegetation is negligible. Some extended effects on aquatic vegetation are possible, however, if the fishway design results in hydraulic and geomorphic modifications that change habitat suitability for vegetation. For example, exit flows from the fishway may lead to localized alteration of substrate conditions (see Section 7.1.1.5 [*Hydraulic and Geomorphic Modifications*] for further discussion). In general, however, any effects associated with aquatic vegetation modifications are expected to be limited in extent and insignificant in terms of stressors imposed on the aquatic community.

7.2.1.5 Hydraulic and Geomorphic Modifications

Fishways are expected to have relatively moderate and localized effects on hydraulic and geomorphic conditions relative to the man-made structures they are intended to bypass. By design, fishway structures are intended to be permeable to water, sediment, and organic material, and allow the upstream and downstream passage of fish. However, certain types of fishway designs, specifically weir fishways, are more prone to sediment accumulation. In certain cases, the degree of accumulation can be significant enough to starve downstream reaches of substrate.

Hydraulic and geomorphic modification related impact submechanisms associated with fishways include:

- Altered flow conditions: Alteration of local hydraulic conditions within the affected reach, specifically accelerated flows at outlets of exit structures.

- Altered channel geometry: Bank hardening along the length of structure and potential scour at outlet.

- Altered substrate composition and stability: Potential scour and coarsening of substrates at exit point. Possible sediment accumulation within the structure due to design limitations, leading to sediment starvation in downstream reaches.

The effects of these impact submechanisms and the stressors they impose upon HCP species are common among all fish passage subactivity types, and are discussed in Section 7.6.1.5 (*Hydraulic and Geomorphic Modifications*) under Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors).*

When interpreting the effects of fishways using this information, it is important to recognize that the hydraulic and geomorphic effects of fishways and the effects of related stressors are, on the whole, expected to be limited. However, fishway designs that fail to accommodate the geomorphic context present in the system may lead to their eventual failure to pass fish, as well as alteration of habitat conditions downstream of the structure (e.g., through gravel starvation). Specifically, poorly designed and/or improperly maintained fishways can accumulate sediment or jam with woody debris to the point that they no longer pass fish safely and effectively. The effects of passage barrier related stressors are addressed in the following section (Ecosystem Fragmentation).

7.2.1.6 Ecosystem Fragmentation

Fishways can result in ecosystem fragmentation through a number of pathways. Because these structures are intended to improve passage, an inherent objective of their design is to reduce ecosystem fragmentation by promoting connectivity of habitats along the river continuum. Improved fish passage promotes additional benefits from ecological connectivity. However, fishways may unintentionally result in ecosystem fragmentation through the following impact submechanisms:

- Passage barriers: Fishways may impose intentional or unintentional passage barriers, or passability may decrease over time due to design failure or improper maintenance.

- Modified upstream transport of allochthonous nutrients: Intentional or unintentional effects of fish passage may in turn alter the upstream transport of nutrients from distant sources, particularly marine-derived nutrients (e.g., in the form of salmon carcasses), affecting ecosystem productivity.

These impact submechanisms are imposed by fishways that fail to provide fish passage because they were improperly designed for their ecological context, or because of decreased passage performance over time due to improper maintenance or other factors. In many cases, fishways have been designed and installed without a definition of specific performance objectives, so their performance is difficult to rate (Cada and Sale 1993). However, many studies have identified structures that fail to provide adequate fish passage for the species they are intended to benefit, or that unintentionally limit passage of nontarget species (Agostinho et al. 2007; Boggs et al. 2004; Bunt et al. 1999; Caudill et al. 2007; Moser et al. 2000; Moser et al. 2002; Naughton et al.

2007). The potential effects of fishways on ecosystem fragmentation should be viewed in this context when assessing the potential effects on HCP species.

These impact mechanisms and their resulting effects on HCP species are discussed in detail in Section 7.6.1.6 (*Ecosystem Fragmentation*) under Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors).*

7.2.2 Summary of Effects on HCP Species

Permitting of fishways can result in a number of potential effects on HCP species, depending on the nature of the structure in question and the context in which the structure is constructed and operated. For the purpose of this white paper, the potential effects of each impact mechanism are assessed on the basis of the worst-case scenario.

With regard to construction and maintenance, the most extensive effects are likely to be associated with fishways that are retrofitted onto existing structures that require disturbance of previously modified habitat that has since reached a new equilibrium state. This type of project will require habitat disturbance, equipment operation and materials placement, probable in-water work (potentially including dewatering and handling, and dredge and fill), and attendant temporary effects on water quality. The effects of exposure to stressors associated with these submechanisms range from relatively minor, short-term behavioral alteration to potential direct injury and mortality (see Sections 7.6.1.1 [*Construction and Maintenance*] and 7.6.1.2 [*Water Quality Modifications*] for details).

Stressors imposed by modifications of riparian and aquatic vegetation, and hydraulic and geomorphic conditions are also likely to be most pronounced in this type of circumstance. The structural footprint will require effectively permanent alteration of the shoreline and riparian vegetation. In contrast, effects on aquatic vegetation and the extent of resulting stressors are likely to be limited because the in-water footprint of the structure is small. Stressors imposed by hydraulic and geomorphic modifications may also occur (see Sections 7.6.1.3 [*Riparian Vegetation Modifications*], 7.6.1.4 [*Aquatic Vegetation Modifications*], and 7.6.1.5 [*Hydraulic and Geomorphic Modifications*] for details). The effects of fishways around man-made barriers are likely to be even less extensive. In most cases, the fishway will be integrated into the existing structure or surrounding disturbed areas, meaning that the affected habitat has already been permanently modified. In comparison to the dam or the weir, the additional incremental effects of the structure and the ecological stressors imposed are likely to be relatively limited.

The fishway-related impact mechanism of greatest concern is ecosystem fragmentation. As noted, fishways may not meet objectives for passage of target fish species for various reasons, or may have unanticipated effects on the passage of nontarget species. Moreover, a fishway may initially function appropriately but may lose effectiveness over time if the structure becomes compromised by changing channel conditions or improper maintenance. As an example, the fishway around the hatchery weir at the Quilcene National Fish Hatchery (Big Quilcene River, Washington State) has become increasingly less effective at passing winter steelhead due to the combination of cobble aggradation and high-flow velocity at the upstream exit of the weir, which redirects fish along a path that results in a high rate of "fallback" (fallback occurs when fishway exits are located in areas where high current velocities wash fish back over the barrier the passage structure is intended to bypass). The effects of diminished access to productive habitats on HCP species are broad and significant, as discussed in Section 7.6.1.6 (*Ecosystem Fragmentation)*.

7.3 Roughened Channels

Roughened channels have been seen as a more aesthetically pleasing and "natural" way to pass fish around a barrier than fishways, particularly in areas where land adjacent to a barrier is available and inexpensive. Generally speaking, the channel bottom is comprised of naturally occurring or processed quarry rock that is rounded and of sufficient size to ensure stability of the channel. Sometimes designers of these channels impose channel structure by designing the channel with a series of small steps or meanders, although this is not always the case.

Roughened channels can be broken into two broad categories:

- Roughened channels that exploit an existing channel or side channel.
  - Advantages: Can utilize existing streamflow without diversion.
  - Disadvantages: Large impact on existing ecologic communities.
- Roughened channels that are constructed through an upland area where no channel existed before.
  - Advantages: Limited or nonexistent impacts on existing ecology.
  - Disadvantages: More difficult to design; more prone to hydraulic and geomorphic effects that may lead to decreasing function over time.

Roughened channels are currently in the experimental stage of development. While conceptually simple, the design of a roughened channel is not as straightforward as one might expect. Natural channels are the result of extended periods of geomorphic evolution. The structure within the channel (riffle-pools, step-pools) is in dynamic equilibrium with material both underlying the channel and sediment supplied from upstream. Duplicating these relationships in an engineering or other design is extremely difficult. Also, natural channels often have riparian vegetation on the immediate edges of the channel, while newly constructed roughened channels must remove some vegetation in the vicinity of the channel to construct it. This may compromise the utility of the roughened channel for aquatic species. Roughened channels, particularly those sited in upland areas, can have longitudinal slopes that are out of equilibrium with respect to water flow and sediment supply. If out of balance with these factors, channels either erode or aggrade (accumulate) sediment such that they ultimately block fish passage and have negative impacts on the geomorphic character of adjacent water bodies. In addition, the coarse sizes of rock often used in roughened channel projects can initiate unnaturally high groundwater recharge, causing subsurface flow conditions during drier periods, limiting habitat capacity, presenting the potential for stranding and mortality of aquatic organisms, and posing barriers to fish passage.

The impact mechanisms associated with roughened channel construction and maintenance, and effects on HCP species are summarized in the following sections. It is important to note here that for the purpose of this white paper, the scope of this evaluation is limited to the effects of the construction, operation, and maintenance of roughened channels, and not the effects of man-made structures (e.g., dams and weirs) that are bypassed. The effects of these structures on the environment are addressed in detail in the Flow Control Structures white paper (Herrera 2007b). Because the impact mechanisms and related stressors considered are common with those imposed by other fish passage subactivity types, this discussion incorporates by reference the information presented in Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors)* as appropriate.

7.3.1 Impact Mechanisms

Impact mechanisms associated with roughened channels include the following:

- Construction and maintenance
- Water quality modifications
- Riparian vegetation modifications
- Aquatic vegetation modifications
- Hydraulic and geomorphic modifications
- Ecosystem fragmentation.

Each of these impact mechanisms is associated with a range of more specific submechanisms that can cause stressors having potential effects on HCP species. These submechanisms, related ecological stressors, and their relative magnitude in comparison to those imposed by other fish passage subactivity types are described in the following sections. Where appropriate, the reader is directed to the discussion of ecological stressors and their effects provided in Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors*). Impact mechanisms with potential effects that are unique to this subactivity type are described in detail below.

7.3.1.1 Construction and Maintenance

If the roughened channel is sited in an upland area, there are limited to nonexistent impacts on HCP species associated with construction if typical construction best management practices (BMPs) are followed with regards to sediment production and toxic releases.

If the roughened channel is placed in the location of an existing channel or side channel, the effects of construction and maintenance of roughened channels are expected to be generally similar to other types of channel modification activities. Specifically, placement of roughened channels is expected to impose a number of construction-related impact submechanisms, including noise, visual and physical disturbance, stressors associated with dredging and fill and dewatering and handling, and construction-related water quality effects. These construction-related impact submechanisms are expected to be common across all fish passage subactivity types (with the exception of trap-and-haul operations). Therefore, the discussion of common impact mechanisms and stressor response provided in Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors*) applies to roughened channel construction.

Common impact submechanisms that are associated with construction and maintenance of roughened channels include:

- Elevated underwater noise and visual and physical disturbance: Caused by equipment operation and materials placement (see Section 7.6.1.1.1 [*Equipment Operation and Materials Placement*]).
- Dewatering and handling: Associated with creation of exclusion areas and capture and relocation of fish and invertebrates (see Section 7.6.1.1.2 [*Dewatering and Handling*]).
- Dredging and fill: Associated with removal of the old structure and placement of new materials (see Section 7.6.1.1.3 [*Dredging and Fill*]).

7.3.1.2 Water Quality Modifications

Several water quality related impact submechanisms may occur as a result of roughened channel creation. These submechanisms include the following:

- Elevated suspended sediments: May occur over periods ranging from temporary sediment pulses associated with construction effects, to intermediate-term chronic seasonal elevation associated with altered hydraulic, geomorphic, and riparian conditions (see Section 7.6.1.2.2 [*Elevated Suspended Sediments*]).
- Altered dissolved oxygen: May occur on a short-term basis as a result of changes in nutrient cycling, particularly if existing channels are dewatered to place a new roughened channel (see Section 7.6.1.2.3 [*Altered Dissolved Oxygen*]).
- Introduction of toxic substances: Temporary episodes may occur as a result of accidental spills during construction and maintenance (see Section 7.6.1.2.5 [*Introduction of Toxic Substances*]).

- Altered nutrient cycling: Intermediate-term episodes may occur as a result of dewatering associated with loss of flow due to increased groundwater recharge (see Section 7.6.1.2.6 [*Altered Nutrient Cycling*]).

- Elevated temperature: Intermediate-term episodes may occur associated with modifications of riparian vegetation, as well as associated with geomorphic modifications that can alter channel morphology (see Section 7.6.1.2.1 [*Altered Water Temperature*]).

These water quality modification impact submechanisms are considered similar to those caused by other fish passage subactivity types. Common submechanisms and their effects on HCP species are discussed in detail Section 7.6.1.2 (*Water Quality Modifications*) under Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors).*

7.3.1.3 Riparian Vegetation Modifications

If a roughened channel is placed in or alongside an existing stream channel, it has the potential to affect existing riparian vegetation. Roughened channels integrated into existing side channels may require relatively limited riparian disturbance. In contrast, creation of an entirely new channel will require more extensive disturbance. The potential effects of roughened channels on riparian vegetation should be viewed from this worst-case scenario perspective.

Potential impact submechanisms associated with roughened channel installation include the following:

- Alteration of shade, solar exposure, and ambient temperature regime: Caused by alteration of vegetation canopy cover and insulating effect of boundary layer condition created by riparian forest.

- Altered bank stability: Caused by degradation of riparian vegetation, loss of vegetative cover and/or root cohesion, and reduced resistance to erosive forces.

- Altered allochthonous inputs: Caused by reduced inputs of leaf litter, woody debris, and terrestrial insects and other biota associated with riparian vegetation.

- Altered groundwater/surface water interactions: Due to the influence of altered riparian vegetation on hyporheic zone functions.

- Altered habitat complexity: Due to loss of LWD recruitment sources and reduced bank stability, leading to simplification of complex riparian habitat.

The effects of riparian modifications on temperature conditions and nutrient and pollutant loading and resulting effects on HCP species are discussed in Section 7.6.1.2 (*Water Quality Modifications*). The ecological stressors imposed by the remaining impact submechanisms and their effects on HCP species are discussed in Section 7.6.1.3 (*Riparian Vegetation Modifications*).

7.3.1.4 Aquatic Vegetation Modifications

If the roughened channel is placed in an existing channel, its construction has the potential to modify aquatic vegetation through short-term construction-related effects, and more broadly through hydraulic and geomorphic modifications that induce changes in habitat suitability for the vegetation community. The following impact submechanisms may occur as a result of aquatic vegetation modifications associated with roughened channel fish passage projects:

- Altered autochthonous production: Alteration of nutrient cycling and conversion of dissolved organic material into biomass available for grazers, affecting food web productivity.

- Altered habitat complexity: Through changes or reduction in three-dimensional structure, refuge and edge habitat, and foraging opportunities.

The effects of stressors imposed by these submechanisms are discussed in Section 7.6.1.4 (*Aquatic Vegetation Modifications*) under Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors)*. The following context should be considered, however, when using this information to interpret the likely magnitude of effects on HCP species.

The potential for roughened channel projects to result in aquatic vegetation modification is generally more limited in comparison to other types of HPA-permitted activity types. This is due to the fact that the in-water footprint of roughened channels is typically small or nonexistent (in the case of channels constructed through uplands). Some extended effects on aquatic vegetation are possible, however, if the roughened channel design results in hydraulic and geomorphic modifications that change habitat suitability for vegetation immediately upstream or downstream. For example, exit flows from the roughened channel may lead to localized alteration of substrate conditions (see Section 7.1.1.5 [*Hydraulic and Geomorphic Modifications*] for further discussion). In general, however, any effects associated with aquatic vegetation modifications are expected to be limited in extent and insignificant in terms of stressors imposed on the aquatic community.

7.3.1.5 Hydraulic and Geomorphic Modifications

Fish passage structures are expected to have relatively moderate and localized effects on hydraulic and geomorphic conditions relative to the man-made structures they are intended to bypass. By design, roughened channels are intended to be permeable to water, sediment, and organic material, and allow the upstream and downstream passage of fish.

Hydraulic and geomorphic modification related impact submechanisms associated with roughened channels include:

- Altered flow conditions: Alteration of local hydraulic conditions within the affected reach, specifically accelerated flows at the inlet or outlet.
- Altered channel geometry: Upstream or downstream scour impacting channel-floodplain connectivity.
- Altered substrate composition and stability: Altered substrate composition (through the addition of coarse material and altered transport capacity), possible scour, or aggradation due to inappropriate design.

The effects of these impact submechanisms and the stressors they impose upon HCP species are common among all fish passage subactivity types and are discussed in Section 7.6.1.5 (*Hydraulic and Geomorphic Modifications*).

When interpreting the effects of roughened channels using this information, it is important to recognize that the hydraulic and geomorphic effects of roughened channels and the effects of related stressors on the whole are expected to be limited. However, roughened channels, particularly those that are placed through uplands, are prone to alter the surrounding geomorphic nature of the adjacent stream system, which may lead to their eventual failure to pass fish. Specifically, poorly designed and/or improperly maintained roughened channels can accumulate sediment or jam with woody debris to the point that they no longer pass fish safely and effectively. Roughened channels placed through uplands may also have a tendency to produce fine-grained sediments if they are sized improperly and flood the adjacent landscape.

An additional problem in roughened channels is the permeability of the designed substrate. To maintain channel form and to increase frictional losses, often over steep slopes, coarse rock is often used as the substrate within the channel. Because the permeability of these materials is extremely high, the water flow in the channel may be insufficient to compensate for groundwater recharge during low-flow periods. In some cases, surface flows through the roughened channels may become low enough to pose a fish barrier, and may create isolated pools resulting in fish stranding. In a worst-case scenario, pools holding stranded fish may develop lethal temperature and DO conditions or they may dewater entirely. They could also accumulate organic material, which would be released in a pulse once flow is restored to the channel, possibly producing overly productive conditions downstream. The effects of passage barrier related stressors are addressed in the following section (*Ecosystem Fragmentation*).

7.3.1.6 Ecosystem Fragmentation

Roughened channels can result in ecosystem fragmentation through a number of pathways. Because these structures are intended to improve passage, an inherent objective of their design is to reduce ecosystem fragmentation by promoting connectivity of habitats along the river continuum. Improved fish passage promotes additional benefits from ecological connectivity.

However, roughened channels may unintentionally result in ecosystem fragmentation through the following impact submechanisms:

- Passage barriers: Roughened channels may impose intentional or unintentional passage barriers, or passability may decrease over time due to design failure.
- Modified upstream transport of allochthonous nutrients: Intentional or unintentional effects on fish passage may in turn alter the upstream transport of nutrients from distant sources, particularly marine-derived nutrients, affecting ecosystem productivity.
- Modified downstream transport of organic material: Unintentional loss of flow can cause organic material to accumulate in the channel bed, only to be released in a large pulse when flow is restored.
- Modified downstream transport of sediment: Undersized roughened channels may flood lands never flooded in the past and produce large quantities of fine-grained sediment.

These impact submechanisms are imposed by roughened channels that fail to provide fish passage because they were improperly designed for their ecologic or geomorphic context, or because of decreased passage performance over time due to improper maintenance or other factors. Many studies have identified fish passage structures that fail to provide adequate fish passage for the species they are intended to benefit, or that unintentionally limit passage of nontarget species (Agostinho et al. 2007; Boggs et al. 2004; Bunt et al. 1999; Caudill et al. 2007; Moser et al. 2000; Moser et al. 2002; Naughton et al. 2007). The potential effects of roughened channels on ecosystem fragmentation should be viewed in this context when assessing the potential effects on HCP species.

These impact mechanisms and their resulting effects on HCP species are discussed in detail in Section 7.6.1.6 (*Ecosystem Fragmentation)* under Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors).*

7.3.2 Summary of Effects on HCP Species

The net effects of roughened channels on HCP species will be variable depending on the extent and configuration of the specific action in question. In general, roughened channel projects fall into two categories: reconfiguration of an existing channel or side-channel to provide passage, or the creation of an entirely new channel through adjacent uplands or floodplain. A comparison of the general range of effects associated with each of these configurations by impact mechanism is presented below.

The extent of construction-related impact submechanisms and resulting stressor exposure clearly differs between these two design forms. Roughening of an existing channel by definition requires in-water work, likely affecting an extensive length of channel. This suggests the need for in-water equipment use and materials placement, dredging, and/or dewatering of the work area. All of these activities present the potential for direct effects on HCP species, ranging from temporary disturbance and displacement to direct physical injury or even mortality. The more severe of these effects are likely to be realized by relatively nonmotile species and life-history stages that cannot readily avoid construction-related disturbance.

In contrast, creation of an entirely new channel avoids the majority of these effects because the extent of in-water work is limited to the disturbance necessary to connect the new channel to existing flow at the upstream and downstream ends. Under these circumstances, the potential for adverse effects on most HCP species occurring in suitable habitats for this type of project would be limited to dredging disturbance with a relatively small in-water footprint, as well as downstream water quality impacts. Water quality effects, principally elevated turbidity, will occur during and following the initial watering of the channel. Suspended sediment levels during this period could be relatively high, potentially resulting in behavioral modification and stress that could affect survival, growth, and fitness of exposed organisms. Sensitive organisms or life-history stages (e.g., incubating salmon eggs) could experience direct mortality as a result of these stressors. The effects of elevated suspended sediments are discussed in more detail in Section 7.6.1.2 (*Water Quality Modifications*).

The effects of these two types of channel configurations on riparian and aquatic vegetation are similarly variable. Construction of new channels will have negligible effects on aquatic vegetation, while effects on terrestrial vegetation will be extensive. In contrast, alteration of an existing channel may require alteration of both riparian and aquatic vegetation for construction purposes. On this basis, the effects of riparian vegetation modification on HCP species as a result of roughened channel creation are expected to be relatively extensive. These effects are discussed in Section 7.6.1.3 (*Riparian Vegetation Modifications)*.

For aquatic vegetation modifications, it is useful to note that roughened channels are often implemented to aid passage in high-velocity channels. This type of environment is less than ideal for aquatic vegetation and typically does not support extensive communities. Therefore, the direct effects of construction are expected to be limited overall. However, construction-related water quality impacts in the form of elevated suspended sediments following construction or subsequent hydraulic and geomorphic effects may affect aquatic vegetation in downstream areas, suggesting that some effects on HCP species are probable (see Section 7.6.1.4 [*Aquatic Vegetation Modifications*]).

Hydraulic and geomorphic modifications associated with roughened channel creation are likely to result in the most pronounced ecological stressors and the most extensive effects on HCP species. As noted, natural channels form through long-term evolution of geomorphic processes that are difficult to mimic with engineered designs. Alteration of hydraulic and geomorphic processes by splitting flows or placing artificial roughness features in the channel may lead to unintended changes in environmental conditions that are undesirable. This has the potential to impose multiple ecological stressors on HCP species. The nature of these stressors and the effects of exposure are discussed in Section 7.6.1.5 (*Hydraulic and Geomorphic Modifications).*

An advantage of roughened channels is that they are relatively transparent to the downstream movement of organic material, water, wood, and sediment. Therefore, the degree to which these structures result in ecological fragmentation is limited. However, improperly conceived or implemented designs may impose unintended barriers to the passage of fish or other organisms, fragmenting access to upstream habitats. The potential ecological effects of passage barriers and fragmented upstream transport of allochthonous nutrients are described in Section 7.6.1.6 (*Ecosystem Fragmentation*).

7.4 Weirs

The term "weir" applies to a number of different structure types that are intended to serve a variety of purposes. For example, weirs may include structures ranging from large river spanning barriers that effectively act like small dams, to temporary structures used to control fish movement for population studies and other purposes. This white paper focuses strictly on weirs intended specifically to manage fish passage, while the effects of other types of weirs are addressed in separate white papers. To clarify, the following types of structures are commonly referred to as weirs:

- Large channel-spanning structures, typically made of concrete, such as hatchery weirs. The effects of this type of weir are addressed in the Flow Control Structures white paper (Herrera 2007b).
- Grade control structures, log controls, and similar structures typically composed of large wood and rock intended to restore channel bed profile. The effects of this type of weir are addressed in the Habitat Modifications white paper (Herrera 2007a).
- Fish passage control weirs constructed of natural or man-made materials intended to prevent upstream dispersal of invasive species (these structures may integrate electrical barriers to increase the selectivity of fish passage management).
- Temporary or movable weirs, such as smolt panels, fence weirs, and similar structures intended to control upstream and downstream fish migrations for population studies.

The latter two types of weir structures are the focus of this white paper. This section addresses the direct and indirect impacts of weirs on fish and invertebrates, their habitats, and ecological processes.

7.4.1 Impact Mechanisms

Impact mechanisms associated with fish passage weirs include the following:

- Construction and maintenance
- Water quality modifications
- Riparian vegetation modifications
- Aquatic vegetation modifications
- Hydraulic and geomorphic modifications
- Ecosystem fragmentation.

The submechanisms associated with each of these impact mechanisms are identified in the following sections. As noted, many of the impact submechanisms, ecological stressors, and their effects associated with fish passage weirs are similar to those caused by other fish passage subactivity types. Therefore, where appropriate, the reader is directed to the discussion of ecological stressors and their effects provided in Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors*). Impact mechanisms with potential effects that are unique to this subactivity type are described in detail below.

7.4.1.1 Construction and Maintenance

This section focuses primarily on the effects associated with the construction and maintenance of permanent fish passage control weirs on the environment. In general, temporary barrier weirs intended to block upstream dispersal of invasive fish and invertebrate species are typically placed by hand and removed each year. The effects of construction and maintenance of this type of weir structure are expected to be minimal in comparison to the construction of more permanent fish passage control structures. Therefore, this section focuses on the effects of these more permanent types of structures.

Impact submechanisms associated with weir construction and maintenance are likely to impose a variety of stressors. Equipment operation and materials placement (e.g., placement of large wood or metal structures) will cause elevated underwater noise levels and visual and physical disturbance. Bank and bed disturbance during construction will lead to increased suspended sediment levels and turbidity. Accidental spills from construction equipment, concrete leachate, and other vectors may introduce toxic substances to surface waters or cause detrimental changes in water chemistry. Construction activities may also include dredge and fill activities that can entrain organisms or permanently displace habitat for burrowing and benthic animals. The effects of the various stressors imposed by construction of weirs are described in detail in Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors*).

7.4.1.2 Water Quality Modifications

Several water quality related impact submechanisms may occur as a result of fish passage weir construction and operation. These include the following:

- Elevated suspended sediments: May occur over periods ranging from temporary sediment pulses associated with construction effects, to intermediate-term chronic seasonal elevation associated with altered hydraulic and geomorphic and riparian conditions (for effects on HCP species, see Section 7.6.1.2.2 [*Elevated Suspended Sediments*]).

- Altered dissolved oxygen: May occur on a short-term basis as a result of changes in nutrient cycling from increased or decreased upstream transport of nutrients caused by changes in fish passage (for effects on HCP species, see Section 7.6.1.2.3 [*Altered Dissolved Oxygen*]).

- Altered pH: Short-term episodes may occur during construction and maintenance as a result of in-water concrete curing or discharge of concrete leakage to surface waters (for effects on HCP species, see Section 7.6.1.2.4 [*Altered pH]*).

- Introduction of toxic substances: Temporary episodes may occur as a result of accidental spills during construction and maintenance (for effects on HCP species, see Section 7.6.1.2.5 [*Introduction of Toxic Substances*]).

These water quality modification impact submechanisms associated with fish passage weirs are considered similar to those caused by other fish passage subactivity types. These common submechanisms and their effects on HCP species are described in Section 7.6.1.2 (*Water Quality Modifications*) under Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors).*

7.4.1.3 Riparian Vegetation Modifications

Riparian vegetation modifications associated with the construction of fish passage weirs may occur during construction and maintenance activities, and also as a result of bank failures caused by altered hydraulic and geomorphic processes. Removal or disturbance of riparian vegetation during HPA-permitted construction activities can expose HCP species to stressors caused by a variety of impact mechanisms, including:

- Alteration of shade, solar exposure, and ambient temperature regime: Caused by alteration of vegetation canopy cover and insulating effect of boundary layer condition created by riparian forest.

- Altered bank stability: Caused by degradation of riparian vegetation, loss of vegetative cover and/or root cohesion, and reduced resistance to erosive forces.

- Altered allochthonous inputs: Caused by reduced inputs of leaf litter, woody debris, and terrestrial insects and other biota associated with riparian vegetation.

- Altered groundwater/surface water interactions: Due to the influence of altered riparian vegetation on hyporheic zone functions.

- Altered habitat complexity: Due to loss of LWD recruitment sources and reduced bank stability, leading to simplification of complex riparian habitat.

The effects of stressor exposure associated with riparian vegetation modifications are discussed in Section 7.6.1.3 (*Riparian Vegetation Modifications*) under Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors).*

7.4.1.4 Aquatic Vegetation Modifications

Construction of fish passage weirs and their subsequent effects on hydraulic and geomorphic conditions and ecosystem fragmentation can lead to alterations in the aquatic vegetation community. Depending on the nature of the system in question and the role of aquatic vegetation in food web productivity, these effects can range from relatively minor to more extensive on a localized basis. Impact submechanisms associated with aquatic vegetation modifications include:

- Altered autochthonous production: Changes in nutrient cycling and food web productivity due to the loss of vegetation capable of capturing and converting dissolved nutrients into biomass.

- Altered habitat complexity: Loss of the habitat structure and diversity provided by aquatic vegetation patches within the riverine ecosystem.

The effects of these impact submechanisms and the stressors they impose upon HCP species are common among all fish passage subactivity types, and are discussed in Section 7.6.1.4 (*Aquatic Vegetation Modifications*) under Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors).*

7.4.1.5 Hydraulic and Geomorphic Modifications

Depending on the specific nature of the subactivity, the effects of fish passage weirs on hydraulic and geomorphic conditions can range from relatively minor, short-term perturbations to more significant long-term modifications.

To be more specific, weirs erected for fisheries management purposes (such as population assessments and mark-recapture studies) are often temporary in nature, or involve foldable or removable gates that are relatively permeable to water, wood, and sediment transport. These types of structures are likely to have limited effects on hydraulic and geomorphic conditions in the affected reach.

In contrast, permanent barrier weirs are likely to have more extensive effects. Depending on design, these structures may perturb hydraulic and geomorphic conditions in ways essentially similar to flow control weirs and similar structures. For the purpose of this white paper, this type of weir represents the worst-case scenario for potential effects on HCP species.

Hydraulic and geomorphic modification related impact submechanisms associated with weirs include:

- Altered flow conditions: Alteration of hydraulic conditions within the affected reach, including creation of backwater effects upstream of the structure, and creation of hydraulic jumps and accelerated flows at the downstream ends of exit structures.

- Altered channel geometry: Creation of impoundment conditions upstream of the structure, and potential changes in channel profile in downstream reaches, including narrowing and increased incision.

- Altered substrate composition and stability: Disruption of sediment transport with deposition of fine substrates upstream of the structure, and channel incision and coarsening of substrates downstream.

- Altered groundwater/surface water interactions: Creation of head differentials upstream of the structure that alter hyporheic exchange. Deposition of fine sediments in the impoundment may lead to decreased downwelling over time.

The effects of these impact submechanisms and the stressors they impose upon HCP species are common among all fish passage subactivity types, and are discussed in Section 7.6.1.5 (*Hydraulic and Geomorphic Modifications*) under Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors).*

7.4.1.6 Ecosystem Fragmentation

Fish passage weirs can result in ecosystem fragmentation through a number of pathways. For example, some weir structures are specifically intended to control the upstream passage of undesirable fish species. This objective may lead to designs that unintentionally impose barriers to nontarget fish species. Ecosystem fragmentation effects associated with weir type structures may occur through the following impact submechanisms:

- Passage barriers: Weirs may impose intentional or unintentional passage barriers, or passability may decrease over time due to design failure.

- Modified upstream transport of allochthonous nutrients: Intentional or unintentional effects on fish passage may in turn alter the upstream transport of nutrients from distant sources, particularly marine-derived nutrients in the form of salmon carcasses, affecting ecosystem productivity.

- Modified downstream transport of sediment, LWD, and organic material: Weirs may create impoundment conditions that may alter the downstream transport of woody debris and organic material, affecting habitat complexity and food web productivity in downstream reaches.

These common impact submechanisms and resulting effects on HCP species are discussed in detail in Section 7.6.1.6 (*Ecosystem Fragmentation*) under Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors).*

7.4.2 Summary of Effects on HCP Species

The probable net effects of fish passage weirs on HCP species range from relatively benign, in the case of temporary or removable structures used for fisheries population studies, to wide-ranging and potentially significant in the case of barrier weirs intended to control the upstream passage of undesirable species.

Temporary weirs are, by design, limited in effects. These structures are typically semipermiable to water, wood, sediment, and organic debris transport while in place, and transparent to these processes when not in use. The degree to which these structures alter ecological connectivity, riparian conditions, and aquatic vegetation is expected to be minor in extent and limited to short-term construction and operational effects. Potential water quality modifications associated with these types of structures are expected to vary, ranging from limited pulses of suspended sediments during installation and removal, to more extensive short-term effects during the construction of movable structures (e.g., from equipment operation and materials placement, curing of concrete). Following construction and installation, however, water quality effects of operations are expected to be negligible.

In contrast, permanent barrier weirs are expected to impose a broader suite of potential effects on HCP species. The construction-related impacts of these types of structures are similar to those that would be expected for other channel-spanning types of structures (such as diversion weirs and small dams), as are broader effects caused by hydraulic and geomorphic modifications, riparian and aquatic vegetation modifications, ecosystem fragmentation, and water quality impacts. The effects of stressors caused by these impact mechanisms on HCP species are described in detail in Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors*).

7.5 Trap and Haul

Trap-and-haul facilities are expected to be associated with a dam, weir, fishway, or some other type of flow control structure. The relatively limited number of trap-and-haul facilities operating in Washington State are associated with a dam or, in one case, at the base of a natural falls. The effects of construction and maintenance of fishways/fish ladders and fish passage weirs on the aquatic environment are addressed in Sections 7.2 (*Fish Ladders/Fishways*) and 7.4 (*Weirs*), respectively. The effects of dams and other types of weirs on the environment are addressed in the Flow Control Structures white paper (Herrera 2007b).

7.5.1 Impact Mechanisms

Because the physical effects of dam and weir structures typically associated with the trap-and-haul subactivity type are addressed elsewhere, this white paper focuses specifically on the effects of the operational elements of the trap-and-haul subactivity type on HCP species. Impact mechanisms associated with trap-and-haul operations include fish capture, transport, and release, as well as ecosystem fragmentation. Because the majority of impact submechanisms associated with this subactivity type are somewhat unique, this section provides a specific discussion of these submechanisms and the effects of the ecological stressors they impose on HCP species where appropriate. Discussion of the effects of impact submechanisms and stressors common to all fish passage activity types is incorporated by reference to Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors).*

7.5.1.1 Operational Activities

Trap-and-haul programs are most often used to mitigate the effects of artificial barriers to fish passage that cannot be retrofitted with a fish ladder or other type of bypass structure to provide volitional (voluntary) passage. Trap and haul of sockeye salmon around barrier dams on the Baker River (Skagit River system) and downstream barge transport of migratory salmon smolts are two examples of these types of programs. In some cases, trap-and-haul programs are used to introduce fish above natural barriers where other fish passage alternatives are not practicable. The annual release of salmon, steelhead, and native char above Sunset Falls on the Skykomish River is an example of this type of program. Current WDFW policy does not permit for construction of fish passage around natural barriers however, suggesting that future trap-and-haul programs around natural barriers would not be permitted.

Fish trap-and-haul operations involve three operational steps: (1) the capture of fish within some type of permanent structure, such as a weir or dam with an integrated trap structure, or using a temporarily placed trap device (e.g., a screw trap for capturing smolts); (2) the transport of the fish in a truck or barge to an upstream or downstream release point; and (3) release into the aquatic environment. The following impact submechanisms are associated with trap-and-haul operations:

- Fish capture, transport, and release
- Introduction of toxic substances: From accidental spills during operational activities.

These impact submechanisms, the stressors they impose, and the effects of stressor exposure on HCP species are discussed in the following sections.

7.5.1.1.1 Fish Capture, Transport, and Release

Trap-and-haul operations by definition involve the capture, transport, and release of the target fish population. Fish capture and handling are inherently stressful actions that present the potential for injury and mortality of the target species. A detailed discussion of the effects of handling-related stress is provided in Section 7.6.1.1.2 (*Dewatering and Handling*). In reference to this discussion, the handling and transfer of live fish, particularly large adults, between traps, transport vehicles, and release points present numerous opportunities for injury and mortality. Fish may be dropped, may flail or abrade themselves against hard surfaces, or may lose their protective slime coat or scales as a result of rough handling. Even with the most careful handling to avoid injury, these practices unavoidably induce stress that can affect survival following successful release (Olla et al. 1995). For example, Hinson et al. (2007) used radiotelemetry to study the behavior and fate of adult coho salmon and steelhead trapped and transported around an impassable barrier dam and found evidence of high mortality. They speculated that probable causes include transport-related injury and stress, as well as increased susceptibility to predation.

7.5.1.1.2 Introduction of Toxic Substances

Accidental spills of lubricants, fuel, or other materials involved with trap-and-haul operations may lead to the introduction of hydrocarbons and related substances to the aquatic environment. The effects of exposure to these types of stressors are examined in Section 7.6.1.2.5 (*Introduction of Toxic Substances*) in Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors*).

7.5.1.2 Ecosystem Fragmentation

Fish trap-and-haul activities have the potential to impose three specific forms of ecosystem fragmentation, all specifically related to the selective effects on fish that they intentionally or unintentionally impose:

- Passage barriers: Several forms of passage barriers may occur (e.g., operational challenges may result in failure to successfully pass fish in a given year), and unintentional selection pressures (e.g., size, run timing) may be imposed on the affected population.

- Modified upstream transport of allochthonous nutrients: Trap-and-haul programs will affect the upstream transport of nutrients by the affected organisms.

- Alteration of migratory patterns: Trap-and-haul operations may introduce fish into tributaries they did not originally occupy, or release fish upstream of natal streams, frustrating migration behavior by bypassing olfactory cues used in homing.

The first two impact submechanisms, related ecological stressors, and the effects of stressor exposure on HCP species are common to all fish passage structure types and are discussed under the *Barriers to Fish Passage* and *Modified Upstream Transport of Allochthonous Nutrients* subsections under Section 7.6.1.6 (*Ecosystem Fragmentation*). Alteration of migratory patterns is a unique impact submechanism imposed by the trap-and-haul subactivity type and is addressed in more detail here.

7.5.1.2.1 Alteration of Migratory Patterns

While trap-and-haul programs are intended to mitigate or address passage barriers, in certain cases these programs may alter or frustrate the migratory behavior of the target species with unintended effects on their viability. As an example, WDFW (in cooperation with the U.S. Army Corps of Engineers) has operated a trap-and-haul program to pass adult salmonids around the sediment retention structure on the North Fork Toutle River. The structure was placed to intercept mass wasting associated with the 1980 eruption of Mount St. Helens. The program currently transports Chinook, coho salmon, and steelhead around the structure, which is a complete barrier to passage. However, due to access issues, the fish must be released several miles upstream of former mainstem and existing tributary spawning and rearing areas. Hinson et al. (2007) examined the migratory behavior of coho salmon and steelhead released in non-natal tributaries using radiotelemetry and found that the released fish did not migrate to their birth streams as anticipated. In effect, the release location has altered the migratory pathway for the affected stocks, increasing the travel distance to their habitats by several miles and requiring adaptation to new habitats.

7.5.2 Summary of Effects on HCP Species

Trap-and-haul programs are somewhat effective approaches to providing fish passage around man-made barriers. Ideally, this approach would be used as an interim measure until volitional passage around the barrier can be established (e.g., by removal of the barrier or by construction of a fishway, ladder, or other type of passage structure). This type of approach has been recommended to support conservation of native salmonids. For example, Schmetterling (2003) studied the behavior of tagged bull trout and westslope cutthroat trout transported above Milltown Dam on the Clark Fork River to determine the likelihood of reoccupation of historic habitats. All the test subjects migrated at least some distance upstream, and he found that some individuals moved upstream as far as 62 miles (100 kilometers) or more. Based on these findings, Schmetterling (2003) concluded that a trap-and-haul program could be used to initiate recovery of adfluvial populations while options for volitional passage were being decided.

As discussed, stressors imposed by trap-and-haul programs include unintentional degradation of water quality effects through accidental spills of lubricants and other toxic substances; fish passage effects; altered upstream transport of nutrients (with attendant effects on food web productivity and habitat structure); and alteration of migratory pathways. Any water quality related effects would be expected to be episodic (i.e., associated with annual trap-and-release activities) and short term in duration. The fish passage related effects are more difficult to assess and potentially more significant. Even the most carefully operated trap-and-haul program has the potential to introduce some type of selection pressure on the affected population, which could alter genetic diversity. Because the selection pressures imposed are associated with artificial environments, these changes are likely to be detrimental. Additional discussion of the effects of selection pressures imposed by artificial manipulation of fish passage barriers is provided in Section 7.6.1.6 (*Ecosystem Fragmentation*).

The extent to which migration delays caused by alteration of migratory pathways affect fish will depend in many respects on the specific life history and physiology of the species affected. Salmonid species that enter river systems sexually immature and spend lengthier periods in fresh water, such as spring- and summer-run Chinook and summer-run steelhead, are likely to be less prone to adverse effects than sympatric ocean type races. These types of salmonids enter their natal streams ready to spawn; therefore, their reproductive success is more sensitive to the effects of migration delay.

Consider that summer-run steelhead populations in the interior Columbia Basin migrate several hundred miles to reach natal streams. In doing so, individual fish from these populations may explore non-natal streams over periods lasting from days to weeks and may migrate upstream for considerable distances (tens of miles or more). For example, steelhead from the Clearwater River basin, Idaho, are commonly caught by anglers in the Deschutes River in Oregon 10 or more miles upstream of its confluence with the Columbia River. In contrast, ocean-type fall-run Chinook in Puget Sound enter their natal streams essentially ready to spawn, suggesting that delayed migration would impose greater consequences on reproductive success.

However, it is useful to note that salmonids have demonstrable behavioral and evolutionary capacity to adapt to large changes in their migratory corridors. Washington State has witnessed two pertinent examples. First, consider that Lake Washington basin Chinook salmon and steelhead historically migrated into the Cedar River and other tributaries from Elliot Bay via the Black River by way of the Duwamish River. The creation of the Lake Washington Ship Canal created a new entrance to the Lake at Shilshole Bay and dewatered the original migratory path through the Black River. Within a period of approximately 5 years, the native salmonid populations had adapted to this alteration and today access the lake and its tributaries through the ship canal. As another example, Toutle River Chinook, coho, and steelhead were forced to alter their migratory pathway by the heavy load of ash delivered to the system by the eruption of Mount St. Helens. These populations adopted alternate spawning locations in other watersheds and recolonized their former habitats after it had recovered sufficiently. While the potential effects of migratory corridor alteration on population abundance and diversity should not be discounted, these and other examples demonstrate the adaptive capacity of migratory fish species.

The effects of migratory corridor alteration on HCP invertebrate species are expected to be limited. Alteration of the migratory path of fish species targeted by trap-and-haul programs would have no discernable effects on marine invertebrate species. Effects on giant Columbia River limpet and great Columbia River spire snail, which are not directly linked to fish migration patterns by life history, would be similarly unaffected. In contrast, alteration of fish migratory pathways could alter the dispersal of the glochidia larvae of western ridged mussels, potentially introducing these species into new habitats. However, as most trap-and-haul programs are transporting fish within their original ranges, the extent of these effects is considered to be minimal.

7.6 Ecological Effects of Common Impact Mechanisms and Stressors

This section provides a discussion of the ecological stressors imposed by impact mechanisms that are common across all the subactivity types addressed in this white paper, and the effects on HCP species resulting from exposure to these stressors. The intent of providing a single, organized discussion of these effects is to reduce redundancy and promote readability. Section 7.6.1 (*Common Impact Mechanisms*) provides a detailed description of each impact mechanism by component submechanism, the ecological stressors they impose, and the effects of stressor exposure on HCP species. The discussion of effects on HCP species is organized somewhat differently between impact mechanisms, again to promote readability. In most cases, the effects discussion is combined at the impact mechanism level because the stressors imposed by each component submechanism are fundamentally interrelated. In specific cases, the stressors imposed by each impact submechanism are sufficiently unique that a separate discussion of their effects is useful.

Section 7.6.2 (*Common Impact Submechanisms Imposed by Multiple Impact Mechanisms*) provides a similar discussion of common submechanisms that are imposed by multiple impact mechanisms. Again, the intent of this consolidated discussion is to reduce redundancy and promote ease of reference.

The discussion provided in this section presents a worst-case scenario view of the effects of stressor exposure resulting from these common impact mechanisms. For many of the subactivity types in question, the magnitude of stressor exposure may be less than what is presented here. Therefore, interpretation of the potential effects on HCP species should be considered by taking into account the anticipated magnitude of these impact mechanisms and the resulting level of effects for each subactivity type provided in Sections 7.1 through 7.5.

7.6.1 Common Impact Mechanisms

The following are common impact mechanisms associated with all fish passage subactivity types (with the exception of trap-and-haul programs):

- Construction and maintenance

- Water quality modifications
- Riparian vegetation modifications
- Aquatic vegetation modifications
- Hydraulic and geomorphic modifications
- Ecosystem fragmentation.

The trap-and-haul subactivity type is somewhat unique in that it does not explicitly involve the creation of any structures. Rather, it is purely an operational activity that involves the capture and relocation of fish beyond man-made barriers in an upstream or downstream direction. As noted in Section 7.5 (*Trap and Haul)*, impact mechanisms associated with this subactivity type include operations (capture and relocation) and ecosystem fragmentation. Fish capture and handling and fish passage barriers are common impact mechanism types discussed herein. Unique submechanisms associated with this subactivity type and their effects are discussed in Section 7.5 (*Trap and Haul*).

7.6.1.1 Construction and Maintenance

With the exception of trap-and-haul operations, each of the subactivity types addressed in this white paper involves either the placement, removal, or retrofitting of an in-water structure. The development of any fish passage subactivity type will require the construction of an in-water structure, producing a range of ecological stressors and related effects. Once placed, any permanent fish passage structure will require at least some degree of ongoing maintenance, such as dredging of accumulated sediments, debris removal, and/or repair of failing elements.

Applying the worst-case scenario perspective employed throughout this white paper, construction and maintenance activities involve forms of disturbance that are generally similar regardless of the type of structure being developed. Common impact submechanisms resulting from construction and maintenance activities and their related ecological stressors are described below.

In the case of trap-and-haul operations, the trap used to capture and hold fish is considered a component of the associated flow control structure (e.g., the weir, dam, or water diversion). The effects of construction and maintenance of these structures are discussed in the Flow Control Structures white paper (Herrera 2007b).

7.6.1.1.1 Equipment Operation and Materials Placement

Equipment operation and materials placement encompass a range of activities required during construction and maintenance, including the placement or removal of structural materials and debris management, each of which is likely to require some level of in-water equipment use. These activities have the potential to produce various forms of disturbance, specifically visual and physical disturbance and underwater noise, both of which are stressors that can produce effects on HCP species. Stressors produced by visual and physical disturbance are well represented by the effects of dredging, as discussed in detail in Section 7.6.1.1.3 (*Dredging and*

Fill). Therefore, the discussion presented in this section focuses on the effects of underwater noise.

Equipment operation and materials placement can produce underwater noise of varying duration and intensity, depending on the source. In general, noise produced by impulsive sources (i.e., short duration, high intensity noise from sources such as pile driving or materials placement) is likely to produce different effects from noise produced by a more continuous source (e.g., continuous operation of flow bypass pumps). The discussion presented in this section provides the noise-related analytical basis for the development of the exposure-response matrices (Appendix A) and the risk of take analysis (Section 9).

This section summarizes existing information on sources of underwater noise, how underwater noise is characterized, existing and proposed effects thresholds, and the magnitude of noise stressors associated with typical project construction and maintenance activities. This discussion is derived in part from a summary of current science on the subject developed by WSDOT (2006).

Characterization of Underwater Noise

Underwater sound levels are measured with a hydrophone, or underwater microphone, which converts sound pressure to voltage, which is then converted back to pressure, expressed in pascals (Pa), pounds per square inch (psi), or decibel (dB) units. Derivatives of dB units are most commonly used to describe the magnitude of sound pressure produced by an underwater noise source, with the two most commonly used measurements being the instantaneous peak sound pressure level (dB_{peak}) and the root mean square (dB_{RMS}) pressure level during the impulse, referenced to 1 micropascal (re: 1µPa) (Urick 1983). The dB_{peak} measure represents the instantaneous maximum sound pressure observed during each pulse. The dB_{RMS} level represents the square root of the total sound pressure energy divided by the impulse duration, which provides a measure of the total sound pressure level produced by an impulsive source. The majority of literature uses dB_{peak} sound pressures to evaluate potential injury to fish. However, USFWS and NOAA Fisheries have used both dB_{peak} (for injury) and dB_{RMS} (for behavioral effects) threshold values to evaluate adverse injury and disturbance effects on fish, marine mammals, and diving birds (Stadler 2007; Teachout 2007). dB_{RMS} values are used to define disturbance thresholds in fish species, meaning the sound pressure level at which fish noticeably alter their behavior in response to the stimulus (e.g., through avoidance or a “startle” response). dB_{peak} values are used to define injury thresholds in salmonids, or the sound pressure level at which barotrauma injury is likely to occur (i.e., physical damage to body tissues caused by a sharp pressure gradient between a gas or fluid-filled space inside the body and the surrounding gas or liquid).

Noise behaves in much the same way in air and in water, attenuating gradually over distance as the receptor moves away from the noise source. However, underwater sound exhibits a range of behaviors in response to environmental variables. For example, sound waves bend upward when propagated upstream into currents and downward when propagated downstream in the direction of currents. Sound waves will also bend toward colder, denser water. Haloclines and other forms of stratification can also influence how sound travels. Noise shadows created by bottom topography and intervening land masses or artificial structures can, under certain circumstances, block the transmission of underwater sound waves.

Underwater noise attenuation, or transmission loss, is the reduction of the intensity of the acoustic pressure wave as it propagates, or spreads, outward from a source. Propagation can be categorized using two models, spherical spreading and cylindrical spreading. Spherical (free-field) spreading occurs when the source is free to expand with no refraction or reflection from boundaries (e.g., the bottom or the water surface). Cylindrical spreading applies when sound energy spreads outward in a cylindrical fashion bounded by the sediment and water surface. Because neither model applies perfectly in any given situation, most experts agree that a combination of the two best describes sound propagation in real-world conditions (Vagle 2003).

Currently, USFWS and NOAA Fisheries are using a practical spreading loss calculation, which accommodates this view (Stadler 2007; Teachout 2007). This formula accommodates some of the complexity of underwater noise behavior, but it does not account for a number of other factors that can significantly affect sound propagation. For example, decreasing temperature with depth can create significant shadow zones where actual sound pressure levels can be as much as 30 dB lower than calculated because sound bends toward the colder deeper water (Urick 1983). Haloclines, current mixing, water depth, acoustic wavelength, sound flanking (i.e., sound transmission through bottom sediments), and the reflective properties of the surface and the bottom can all influence sound propagation in ways that are difficult to predict.

Given these complexities, characterizing underwater sound propagation inherently involves a large amount of uncertainty. An alternative calculation approach, known as the Nedwell model (not used by USFWS or NOAA Fisheries), indirectly accounts for some of these factors. Nedwell and Edwards (2002) and Nedwell et al. (2003) measured underwater sound levels associated with pile driving close to and at distance from the source in a number of projects in English rivers. They found that the standard geometric transmission loss formula used in the practical spreading loss model did not fit well to the data, most likely because it does not account for the aforementioned factors that affect sound propagation. They developed an alternative model based on a manufactured formula that produced the best fit to sound attenuation rates measured in the field. This model thereby accounts for uncharacterized site-specific factors that affect noise attenuation, but does not explicitly identify each factor or its specific effects. Because there is considerable uncertainty regarding how to model the many factors affecting underwater noise propagation, and this would require site-specific information that cannot practically be obtained in many instances, the Services (i.e., USFWS and NOAA Fisheries) use the more conservative practical spreading loss model in ESA consultations (Stadler 2007; Teachout 2007).

The underwater noise produced by an HPA-permitted project, either during construction or operation, is defined by the magnitude and duration of underwater noise above ambient noise levels. The action area for underwater noise effects in ESA consultations is defined by the distance required to attenuate construction noise levels to ambient levels, as calculated using the practical spreading loss calculation or other appropriate formula provided in evolving guidance from USFWS and NOAA Fisheries on this subject.

Fish passage projects are most likely to produce underwater noise caused by equipment operation and materials placement during construction. Completed fish passage projects may also alter ambient noise levels by changing local hydraulic conditions; however, these effects are expected to be within the natural range of ambient noise levels found in the affected environment.

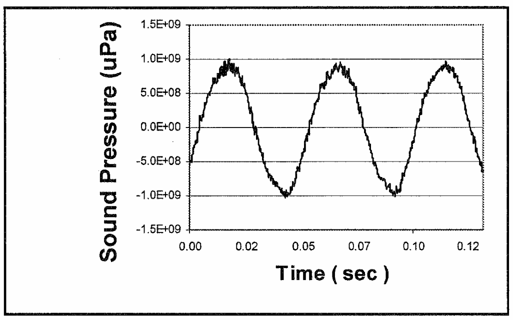
<u>Materials Placement</u>

Underwater noise caused by materials placement is a subject that has received relatively little direct study. Of the potential sources of construction-related noise, pile driving has received the most scrutiny because it produces the highest intensity stressors capable of causing noise-related injury. Other sources of underwater noise, such as the dumping of large rock or underwater tool use, have received less study. Therefore, available data on noise levels associated with pile driving are presented here as a basis for comparison.

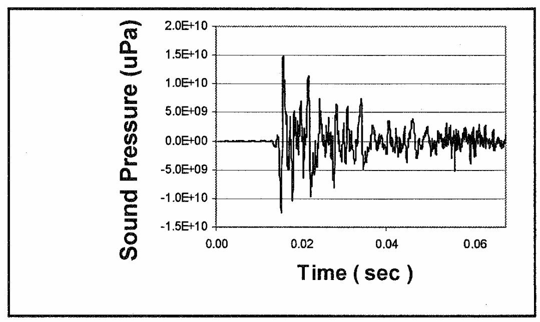
Two major types of pile driving hammers are in common use, vibratory hammers and impact hammers. There are four kinds of impact hammers: diesel, air or steam driven, hydraulic, and drop hammer (typically used for smaller timber piles). Vibratory hammers produce a more rounded sound pressure wave with a slower rise time. In contrast, impact hammers produce sharp sound pressure waves with rapid rise times, the equivalent of a punch versus a push in comparison to vibratory hammers. The sharp sound pressure waves associated with impact hammers represent a rapid change in water pressure level with greater potential to cause injury or mortality in fish and invertebrates. Because the more rounded sound pressure wave produced by vibratory hammers produces a slower increase in pressure, the potential for injury and mortality is reduced. (Note that while vibratory hammers are often used to drive piles to depth, load-bearing piles must be “proofed” with some form of impact hammer to establish structural integrity.) The changes in pressure waveform generated by these different types of hammers are pictured in Figure 7-1.

Piling composition also influences the nature and magnitude of underwater noise produced during pile driving. Driven piles are typically composed of one of three basic material types: timber, concrete, or steel (although other specialized materials such as plastic may be used). Steel piles are often used as casings for pouring concrete piles. Noise levels associated with each of these types of piles are summarized in Table 7-1. Reference noise levels are denoted in both dB_{peak} and dB_{RMS} values, at the specified measurement reference distance.

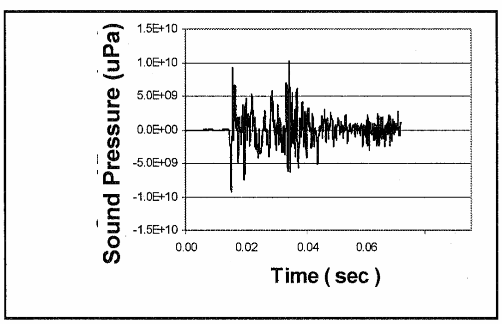
In comparison to pile driving, data on noise levels produced by placement of other construction-related materials is limited. For example, measured noise levels associated with work on the Friday Harbor ferry terminal ranged between 133 and 140 dB_{peak}, excluding pile driving. These noise levels were slightly higher than ambient levels, which include routine vessel traffic (WSDOT 2005). Nedwell et al. (1993) measured noise produced by underwater construction tools such as drills, grinders, and impact wrenches at 3.28 ft (1 m) from the source. When corrected for a reference distance 32.8 ft (10 m) from the source using the practical spreading loss model, the noise associated with these sources ranged from approximately 120 to 165 dB_{peak}. These data suggest that noise associated with these activities, such as tool use, placement of large rock and similar material, and in-water operation of heavy machinery, will generally produce substantially lower noise levels than those associated with pile driving. However, other construction-related noises, such as the continuous operation of flow bypass pumps, may generate continuous noise for longer periods. This would have the effect of elevating ambient noise levels or masking ambient noises in the aquatic environment that fish would ordinarily use to identify prey and predators.



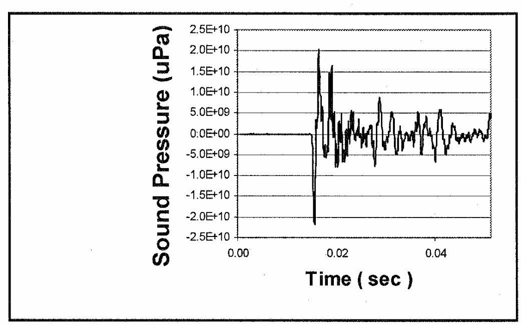
Vibratory Hammer wave form—set duration



Air or steam-driven hammer wave form—single strike



Diesel hammer wave form—single strike



Hydraulic hammer wave form—single strike

Figure 7-1. Sound pressure changes (or waveform) generated by different pile driving hammer types (WSDOT 2006).

Table 7-1. Reference noise levels, by pile structural material type.

Material Type and Size	Impact Hammer Type	Reference Noise Levels[a]		Environment Type	Source
		dB_{peak}	dB_{RMS}		
12-inch timber	Drop	177 @ 10 m	165 @ 10 m	Marine	Illingworth and Rodkin 2001
24-inch concrete piles	Unspecified	188 @ 10 m	173 @ 10 m	Unspecified	DesJardin 2003, personal communication cited by WSDOT (2006); Hastings and Popper 2005
Steel H-piles	Diesel	190 @ 10 m	175 @ 10 m	Marine	Hastings and Popper 2005; Illingworth and Rodkin 2001
12-inch steel piles	Diesel	190 @ 10 m	190 @ 10 m	Marine	Illingworth and Rodkin 2001
14-inch steel piles	Hydraulic	195 @ 30 m	180 @ 30 m	Marine	Reyff et al. 2003
16-inch steel piles	Diesel	198 @ 10 m	187 @ 9 m	Freshwater	Laughlin 2004
24-inch steel piles	Diesel	217 @ 10 m	203 @ 10 m	Unspecified	WSDOT 2006
24-inch steel piles	Diesel	217 @ 10 m	203 @ 10 m	Unspecified	Hastings and Popper 2005
30-inch steel piles	Diesel	208 @ 10 m	192 @10 m	Marine	Hastings and Popper 2005
66-inch steel piles	Hydraulic	210 @ 10 m	195 @ 10 m	Marine	Reyff et al. 2003
96-inch steel piles	Hydraulic	220 @ 10 m	205 @ 10 m	Marine	Reyff et al. 2003
126-inch steel piles	Hydraulic	191 @ 11 m	180–206 @ 11 m	Marine	Reyff et al. 2003
150-inch steel piles	Hydraulic	200 @ 100 m	185 @ 100 m	Marine	Reyff et al. 2003

[a] Metric distances are listed as they were provided in the literature source; 9 m = 29.5 ft; 10 m = 32.8 ft; 11 m = 36 ft; 30 m = 98 ft; 100 m = 328 ft.

Ambient underwater noise levels serve as the baseline for measuring the disturbance created by project construction or maintenance. Both natural environmental noise sources and mechanical or human-generated noise contribute to the ambient or baseline noise conditions within and surrounding a project site. Therefore, these noise measurements, particularly those recorded in the vicinity of ferry terminals and other high-activity locations, are indicative of the level of noise levels that could be produced by project construction and operation.

Ambient noise levels have been measured in several different marine environments on the West Coast and are variable depending on a number of factors, such as site bathymetry and human activity. For example, measured ambient levels in Puget Sound are typically around 130 dB_{peak} (Laughlin 2005). However, ambient levels at the Mukilteo ferry terminal reached approximately 145 dB_{peak} in the absence of ferry traffic (WSDOT 2006). Ambient underwater noise levels measured in the vicinity of the Friday Harbor ferry terminal project ranged between 131 and 136 dB_{peak} (WSDOT 2005). Carlson et al. (2005) measured the underwater baseline for Hood

Canal and found it to range from 115 to 135 dB_{RMS}. Heathershaw et al. (2001) reported open-ocean ambient noise levels to be between 74 and 100 dB_{peak} off the coast of central California. Note, however, that these ambient noise levels are typical conditions, and typical conditions can be punctuated by atypical natural events. For example, lightning strikes can produce underwater noise levels as high as 260 dB_{peak} in the immediate vicinity (Urick 1983).

Limited data are available on ambient noise levels in freshwater environments, but it is reasonable to conclude that they vary considerably based on the available information. For example, high-gradient rivers, fast-flowing rivers, and large rivers and lakes with significant human activity are likely to produce more noise than lakes and slow-flowing rivers in more natural environments. Burgess and Blackwell (2003) measured ambient sounds in the Duwamish River in Seattle, Washington (averaged over 20 seconds to 5 minutes) and found the sound to vary between 110 and 130 dB continuous sound pressure sound exposure level (SEL) (SEL provides a measure of total sound pressure exposure and is expressed as dB re: $1\mu Pa^2$/second). Amoser and Ladich (2005) measured ambient noise levels in the mainstem Danube River, a smaller, fast-flowing tributary stream, a small lake, and a quiet river backwater. The river and stream represented fast-flowing habitats, the lake and backwater quiet, slow-flowing habitats. Sound behavior was complex. They found that ambient noise levels ranged from as low as 60 to as high as 120 dB_{peak} in the fast-flowing habitats, depending on the sound frequency (lower frequency sound was typically louder). Ambient noise in the slackwater habitats was considerably lower, ranging from 40 to 80 dB_{peak} across the frequency range (again with lower frequency sounds being loudest).

<u>Effects on Fish and Invertebrates</u>

Most fish sense sounds, vibrations, and other displacements of water in their environment through their inner ear and with the lateral line running the length of each side of the fish and on the head. The lateral line is a mechano-sensory system that plays an indirect role in hearing through its sensitivity to pressure changes at close range. The hearing organs and lateral line system are collectively referred to as the acoustico-lateralis system. The hearing thresholds of different fish species vary depending on the structure and sensitivity of this system. Those families of fish known as hearing specialists include cyprinids (dace [e.g., Umatilla and leopard dace], minnows, and carp), catastomids (suckers [e.g., mountain sucker]), and ictalurids (catfish), which collectively belong to the Ostariophysan taxonomic grouping of fishes. These fish possess a physical connection between the swim bladder and the inner ear, with the swimbladder acting as an amplifier that transforms the pressure component of sound into particle velocity component, to which the inner ear is sensitive (Moyle and Cech Jr. 1988). In contrast, the hearing capacity of salmonids is limited both in bandwidth and intensity threshold by the less sophisticated nature of their hearing organs. The Atlantic salmon, for example, is functionally deaf at sound pressure wavelengths above 380 hertz (Hz) (Hawkins and Johnstone 1978). In these fish, the swimbladder does not likely enhance hearing.

Noise sources such as pile driving that produce high intensity sound pressure waves can result in direct effects on fish ranging from effects as limited as temporary stress and behavioral avoidance, to temporary or permanent injury in multiple organ systems (including hearing, heart, kidney, swim bladder, and other vascular tissue), to direct mortality (Popper and Fay 1973, 1993). Another potential effect includes masking of existing ambient noise, reducing the ability of fish to sense predators or prey. These activities may also have indirect effects such as reducing the foraging success of these fish by affecting the distribution or viability of potential prey species. Numerous studies have examined the effects on fish associated with underwater noise and are discussed more fully below.

In general, injury and mortality effects from underwater noise are caused by rapid pressure changes, especially on gas-filled spaces in the body. Rapid volume changes of the swim bladder may cause it to tear, resulting in a loss of hearing sensitivity and hydrostatic control. Intense noise may also damage the tissue in hearing organs, as well as the heart, kidneys, and other highly vascular tissue. Susceptibility to injury is variable and depends on species-specific physiology, auditory injury, and auditory thresholds (Popper and Fay 1973, 1993). While species-specific data are limited, the available information indicates variable effects related to physiology, size, and age, as well as the intensity, wavelength, and duration of sound exposure.

Hardyniec and Skeen (2005) and Hastings and Popper (2005) summarized available information on the effects of pile driving-related noise on fish. Pile driving effects observed in the studies reviewed ranged broadly from brief startle responses followed by habituation to instantaneous lethal injury. The difference in effect is dependent on a number of factors, including piling material, the type and size of equipment used, and mitigation measures; site-specific depth, substrate, and water conditions; and the species, size, and life-history stage of fish exposed.

Popper et al. (2005) exposed three species of fish to high-intensity percussive sounds from a seismic air gun at sound levels ranging between 205 and 209 dB_{peak}, intending to mimic exposure to pile driving. Subject species included a hearing generalist (broad whitefish), a hearing specialist (lake chub), and a species that is intermediate in hearing (northern pike). They found that the broad whitefish suffered no significant effects from noise exposure, the lake chub demonstrated a pronounced temporary threshold shift in hearing sensitivity (i.e., hearing loss), and the northern pike showed a significant temporary hearing loss but less than that of the lake chub. The hearing sensitivity of lake chub and northern pike returned to their respective normal thresholds after 18 to 24 hours. High-intensity sounds can also permanently damage fish hearing (Cox et al. 1987; Enger 1981; Popper and Clarke 1976).

Enger (1981) found that pulsed sound at 180 dB was sufficient to damage the hearing organs of codfish (genus *Gadus*), resulting in permanent hearing loss. Hastings (1995) found that goldfish exposed to continuous tones of 189, 192, and 204 dB_{peak} at 250 Hz for 1 hour suffered permanent damage to auditory sensory cells. Injury effects may also vary depending on noise frequency and duration. Hastings et al. (1996) found destruction of sensory cells in the inner ears of oscars 4 days after exposure to continuous sound for 1 hour at 180 dB_{peak} at 300 Hz. In contrast, when the two groups of the same species were exposed to continuous and impulsive sound at 180 dB_{peak} at 60 Hz for 1 hour, and to impulsive sound at 180 dB_{peak} at 300 Hz repeatedly over 1 hour, they showed no apparent injury. Susceptibility to injury may also be life-history specific. Banner and Hyatt (1973) demonstrated increased mortality of sheepshead minnow eggs and embryos when exposed to broadband noise approximately 15 dB above the ambient sound level. However, hatched sheepshead minnow fry were unaffected by the same exposure.

Even in the absence of injury, noise can produce sublethal effects. Behavioral responses to sound stimuli are well established in the literature for many fish species. For example, Moore and Newman (1956) reported that the classic fright response of salmonids to instantaneous sound stimuli was the "startle" or "start" behavior, where a fish rapidly darts away from the noise source. Knudsen et al. (1992) found that in response to low-frequency (10 Hz range) sound, salmonids 1.6–2.4 in (40–60 mm) in length exhibited an initial startle response followed by habituation, while higher frequency sound caused no response even at high intensity. In a study of the effects of observed pile driving activities on the behavior and distribution of juvenile pink and chum salmon, Feist et al. (1992) found that pile-driving operations were associated with changes in the distribution and behavior of fish schools in the vicinity. Fish schools were two-fold more abundant during normal construction days in comparison to periods when pile driving took place. Blaxter et al. (1981) found Atlantic herring to exhibit an avoidance response to both continuous pulsed sound stimuli with habituation to more continuous stimuli occurring over time, and Schwarz and Greer (1984) found similar responses on the part of Pacific herring. Sound has also been shown to affect growth rates, fat stores, and reproduction (Banner and Hyatt 1973; Meier and Horseman 1977).

Prolonged underwater noise can also reduce the sensitivity of fish to underwater noise stimuli, with potentially important effects on survival, growth, and fitness. The fish auditory system is likely one of the most important mechanisms fish use to detect and respond to prey, predators, and social interaction (Amoser and Ladich 2005; Fay 1988; Hawkins 1986; Kalmijn 1988; Myrberg 1972; Myrberg and Riggio 1985; Nelson 1965; Nelson et al. 1969; Richard 1968; Scholik and Yan 2001; Scholik and Yan 2002; Wisby et al. 1964). Scholik and Yan (2001) studied the auditory responses of the cyprinid fathead minnow to underwater noise levels typical of human-related activities (e.g., a 50-horsepower outboard motor). They found that prolonged exposure decreased noise sensitivity, increasing the threshold level required to elicit a disturbance response for as long as 14 days after the exposure. Amoser and Ladich (2005) reported similar findings in common carp in the Danube River, noting that auditory ability in this hearing specialist species was measurably masked in environments with higher background noise. They reported similar but far less pronounced responses in hearing generalist species such as perch. These data suggest that elevated ambient noise levels have the potential to impair hearing ability in a variety of fish species, which may in turn adversely affect the ability to detect prey and avoid predators, but that this effect is variable depending on the specific sensitivity of the species in question. Feist et al. (1992) similarly theorized that it was possible that auditory masking and habituation to loud continuous noise from machinery may decrease the ability of salmonids to detect approaching predators.

With regards to invertebrates, information on the effects of elevated underwater noise is generally lacking, indicating that additional research on the subject is needed. What little data are available suggest some sensitivity to intense percussive underwater noise. In a study completed by Turnpenny et al. (1994), mussels, periwinkles, amphipods, squid, scallops, and sea urchins were exposed to high air gun and slow-rise-time sounds at between 217 and 260 dB, analogous to extremely loud pile driving. One scallop suffered a split shell following exposure to impulsive sound at 217 dB_{peak}, suggesting the potential for injury or mortality when underwater noise exceeds these levels.

No research has been identified regarding the effects of lower intensity continuous underwater noise on invertebrates. However, continuous construction and operational noise is typically associated with sound pressures well below levels that have been observed to cause injury in shellfish, suggesting that HCP invertebrate species would not be subject to these effects. Because HCP invertebrates with the potential for stressor exposure are either filter feeders or grazers and are essentially nonmotile, these species are unlikely to be subject to auditory masking effects that would limit the ability to sense predators and prey. Some potential may exist for disturbance-induced interruption of feeding behavior, but more research on this subject is necessary to determine this definitively, and this subject is considered a data gap.

7.6.1.1.2 Dewatering and Handling

In many cases, construction of HPA-permitted projects may require the exclusion of streamflows or even the dewatering of the work area to protect aquatic life and/or provide a suitable environment for construction. These activities have the potential to cause direct and indirect effects on HCP species. Fish exclusion and dewatering involve the placement of barriers (e.g., block nets, temporary berms, cofferdams) around a work area and the capture and removal of fish and other aquatic life within the work area. Electrofishing is a common practice used for fish capture in freshwater environments, as is the use of minnow traps, hand nets, beach seines, and other net-based capture methods. Because electrofishing is ineffective in brackish or salt water, net-based capture methods are used in these environment types.

The direct effects of fish exclusion and dewatering include:

- Direct mortality, injury, and stress from electrical field exposure (i.e., electrofishing)
- Capture by netting, leading to direct mortality, injury, and stress
- Physical and thermal stress and possible trauma associated with handling and transfer during capture and transfer between temporary holding containers and release locations
- Stranding and asphyxiation
- Entrainment or impingement in block nets, dewatering pumps, and bypass equipment
- Increased stress, predation exposure, and habitat competition once relocated

- Increased competition for aquatic species forced to compete with relocated animals.

Exclusion areas may also create temporary barriers to fish passage, with attendant effects on migratory species similar to those described for temporary weirs in Section 7.4.1.6 (*Ecosystem Fragmentation*).

<u>Effects on Fish</u>

Of the various methods used for dewatering and handling, the majority of research has been conducted on incidental mortality and injury rates associated with electrofishing. Much of this research has focused on adult salmonids greater than 12 inches in length (Dalbey et al. 1996). The relatively few studies that have been conducted on juvenile salmonids suggest spinal injury rates lower than those observed for large fish, perhaps because juvenile fish generate less total electrical potential along a shorter body length (Dalbey et al. 1996; Sharber and Carothers 1988; Thompson et al. 1997). Electrofishing-related injury rates are variable, reflecting a range of factors from fish size and sensitivity, individual site conditions, to crew experience and the type of equipment used, with the equipment type being a particularly important factor (Dalbey et al. 1996; Dwyer and White 1997; Sharber and Carothers 1988). Electrofishing equipment typically uses continuous direct current (DC) or low-frequency pulsed DC equipment. The use of low-frequency DC (equal to or less than 30 Hz) is the recommended electrofishing method because it is associated with lower spinal injury rates (Ainslie et al. 1998; Dalbey et al. 1996; Fredenberg 1992). Even with careful selection of equipment, observed injury rates can vary. For example, one study in the Yakima River basin (McMichael et al. 1998) observed a 5.1 percent injury rate for juvenile steelhead captured using 30 Hz pulsed DC equipment. Ainslie et al. (1998) reported injury rates of 15–39 percent in juvenile rainbow trout using continuous and pulsed DC equipment, and found that while pulsed DC equipment produced injury more frequently, these injuries were less severe in nature.

It is notable that electrofishing capture typically has a low direct mortality rate, but it is reasonable to conclude that injuries induced by electrofishing could have long-term effects on survival, growth, and fitness. The few studies that have examined this question found that few juvenile salmonids die as a result of electrofishing-induced spinal injury (Ainslie et al. 1998; Dalbey et al. 1996). However, fish with more injuries demonstrated a clear decrease in growth rates, and in some cases growth was entirely arrested (Dalbey et al. 1996). In the absence of additional supporting information, it is reasonable to conclude that these same effects would affect many of the HCP fish species, but this conservative assumption may not be universally accurate. Studies of the effects of electrofishing on other fish species are more limited, but available data indicate that at least some HCP species may be less sensitive to injury-related effects. Holliman et al. (2003) exposed a threatened cyprinid (minnow) species to electrofishing techniques in the laboratory and found that the typical current and voltage parameters used to minimize adverse effects on salmonid species produced no evidence of injury. This suggests that other cyprinids such as leopard and spotted dace, lake chub, and suckers may also be less sensitive.

Beyond the effects of electrofishing, the act of capture and handling demonstrably increases physiological stress in fishes (Frisch and Anderson 2000). Primary contributing factors to handling-induced stress and death include exposure to large changes in water temperatures and dissolved oxygen conditions (caused by large differences between the capture, holding, and release environments); duration of time held out of the water; and physical trauma (e.g., due to net abrasion, squeezing, accidental dropping). Even in the absence of injury, stress induced by capture and handling can have a lingering effect on survival and productivity. One study found that stress from handling impaired the salmonids' ability to evade predators for up to 24 hours following release and caused other forms of mortality (Olla et al. 1995).

Use of a bypass system is a common means of creating exclusion areas via dewatering and flow reduction. Partial dewatering is a technique used to reduce the volume of water in the work area to make capture methods more efficient. In riverine habitats, this method is used to move fish out of affected habitats to reduce the number of individuals exposed to capture and handling stress and potential injury and mortality. Based on interviews with state fisheries agency staff, NOAA Fisheries has estimated that 50–75 percent of fish in an affected reach will volitionally move out of an affected reach when flows are reduced by 80 percent (NMFS 2006). However, volitional movement will lead to concentration of fish in unaffected habitats, increasing competition for available space and resources.

Failure to capture and remove fish or invertebrates from work areas must also be considered. Organisms left in the exclusion area would potentially be directly exposed to stranding and asphyxiation during dewatering or, if left inundated, to mechanical injury and/or high-intensity noise, turbidity, and other pollutants. Many species of fish, such as salmonids and larval lamprey, are highly cryptic and can avoid being detected even when using multiple pass electrofishing because they hide in large interstices or are buried in sediments (Peterson et al. 2005; Peterson et al. 2004; Wydoski and Whitney 2003).

NOAA Fisheries has estimated incidental take resulting from dewatering and handling associated with stream crossing projects. One factor used in calculating incidental take from these activities was an estimated stranding rate of 8 percent for ESA-listed salmonids (which equates to 8 percent mortality) (NMFS 2006), which was based on expected 45 percent capture efficiency using three-pass electrofishing (Peterson et al. 2004). The assumed electrofishing injury rate for this type of activity was 25 percent (NMFS 2006).

As noted, research on fish injury and mortality associated with dewatering has focused predominantly on salmonids, relatively large fish species that respond well to this exclusion technique. Other species may have nonmotile or cryptic life-history stages (e.g., lamprey ammocoetes buried in fine sediments) or life-history stages that cannot easily move to adjust to changes in flow or are not easily captured and relocated (e.g., adhesive eggs of eulachon, juvenile rockfish, and lingcod). In freshwater environments, examples of species and life-history stages that are sensitive to dewatering impacts include incubating salmonid eggs and alevins; lamprey ammocoetes; and the adhesive eggs of eulachon, sturgeon, and other species. These life-history stages are relatively immobile and also difficult to capture and relocate efficiently.

Therefore, they face a higher likelihood of exposure to stranding or entrainment in dewatering pumps, which would be expected to lead to mortality.

Installation, operation, and removal of a stream bypass system to rewater a channel can increase turbidity. The in-water installation and removal work poses the highest risk of disturbing the stream bank and substrate, thereby resuspending sediments and increasing turbidity. Fish may experience short-term, adverse effects as a result of increased turbidity. The effects of increased turbidity during rewatering are discussed in Section 7.6.1.2.2 (*Elevated Suspended Sediments*).

<u>Effects on Invertebrates</u>

HCP invertebrate species demonstrate different sensitivity to the effects of dewatering and relocation than fish, with many species being relatively insensitive to the effects of handling, at least during adult life-history stages. For example, Krueger et al. (2007) studied the effects of suction dredge entrainment on adult western ridged and western pearlshell mussels in the Similkameen River (Washington) and found no evidence of mortality or significant injury. Suction dredge entrainment is expected to be a more traumatic stressor than removal and relocation by hand. These findings suggest that careful handling would be unlikely to cause injury. However, the authors cautioned that these findings were limited to adult mussels, and the potential for injury and mortality in juveniles remains unknown.

The sensitivity of other HCP invertebrate species, such as giant Columbia River limpet and great Columbia River spire snail, is somewhat less certain. Adults may be easily removed and relocated during dewatering, but juveniles and eggs may be difficult to locate and remove effectively. This suggests the potential for mortality from stranding. Failure to locate and remove small or cryptic invertebrate species or life-history stages may result in stranding or concentrated exposure to other stressors within the exclusion area. Stranding caused by operational water level fluctuations was associated with mass mortality of California floater and western ridged mussels in Snake River reservoir impoundments (Nedeau et al. 2005).

While handling-related injury and mortality are relatively unlikely, relocation may lead to notable nonlethal effects. For example, scattering of closely packed groups of adult mussels may affect reproductive success if mussels are scattered outside a certain proximity. Because female freshwater mussels filter male gametes from the water column, successful fertilization is density dependent (Downing et al. 1993).

7.6.1.1.3 Dredging and Fill

Construction of fish passage structures may require excavation dredging and placement of fill within the ordinary high water mark (OHWM). This impact submechanism can impose direct stressors on aquatic organisms in the form of dredge entrainment and burial, and indirect stressors through alteration of hydraulic and geomorphic conditions. The effects of burial and entrainment related stressors are discussed in Section 7.6.2.2 (*Burial and Entrainment*). The effects of this submechanism on channel morphology conditions are addressed in Section 7.6.1.5 (*Hydraulic and Geomorphic Modifications*).

7.6.1.2 Water Quality Modifications

HCP-permitted projects falling under the fish passage activity type are likely to result in varying degrees of water quality modifications. The impact submechanisms and related stressors imposed will range from temporary to short-term perturbations associated with construction and maintenance activities, such as accidental spills of contaminants or construction-related turbidity, to longer term alterations in nutrient loading and cycling due to riparian and hydraulic and geomorphic modifications.

The discussion of the effects of each water quality related stressor presented in the following section represents a worst-case scenario perspective. When interpreting the effects of stressor exposure, the magnitude of impact submechanisms and stressors anticipated to result from each subactivity type must be considered. This discussion is provided in the *Water Quality Modifications* subsection for each type of fish passage project or subactivity (see Sections 7.1.1.2, 7.2.1.2, 7.3.1.2, and 7.4.1.2).

7.6.1.2.1 Altered Water Temperature

Modification of water temperature regime is a stressor that can occur as a result of several different impact mechanisms. Two primary mechanisms through which water temperature modification can occur are modifications of riparian vegetation, altering stream shading, ambient temperature regime, and groundwater/surface water interactions; and hydraulic and geomorphic modifications that can alter channel morphology, and flow regime. Both of these mechanisms can alter water temperature conditions.

Temperature is a primary metric of aquatic ecosystem health, as aquatic organisms have adapted to live within specific thermal regimes. Alterations to these thermal regimes occur at the detriment of local organisms. Thermal stress can occur through multiple direct and indirect pathways in fish and invertebrates. These include direct mortality, altered migration and distribution, increased susceptibility to disease and toxicity, and altered development, spawning, and swimming speeds (Sullivan et al. 2000). Motile organisms have the ability to avoid or evacuate those areas of extreme temperature, but even then the stress induced from periodic exposure and resulting habitat avoidance can affect organism health and contribute to mortality (Groberg et al. 1978). All of the HCP species are ectothermic (cold-blooded); consequently, temperature is a resource that organisms use for energetic means. With organism metabolism dependent on water temperature, thermal regime may be the single-most important habitat feature controlling aquatic organisms.

<u>Effects on Fish and Invertebrates</u>

A substantial amount of information is available regarding tolerances of HCP species (particularly salmonids) to thermal stress. These effects have been documented in many studies, which have been well summarized in meta-analyses. In the case of salmonids, summary analyses have been used as the basis for developing thermal tolerance ranges and threshold criteria for regulatory purposes. Poole et al. (2001) provides a useful example.

The majority of research on temperature impacts on aquatic species has focused on salmonids. Different species of salmonids have evolved to use different thermal regimes. Despite these differences, the majority of salmonids prefer the same temperature ranges during most life-history stages. The primary exception to this is that char (bull trout and Dolly Varden) require lower temperatures for optimal incubation, growth, and spawning (Richter and Kolmes 2005). Temperatures outside the optimal growth range can lead to decreased growth and competitive ability with sympatric species having broader temperature tolerances, as well as behavioral effects that are limiting to population productivity. For example, Selong et al. (2001) found that bull trout tend to exhibit avoidance behavior toward otherwise suitable habitats when water temperatures exceeded optimal growth ranges, and postulated that other species of salmonids would demonstrate similar behavior. McMahon et al. (2007) found that temperature-mediated competition in lower elevation reaches was one of several factors that gave introduced brook trout a competitive advantage over native bull trout, which tended to retreat to higher elevation refugia.

Water temperature demonstrably affects growth and development. For instance, it has been found that coho egg, alevin, and fry development is most rapid at 39°F (4°C), while alevin and fry of pink and chum salmon develop fastest at 46°F (8°C) (Beacham and Murray 1990). Elevated water temperatures can also impair adult migration and spawning. Adult migration blockages occur consistently when temperatures exceed 70–72°F (21–22°C) (Poole et al. 2001). Thermal barriers to migration can isolate extensive areas of potentially suitable spawning habitat and contribute to prespawning mortality. If salmon are exposed to temperatures above 57°F (14°C) during spawning, gametes can be severely affected, resulting in reduced fertilization rates and embryo survival (Flett et al. 1996). Ideal temperatures for salmonid spawning are in the range of 44–57°F (7–14°C) (Brannon et al. 2004; McCullough et al. 2001).

A matrix of optimal temperature ranges for anadromous salmon and bull trout is presented in Table 7-2. As shown, each group of species has a different range of optimal temperatures at each life-history stage. These same temperature ranges have been adopted by the Washington State Department of Ecology (Ecology) and incorporated into the state water quality standards (WAC 173-201A 2006). Table 7-3 presents highest 7-day average maximum thresholds as promulgated in the state standards.

Table 7-2 indicates that there are water quality thresholds for different life-history stages that are considerably lower than the lethal limit. Fish are susceptible to a number of sublethal effects related to temperature. For instance, elevated but sublethal temperatures during smolting may result in desmoltification, altered emigration timing, and emigration barriers. Temperatures that impair smolting are above a range of between 52 and 59°F (11 and 15°C) (Poole et al. 2001, Wedemeyer et al. 1980). Temperatures in this range have been shown to reduce the activity of gill ATPase (McCullough et al. 2001), an enzyme that prepares juvenile fish for osmoregulation in saline waters (Beeman et al. 1994). Temperature-induced decreased gill ATPase has been correlated with loss of migratory behavior in numerous salmonid species (Babanin 2006; Marine and Cech 2004; McCormick et al. 1999) and constitutes a significant impairment to juvenile survival.

Table 7-2. Estimates of thermal conditions known to support various life-history stages and biological functions of bull trout (a species extremely intolerant of warm water) and anadromous (ocean-reared) salmon.

Consideration	Anadromous Salmon	Bull Trout
Temperature of common summer habitat use	10–17°C (50–63°F)	6–12°C (43–54°F)
Lethal temperatures (1-week exposure)	Adults: >21–22°C (70–72°F)	—
	Juveniles: >23–24°C (73–75°F)	Juveniles: 22–23°C (72–73°F)
Adult migration	Blocked: >21–22°C (70–72°F)	Cued:10–13°C 50–55°F)
Swimming speed	Reduced: >20°C (68°F)	—
	Optimal: 15–19°C (59–66°F)	—
Gamete viability during holding	Reduced: >13–16°C (55–61°F)	—
Disease rates	Severe: >18–20°C (64–68°F)	—
	Elevated: 14–17°C (57–63°F)	—
	Minimized: <12–13°C (54–55°F)	—
Spawning	Initiated: 7–14°C (45–57°F)	Initiated:<9°C (48°F)
Egg incubation	Optimal: 6–10°C (43–50°F)	Optimal: 2-6°C (36–43°F)
Optimal growth	Unlimited food: 13–19°C (55–66°F)	Unlimited food: 12–16°C (54–61°F)
	Limited food: 10–16°C (50–61°F)	Limited food: 8–12°C (46–54°F)
Smoltification	Suppressed: >11–15°C (52–59°F)	—

Source: Poole et al. 2001.
Note: These numbers do not represent rigid thresholds, but rather temperatures above which adverse effects are more likely to occur. In the interest of simplicity, important differences between various species of anadromous salmon are not reflected in this table, and requirements for other salmonids are not listed. Likewise, important differences in how temperatures are expressed are not included (e.g., instantaneous maximums, daily averages).

Table 7-3. Aquatic life temperature criteria in fresh water.

Category	Highest 7-DADMax
Char spawning	9°C (48.2°F)
Char spawning and rearing	12°C (53.6°F)
Salmon and trout spawning habitat	13°C (55.4°F)
Core summer salmonid habitat	16°C (60.8°F)
Salmonid spawning, rearing, and migration	17.5°C (63.5°F)
Salmonid rearing and migration **Only**	17.5°C (63.5°F)
Nonanadromous interior redband trout	18°C (64.4°F)
Indigenous warm water species	20°C (68°F)

Source: WAC 173-201A 2006 Table 200(1)(c).
Note: Aquatic life temperature criteria. Except where noted, water temperature is measured by the 7-day average of the daily maximum temperatures (7-DADMax). Table 200(1)(c) lists the temperature criteria for each of the aquatic life use categories.

Elevated water temperatures can impair adult migration. Adult migration blockages occur consistently when temperatures exceed 69.8–71.6°F (21–22°C) (Poole and Berman 2001a). Thermal barriers to migration can isolate extensive areas of potentially suitable spawning habitat and contribute to prespawning mortality. Elevated temperature regimes also affect salmonid species by altering behavior and reducing resistance to disease and toxic substances. Studies have indicated that under chronic thermal exposure conditions, the susceptibility of aquatic organisms to toxic substances may increase. Because elevated temperatures increase metabolic processes, gill ventilation also rises proportionately (Heath and Hughes 1973). Black et al. (1991) showed that an increase in water flow over the gills that results from increased gill ventilation at increased temperature leads to the rapid uptake of toxicants, including metals and organic chemicals, via the gills. Salmonids also become more susceptible to infectious diseases at elevated temperatures (57–68°F [14–20°C]) because immune systems are compromised (Harrahy et al. 2001), while bacterial and viral activity is accelerated (Tops et al. 2006). In nearshore areas where temperature (as well as pollutant levels) may be elevated, the combined effect of thermal and water pollution may be a primary driver of salmonid decline.

Additional studies, mainly in the laboratory, have developed limits for other HCP species. Wagner et al. (1997), showed that rainbow trout mortality occurred at temperatures of 67.8 to 73.0°F (19.9 to 22.8°C). Temperatures above 71.6°F (22°C) can cause deformities in developing white sturgeon, with best performance between 59 and 66°F (15 and 19°C) (Mayfield and Cech 2004). Furthermore, elevated temperatures can make white sturgeon more susceptible to infection from viruses (Watson et al. 1998). Temperatures between 73 and 79°F (23 and 26°C) can cause complete mortality in developing green sturgeon embryos, with upper limits for survival around 62.6–64.4°F (17–18°C) (Van Eenennaam et al. 2005). Dolly Varden show decreased appetite above 60.8°F (16°C) and lethal temperatures are observed above 68°F (20°C) (Takami et al. 1997). A lab study of the early lifestages of Pacific lamprey and western brook lamprey showed that growth and development in these species effectively ceased at experimental temperatures of 40.7°F (4.85°C) and 40.9°F (4.97°C), respectively, with survival greatest for both at 64°F (18°C) and lowest at 71.6°F (22°C). Ammocoete exposure to a treatment temperature of 71.6°F (22°C) resulted in a high rate of developmental abnormalities (Meeuwig et al. 2005).

Considerably less research exists defining thermal criteria for freshwater mollusk species, which are the most likely HCP invertebrate species to be affected by temperature-related stressors imposed by fish passage subactivity types. However, Vaughn and Taylor (1999) reviewed several studies of freshwater mussel populations in river systems affected by dams and found multiple instances of decreased population persistence and abundance in reaches downstream of dams. They postulated that because abundance increased as temperature conditions moderated in downstream reaches, sensitivity to altered temperature regime was a primary factor controlling distribution. These findings imply that alteration of water temperature regime, in combination with other stressors, may adversely affect HCP invertebrate species.

7.6.1.2.2 Elevated Suspended Sediments

Elevated suspended sediments can result from a number of different impact mechanisms associated with fish passage projects. However, construction and maintenance activities are typically the primary cause of this stressor. Modifications of riparian vegetation and hydraulic and geomorphic processes may also lead to elevated suspended sediments, but the magnitude of these impact mechanisms as caused by fish passage subactivity types is likely to be limited.

Elevated suspended sediments have a number of effects on HCP species. In general, the response of aquatic biota to elevated suspended solids concentrations is highly variable and dependent on life-history stage, species, background suspended solids concentrations, and ambient water quality. The following sections summarize pertinent research on the effects of stressor exposure on HCP fish and invertebrate species.

Several of the studies cited in this section present information on the effects of suspended sediments using turbidity units in the place of suspended sediment concentrations. Turbidity is commonly used as a surrogate for suspended sediment concentrations, but the relationship between these measures is site specific. Where available the equivalent suspended sediment concentration is provided, otherwise the turbidity value is provided. Because this complicates the interpretation of this information, a brief discussion of the relationship between turbidity and suspended sediment concentrations is provided here.

The International Standards Organization (ISO) defines turbidity as the "reduction of transparency of a liquid caused by the presence of undissolved matter" (Lawler 2005), as measured by turbidimetry or nephelometry. Turbidity can be caused by a range of suspended particles of varying origin and composition. These include inorganic materials like silt and clay, as well as organic materials such as tannins, algae, plankton, micro-organisms and other organic matter. The term suspended sediments refers to inorganic particulate materials in the water column. Suspended sediments can range in size from fine clay to boulders, but the term applies most commonly to suspended fines (i.e., sand size or finer material). Because suspended sediments are a component of turbidity, turbidity is commonly used as a surrogate measure for this parameter. However, the accuracy of the results is dependent on establishing a clear correlation between turbidity and suspended sediment concentrations to account for the influence of organic materials. This correlation is site specific, given the highly variable nature of organic and inorganic material likely to occur in a given setting.

<u>Effects on Fish and Invertebrates</u>

A broad range of research has demonstrated that suspended sediment and elevated turbidity can have a broad range of adverse effects on aquatic organisms, ranging from minor, short-term behavioral alterations, to effects on food web productivity and forage success that influence survival, growth, and fitness, to direct injury and mortality (Henley et al. 2000). As would be expected, these effects are complex and variable depending on the magnitude of the sediment impact in question relative to natural background conditions and the specific sensitivity of the organisms exposed to the stressor. For example, juveniles of many fish species such as salmonids thrive in rivers and estuaries with naturally high concentrations of suspended solids. However, studies have shown that the suspended solids concentration (as well as the duration of exposure) can be an important factor in assessing risks posed to salmonid populations (McLeay et al. 1987; Newcombe and MacDonald 1991; Servizi and Martens 1987). Given this complexity, some understanding of the level of exposure associated with a given HCP activity type is necessary to understand the range of likely effects. Suspended sediment levels associated with injury or mortality are typically quite high. Lake and Hinch (1999) found suspended solids concentrations in excess of 40,000 ppm to elicit stress responses in juvenile coho salmon. Suspended solids concentrations this high would likely only be associated with the most extreme construction-related impacts. However, other studies have shown lethal effects at much lower concentrations in salmonids, indicating that the issue is complex, and a precautionary approach to sediment impacts is desirable to limit the potential for adverse effects.

For example, Servizi and Martens (1991) exposed juvenile coho salmon to natural Fraser River suspended solids and found a 96-hour LC_{50} (the concentration at which a 50 percent population mortality was observed) of only 22,700 ppm. Using the identical apparatus and sediment source, juvenile sockeye salmon had a 96-hour LC_{50} of 17,600 ppm (Servizi and Martens 1987), and juvenile Chinook salmon had an LC_{50} of 31,000 ppm (Servizi and Gordon 1990).

For white sturgeon, laboratory studies have shown that the survival of developing embryos was reduced to 5 percent in the presence of 0.19–0.8 in (5–20 mm) thick layers of sediment compared to over 80 percent survival in controls (Kock et al. 2006).

Sublethal Effects

Studies on a variety of fishes, including sockeye and Chinook (Newcomb and Flagg 1983), coho, four-spine stickleback, cunner, and sheepshead minnow (Noggle 1978), attribute the observed chronic and acute impacts from high suspended solids to a reduced oxygen uptake (Wilber and Clarke 2001). Fish must keep their gills clear for oxygen exchange. In the presence of high loadings of suspended solids, they engage a cough reflex to perform that function. Due to increased metabolic oxygen demand with increased temperatures and the need to keep pathways free of sediments for oxygen uptake, increased temperature and reduced oxygen levels combine to reduce the ability of fish to cough and maintain ventilation rates. The stress induced by these conditions can lead to compromised immune defenses and reduced growth rates (Au et al. 2004). Sigler et al. (1984) noted reduced growth rates in juvenile steelhead and coho salmon at suspended solids concentrations as low as 100 ppm, while Servizi and Martens (1992) noted increased cough frequency in juvenile coho at concentrations of approximately 240 ppm.

Indirect effects on fish through alteration of their food source have been documented. Suttle et al. (2004) observed that steelhead trout were affected by increased sediments because it caused a shift to burrowing macroinvertebrate taxa that then became unavailable to them as a food source.

The nonlethal effects of elevated suspended sediment levels are not uniformly negative. Experiments have shown that white sturgeon larvae predation by prickly sculpin increased in the presence of low-turbidity water (Gadomski and Parsley 2005). This suggests that some species rely on turbidity as cover to some extent.

Behavioral Effects

Aksnes and Utne (1997), Mazur and Beauchamp (2003), and Vogel and Beauchamp (1999) all report that suspended solids at sublethal concentrations have been shown to affect fish functions such as avoidance responses, territoriality, feeding, and homing behavior. Similarly, Wildish and Power (1985) reported avoidance of suspended solids by rainbow smelt and Atlantic herring to be at 20 ppm and 10 ppm, respectively. While these species are unlikely to be directly affected by fish passage projects, the general sensitivity of different fish species to suspended sediments is illustrative of potential effects on species for which data are lacking. However, it is important to note that under certain circumstances, elevated suspended solids may actually benefit certain species, such as salmonids, by providing cover (Gregory and Levings 1998) or triggering a sense of refuge from predation (Gregory 1993). The studies of Gregory and Northcote (1993) indicated that when suspended solids concentrations exceeded 200 ppm, juvenile salmon increased their feeding rates while demonstrating pronounced behavioral changes in prey reaction and predator avoidance.

In studies of coho behavior in the presence of short-term pulses of suspended solids, Berg and Northcote (1985) found that salmonid behavior is disrupted by elevated turbidity levels, as evidenced by changes in territorial, gill flaring, and feeding behaviors. At turbidity levels of between 30 and 60 nephelometric turbidity units (NTUs), social organization broke down, gill flaring occurred more frequently, and only after a return to a turbidity of 1–20 NTUs was the social organization re-established. Similarly, feeding success was also found to be linked to turbidity levels, with higher turbidity levels reducing prey capture success.

Finally, in a study of dredging impacts on juvenile chum in Hood Canal, Salo et al. (1980) found that juvenile chum salmon showed avoidance reactions to high turbidity levels. These behavioral thresholds vary across species and life-history stages. Consistent with their early reliance on nearshore estuarine habitats with relatively high turbidities compared to pelagic or freshwater habitats, juvenile chum are classified as turbidity tolerant compared to other fishes (Salo et al. 1980).

Effects on Invertebrates

Invertebrates tend to thrive across a wide range of suspended solids concentrations. Negative impacts on eastern oyster egg development have been shown to occur at 188 ppm total suspended solids (Cake 1983). Hardshell clam eggs appear to be more resilient, with egg development affected only after total suspended solids concentrations exceeded 1,000 ppm (Mulholland 1984). Mulholland (1984) showed that suspended solids concentrations of <750 ppm allowed for continued larval development, but higher concentrations for durations of 10–12 days showed lethal effects for both clams and oysters.

For bivalves, when suspended solids concentrations rise above their filtering capacities, their food becomes diluted (Widdows et al. 1979). Studies have shown that the addition of silt, in relatively low concentrations in environments with high algal concentrations, can be marked by the increased growth of mussels (Kiorboe et al. 1981), surf clams (Mohlenberg and Kiorboe 1981), and eastern oysters (Urban and Langdon 1984). Bricelj and Malouf (1984), however, found that hardshell clams decreased their algal ingestion with increased sediment loads, and no growth rate differences were observed between clams exposed to algal diets alone and clams with added sediment loads (Bricelj et al. 1984). Urban and Kirchman (1992) reported similarly ambiguous results concerning suspended clay. Suspended clay (20 ppm) interfered with juvenile eastern oyster ingestion of algae but it did not reduce the overall amount of algae ingested. Grant et al. (1990) found that the summer growth of European oysters was enhanced at low levels of sediment resuspension and inhibited with increased deposition. It was hypothesized that the chlorophyll in suspended solids may act as a food supplement that could enhance growth, but higher levels may dilute planktonic food resources, thereby suppressing food ingestion. Changes in behavior in response to sediment loadings were also noted for soft-shelled clams in sediment loads of 100–200 ppm, with changes in their siphon and mantles over time (Grant and Thorpe 1991).

Collectively, these studies show no clear pattern of sublethal effects from elevated concentrations of suspended solids (and thereby turbidity) that could be generally applied across aquatic mollusks. This uncertainty is further complicated by the fact that many of the HCP invertebrate species are poorly studied. This indicates the need for directed studies on the sensitivity of these species before effects thresholds can be set. In the absence of this information, however, it is useful to consider that HCP invertebrates are all bottom-dwelling mollusks that have evolved to live in dynamic environments under conditions of variable turbidity. Therefore, sensitivity to turbidity-related stressors would be expected to occur only when conditions exceed the range of natural variability occurring in their native habitats.

7.6.1.2.3 Altered Dissolved Oxygen

Dissolved oxygen (DO) content is critical to the growth and survival of all 52 HCP species. The amount of oxygen dissolved in water is dependent on temperature, physical mixing, respiration, photosynthesis, and, to a lesser degree, atmospheric pressure. These parameters can vary diurnally and seasonally and depend on activities such as daytime photosynthesis oxygen inputs and night-time plant respiration processes that deplete dissolved oxygen levels. Dissolved oxygen concentration is temperature dependent; as temperatures rise, the gas-absorbing capacity of the water decreases and the dissolved oxygen saturation level decreases. Reduced dissolved oxygen levels can be due to increased temperature (Snoeyink and Jenkins 1980), organic or nutrient loading (Ahearn et al. 2006), increased benthic sedimentation (Welch et al. 1998), or chemical weathering of iron and other minerals (Schlesinger 1997).

In the context of fish passage subactivity types, decreased DO levels are likely to occur only in specific and limited circumstances where the activity imposes additional nutrient loading on a system that is eutrophic or close to a eutrophic condition. For example, a culvert replacement that results in dewatering of an upstream impoundment may result in the rapid export of sequestered nutrients. In eutrophic conditions, this may lead to decreased DO levels. Restoration of fish passage may have the unintended consequence of depleting DO levels if large numbers of spawning salmon are allowed to access a system where eutrophic conditions are already occurring. Under most circumstances, these effects will be short term in duration. However, the consequences for HCP species can be significant.

Effects on Fish and Invertebrates

Juvenile salmon are highly sensitive to low dissolved oxygen concentrations (USFWS 1986) and, consequently, are among the more vulnerable HCP species with regard to dissolved oxygen impairment. Salmon generally require dissolved oxygen levels of greater than 6 ppm for optimal survival and growth, with lethal 1-day minimum concentrations of around 3.9 ppm (Ecology 2002). Different organisms at different life-history stages require different levels of dissolved oxygen to thrive. Tolerance for low oxygen levels varies across other species as well. For example, pygmy whitefish can withstand dissolved oxygen conditions below 5 ppm (Zemlak and McPhail 2006). Table 7-4 lists the minimum recommended dissolved oxygen concentrations for salmonids and stream-dwelling macroinvertebrates (Ecology 2002). The dissolved oxygen thresholds presented in this table were derived from more than 100 studies representing over 40 years of research.

Table 7-4. Summary of recommended dissolved oxygen levels for full protection (approximately less than 1 percent lethality, 5 percent reduction in growth, and 7 percent reduction in swim speed) of salmonid species and associated macroinvertebrates.

Life-history Stage or Activity	Oxygen Concentration (ppm)	Intended Application Conditions
Incubation through emergence	≥9.0–11.5 *(30 to 90-DADMin)* and No measurable change when waters are above 52°F (11°C) (weekly average) during incubation.	Applies throughout the period from spawning through emergence Assumes 1-3 ppm will be lost between the water column and the incubating eggs
Growth of juvenile fish	≥8.0–8.5 *(30-DADMin)* and ≥5.0-6.0 *(1-DMin)*	In areas and at times where incubation is not occurring
Swimming performance	≥8.0-9.0 *(1-DMin)*	Year-round in all salmonid waters
Avoidance	≥5.0-6.0 *(1-DMin)*	Year-round in all salmonid waters
Acute lethality	≥3.9 *(1-DMin)* ≥4.6 *(7 to 30-DADMin)*	Year-round in all salmonid waters
Macroinvertebrates *(stream insects)*	≥8.5-9.0 *(1-DMin or 1-DAve)*	Mountainous headwater streams
—	≥7.5-8.0 *(1-DMin or 1-DAve)*	Mid-elevation spawning streams
—	≥5.5-6.0 *(1-DMin or 1-DAve)*	Low-elevation streams, lakes, and nonsalmonid waters
Synergistic effect protection	≥8.5 *(1-DAve)*	Year-round in all salmonid waters to minimize synergistic effect with toxic substances

Source: Ecology 2002.
1-DMin = annual lowest single daily minimum oxygen concentration.
1-DAve = annual lowest single daily average concentration.
7-, 30-, 90-DADMin = lowest 7-, 30- or 90-day average of daily minimum concentrations during incubation period.

It should be noted that recommendations are presented in Table 7-4 for dissolved oxygen thresholds in categories other than lethality. Fish are motile organisms and, where possible, will avoid dissolved oxygen levels that would cause direct mortality. However, this avoidance behavior in and of itself can affect fishes. Stanley and Wilson (2004) found that fish aggregate above the seasonal hypoxic benthic foraging habitat in the Gulf of Mexico, while Eby et al. (2005) found that fish in the Neuse River estuary (North Carolina) were restricted by hypoxic zones to shallow, oxygenated areas where in the early part of the summer about one-third fewer prey resources were available. Studies such as these reveal how dissolved oxygen can change fish distributions relative to habitat and potentially exclude fishes from reaching spawning, foraging, and rearing areas. Sublethal dissolved oxygen levels can also cause increased susceptibility to infection (Welker et al. 2007) and reduced swim speeds (Ecology 2002), both of which may cause indirect impacts on HCP fish species.

Little consensus exists concerning low dissolved oxygen criteria for macroinvertebrates, and tolerances to hypoxic conditions are taxonomically specific. Many invertebrates are adapted to live in benthic, low-energy environments where dissolved oxygen concentrations are naturally low; consequently, these organisms can withstand hypoxic conditions. Other taxa, including Hirudinea, Decapoda, and many aquatic insects, tolerate dissolved oxygen levels below 1.0 ppm (Hart and Fuller 1974; Nebeker et al. 1992). For example, in Chen et al. (2001), freshwater mussels (Unionidae) showed a wide range of tolerance for low DO levels depending on the types of habitats they inhabit. As would be expected, they found that species that inhabit slack water and warm water environments show greater tolerance for low DO levels, while species that are found in flowing water and cold water environments were far more sensitive.

Depleted DO levels can affect other invertebrate species as well, with implications for food web productivity. However, the range of sensitivity varies significantly across taxa. For example, leaches (Hirudinea), crustaceans (Decapoda), and many species of aquatic insects, tolerate DO levels below 1.0 ppm (Hart and Fuller 1974; Nebeker et al. 1992), while other aquatic invertebrate species (e.g., Ephemeroptera, Plecoptera, Trichoptera) show variable sensitivity depending on the environments to which they are adapted. In general, organisms adapted to colder flowing water environments where DO levels are naturally high are expected to have lower tolerance for DO depletion (Nebeker 1972).

Kaller and Kelso (2007) found benthic macroinvertebrate density, including mollusks, greatest in low dissolved oxygen areas of a Louisiana wetland, while a literature review by Gray et al. (2002) noted that in marine environments, invertebrates were not affected by low dissolved oxygen until concentrations fell below 1–2 ppm. Benthic dissolved oxygen levels can seasonally drop below this threshold in productive systems that receive high biochemical oxygen demand (BOD) loadings. For instance, depressed benthic dissolved oxygen levels in Hood Canal, Washington, have been associated with spot shrimp decline (Peterson and Amiotte 2006). This dissolved oxygen decline in turn has been linked to BOD loadings from leaking or improperly functioning on-site wastewater systems. These conditions in Puget Sound highlight the importance of reducing anthropogenically generated BOD.

7.6.1.2.4 Altered pH

When concrete is used in the construction of weirs, fish ladders, culverts, or other fish passage structures, discharge of concrete leachate or curing of concrete in contact with surface waters can drastically alter the pH of the receiving body. Uncured concrete can dissolve in water and, depending on water temperatures and dilution rates, can raise the pH level to as high as 12, which is far outside the livable range for all of the HCP species (Ecology 1999).

The pH of fresh and salt water normally ranges from 6.5–8.5 (Schlesinger 1997). The construction of fish passage structures using concrete can affect the pH of surrounding waters if the uncured concrete is allowed to contact the receiving water body. This impact will be greatest during construction when concrete wash-off and slurries come into contact with water (Dooley et al. 1999), but once construction is complete, concrete may still impact the surrounding environment. Curing concrete surfaces can exhibit pH values as high as 13 during the 3 to 6 months it takes for concrete to cure underwater (Dooley et al. 1999). This elevated pH prevents attached macroalgae growth during this period.

Altered pH from curing concrete will increase pH to levels which can affect fish, invertebrates, and their food. But this effect is localized and, as stated above, should last no more than 6 months. Consequently, it is estimated that this impact mechanism will be most significant for large projects in areas with poor water circulation.

<u>Effects on Fish and Invertebrates</u>

Fish have adapted to the ambient pH levels of their particular habitat and tend to have narrow ranges of pH tolerance. The effects of high pH levels outside of their tolerance range can include death; damage to gills, eyes, and skin; and an inability to excrete metabolic wastes (DFO 2007). When ambient conditions are characterized by elevated ammonia and pH, ammonia toxicity in fish can occur because the organisms have difficulty excreting ammonia waste through their gills. At ambient ammonia concentrations of 5 ppm, the mortality of tambaqui (*Colosoma macropomum*; also known as pacu), a neotropical fish, increased from 0 to 15 to 100 percent at a pH of 7, 8, and 9, respectively (de Croux et al. 2004). Consequently, if ammonia concentrations are elevated due to waste dumping from recreational vessels or from upland sources, the toxicity may be compounded by elevated pH from construction activities.

pH alone can affect fish exposed to alkaline conditions. In a toxicity study of rainbow trout, a pH above 8.4 caused an increase in glucose and cortisol levels, and a pH above 9.3 caused mortality (Wagner et al. 1997). In white sturgeon, decreased sperm motility was observed when fish were exposed to pH levels below 7.5 (Ingermann et al. 2002).

Alterations in pH can also affect invertebrates. The majority of research on the effect of pH on invertebrates is related to the impact of acidification on abundance and diversity; consequently, there is little research on the impact of elevated pH on invertebrates. In a study of the freshwater Malaysian prawn, Cheng and Chen (2000) noted a 38 percent decrease in haemocyte (invertebrate blood cell) count when pH dropped below 5 or rose above 9. In another study, Bowman and Bailey (1998) found that zebra mussels have an upper pH tolerance limit of 9.3 through 9.6. From these studies, it can be assumed that pH levels that exceed a pH of between 9 and 10 will have a negative impact on invertebrate HCP species. As indicated above, pH levels on and around curing concrete can exceed this pH threshold; therefore, there is the potential for impact on local invertebrate communities.

7.6.1.2.5 Introduction of Toxic Substances

Operation of backhoes, excavators, and other construction equipment will require the use of products such as fuel and lubricants. This presents the potential for the accidental introduction of these toxic substances to the environment through accidental spills and other sources. Heavy equipment use may also be a pathway for introduction of metals (e.g., copper and zinc from brake pad wear), which have the potential for toxic effects. Riparian vegetation modifications associated with fish passage projects may lead to decreased buffering capacity, increasing delivery of pollutants to surface waters via stormwater runoff from adjacent impervious surfaces. The effects of exposure to these types of pollutants are described in the following section.

<u>Effects on Fish and Invertebrates</u>

The introduction of toxic substances to the water column can injure or kill aquatic organisms (NMFS 2005). Petroleum-based contaminants, such as fuel, oil, and some hydraulic fluids, contain polycyclic aromatic hydrocarbons (PAHs) that could be acutely toxic to salmonids at high levels of exposure and could also cause chronic lethal, and acute and chronic sublethal effects on aquatic organisms (Hatch and Burton 1999). Misitano et al. (1994) exposed larval surf smelt to Puget Sound (Eagle Harbor) sediments with high concentrations of PAHs and found 100 percent mortality after 96 hours of exposure. After diluting the sediments and repeating the experiments, they found that those larvae that did not expire within 96 hours suffered from decreased growth rates. Table 7-5, adapted from Jones & Stokes (2006a) and Stratus (2005), depicts effects thresholds for PAHs in surface water for Pacific herring, zooplankton, mysids and marine amphipods, and trout.

Organic chemical contaminants can also impact prey production by limiting the suitability of substrates in the impacted area. Fish eggs can be particularly vulnerable to chemical contaminant exposure due to their inability to move out of the impacted area. Invertebrates can be similarly vulnerable due to the inability to move (or move quickly) out of the impacted area.

In urban environments, metals loading to local waterways and water bodies from anthropogenic sources is a major pathway for aquatic habitat degradation. The primary metals of concern in the surface waters of Washington State are copper, zinc, arsenic, lead, and nickel (Embrey and Moran 2006).

Metals above threshold concentrations act as carcinogens, mutagens, and teratogens in fish and invertebrates (Wohl 2004). Additionally, the sublethal effects of copper toxicity have been extensively studied, with reported effects including impaired predator avoidance and homing behavior (Baldwin et al. 2003). Ecology has established water quality standards for marine waters for each of these constituents. These standards, issued in WAC 173-201A, are listed in Table 7-6. Freshwater toxicity thresholds are hardness-dependent and can vary widely depending on calcium and magnesium carbonate concentrations. The standards presented here are based on median freshwater hardness concentrations, estimated from an extensive 3-year data set (2001–2003) from the Green River watershed (Herrera 2007d).

Table 7-5. Organism effects thresholds for PAHs in surface water.

Organism	Exposure Source	Toxicity	Concentration (parts per billion)	Citation
Mysid (*Mysidopsis bahia*)	Elizabeth River, Virginia, sediment extracts	24-hr lethal concentration of a chemical within a medium that kills 50% of sample population	180	Padma et al. 1999
Amphipod (*Rhepoxynius abronius*)	Eagle Harbor, WA sediment extracts	96-hour and 24-hr lethal concentration of a chemical within a medium that kills 50% of sample population	1,800	Swartz 1989
Pacific herring	PAHs leaching from 40-year old pilings	24-hr lethal concentration of a chemical within a medium that kills 50% of sample population	50	Vines et al. 2000
	PAHs leaching from 40-year old pilings	Significant reduction in hatching success and increased abnormalities in surviving larvae	3	Vines et al. 2000
Zooplankton	PAHs leaching from pilings placed in microcosms	No observable effects concentration	11.1	Sibley et al. 2004
	Commercial creosote added to microcosms	No observable effects concentration	3.7	Sibley et al. 2001
Trout	Commercial creosote added to microcosms	Lowest observable effects concentration for immune effects	0.6	Karrow et al. 1999

Sources: Jones & Stokes 2006a and Stratus 2005.

Table 7-6. Water quality criteria for metals in marine and freshwaters of the state of Washington.

Constituent	Freshwater Acute	Freshwater Chronic	Marine Acute	Marine Chronic
Arsenic	360	190	69	36
Copper	7	7.5	4.8	3.1
Lead	22.9	1.5	210	8.1
Nickel	640	104	74	8.2
Zinc	51.6	69.2	90	81

Units: ports per billion (ppb).
Adapted from: WAC 173-201A.

7.6.1.2.6 Altered Nutrient Cycling

The introduction of nutrients and altered nutrient cycling can arise as the result of multiple impact mechanisms associated with the construction and operation of fish passage structures.

Principally, riparian zone modification, ecosystem fragmentation, and hydraulic and geomorphic modifications are the primary sources of this stressor. Introduction of increased nutrients can result in eutrophication, which in turn can lead to decreased dissolved oxygen levels. Decreased dissolved oxygen is a stressor in its own right that has demonstrable adverse effects on fish and invertebrate species.

For example, any activity that affects riparian areas will degrade the buffering capability of the terrestrial–aquatic ecotone. Numerous studies have shown that wide stream buffers are effective at attenuating nutrients (Feller 2005; Mayer et al. 2005), herbicides (Gay et al. 2006), and sediment loading (Jackson et al. 2001). Riparian vegetation retards overland flow, promotes infiltration, and assimilates shallow groundwater nutrients. When this vegetation is removed through any HPA-permitted activity, nutrients and pollutants will be more efficiently transported from upland sources to downgradient water bodies. Forested buffers can effectively remove nutrients in shallow groundwater. In a study of a forested buffer in Alabama, a 33-ft (10-m) buffer reduced the groundwater nitrate concentration by 61 percent (Schoonover and Williard 2003). In a subsequent study of a forested wetland buffer, a buffer averaging 125 ft (38 m) wide reduced the nitrate concentration by 78 percent and total phosphorus by 66 percent (Vellidis et al. 2003).

<u>Effects on Fish and Invertebrates</u>

Increased nutrient loading may be beneficial to fish in pristine upland systems. When riparian canopies are opened, increased photosynthetic active radiation reaches the channel, temperatures increase, and nutrient loading increases. These alterations can increase macroinvertebrate abundance and biomass as well as algal biomass (Fuchs et al. 2003; Hetrick et al. 1998). However, the cumulative effect of increased nutrient loading contributes to eutrophication in downstream receiving waters. Eutrophication refers to the increase in nutrient pollution to receiving waters and has been identified as a major source of environmental degradation in receiving waters throughout Washington State (Nelson et al. 2003; Pickett 1997). Eutrophication occurs when limits to vegetative growth are reduced. In Washington, the primary limiting nutrient in freshwater environments most likely to be affected by fish passage projects is phosphorus. This is due to the fact that abundant iron in freshwater systems binds with phosphorus (P) and reduces the availability of P for biotic assimilation. When nutrient limitations are eliminated, vegetative growth increases. This process accelerates carbon fixation; the additional carbon loading to the aquatic system increases respiration as heterotrophs use carbon for energy. Through the process of carbon oxidation, oxygen is converted to carbon dioxide (CO_2) and ambient dissolved oxygen levels decrease. Eutrophication-induced hypoxia is a nationwide problem (Scavia and Bricker 2006). The ramifications of low dissolved oxygen on HCP species are addressed above and in Section 9 (*Potential Risk of Take*).

It is important, however, to place the anticipated changes in nutrient cycling caused by improved fish passage into proper context. As discussed in the *Modified Upstream Transport of Allochthonous Nutrients* subsection of Section 7.6.1.6 (*Ecosystem Fragmentation*), a recently recognized benefit of certain types of fish passage projects, specifically those intended to restore habitat access for anadromous species, is the increased delivery of marine-derived nutrients to the aquatic ecosystem. In many cases, the ecological productivity of these naturally oligotrophic systems increases significantly as a result of nutrient delivery.

7.6.1.3 Riparian Vegetation Modifications

Riparian vegetation modifications are commonly required for the construction and maintenance of HCP-permitted projects, including projects that fall under the fish passage activity type. The discussion of resulting stressors and the effects of stressor exposure presented in the following sections represents a worst-case scenario perspective on the effects of this impact mechanism. As discussed in the *Riparian Vegetation Modifications* subsection of each subactivity type (Sections 7.1.1.3, 7.2.1.3, 7.3.1.3, and 7.4.1.3), the degree to which fish passage subactivity types result in riparian vegetation modification is expected to vary considerably. Therefore, when interpreting the potential effects of stressor exposure resulting from each subactivity type, the anticipated extent of riparian vegetation modifications they are likely to impose must be considered.

7.6.1.3.1 Impact Submechanisms

Riparian vegetation modifications are expected to result in the following impact submechanisms:

- Altered shading, solar input, and ambient air temperature
- Altered bank and shoreline stability
- Altered allochthonous inputs
- Altered habitat complexity
- Altered groundwater/surface water interactions.

These impact submechanisms and the resulting ecological stressors they impose are described below.

<u>Altered Shading, Solar Exposure, and Ambient Air Temperature</u>

Removal of riparian vegetation in conjunction with the construction and maintenance of fish passage projects can affect water temperature in riverine environments through a number of mechanisms. The dominant effect pathway is that of reduced shading on solar radiation exposure. As streams increase in size, the influence of riparian vegetation on stream temperatures decreases. More surface area is exposed to insulation, and the ability of riparian vegetation to buffer ambient air temperatures decreases (Knutson and Naef 1997; Murphy and Meehan 1991; Poole and Berman 2001a; Quinn 2005). Similarly, riparian vegetation removal and alteration can cause surface waters to gain or lose heat more rapidly because shade decreases and the ability to regulate ambient temperatures is reduced (Bolton and Shellberg 2001; Knutson and Naef 1997; Murphy and Meehan 1991; Poole and Berman 2001a; Quinn 2005). For example, in a study of 12 streams in Japan, it was shown that forest practices (i.e., logging) resulted in increased temperatures and decreased abundance of resident Dolly Varden (Kishi et al. 2004).

In addition to the effects of shading, a broad array of research indicates that alterations of riparian vegetation can strongly affect temperatures even when adequate stream shading is still provided. Riparian vegetation restricts air movement, providing an insulating effect that regulates ambient air temperatures. Alterations of the riparian buffer width and vegetation composition can degrade this insulating effect, leading to greater variability in ambient air temperatures that in turn influence water temperatures (AFS and SER 2000; Bartholow 2002; Barton et al. 1985; Beschta 1991, 1997; Beschta et al. 1988; Beschta and Taylor 1988; Brosofske et al. 1997; Brown 1970; Chen et al. 1992, 1993, 1995; Chen et al. 1999; Johnson and Jones 2000; Macdonald et al. 2003; May 2003; Murphy and Meehan 1991; Spence et al. 1996; Sridhar et al. 2004; Sullivan et al. 1990; Theurer et al. 1984; USFS et al. 1993). For example, Chen et al. (1995) found that maximum air temperatures at the margins of old-growth forest stands are elevated 3–29°F (2–16°C) relative to interior temperatures. Riparian buffer widths of 100–300 ft may be necessary to provide full ambient temperature regulation (AFS and SER 2000; Brosofske et al. 1997). Loss or degradation of the shading and ambient temperature regulation functions provided by riparian vegetation can increase water temperatures in summer when solar radiation exposure and ambient air temperatures are highest. In winter, loss or degradation of the insulating capacity of riparian vegetation can decrease water temperatures and increase the incidence of ice scour. Increased stream temperatures can also cause a concomitant decrease in dissolved oxygen levels, an additional stressor with additive deleterious effects.

<u>Altered Bank and Shoreline Stability</u>

Many HPA-permitted activities involve the temporary or permanent modification of riparian vegetation structure. Riparian vegetation is an important component of the aquatic ecosystem that serves a variety of functions for habitat structure, water quality, and biological productivity. The specific nature of these functions varies depending on the type of environment, but increasing bank cohesion plays an important role in regulating channel width and substrate.

The root structure supporting riparian vegetation naturally resists the shear stresses created by flowing water and thus retards bank erosion, stabilizing stream banks and shorelines, and maintaining valuable habitat features along stream margins, such as undercut banks. By dissipating the erosive energy of flood waters, wind, and rain, and by filtering sheet flows, riparian vegetation limits the amount of fine sediment entering river and stream systems (Brennan and Culverwell 2004; Knutson and Naef 1997; Levings and Jamieson 2001). If riparian vegetation is removed as part of an HPA-permitted activity, stream banks and shorelines will likely be exposed to the erosive effects of wind, rain, and current. The removal of riparian trees and understory can dramatically alter stream bank stability and the filtering of sediments from overland flow (Kondolf and Curry 1986; Shields 1991; Shields and Gray 1992; Simon 1994; Simon and Hupp 1992; Waters 1995), increasing erosion and inputs of fine sediment (Bolton and Shellberg 2001).

<u>Altered Allochthonous Input</u>

Riparian detritus and other externally derived (allochthonous) materials are the primary sources of organic matter in headwater streams, forming the basis of the food web (MacBroom 1998).

This material includes terrestrial macroinvertebrates along with leaves, branches, and other vegetative materials, the latter providing food sources for benthic macroinvertebrates (Bilby and Bisson 1998; Knutson and Naef 1997; Murphy and Meehan 1991). As rivers increase in order and grow in size, these materials are processed and recycled by an increasing diversity of organisms (Vanotte et al. 1980). Without allochthonous inputs, the forage detritus available for benthic macroinvertebrates is compromised, also diminishing the habitat and species diversity of these prey items (Murphy and Meehan 1991). Removal of freshwater riparian vegetation as part of HPA-permitted activities would cause an incremental decrease in the input of allochthonous materials to the nearby aquatic environment and food web.

<u>Altered Groundwater/Surface Water Interactions</u>

Alteration or removal of riparian vegetation would appreciably change the interface between plants, soil, and water on and near the bank surface. Riparian vegetation also acts as a filter for groundwater, removing sediments and taking up nutrients (Knutson and Naef 1997). In conjunction with upland vegetation, riparian vegetation moderates streamflow by intercepting rainfall, contributing to water infiltration, and using water via evapotranspiration. Plant roots increase soil porosity, and vegetation helps to trap water flowing on the surface, thereby aiding in infiltration as the water stored in the soil is later released to streams through subsurface flows. Through these processes, riparian and upland vegetation help to moderate storm-related flows and reduce the magnitude of peak flows and the frequency of flooding. Riparian vegetation, the litter layer, and silty soils absorb and store water during wet periods and release it slowly over a period of months, maintaining streamflows during low rainfall periods (Knutson and Naef 1997).

HPA-permitted activities that create a physical barrier between the bank and hyporheic flow (e.g., riparian vegetation removal) may prevent exchange between the bank and with the aquatic ecosystem. Because the interface between flow within the hyporheic zone and the stream channel is an important buffer for stream temperatures (Poole and Berman 2001b), alteration of groundwater flow can affect stream temperature. The magnitude of the influence depends on many factors, such as stream channel pattern and depth of the aquifer (Poole and Berman 2001b).

The direct and indirect effects of altered groundwater/surface water interactions on HCP fish and invertebrate species are discussed in Section 7.6.2 (*Common Impact Submechanisms Imposed by Multiple Impact Mechanisms*).

<u>Altered Habitat Complexity</u>

Modifications of riparian vegetation as a result of HCP-permitted projects will inevitably have some effects on aquatic habitat complexity. The contribution of riparian vegetation to ecosystem structure and function is a defining characteristic of the aquatic ecosystems in Washington State likely to be affected by fish passage projects. Specifically, riparian vegetation plays a key role in habitat complexity by serving as a source of LWD which provides habitat structure and influences channel form, and by providing bank structure and overhanging vegetation which contribute to cover and structural complexity. Alteration of riparian vegetation will affect these dynamics. For example, logging practices in northwestern Montana have been shown to decrease habitat complexity through the reduction of LWD inputs (Hauer et al. 1999). LWD density can also be affected by alteration of hydraulic and geomorphic processes and ecosystem fragmentation that affect the transport and retention of woody debris.

The direct and indirect effects of altered habitat complexity on HCP fish and invertebrate species are discussed in Section 7.6.2 (*Common Impact Submechanisms Imposed by Multiple Impact Mechanisms*).

7.6.1.3.2 Effects on Fish and Invertebrates

Riparian vegetation modifications can impose a number of stressors on fish and aquatic invertebrate species, with potentially detrimental effects on survival, growth, and fitness. These stressors are manifold and are often associated with interrelated impact submechanisms that occur as a result of riparian modification. For example, riparian modification can cause hydraulic and geomorphic changes in the stream channel due to by reduced LWD recruitment and increased bank erosion. Reduced riparian buffer width can lead to decreased buffering capacity and an associated increase in pollutant and nutrient loading.

Alteration of the temperature regime in riverine systems due to the alteration of riparian vegetation is a well-documented stressor on native fish populations. The effects of altered temperature regime on HCP species are discussed in Section 7.6.1.2.1 (*Altered Water Temperature*). However, it is useful to note that the effects of altered stream temperatures are not uniformly negative in all cases. For example, in light-limited streams, selective thinning of forests can have a positive effect on fish. In northern California, cutthroat and rainbow trout responded positively to increased light from riparian thinning through increased primary productivity that stimulated the food web (Wilzbach et al. 2005).

Bank instability induced by riparian modification can induce a number of ecological stressors. First, slope instability can increase delivery of coarse and fine-grained sediment to a river, affecting water quality and habitat conditions. The effects of elevated suspended sediments on HCP species are discussed in Section 7.6.1.2.2 (*Elevated Suspended Sediments*). In addition, slumping of unstable banks caused by a loss of riparian vegetation can bury eggs and larval fish, as well as HCP invertebrates. Burial is a stressor potentially produced by several impact mechanisms. The effects of this common stressor on HCP species are discussed in Section 7.6.2.2 (*Burial and Entrainment*).

Riparian vegetation influences hydraulic and geomorphic conditions within the stream channel, providing habitat structure and complexity. Alterations of riparian vegetation that lead to bank instability and decreased recruitment of LWD are likely to affect habitat complexity in ways that are detrimental to HCP species. Altered habitat complexity is a common submechanism potentially imposed by several impact mechanisms. The effects of related stressors on HCP species are discussed in Section 7.6.2.1 (*Altered Habitat Complexity*).

Riparian vegetation is a known source of organic matter, nutrients, and macroinvertebrate prey items for HCP species, and the recruitment of these materials is diminished when riparian vegetation is removed or modified (Brennan et al. 2004; Lemieux et al. 2004; Maser and Sedell 1994; Miller et al. 2001; Sobocinski 2003; Williams et al. 2001). Sobocinski (2003) has documented the importance of insect communities and benthic fauna that are either recruited to the aquatic ecosystem directly from riparian vegetation or are supported by allochthonous inputs from riparian vegetation. These lower trophic organisms serve as the basis of the food web, and a reduction in allochthonous food sources to rivers diminishes the ability of the system to support higher trophic organisms, including most of the HCP fish species that use the riverine environment. Therefore, it follows that riparian vegetation modifications that reduce food web productivity are likely to affect the survival, growth, and fitness of HCP species.

Riparian vegetation modifications can also affect groundwater–surface water interactions, which in turn can influence nutrient loading, temperature regime, and habitat complexity. Alteration of groundwater–surface water interactions is a common submechanism potentially produced by several impact mechanisms. The effects of related stressors on HCP species are discussed in Section 7.6.2.3 (*Altered Groundwater/Surface Water Interactions*).

7.6.1.4 Aquatic Vegetation Modifications

Placement of fish passage structures in the stream channel has the potential to modify aquatic vegetation through three key pathways. First, aquatic vegetation in the planned footprint of the structure is likely to be permanently displaced. Second, hydraulic and geomorphic modifications that induce changes in substrate composition and stability may alter habitat suitability for aquatic vegetation in upstream and downstream reaches. Finally, short-term construction-related impacts may temporarily modify vegetation. The first two pathways create effects that range from intermediate term to permanent in nature, while construction-related effects are most likely to be short term in duration.

The discussion of resulting stressors and the effects of stressor exposure presented in the following sections represents a worst-case scenario perspective on the effects of this impact mechanism. As discussed in the *Aquatic Vegetation Modifications* subsection of each subactivity type (see Sections 7.1.1.4, 7.2.1.4, 7.3.1.4, and 7.4.1.4), the degree to which fish passage subactivity types result in riparian vegetation modification is expected to vary considerably. Therefore, the interpretation of the potential effects of stressor exposure resulting from each subactivity type should consider the anticipated extent of aquatic vegetation modifications they are likely to impose.

7.6.1.4.1 Impact Submechanisms and Stressors

Impact submechanisms associated with aquatic vegetation modifications include altered autochthonous production (including changes in nutrient cycling) and altered habitat complexity. Aquatic vegetation can be altered by changes in sediment transport (burial), scour from altered flow velocities, and the disturbance related to construction, maintenance, and operational activities.

Altered Autochthonous Production

Aquatic primary producers, such as benthic algae, macrophytes, and phytoplankton, play key roles in the trophic support of stream ecosystems. In general, benthic algae occur in the form of microscopic unicellular algae, forming thin layers or assemblages called periphyton. Macrophytes include angiosperms rooted in the stream bottom, along with mosses and other bryophytes. These include many forms such as rooted plants with aerial leaves, floating attached plants with submerged roots, floating unattached plants, and rooted submerged plants (Murphy 1998). A small algal biomass in a stream can support a much larger biomass of consumers due to the rapid turnover in biomass (Hershey and Lamberti 1992; Murphy 1998). Although aquatic primary production is sometimes underrated due to the small amount of algae and plants present in many streams, it is a basic energy source for freshwater ecosystems. Because aquatic vegetation uses nutrients for growth, a reduction in aquatic vegetation will alter nutrient loading within stream and river ecosystems. Modification or removal of aquatic vegetation will result in reduced autochthonous (instream) production, which provides important energy sources in aquatic food webs.

Altered Habitat Complexity

Aquatic vegetation loss can reduce habitat complexity through a reduction in cover for fish species, as well as changes in surface water flow patterns. Fish passage structures can cause losses of aquatic vegetation by several pathways. Increased flow velocities and substrate characteristics caused by hydraulic and geomorphic modifications can scour algae downstream and damage macrophytes, reducing cover for fish. Second, changes in substrate composition with an increase in fine sediment transport can bury aquatic vegetation. Finally, modifications may occur directly from construction and maintenance activities.

Altered habitat complexity is a common submechanism that can occur as a result of many impact mechanisms. The effects of stressors produced by this submechanism on fish and invertebrates are discussed in Section 7.6.2.1 (*Altered Habitat Complexity*).

7.6.1.4.2 Effects on Fish and Invertebrates

The uptake of carbon, nitrogen, and phosphorous by aquatic vegetation and conversion into biologically available biomass provides important nutrients to fish and invertebrate consumers. This aquatic primary production is the source of autochthonous (instream) organic matter and part of the source of allochthonous (terrestrial) matter in each stream reach. Invertebrate grazing of these primary producers by snails, caddisflies, isopods, minnows, and other organisms is an important pathway of energy flow. For stream herbivores, for example, benthic diatoms are the most nutritious and easily assimilated food source (Lamberti et al. 1989). The availability of algae regulates the distribution, abundance, and growth of invertebrate scrapers (Hawkins and Sedell 1981), an important food source for fish. As drift-feeders, juvenile salmonids focus on food from autochthonous pathways. Invertebrate scrapers and collector–gatherers are known to be most frequently eaten by salmonids (Bilby and Bisson 1992; Hawkins et al. 1983; Murphy and Meehan 1991). Although terrestrial and adult aquatic insects are important (Bjornn and

Reiser 1991), juvenile salmon in streams have been found to be primarily supported by autochthonous organic matter (Bilby and Bisson 1992).

Numerous studies have shown that macrophytes and algae in both marine and freshwater environments reduce ambient concentrations of suspended sediment (Abdelrhman 2003; Moore 2004), nutrients (Moore 2004), and metals (Fritioff and Greger 2003). In a study of macrophyte effects on sediment and nutrient retention in Danish streams, Sand-Jensen (1998) reported that dense-stemmed macrophytes created conditions conducive to sediment deposition and that the sediments retained within the macrophyte stands were fine-grained and nutrient-rich. He noted that enrichment of sediment within macrophyte beds relative to the surrounding substratum was 0.1597 lb organic matter per ft^2 (780 g/m^2), 0.006 lb nitrogen per ft^2 (30 g/m^2), and 0.005 lb phosphorus per ft^2 (25 g/m^2). Therefore, any large-scale modification of aquatic vegetation will likely result in increased suspended sediments, increased nutrient loading, and changes in hyporheic exchange, all adversely affecting HCP species.

Aquatic vegetation does more than reduce nutrient and sediment concentrations; the plants themselves can sequester harmful trace metal pollutants and are frequently planted in wetland treatment systems with that intended function. In a comparative study of heavy metal uptake in terrestrial, emergent, and submerged vegetation, Fritioff and Greger (2003) noted that submerged vegetation was efficient at removing zinc, copper, cadmium, and lead from influent stormwater.

As a result of the many benefits of aquatic vegetation described above, the loss of aquatic vegetation in riverine environments poses both direct and indirect effects on HCP species. Many of these species depend on aquatic vegetation for any one of their life-history stages, such as white sturgeon, California floater and western ridged mussel, mountain sucker, giant Columbia River limpet, pygmy whitefish, leopard and Umatilla dace, bull trout, and Pacific salmon (Frest and Johannes 1995; Hughes and Peden 1989; Mongillo and Hallock 1998; Mongillo and Hallock 1999; Watters 1999). More specifically, adhesive eggs of the Olympic mudminnow rely on attachment to aquatic vegetation for egg and larval development (Coutant 2004).

The summer density of coho salmon fry has been found to be directly related to the abundance of algae. A high density of fry can result from smaller feeding territories (Dill et al. 1981) due to increased invertebrate prey (Hawkins et al. 1983; Murphy et al. 1981). Increases in vertebrate production have been found to occur primarily in the spring and early summer, coincident with the primary production cycle of benthic algae (Murphy 1998). Therefore, the removal of or permanent disturbance to algal communities could have an adverse effect on local freshwater ecosystems and the HCP species that depend on these ecosystems. For coho salmon fry, the reduction in prey area (i.e., smaller feeding territories) results in a direct effect on fitness, growth, and survival.

The direct and indirect effects of aquatic vegetation removal on invertebrates are less well known. However, the California floater in the Eel River (California) is commonly associated with aquatic vegetation, which is used for protection from high flows (Howard and Cuffey 2003).

Finally, any activity that mechanically removes or by other means affects aquatic vegetation will reduce the sediment, nutrient, and pollutant retention and reduction capabilities of the system. Indirect impacts from the removal of aquatic vegetation will cause increased nutrient and pollutant loading to receiving waters, which could exacerbate eutrophic conditions and/or metals toxicity. A detailed discussion of the impact on various species from nutrient loading is presented in Section 7.6.1.2.6 (*Altered Nutrient Cycling)*.

7.6.1.5 Hydraulic and Geomorphic Modifications

Riverine hydraulic and geomorphic processes distribute water, sediment, and organic materials along a linear path toward lower elevations. Fishes and invertebrates depend upon the diversity of habitats created by hydraulic and geomorphic forces that scour, transport, and deposit diverse sediments, LWD, nutrients, and organic material along the river profile (Montgomery et al. 1999). HCP species, such as sturgeon, char, bull trout, salmonids, and freshwater mussels, depend on particular riverine sediment types and habitats. In short, the reproduction, growth, and survival of these HCP species depend on particular hydraulic and geomorphic regimes to maintain suitable habitats. Alterations to river form that change the flow of water and the ability of the water to move sediments, LWD, and organic material can have direct and indirect effects on HCP species.

Fish passage projects are generally expected to have relatively minor effects on hydraulic and geomorphic processes relative to other HCP-permitted activities, such as flow control structures and channel modifications. However, some structure types, such as weirs specifically designed to aid or prevent upstream migration of certain fish species, may have unavoidable effects of greater magnitude. This section describes the impact submechanisms and ecological stressors potentially imposed by fish passage structures, applying the worst-case scenario perspective.

7.6.1.5.1 Impact Mechanisms and Stressors

The following hydraulic and geomorphic modification impact submechanisms may result from implementation of a fish passage subactivity type:

- Altered flow conditions
- Altered channel geometry
- Altered substrate composition and stability
- Altered groundwater/surface water interactions.

The ecological stressors imposed by these impact submechanisms are described below, followed by the effects of stressor exposure on HCP fish and invertebrate species.

<u>Altered Flow Conditions</u>

Fish passage projects can alter flow conditions in the vicinity of the structure by altering channel morphology and hydraulics. Inherent in altered flow variability is the change in flow velocities. Fish and invertebrates inhabiting riverine environments require certain flow velocities for spawning, rearing, migration, and foraging. For example, Chinook salmon tolerate velocities up to 49.9 ft/sec (15.2 m/sec) (Johnson et al. 2003) during migration, whereas Pacific lamprey seek out slower velocities (0–0.33 ft/sec) for rearing (Stone and Barndt 2005). Optimal velocities for spawning habitat for mountain suckers in Lost Creek, Utah, are 2.4–7.9 in/sec (0.06–0.2 m/sec) (Wydoski and Wydoski 2002). Spawning velocities for Columbia River white sturgeon are similarly low (~2.6 ft/sec [0.8 m/sec]) (Paragamian et al. 2001), although this species spawns successfully in areas with higher average velocities by using river bed dunes and similar features for hydraulic refuge (Young and Scarnecchia 2005).

Flow velocities also influence swimming activity and respiration in fish species. Increased flow velocities during water releases can also force fish species to rest in areas of slower moving water to recover from increased activity. This behavior can result in unsuccessful recruitment from delayed migration upstream for anadromous species (e.g., salmonids, sturgeon, lamprey), or increased predation from remaining longer in slow pools downstream of weirs and high-velocity reaches.

Changes in flow velocities may also significantly alter sediment transport. The presence of a fish passage structure may accelerate or slow streamflow in different portions of its zone of influence. For example, if a permanent weir installed to prevent upstream dispersal of invasive species creates an impoundment, altered flow velocities in the impoundment will cause increased sediment deposition. In contrast, a structure such as a roughened channel may increase flow velocities in slackwater areas to moderate flows elsewhere. Increased velocities can scour bed material and benthic organisms (Camargo and Voelz 1998).

Altered Channel Geometry

Depending on configuration, fish passage structures may also change channel geometry. For example, an impoundment formed by a permanent barrier weir may cause upstream channels to widen, and downstream channels will likely become narrower. Furthermore, flow velocity in a channel is proportional to the hydraulic radius (the cross-sectional area of the channel divided by the wetted perimeter) and inversely proportional to roughness (Leopold et al. 1964). Therefore, any change in flow velocity will ultimately change the channel geometry. Finally, altered depth and width downstream of a fish passage structure may disconnect the river from its floodplain and side channel habitats, potentially reducing habitat accessibility.

Altered Substrate Composition and Stability

The effects of fish passage structures on sediment composition and stability may range from relatively benign in the case of roughened channels, to more extensive in the case of barrier weirs that create impoundments and interrupt sediment transport.

Permanent weirs are most likely to affect reach-level sediment sorting, without necessarily having a broad effect on sediment transport and, by extension, sediment composition. In contrast to dams, weirs do not create large impoundments and therefore have less capacity to affect transport. In addition, fish passage weirs are intended purely to block fish passage; they can be designed to not interrupt the transport of sediment, LWD, and organic material.

Localized changes in substrate composition are coupled with reach-level alterations in sediment sorting. In this white paper, substrate composition is defined as those size portions that comprise the substrate (e.g., fines, sand, gravel, and cobble). These alterations in turn alter the composition of streambed substrates. Because HCP species depend on the presence or absence of particular substrate types to support important life-history functions, changes in substrate composition can have direct and indirect effects on those species. Again, these effects are typically localized because fish passage weirs are typically designed to be transparent to sediment transport.

Increased velocities associated with weirs can indirectly affect HCP species by causing local bed scour around structures and result in a corresponding deposition of sediment downstream. Bed scour into a substrate of mixed particle sizes (e.g., sand and gravel) can selectively remove finer sediment and cause the substrate to coarsen. Likewise, increased deposition of the finer sediment downstream can bury organisms and result in finer substrate.

Altered Groundwater/Surface Water Interactions

Hydraulic and geomorphic modifications can result in altered groundwater/surface water exchange through several pathways. Principally, channel aggradation or downcutting will lead to altered surface water elevations, which will affect the groundwater/surface elevation and groundwater flux to the channel. Changes in channel form can thereby affect the interaction between groundwater and surface water. Bank erosion and substrate alterations can also alter these dynamics. A high level of substrate fines in channel substrate from a dam may hinder the connection between surface and groundwater, limiting vertical and lateral connectivity between these two habitat types (Edwards 1998; Pusch et al. 1998). Effects on ecological functions and freshwater aquatic species associated with degraded groundwater/surface water connectivity are well documented (Bilby and Bisson 1998; Hershey and Lamberti 1992; Karr 1991; Kelsey and West 1998; Montgomery et al. 1999; Naiman et al. 1992; Reiman and McIntyre 1993; Stanford and Ward 1992; Stanford et al. 1996). Changes in flow regime, sediment transport, and substrate composition all affect in-channel hyporheic exchange. This lack of connectivity can degrade conditions for riparian zone vegetation, reducing LWD recruitment to the stream channel and subsequently limiting habitat-forming and maintaining processes and habitat complexity.

The hyporheic zone does more than promote oxygen exchange in subsurface sediments; it effectively acts as a filter and zone of biogeochemical transformations. Increased hyporheic exchange has been associated with nutrient uptake and transformation (Fernald et al. 2006; Lefebvre et al. 2005) and may attenuate the transport of dissolved and particulate metals (Gandy et al. 2007). Elevated metals and nutrients can both have negative ramifications for fish and invertebrate health.

The direct and indirect effects of altered groundwater/surface water interactions on HCP fish and invertebrate species are discussed in Section 7.6.2 (*Common Impact Submechanisms Imposed by Multiple Impact Mechanisms*).

7.6.1.5.2 Effects on Fish and Invertebrates

Fish and invertebrates inhabiting riverine environments require certain flow velocities for spawning, rearing, and foraging. Increases in flow velocities could present potential barriers to fish migration or could exceed thresholds for certain life-history stages of some HCP species. Direct effects from altered velocities include stress to migrating species through increased activity, exhaustion, and delayed migration. Indirect effects include changes in habitat accessibility, habitat quality, and increased predation. For instance, leopard and Umatilla dace inhabit riverine environments where the velocities are less than 1.6 ft/sec (Wydoski and Whitney 2003). Exceeding this velocity as a result of altered flow over a weir would render the habitat unsuitable for these species.

Flow through fish passage structures will commonly increase local velocities and turbulence downstream of the structures, making fish passage difficult (Baker 2003). Again, while fish passage structures are intended to provide passage benefits, when measured against the natural stream baseline, measurable effects on HCP species may occur. For example, lampreys have been observed migrating over weirs, with short bursts of movement followed by extended resting periods (Quintella et al. 2004). The sea lampreys seemed affected by increasing fatigue, which the authors attributed to initiating a new burst of movement without fully recovering from the previous exertion.

Direct and indirect effects of altered flow velocities on invertebrates are not well understood and represent an area for further research. However, for the HCP invertebrate species that are filter feeders (e.g., California floater and western ridged mussel) or rely on stable substrate for habitat structure, altered sediment transport is likely more important than changes in flow velocities.

Alteration of channel geometry has both direct and indirect effects on fish and invertebrates. Fish and invertebrates require certain widths and depths for habitat, spawning, and cover. For example, mountain suckers in Lost Creek, Utah, showed a preference for spawning depths of 4.3–11.8 inches (11–30 cm) (Wydoski and Wydoski 2002). Indirect impacts arising from the alteration of channel geometry include the modification of natural sediment transport, a reduction in habitat connectivity, and a reduction in habitat complexity. The effects of altered substrate composition and stability on HCP species are described below. The effects of reduced habitat connectivity are discussed in Section 7.6.1.6 (*Ecosystem Fragmentation*). The effects of altered habitat complexity are discussed in Section 7.6.2.1 (*Altered Habitat Complexity*).

Alteration of the substrate composition through coarsening or fining of the bed materials can have direct and indirect effects on HCP species. The ecological effects of substrate coarsening and fining on salmonids in riverine environments are well known. Far less is known about the effects of these disturbances on the life-history stages of other freshwater fish and invertebrate species. Large substrates, exceeding the maximum size mobilized by spawning salmonids, are avoided during redd building (Kondolf and Wolman 1993; Kondolf al. 1993). This includes areas where erosion to bedrock has occurred. Field observations have shown that salmonids can build redds where the average substrate size (D_{50}) is up to 10 percent of the average body length (Kondolf and Wolman 1993). The optimal range of spawning gravels for salmonids is listed in Table 7-7.

Table 7-7. Spawning gravel criteria for salmonids.

Gravel bed criteria	Small-bodied Salmonids <13.8 in (<35 cm)	Large-bodied Salmonids >13.8 in (>35 cm)
Dominant substrate particle size	0.3–2.5 in (8–64 mm)	0.6–5 in (16–128 mm)
Minimum gravel patch size	10.8 ft^2 (1 m^2)	21.5 ft^2 (2 m^2)

Adapted from (Schuett-Hames et al. 1996).
Note: Small-bodied salmonids include cutthroat trout; large-bodied salmonids include coho and Chinook salmon and steelhead trout.

Altered substrate composition and stability can affect habitat suitability for spawning by salmonids and other fish species. Salmon require a range of sediment sizes, and spawning success depends on how well they can mobilize sediment with their tail to create a redd. As a result, different species use gravels of different size and can effectively move only certain size classes of sediment (Kondolf 1997; Kondolf and Wolman 1993). Gravel and cobble substrate is preferred by spawning white sturgeon because their adhesive eggs are susceptible to burial by sand and silt-sized substrate (Paragamian et al. 2001). Gravel substrate is also preferred spawning habitat for Dolly Varden (Kitano and Shimazaki 1995). Mobilization and redeposition of fines can affect incubation success. Excessive deposition of fines can lead to substrate embeddedness, reducing the water circulation necessary to oxygenate the eggs and flush metabolic wastes (Zimmermann and Lapointe 2005). Embryo mortality has been found to occur from poor water circulation and lack of oxygenation associated with the filling of intergravel pore spaces by fine sediment (Bennett et al. 2003; Chapman 1988; Cooper 1965; Lisle and Lewis 1992). In a study of spawning chum salmon in low-gradient, gravel-bed channels of Washington and Alaska, Montgomery et al. (1996) found that minor increases in the depth of scour caused by bed fining and a reduction in hydraulic roughness, significantly reduced embryo survival.

Increased bed scour and substrate coarsening are also detrimental to habitat suitability. As finer materials are scoured away, substrate coarsens. This process may lead to bed armoring as the interlocking strength of larger bed particles increases (Church et al. 1998; Konrad 2000; Lane 1955).

With regard to effects on invertebrates, burial and entrainment in mobilized sediments and habitat modification are primary stressors resulting from hydraulic and geomorphic modifications. The effects of these on HCP invertebrate species are discussed in greater detail in Sections 7.6.2.1 (*Altered Habitat Complexity*) and 7.6.2.2 (*Burial and Entrainment*).

Hyporheic exchange, characterized by exchange between surface water and subsurface water in streams and rivers, is extremely important for the health of riverine systems (Jones et al. 1995;

Mulholland et al. 1997; Sheibley, Duff, et al. 2003; Triska et al. 1989). Increased hyporheic exchange between surface and subsurface waters will benefit aquatic biota by increasing benthic dissolved oxygen levels and promoting solute uptake, filtration, and transformation. Studies have shown that the availability of dissolved oxygen to incubating salmonid embryos is dependent on hyporheic exchange (Geist 2000; Greig et al. 2007) and that the occlusion of this exchange through siltation can lead to hypoxia within redds and decreased embryo survival.

7.6.1.6 Ecosystem Fragmentation

Ecosystem fragmentation refers to the disruption of ecological processes by reducing the connectivity between different components of the ecosystem, or the disruption of ecological processes. Examples include the following: fragmentation of riverine habitats by the placement of a weir or other type of barrier that blocks the upstream movement of fish and the downstream movement of organic material, or lateral and longitudinal habitat fragmentation caused by headcut migration. The former type of ecosystem fragmentation can be caused by any type of fish passage structure that is not able to provide passage for all species in all circumstances, or poses a barrier to the downstream transport of wood, organic debris, and sediment. The latter example applies specifically to situations where culvert removal or replacement allows an arrested headcut to continue migrating upstream, causing channel incision. As noted in Section 7.1.1.5 (*Hydraulic and Geomorphic Modifications*), these types of effects can be avoided through additional habitat or channel modifications with the acknowledgement that these activities will impose their own effects on HCP species.

7.6.1.6.1 Impact Submechanisms and Stressors

The following impact submechanisms describe the ecosystem fragmentation effects potentially imposed by fish passage projects:

- Barriers to fish passage
- Modified upstream transport of allochthonous nutrients
- Modified downstream transport of LWD, sediment, and organic material
- Lateral and longitudinal habitat fragmentation.

These impact submechanisms, the ecological stressors they impose, and the effects of stressor exposure on HCP species are described in the following sections.

<u>Barriers to Fish Passage</u>

With the exception of certain types of weirs and gated culverts, all of the subactivity types addressed in this white paper are intended to improve access to habitats that are unavailable due to man-made barrier conditions. In other words, this activity type is intended to reverse ecosystem fragmentation in ways that are beneficial to aquatic species. As such, the discussion of the effects of habitat loss is appropriately limited here. The implications of this stressor are discussed in greater detail in the Flow Control Structures and Water Crossings white papers (Herrera 2007b; Jones and Stokes 2006b).

However, for the purpose of this white paper, the baseline condition for assessing the effects of this activity type is the aquatic ecosystem in its natural condition (i.e., before the presence of man-made passage barriers). In this context, all fish passage subactivity types, with the exception of culvert removal, have some potential to impose barriers to fish passage. Providing passage for all HCP species during all pertinent life-history stages is a guiding principle governing the design of fish passage structures, but it is nonetheless a difficult challenge. In addition, fish passage structures may provide less effective passage over time depending on how appropriate the design is for its ecological context and frequency of maintenance. As such, barriers to fish passage may occur.

The following ecological stressors may result from this impact submechanism:

- Loss of habitat access
- Delayed migration, injury, and energy expenditure
- Phenotypic and life history selectivity
- Species selectivity.

Weirs designed to intentionally block fish passage have the potential to impose this full range of stressors. Gated culverts are also likely to impose these stressors on HCP species that migrate or disperse to affected habitats. Even gated culverts that are designed or retrofitted to promote fish passage (e.g., self-regulating tide gates) are likely to cause at least some degree of barrier condition (Novak and Goodell 2006). Because this type of culvert is typically found in estuarine environments, gated culverts have the potential to affect HCP species that use estuarine floodplain habitats, such as juvenile anadromous salmonids. These ecological stressors can have a broad range of effects on HCP species. These effects are described below in Section 7.6.1.6.2 (*Effects on Fish and Invertebrates*).

<u>Modified Upstream Transport of Allochthonous Nutrients</u>

Alteration of fish migration patterns can in turn lead to the alteration of upstream transport of organic material, particularly marine-derived nutrients associated with the carcasses of anadromous fish species. Numerous studies have documented the contribution of marine-derived nutrients provided by anadromous fish on food web productivity (Brock et al. 2007; Chaloner et al. 2007; Chaloner et al. 2002; Chaloner and Wipfli 2002; Gross et al. 1998; Hicks et al. 2005; Lessard and Merritt 2006; MacAvoy et al. 2000; Merz and Moyle 2006; Minakawa et al. 2002; Mitchell and Lamberti 2005; Moore et al. 2007; Nagasaka et al. 2006; Scheuerell et al. 2005; Schindler et al. 2005; Yanai and Kochi 2005; Zhang et al. 2003). Several additional studies have examined the influence of marine-derived nutrients on the productivity of riparian vegetation, which in turn affects habitat structure (Bartz and Naiman 2005; Ben-David et al. 1998; Helfield and Naiman 2001, 2002; Merz and Moyle 2006; Nagasaka et al. 2006; Naiman et al. 2002; Scheuerell et al. 2005). Given this broad base of evidence, it is reasonable to conclude that fish passage structures that improve passage of native fish species will produce beneficial effects on food web productivity and habitat structure, with attendant benefits on HCP species dependent on these habitats. The opposite conclusions can be reasonably drawn if a structure restricts passage.

Modified Downstream Transport of LWD, Sediment, and Organic Material

While these effects are more commonly associated with structures that impose barriers to fish passage, fish passage structures may alter the downstream transport of wood, sediment, and organic materials. This is particularly true when the effects of these structures are measured against the natural stream condition as the environmental baseline.

Should a fish passage structure cause sufficient interruption of wood and sediment transport to change woody debris density and sediment transport conditions in downstream reaches relative to the natural stream baseline, simplification of habitat structure may result. Alteration of habitat complexity can have a variety of detrimental effects on HCP species. These effects are discussed in Section 7.6.2.1 (*Altered Habitat Complexity*).

Altered Lateral and Longitudinal Connectivity

Channel incision caused by headcut migration can disconnect the active channel from the floodplain and simplify channel habitat (Castro 2003). This process can in turn produce lateral and longitudinal habitat fragmentation. This scenario occurs most commonly in cases where headcut migration has been arrested by the existing culvert structure. Over time, headcut migration would be expected to return the channel gradient and floodplain connectivity to an equilibrium condition, provided that other factors occur (principally, that LWD of sufficient size to trap and retain sediments is available for recruitment).

If a culvert is providing grade control, replacement or removal of the culvert may result in the following intermediate-term responses (Castro 2003):

1. Headcut migration upstream and subsequent deepening of the stream channel

2. Relatively higher channel banks that may exceed critical height, resulting in slope failure and bank erosion

3. Addition of sediment to the stream system due to erosion of the channel boundary

4. Disconnection of floodplains from active stream channels

5. Prematurely dewatered or disconnected backwater habitat

6. Locally increased channel slope and loss of pool habitat

7. Drainage of shallow aquifers affecting riparian vegetation

8. Meander cut-offs due to knickpoint migration across a meander neck caused by an increased elevation drop between the old floodplain and active channel bed

9. Deposition of large masses of sediment causing localized channel braiding and instability of the stream banks.

Headcuts induced or reinitiated by culvert removal or replacement can result in changes in channel geometry such as incision that affect habitat complexity. These changes can also influence the recruitment, transport, and retention of sediment and LWD, leading to longer term impacts on habitat complexity. These impacts include altered storage and retention of sediment and particulate organic matter, as well as hydraulic simplification (which reduces the diversity of instream habitats available for fish). Channel incision may also alter the functional relationship between LWD and the stream channel. For example, spanning LWD that would be functional under natural channel conditions may not interact with surface water under the same range of flow conditions in a degraded channel. This would reduce the influence that woody debris has on habitat conditions in the stream channel.

Where the interaction of LWD with the channel is affected by channel incision, the ability of debris jams to promote access to floodplain habitats may be diminished. Fish use LWD for cover and refuge, and the complex environments created by LWD increase aquatic species' access to floodplain habitat (Cederholm et al. 1997; Everett and Ruiz 1993; Harvey et al. 1999). In a study of Smith Creek in northwest California, Harvey et al. (1999) found that tagged adult coastal cutthroat trout moved more frequently from pools without LWD than from pools with LWD. They hypothesized that the habitat created by LWD attracts fish, and once fish establish territory within the desirable habitat, they remain there longer. A study by Cederholm et al. (1997) on a tributary of the Chehalis River found that LWD additions caused an increase in winter populations of juvenile coho salmon and age-0 steelhead populations. Based on these studies, it follows that the loss of LWD to a channel would reduce floodplain–channel resource exchange and habitat accessibility, which would likely adversely impact the HCP species, especially those that favor floodplain habitat.

Headcut-induced channel incision can also affect lateral habitat connectivity. Channel incision lowers water surface elevations, potentially disconnecting off-channel habitats from the stream system. Decreased lateral connectivity with side-channel, slough, and floodplain ponds can have a range of effects on HCP species. Side channels create refugia for juvenile fish (Jungwirth et al. 1993), while floodplain ponds and backwater sloughs create zones of high retention and productivity that provide vital rearing habitat (Hall and Wissmar 2004; Sommer et al. 2005) and important sources of organic material for the channel (Tockner et al. 1999). The loss of connectivity between the river and these habitats can result in a decrease in organic matter recruitment (Tockner et al. 1999; Valett et al. 2005) and reduced access to valuable foraging and rearing habitats (Henning et al. 2006). Floodplains can act as nutrient sinks and carbon sources for adjacent channels (Tockner et al. 1999; Valett et al. 2005). Consequently, floodplain–channel connection augments allochthonous carbon budgets in restored channels and engages habitat that would otherwise be inaccessible.

While these potential effects are of concern, care should be taken not to assume that they are universal in extent or severity. In many instances, it may be appropriate to allow a stream system to return to a natural equilibrium gradient through channel incision. For example, many culverts occur in smaller stream systems with naturally limited floodplains and off-channel habitat. Regrading this type of channel and placing grade control structures will produce extensive short-term adverse effects on aquatic habitat conditions and HCP species occurring in these environments. These effects may significantly outweigh those that result from allowing a natural channel response to proceed, while the intermediate- to long-term benefits of both approaches are comparable. In such cases, the cost and the short-term effects of channel regrading would not be justified, unless property or infrastructure faces unacceptable risk. Given these complexities, it is desirable to include a licensed geologist and a qualified aquatic biologist in the design process to avoid unnecessary actions and/or undesirable outcomes.

7.6.1.6.2 Effects on Fish and Invertebrates

The majority of subactivity types addressed in this white paper are intended to improve habitat access rather than diminish it. Therefore, loss of habitat access is not a pertinent stressor for most projects in comparison to passage selectivity, migration delays, or other factors that diminish population productivity relative to the baseline of the natural stream. The exception is the placement of weir structures specifically designed to prevent upstream migration of certain species of fish. This subactivity type is most often implemented to prevent or limit invasions by introduced species that could be detrimental to native fish species. For example, competition for forage and habitat and genetic introgression and hybridization with non-native species have been demonstrated to adversely affect native salmonid populations (Reiman et al. 2006; Shephard et al. 2002; Utter 2001).

Weirs and other structures intentionally designed to prevent or limit fish access have been broadly employed to restrict exotic species invasions. For example, man-made barrier structures have been installed in many tributaries in the Laurentian Great Lakes to limit the distribution of sea lamprey (McLaughlin 2006), with the understanding that these barriers may unintentionally limit migration and dispersal of native fish species and obligate invertebrates such as freshwater mussels. In the Western U.S., barrier weirs have been successfully employed to prevent habitat recolonization by brook trout following their eradication, supporting recovery of depressed westslope cutthroat and bull trout populations (Shephard et al. 2002).

<u>Effects of Barriers to Fish Passage</u>

In comparison to the natural stream baseline, fish passage projects may lead to detrimental effects on native fish populations by affecting their ability to migrate between important habitats. Even in the absence of well-defined migratory behavior, the ability to move between different habitat types is nonetheless important for many resident fish species (Rodriguez 2002). The ecological implications of decreased habitat access are potentially significant. The effects of restricted access caused by dams and weirs have been broadly implicated in population declines of freshwater fish species from around the world (Northcote 1998). Even when a passage barrier project is intended to protect native fish populations, it could have detrimental effects. For example, projects that prevent brook trout invasions of headwater stream populations may unintentionally fragment genetic exchange between resident and adfluvial populations of bull trout. Maintaining this type of genetic exchange within bull trout metapopulations is considered essential for the long-term conservation of the species (Reiman and McIntyre 1993).

Even when fish passage structures are designed to facilitate migratory behavior, they may still produce unintended adverse effects. Improperly conceived or maintained fish passage structures may delay migration and/or may be physically taxing to navigate. In the case of adult salmonids, the cost of delayed migration and energy expenditure can have a demonstrable effect on survival, as well as spawning productivity. Caudill et al. (2007) examined the relationship between delayed migration, survival, and spawning productivity by using radiotelemetry to track the behavior and fate of Chinook salmon and steelhead navigating fish passage structures. Statistically correcting for other sources of mortality, they found a distinct inverse relationship between the time required for individual fish to transit fish ladders bypassing Columbia and Snake River dams, and survival to reach spawning grounds. While the drivers of this inverse relationship are complex, energy expenditure and stress associated with navigating the structures are primary contributing factors. (However, extant natural barriers eliminated by impoundments are also energetically demanding (Brown et al. 2002)). In combination with other stressors imposed by fish passage structures (e.g., prolonged exposure to elevated water temperatures, increased harvest, and predation pressure), the effects of migration delay induced by fish passage structures appear to be cumulatively significant (Caudill et al. 2007).

Structure design may also lead to unnecessary stress and energy expenditure. For example, high "fallback" rates have been observed at fishways at Columbia River dams. When passage over eight dams was considered, 15 to 22 percent of adult Chinook and 21 percent of adult steelhead fell back over at least one dam (Boggs et al. 2004). Available evidence suggests that the migration delay and energetic costs imposed by fallback could lead to decreased survival and spawning success (Caudill et al. 2007). These structures can be redesigned to decrease the likelihood of fallback.

Fish passage structures can also unintentionally affect passage success based on life-history stage (i.e., by size). As juvenile salmonids migrate downstream on many larger river systems, they must travel past large dams where they are susceptible to injury and mortality if forced to travel through power turbines. Many experimental fish passage structures have been employed to direct downstream migrations through less injurious pathways, with varying degrees of success. For example, juvenile salmonids have been shown to respond preferentially to different velocity conditions when traveling downstream through weirs (Kemp et al. 2006), suggesting that structures designed without proper consideration of attraction flows may be ineffective.

Upstream migration and other movements within freshwater rearing habitats are also recognized as an important factor to consider when designing fish passage. Direct study and reviews of available research have demonstrated that juvenile salmonids are seasonally migratory, moving between refuge and rearing habitats (Bolton et al. 2002; Kahler and Quinn 1998; Kahler et al. 2001). Juveniles may cover considerable distances to occupy available rearing habitats, indicating that this dispersal mechanism is important to survival (Bolton et al. 2002). Therefore, fish passage structures that unintentionally block access to key summer and winter rearing habitats may be key factors limiting juvenile survival, growth, and fitness.

Gated culverts are also known to restrict fish passage to lateral riverine and estuarine habitats, even when designed according to current engineering standards (Novak and Goodell 2006). Loss of access to estuarine and floodplain rearing habitats has been broadly implicated as a contributing factor in the decline of anadromous salmonids in the Pacific Northwest, particularly those species with demonstrated dependence on these habitat types (such as coho, Chinook, and chum salmon) (Beechie et al. 1994; Giannico and Souder 2004; Gregory and Bisson 1997). Loss of access to floodplain and estuarine rearing affects growth and fitness and, in the case of estuarine rearing, limits the potential residence time in brackish water habitats that facilitate the physiological transition from fresh to marine water during smoltification. These factors can influence survival.

The interplay between fish swimming performance and hydraulic conditions in fish passage structures becomes increasingly complex with smaller target species. In their review of multiple sources of research on juvenile salmon passage, Kahler and Quinn (1998) noted that numerous *in situ* observations have demonstrated that extrapolation of adult salmon swimming performance curves to juveniles underpredicted the ability of smaller fish to navigate velocity barriers in fish passage structures. Based on postulations in the sources they reviewed, they concluded that complex hydraulic conditions within fish passage structures created low-velocity zones used by juvenile fish to transit the structures. Research conducted by WDFW supports this hypothesis. Powers and Bates (1997) studied the passage of juvenile coho salmon through culverts composed of several different materials and found significant differences in the velocities that permitted passage. Specifically, they noted that the turbulent boundary layer created by corrugated metal pipes appeared to create a lower velocity zone that enhanced passage relative to culvert pipes with smooth interiors. The presence of these lower velocity zones has been confirmed by subsequent research (Ead et al. 2000; Pearson et al. 2006).

Numerous other factors, such as flow velocity, exposure distance to excess flow velocity without hydraulic refuge areas, and other factors, can influence the ability of juvenile salmonids to effectively pass through culverts and other fish passage structures (Behlke 1991). In a laboratory environment, juvenile fish moving through culverts were observed using low-velocity pathways within turbulent boundary layers and behind baffles. The pathways selected differed between the baffled and unbaffled test environments, and also potentially differed depending on flow rates in the baffled environment (Pearson et al. 2006). In some instances, juvenile fish passed culverts at higher mean velocities in the cross-section than the physiological limits of swimming performance would suggest. This indicates that fish adaptively select low-velocity pathways to navigate through culverts where possible. This further indicates, as suggested by Kahler and Quinn (1998), that design guidance for velocity limits based purely on swimming performance and mean channel hydraulics is likely to be conservative. However, there are many other uncertainties in the design guidance that are not compensated for by these unintentionally conservative assumptions.

Most regional studies on fish passage performance have focused on larger juvenile salmon (e.g., in the 4–5 inch [100–125 millimeter] range), which may not be fully representative of the requirements of smaller juveniles. While the preponderance of research on swimming performance suggests that ability is essentially constant relative to size across the majority of fish species (Katopodis 1992), this relationship may break down when the complexities of low-velocity pathways and individual adaptive ability are considered. Pearson et al. (2006) studied this issue in greater detail and confirmed that simple sized-based extrapolation of swimming performance underpredicted the ability of juvenile coho salmon to pass culverts. A key factor appeared to be the ability of smaller fish to utilize lower velocity zones in the hydraulically complex boundary layer at the culvert surface. They recommended additional studies to confirm whether the design and discharge parameters that provided successful passage for larger individuals are applicable to smaller juveniles (e.g., 1.1–.6 inches [30–40 millimeters]) that migrate during spring flow conditions. It is important to note, however, that this work was conducted in a laboratory setting. It is not clear how any information gleaned from these studies would apply to a range of culvert designs and settings in the field.

The ability of other fish species to navigate fish passage structures may be similarly over- or underestimated if their swimming and jumping abilities are not appropriately considered. For example, in a study of the effects of weir vertical drop heights on the migration behavior of two native diadromous fish species in New Zealand, the common bully and the inanga, Baker (2003) found that juvenile inaga and all life-history stages of common bully were unable to navigate vertical drops of 4 inches (10 cm), and drops of 8 inches (20 cm) were barriers to adult inaga. Vertical drops of this size have also been shown to limit passage of some juvenile salmonids (Pearson et al. 2005). In contrast, adult Atlantic salmon in the Pau River (France) were able to pass over weirs between 59.1 inches (1.5 m) and 98.4 inches (2.5 m) in height (Chanseau et al. 1999), drop heights that would completely block passage for many fish species.

Fish passage structures may unintentionally select for fish of different size classes or run timing. For example, a culvert that is retrofitted for fish passage may provide adequate passage to salmonids during moderate streamflow conditions, but may be impassable during average high and low flows. In effect, the barrier may unintentionally select against individuals with run timing in the late summer low-flow period and during late fall when streamflows increase to high levels, truncating the genetic diversity of the stock. Similarly, a passage structure may prove impassable to fish above or below a certain size, selecting for smaller or larger individuals. Of particular concern, it is increasingly clear that juvenile salmonids are migratory when quite small and that design criteria in existing regulations may not adequately protect juveniles of smaller size. For example, the Washington Administrative Code (WAC 220-110-070) limits the vertical jumps formed by water-crossing structures to no more than 0.8 feet (9.6 inches) to provide for juvenile fish passage. However, research on juvenile salmonid jumping ability indicates that a vertical drop of this size would effectively limit passage of juvenile salmonids 3 inches in length or smaller. Pearson et al. (2005) found that the proportion of juvenile salmon able to navigate vertical jumps decreased steadily as jump height exceeded 2.5 times body length, with effectively no fish able to navigate jumps in excess of three times body length. However, a number of complicating factors must also be considered, such as weir crest shape, ambient approach velocity, shape of the nappe, and downstream approach conditions that can affect this threshold limit.

The degree to which these factors affect population diversity is likely to vary widely depending on the nature of the barrier, but any structure that unintentionally selects against population diversity is likely to be detrimental to its long-term viability (McElhany et al. 2000; Thompson 1991).

Even in the absence of size or run timing selectivity, energetically demanding fish passage barriers have been shown to differentially affect passage by sex. For example, Brown et al. (2002) studied migratory Chinook salmon passage of natural waterfalls and found that males were more successful than females at navigating energetically demanding barriers. Man-made fish passage barriers and their remedies could conceivably have similar effects. Alteration of male to female sex ratios can have significant demographic consequences, potentially affecting the viability of the affected population (McElhany et al. 2000; Thompson 1991). It is notable, however, that differential male to female dispersal around barriers may also be an evolved strategy to avoid inbreeding and genetic introgression in salmonids (Hutchings and Gerber 2002). This suggests that sexual selection effects should not be assumed without population and site-specific research.

Fish passage structures that primarily consider the passage of one species or class of species (e.g., culvert retrofits designed to pass salmonids) may unintentionally limit the passage of other important species. Species selection can alter species composition and community relationships upstream of the passage barrier, with important implications for conservation of individual species and biodiversity (Agostinho et al. 2007).

There are several examples of species-specific selectivity in the available literature. In the Columbia River system, fish ladders designed primarily to provide salmonid passage around mainstem dams perform relatively poorly for passage of Pacific lamprey (Moser et al. 2002). Loss of habitat access is a key factor implicated in the decline of native Pacific and river lamprey populations in the Pacific Northwest. Sturgeon passage may be enhanced by the inclusion of rapid velocity segments in fishways and other passage structures (Cheong et al. 2006; Webber et al. 2007), but these conditions may impede passage of other species with different swimming abilities. Fishways and fish ladders around dams in biodiverse tropical rivers show a strong tendency toward species selection, allowing passage of certain migratory species while truncating the distribution of relatively weak swimming species that nonetheless depend on seasonal dispersal mechanisms (Agostinho et al. 2007). The latter example demonstrates the difficulties inherent in developing "one-size-fits-all" designs for fish passage structures that rely on engineered features rather than approximation of natural fluvial processes.

Similarly, culverts have been shown to affect passage of nonsalmonid species. Warren and Pardew (1998) evaluated the migration of 21 warm water fish species including centrarchids (sunfish), cyprinids (minnows and suckers), and fundulids (killifishes) through four types of culverts in western Arkansas streams. They found that regardless of design, culverts restricted the movement of each species studied by at least an order of magnitude relative to natural conditions. This suggests that even carefully designed fish passage structures have the potential to impose passage barriers on HCP fish species when the knowledge of their specific passage requirements is limited.

In addition to effects on fish, fish passage structures may have the unintended effect of restricting the dispersal of HCP freshwater invertebrate species. This can occur in two ways. First, the structure may restrict the distribution of host fish, affecting the dispersal of parasitic larvae (Vaughan 2002; Watters 1996). Second, the structure may restrict upstream movement of mussels and snails capable of crawling along the stream bottom (Vaughan 2002). Species such as California floater mussels may face demographic risks from the unintentional limitation of fish passage because the full range of their host fish species is poorly understood, meaning that the migration behavior and swimming requirements of these species may not be well accounted for. Likely host-fish species include native minnows (cyprinids) and non-native mosquito fish (Nedeau et al. 2005).

Effects from Modified Transport of Allochthonous Nutrients

Regarding the effects of fish passage projects on upstream transport of marine-derived and other allochthonous nutrient sources, an inference that can be drawn from available literature is that any fish passage project that affects this ecological process will alter habitat productivity and habitat structure. On this basis, it is reasonable to conclude that any reduction in upstream transport of allochthonous nutrients will detrimentally affect the productivity of native fish populations. This inference is supported by research documenting the uptake of marine-derived nutrients by juvenile salmonids and other native fish species (Bilby et al. 1998; Heintz et al. 2004; MacAvoy et al. 2000).

While no data were identified regarding the direct influence of marine-derived nutrients on HCP invertebrate species, it is reasonable to conclude that changes in ecosystem productivity resulting from decreased fish passage would affect the growth and fitness of these species. Marine-derived nutrients distribute broadly in aquatic ecosystems (Cederholm et al. 1989), demonstrably affecting algal growth and nutrient export (Brock et al. 2007; Chaloner et al. 2007; Chaloner et al. 2002; Mitchell and Lamberti 2005; Moore et al. 2007; Schindler et al. 2005; Yanai and Kochi 2005). These effects are demonstrably linked to the forage base for filter feeding and grazing invertebrate species. The availability of marine-derived nutrients also demonstrably affects the productivity of host fish populations (Bilby et al. 1998). Therefore, in addition to the effects of reduced forage availability, it is reasonable to infer that the dispersal of freshwater mussels, which are dependent on fish to transport their parasitic larvae upstream against the current, will be reduced where ecosystem productivity has been adversely affected. These combined effects may ultimately limit population productivity.

Effects of Altered Lateral and Longitudinal Connectivity

Lateral and longitudinal habitat connectivity provides a range of important habitat functions for HCP species. Through inference or direct evidence, it can be shown that fragmentation of this connectivity is likely to have a range of detrimental effects. Floodplain connectivity creates fish forage and refuge habitat for several of the HCP species (Feyrer et al. 2006; Henning 2004). Chinook that rear on floodplains have been shown to grow faster than those rearing in adjacent channels (Sommer et al. 2001). Additionally, in a 2004 study of the Sacramento splittail, a sensitive cyprinid species, fishes rearing in floodplain habitat were healthier and larger than fish from the same cohort that did not rear in this type of environment (Ribeiro et al. 2004). Swales and Levings (1989) found that off-channel habitats in the Coldwater River, British Columbia, were vital rearing areas for coho, while juvenile Chinook, steelhead, and Dolly Varden were most abundant in floodplain ponds. Larval white sturgeon have been shown to disperse to flooded riparian habitats for early rearing. Fragmentation of these habitats may be a factor in the decreased productivity of this species (Coutant 2004).

Channel incision can lead to temporary simplification of channel form, creating relatively uniform hydraulic and geomorphic conditions over extended lengths of channel. This reduction in habitat complexity can have a range of adverse effects on HCP species. These effects are similar to those described in Section 7.6.1.6 (*Ecosystem Fragmentation*).

7.6.2 Common Impact Submechanisms Imposed by Multiple Impact Mechanisms

Select ecological stressors imposed by the construction, operation, and maintenance of fish passage subactivity types can be caused by multiple impact mechanisms. Rather than repeat a discussion of the effects of stressor exposure, this section provides a consolidated discussion of stressor response by HCP fish and invertebrate species to the following common stressors:

- Altered habitat complexity
- Burial and entrainment
- Altered groundwater/surface water interactions.

7.6.2.1 Altered Habitat Complexity

A range of impact mechanisms associated with the fish passage subactivity types addressed in this white paper can affect habitat complexity. Replacement or retrofitting of culverts for fish passage can have unintended effects on habitat complexity through alteration of hydraulic and geomorphic processes, ecosystem fragmentation, and modifications of riparian and aquatic vegetation. Weirs, fish ladders and fishways, and roughened channels can impose effects through these same mechanisms. In contrast, trap-and-haul programs are unlikely to impose significant direct effects on habitat complexity. While this subactivity type requires the use of some form of capture and loading facility, for the purpose of this white paper, these capture structures are considered to be integral with hatchery weirs, dams, or other forms of flow control structure. The effects of flow control structures on habitat complexity are discussed in the Flow Control Structures white paper (Herrera 2007b).

7.6.2.1.1 Effects on Fish and Invertebrates

Studies have indicated that decreased habitat complexity negatively affects the survival and growth of aquatic organisms. Reduced shelter availability will increase predation and is not energetically favorable for fishes. In a recent study by Finstad et al. (2007), it was found that juvenile Atlantic salmon exhibit accelerated mass loss rates with decreasing access to shelter, indicating that the juvenile fish had to expend greater energy when there was no available shelter. In another study by Babbitt and Tanner (1998), tadpole survival was 32 percent greater under high than under low cover, suggesting that increased cover decreased predator foraging efficiency. Although the prey in this study were not HCP species, the effect of cover on predation rates can be extrapolated to HCP species that utilize vegetated cover during early lifestages. Finally, limited habitat availability will lead to density-dependent mortality for those species that cannot find unoccupied cover and may be exposed to increased predation or high-energy environments (Forrester and Steele 2004).

Riparian vegetation and LWD are also important for bank-side habitat and cover from predation and temperature. For example, the use of submerged riparian vegetation during early development has been hypothesized to increase Columbia River white sturgeon recruitment (Coutant 2004). In another study, radio-tagged cutthroat trout were observed using pools associated with LWD for cover (Harvey et al. 1999). In addition, undercut banks provide shade, lower temperatures, and cover from predation.

Fish rely on habitat complexity for cover and refuge (Cederholm et al. 1997; Everett and Ruiz 1993; Harvey et al. 1999). In a study of Smith Creek in northwest California, Harvey et al. (1999) found that tagged adult coastal cutthroat trout moved more frequently from pools without LWD than from pools with LWD. They hypothesized that the habitat created by LWD attracts fish, and once fish establish territory within the desirable habitat, they remain there longer. A study by Cederholm et al. (1997) on a tributary of the Chehalis River found that increasing habitat complexity by adding LWD caused an increase in winter populations of juvenile coho salmon and age-0 steelhead. It should be noted that Fausch et al. (1995) and others have criticized studies such as Harvey et al. (1999) because it is difficult to determine if increased abundance in treatment sites is due to increased populations or simply just concentrations of fishes that would have thrived equally well in other habitat. Nonetheless, several studies have documented fish species utilizing complex habitats with LWD (Bryant et al. 2007).

Freshwater macrophytes are also known to contribute to habitat complexity by changing surface water patterns, slowing water flow, trapping sediments, and altering temperature and water chemistry profiles. Through the trapping of particles by plant fronds, they also change the nature of the surrounding sediments by increasing the organic matter content and capturing smaller grain size sediment than normally occurs in uncolonized areas (Carrasquero 2001). In addition, submerged aquatic vegetation has been shown to increase hyporheic exchange, which in turn will promote nutrient cycling. For example, White (1990) found that dense vegetation hummocks promote upwelling of porewater into the rootmass, which provides nutrients that encourage and sustain vegetation growth. In these ways, aquatic vegetation can contribute to habitat complexity and food web productivity.

An indirect impact from the loss of decreased habitat complexity is an increase in nutrient loading to downstream receiving waters. Channel complexity promotes the retention of water and organic material. This retention plays an important role in the fate of nutrients in the stream channel. In a study by Mulholland et al. (1985), it was suggested that leaf litter in streams promotes nutrient retention as the leaf pack acts as a substrate for nutrient-hungry microbes. Using solute injection techniques, Valett et al. (2002) found that phosphorus uptake in channels with high LWD volumes, frequent debris dams, and fine-grained sediments was significantly greater than in channels in younger forests without these characteristics. Corroborating this finding, Ensign and Doyle (2005) conducted phosphorus injections in streams both before and after the removal of LWD and coarse-particulate organic matter (CPOM) in the channels and found that phosphate uptake decreased by up to 88 percent after LWD removal. These studies show that channel complexity increases water retention and, through CPOM and LWD retention, provides a substrate for biofilm growth. Decreased nutrient retention affects both local waterways and downstream receiving waters. Local waterways are affected through the associated reduction in primary production, and receiving waters (which are primarily located in more nutrient-impacted lowland areas) are affected through additional nutrient loading, which may lead to eutrophication. Alteration of nutrient cycling is likely to affect food web complexity, which can have a range of effects on HCP fish and invertebrate species limiting to survival, growth, and fitness.

Collectively, these studies demonstrate the importance of habitat complexity to the function and productivity of aquatic habitats. It follows that loss of habitat complexity can contribute directly to decreased growth, survival, and population productivity of HCP species.

7.6.2.2 Burial and Entrainment

Burial and entrainment are stressors that can occur as a result of a number of different submechanisms. Burial may occur as a result of excessive levels of elevated suspended sediment, reworking of bottom materials by dredging and excavation, or bank erosion and bed instability caused by riparian vegetation and/or hydraulic and geomorphic modifications. Entrainment may occur as a result of incidental capture in dredged materials, or entrainment within unstable eroding bed materials (e.g., the rapid erosion of bed materials following removal of a road-impounded wetland).

Regardless of cause, these stressors can adversely affect HCP fish and invertebrate species. The nature and magnitude of these effects are discussed in the following sections.

7.6.2.2.1 Effects on Fish and Invertebrates

Entrainment occurs when an organism is trapped in the uptake of sediments and water being removed by dredging machinery during construction and maintenance activities (Reine and Clarke 1998), or in rapid destabilizing bedload mobilized by altered channel geometry. Benthic infauna and nonmotile life-history stages (e.g., salmonid eggs, lamprey amocoetes) are particularly vulnerable to entrainment, but some motile epibenthic and demersal organisms such as burrowing shrimp, crabs, and rearing larvae and juveniles of many fish species also can be susceptible. Entrainment rates are usually described by the number of organisms entrained per cubic yard (cy) of sediment dredged (Armstrong et al. 1982).

Demersal fish, such as sculpins, suckers, and related species, are hypothesized to have the highest rates of entrainment as they reside on or in the bottom substrates. Lamprey ammocoetes also likely have a high risk of vulnerability to entrainment due to the lengthy time of residence this life-history stage spends buried in freshwater sediments. In general, fish eggs and larvae of fish that have no capacity to avoid direct dredge impacts are also at significant risk of entrainment.

Because they are nonmotile, HCP invertebrate species are less able to avoid exposure to burial and entrainment-related stressors. Although some specifics on the effects of burial are known for marine invertebrate species (Hinchey et al. 2006), data on the tolerance limits of HCP freshwater mollusks with respect to burial are more limited. However, sufficient data are available on both marine and freshwater species to draw some conclusions about the effects of burial resulting from impact submechanisms such as elevated suspended sediment levels and other sources such as construction-related dredging and fill.

Stress or mortality resulting from partial and complete burial of various mollusk species has been addressed empirically (Hinchey et al. 2006). Results of these studies indicate that species-specific responses vary as a function of motility, living position, and inferred physiological tolerance of anoxic conditions. Mechanical and physiological adaptations contribute to this tolerance. Olympia oysters have been shown to be intolerant of siltation and do best in the absence of fine-grained materials (WDNR 2006b). Thus, it can be inferred that burial of these organisms would lead to mortality. Increased fine sediment deposition has been shown to adversely affect estuarine mollusk species with low motility (Hinchey et al. 2006). Limpets in intertidal habitat are affected by burial and interference with feeding activity. In a field study in the United Kingdom, grazing by limpets was decreased by 35 percent after the addition of fine sediments, to as little as 0.04 in (1 mm) thick (50 mg/m^2), with mortality and inhibition of feeding at higher levels of fine sediment (200 mg/m^2) (Airoldi and Hawkins 2007). The mechanism of effect is postulated to be the clogging of filtering organs by fine sediments. While these marine species are unlikely to be exposed to burial as a result of fish passage projects, these data provide some insight into the potential sensitivity of freshwater species.

Burial with fine sediments has been associated with high mortality levels in freshwater mollusk species. Mussel mortality rates exceeding 90 percent have been observed following burial with silt (Ellis 1942), and burial with fines has been implicated in large-scale mortality of western pearlshell mussels in the Salmon River in Idaho (Vannote and Minshall 1982). In a survey of native freshwater mussels in the United States and Canada, it was concluded that declines in populations were caused by habitat destruction, dams, siltation, and channel modifications, with siltation a significant issue in some areas (Williams et al. 1993).

Burial with coarse sediment appears to be less problematic, provided that the stressor is short term in duration. Krueger et al. (2007) studied the effects of burial on western ridged and western pearlshell mussel species in the Similkameen River in Washington State. Interestingly, they found that mussels buried under less than 40 cm (15 inches) of coarse sediment (gravel and cobble) were able to extricate themselves. Test subjects buried at or beyond this depth suffered only a 10 percent mortality rate over the 6-week period. However, none of these individuals were able to extricate themselves. This suggests that burial in coarse sediments caused by bedload scouring could lead to high rates of delayed mortality from starvation and other effects.

Krueger et al. (2007) also studied the effects of suction dredge entrainment on these two species of mussels. The test subjects entrained through the dredge showed no evidence of mortality or significant injury. This suggests that freshwater mollusk species may be relatively insensitive to entrainment-related effects. This is intuitively logical, as these species occur in environments where mobilization of coarse bedload is common. This suggests the likelihood of evolutionary adaptation to protect against mechanical injury from bedload mobility. However, the authors cautioned that their findings were applicable only to the adult life-history stages studied. The sensitivity of juvenile mussel species to entrainment remains unknown. This uncertainty would be expected to extend to the juvenile life-history stages of other HCP invertebrate species as well.

Mollusk larvae and juveniles are expected to be highly sensitive to the effects of entrainment and burial and are assumed to suffer high mortality from mechanical injury, smothering, anoxia, starvation, or desiccation. However, in the case of freshwater mussels, stressor exposure would have to be extensive to result in significant population-level effects. As an example, the issue of larval oyster mortality caused by dredge entrainment was studied in detail Chesapeake Bay. Lunz (1985) concluded that even if entrained larvae suffered 100 percent mortality, the absolute effects would be relatively limited because the dredge would entrain only a small fraction of larvae in the vicinity. The estimated mortality rate for oyster larvae ranged between 0.005 and 0.3 percent of total abundance. These effects are insignificant in comparison to natural mortality rates. Many species, particularly marine fish and invertebrates, have planktonic larval life-history stages that suffer naturally high mortality rates (in some cases exceeding 99 percent) (Lunz 1985). Therefore, it is likely that larval mortality from burial and/or entrainment is relatively insignificant when viewed from the perspective of natural population dynamics. Moreover, in the case of freshwater mussels, the potential for adverse effects is further limited by the fact that the parasitic glochidia life-history stage resides in the gills of host-fish where stressor exposure is less likely to occur.

The other freshwater mollusks, great Columbia River spire snail and giant Columbia River limpet, hatch from the egg fully formed. Therefore, these species would be expected to have a higher level of sensitivity to the effects of burial and entrainment.

7.6.2.3 Altered Groundwater/Surface Water Interactions

Alteration of groundwater/surface water interactions can occur as a result of two specific impact mechanisms, riparian vegetation modifications and hydraulic and geomorphic modifications. The interplay between groundwater and surface water in the hyporheic zone has become increasingly recognized as a key process in the ecological functioning of riverine ecosystems. Therefore, perturbation of this important ecological process has potentially broad-reaching consequences.

7.6.2.3.1 Effects on Fish and Invertebrates

The interface between flow within the hyporheic zone and the stream channel is an important buffer for stream temperature (Poole and Berman 2001a); therefore, the alteration of groundwater flow or hyporheic exchange can affect stream temperature. The magnitude of the influence depends on many factors, such as stream channel pattern and depth of the aquifer (Poole and Berman 2001a). Stream temperature has been shown to be an important factor in determining the suitability of habitats for aquatic species. For example, in Montana, the distribution and abundance of bull trout is influenced by hyporheic and groundwater–surface water exchange (Baxter and Hauer 2000). Female bull trout tend to choose areas of groundwater discharge (i.e., cooler temperatures) for locating their spawning, and upwelling sites serve as important thermal refugia for all life-history stages (Baxter and McPhail 1999). The preferential selection of spawning substrates in groundwater upwelling zones is a common behavior among all HCP salmonid species (Baxter and Hauer 2000; Berman and Quinn 1991; Bjornn and Reiser 1991; Ebersole et al. 2003; Geist 2000; Geist and Dauble 1998; Geist et al. 2002; Greig et al. 2007; Zimmermann and Lapointe 2005). Activities that adversely affect groundwater upwelling may limit the availability and suitability of spawning and thermal refuge habitats.

More broadly, hyporheic exchange has been shown to influence water quality and food web productivity in flowing water ecosystems at multiple levels (Anbutsu et al. 2006; Ensign and Doyle 2005; Fernald et al. 2006; Jones et al. 1995; Lefebvre et al. 2005; Mulholland et al. 1997; Sheibley, Duff et al. 2003; Sheibley, Jackman et al. 2003; Tonina and Buffington 2003; Tonina and Buffington 2007; Triska et al. 1989; Valett et al. 2005). Given these dynamics, riparian vegetation or hydraulic and geomorphic modifications that alter hyporheic zone functions are likely to impose some level of indirect effects on aquatic habitat conditions. By extension, this suggests the potential for adverse effects on HCP species dependent on these environments.

8.0 Cumulative Effects

This section provides an assessment of the cumulative effects that each of the fish passage subactivity types evaluated in this white paper may have on the HCP species. This assessment has three primary emphases: (1) the cumulative effect of all direct and indirect effects associated with all the impact mechanisms associated with a given type of project; (2) the cumulative effects of multiple fish passage structures distributed throughout the landscape; and (3) sequential fish passage facilities that have a cumulative effect on individual fish populations.

As frequently stated throughout this white paper, with the exception of specific classes of weirs, all fish passage projects are intended to improve the condition of fisheries resources by restoring fish passage to mitigate the effects of man-made perturbations on the environment. While the benefits of providing fish passage are clear and objectively measured, each fish passage subactivity type is likely to produce an array of intended as well as unforeseen consequences.

The majority of the negative effects associated with fish passage activities occur as a result of two discrete impact mechanisms: construction and maintenance; and subsequent changes resulting in ecosystem fragmentation. The effects of fish passage projects realized through other impact mechanisms, such as hydraulic and geomorphic modifications and effects on aquatic and riparian vegetation, are expected to be minor in comparison. Construction-related effects are temporary to short term in nature, while effects on ecosystem fragmentation are long term in nature and more pervasive. Consequently, cumulative impacts associated with construction phase activities are unlikely to occur unless multiple projects are being constructed simultaneously and in proximity to each other. In contrast, the cumulative effects of altered fish passage and the upstream transport of allochthonous nutrients have significant potential for cumulative effects on ecosystem structure and function.

The latter category of cumulative effects is, on balance, expected to be beneficial. Restoration of access to historic habitats is widely recognized as a key element in strategies for the restoration of native aquatic fauna (Roni et al. 2002). However, it must also be recognized that each of the fish passage subactivity types may not equally restore full access to all migratory species that historically utilized the affected habitat. Equally important, subactivity types intended to block upstream dispersal of non-native species may broadly affect the migration of nontarget species. The cumulative effects of these types of perturbations are twofold. First, altered passage conditions may impose selection pressures on HCP species, altering the genetic diversity of the affected population. Second, altering the range, abundance, and diversity of species able to access historic habitats is likely to alter the adaptive trajectory of the ecosystem in ways that are difficult to predict.

Speculatively, the cumulative effects of the fish passage projects are on balance expected to be beneficial to HCP species as a whole. However, some detrimental effects may occur as a result of the broad application of this activity type across the landscape due to the effects of stressors that are difficult to predict and/or assess.

9.0 Potential Risk of Take

This section provides an assessment of the risk of take resulting from the impact mechanisms associated with the fish passage activity type. In the current regulatory environment, fish passage structures, whether removing/replacing/retrofitting a culvert to provide for increased fish passage or developing a fish ladder over a dam or weir, are often intended to improve fish passage conditions relative to the existing state. Current culvert regulations also require that specific design guidance be followed to ensure that passage is provided under most circumstances. However, while it is acknowledged that fish passage structures often provide beneficial improvements in passage conditions, for the purpose of assessing risk of take, the baseline condition for this analysis is the stream system in the absence of artificial structures affecting fish migration.

Similar to the direct and indirect effects evaluation in Section 7 (*Direct and Indirect Effects*), the risk of take analysis for trap-and-haul operations only considers the effects of the operation itself, and not the effects of the barrier structures that necessitate the operation. Trap-and-haul operations are expected to be associated with weirs, dams, or some other type of flow control structure. The effects of weirs installed solely to manage fish passage and related risk of take are addressed in this white paper, while the effects of dams and other flow control structures are assessed in the Flow Control Structures white paper (Herrera 2007b).

The risk of take resulting from stressor exposure caused by construction and/or operation of fish passage subactivity types will vary by species depending on the nature of stressor exposure, as well as the sensitivity of the species and life-history stage exposed to the stressor. The magnitude, timing, duration, and frequency of each impact mechanism will vary widely with project scale and location. Therefore, the assessment of risk of take associated with each impact mechanism is necessarily broad and applies a “worst-case scenario” standard. This assessment must take into consideration the species occurrence and life-history specific uses of habitats where fish passage facilities are typically developed. The following rating criteria and assumptions are used to rate risk of take:

The risk of take is rated by impact mechanism for each species using the criteria presented in Table 6-3. As noted, the risk of take rating criteria are defined as follows:

- **High risk of take (H)** ratings are associated with:
  - ☐ Stressor exposure is likely to occur with high likelihood of individual take in the form of direct mortality, injury, and/or direct or indirect effects on long-term survival, growth, and fitness potential due to long-term or permanent alteration of habitat capacity or characteristics. Likely to equate to a Likely to Adversely Affect (LTAA) finding.

- **Moderate risk of take (M)** ratings are associated with:
  - Stressor exposure is likely to occur causing take in the form of direct or indirect effects potentially leading to reductions in individual survival, growth, and fitness, and/or short-term to intermediate-term alteration of habitat characteristics. May equate to an LTAA or a Not Likely to Adversely Affect (NLTAA) finding depending on specific circumstances.
- **Low risk of take (L)** ratings are associated with:
  - Stressor exposure is likely to occur causing take in the form of temporary disturbance and minor behavioral alteration. Likely to equate to an NLTAA finding.
- **Insignificant or discountable risk of take (I)** ratings apply to:
  - Stressor exposure may potentially occur, but the likelihood is discountable and/or the effects of stressor exposure are insignificant. Likely to equate to an NLTAA finding.
- **No risk of take (N)** ratings apply to species with no likelihood of stressor exposure because they do not occur in habitats that are suitable for the subactivity type in question, or the impact mechanisms caused by the subactivity type will not produce environmental stressors.
- **Unknown risk of take (?)** ratings apply to cases where insufficient data are available to determine the probability of exposure or to assess stressor response.

The risk of take summary is organized by subactivity and impact mechanism category. In the following subsections, a description of the risk of take associated with each subactivity type is provided by impact mechanism and submechanism, with reference to the general risk of take associated with the impact mechanisms and stressors that are common across each subactivity type. Where appropriate, a specific risk of take discussion is provided where the effects of a given impact submechanism are unique to that subactivity type.

The narrative summary is supported by risk of take assessment matrices for each subactivity type summarizing the overall risk of take for each of the 52 HCP species by impact mechanism category and environment (Tables 9-1 through 9-5, presented at the end of the narrative portion of Section 9). These matrices consolidate the risk of take at the mechanism of impact level. The summary risk of take presented in the narrative and the matrices for each impact mechanism category represents the greatest overall risk of take from each of the impact submechanisms in that category.

9.1 Culverts

Culvert removal, replacement, or retrofitting for fish passage purposes can produce a number of environmental stressors with the potential to impose risk of take of HCP species. The degree of risk associated with each of these impact mechanisms varies depending on the nature of the specific activity and site conditions. Some mechanisms are expected to produce stressors with relatively low risk of take due to their limited extent and/or short-term nature. For example, culvert retrofits are not expected to cause riparian modification of any significance; therefore, the resulting stressors are expected to be minor and the risk of take low. In contrast, some submechanisms may result in stressors with the potential to produce direct mortality or injury, or long-term modifications in habitat conditions detrimental to survival, growth, and fitness. For example, in the case of culvert removal or replacement, construction will require significant in-water work and channel modification. Stressors associated with these activities would be associated with a high risk of take.

The risk of take associated with this subactivity type is summarized by impact mechanism as follows:

- Construction and Maintenance: This impact mechanism is associated with a high risk of take due to the potential for direct injury or mortality from multiple impact submechanisms.

- Water Quality Modifications: This impact mechanism is associated with a high risk of take due to the potential for short-term water quality impacts that can cause direct mortality or injury. In most cases, however, a moderate risk of take is more appropriate.

- Riparian Vegetation Modifications: This impact mechanism is associated with a low risk of take for the majority of cases because the physical extent of riparian vegetation modification is likely to be limited. However, in certain circumstances (i.e., where removal or replacement dewaters upstream impoundments), riparian vegetation effects may be more pronounced, resulting in a moderate risk of take due to their intermediate-term duration.

- Aquatic Vegetation Modifications: This impact mechanism is associated with a low risk of take for the majority of cases because the physical extent of aquatic vegetation modification is likely to be limited. However, in certain circumstances (i.e., where removal/replacement dewaters upstream impoundments), aquatic vegetation effects may be more pronounced, resulting in a low to moderate risk of take (depending on species-specific reliance on aquatic vegetation) due to their intermediate-term duration.

- Hydraulic and Geomorphic Modifications: This impact mechanism is associated with a low risk of take for the majority of cases because the physical extent of hydraulic and geomorphic effects is expected to be limited. However, culverts that created upstream impoundments may cause more extensive hydraulic and geomorphic effects that are intermediate term in duration. These special cases are associated with a high risk of take due to the potential for direct mortality or injury in species reliant on the affected habitats.

- Ecosystem Fragmentation: This impact mechanism is associated with a high risk of take for culvert fish passage projects because even a well-designed structure may pose some risk of long-term ecosystem fragmentation in comparison to the natural system baseline. This may occur through effects on fish passage, or hydraulic and geomorphic effects.

In this white paper, the risk of take ratings for the culvert subactivity type are based on the worst-case scenario anticipated for each of the impact mechanisms. This means that the rating for a given impact mechanism is based on the approach (i.e., removal, replacement, or retrofitting) that is likely to produce stressors of the greatest magnitude. Additional discussion of the impact submechanisms associated with each of these impact mechanisms and justification for associated risk of take ratings is provided in Section 9.6 (*Risk of Take Associated with Common Impact Mechanisms and Stressors*). These risk of take ratings apply to species that occur in habitats suitable for this subactivity type. Species-specific risk of take ratings by impact mechanism are provided in Table 9-1 (presented at the end of the narrative portion of Section 9).

9.2 Fish Ladders/Fishways

The impact mechanisms associated with fish ladders and fishways produce a number of environmental stressors with the potential to impose risk of take of HCP species. The degree of risk associated with each of these impact mechanisms varies. Some mechanisms are expected to produce stressors with relatively low risk of take due to their limited extent and/or short-term nature. In contrast, some submechanisms may result in stressors with the potential to produce direct mortality or injury, or long-term modifications in habitat conditions detrimental to survival, growth, and fitness. These impact mechanisms would be associated with a high risk of take.

The risk of take associated with this subactivity type is summarized by impact mechanism as follows:

- Construction and Maintenance: This impact mechanism is associated with a high risk of take due to the potential for direct injury or mortality from multiple impact submechanisms.

- Water Quality Modifications: This impact mechanism is associated with a high risk of take due to the potential for short-term water quality impacts that can cause direct mortality or injury. In most cases, however, a moderate risk of take is more appropriate.

- Riparian Vegetation Modifications: This impact mechanism is associated with a low risk of take for the majority of fishways because the physical extent of riparian vegetation modification is likely to be limited. However, in certain circumstances riparian vegetation effects may be more pronounced, resulting in a high risk of take.

- Aquatic Vegetation Modifications: This impact mechanism is associated with a low risk of take for the majority of fishways because the physical extent of aquatic vegetation modification is likely to be limited.

- Hydraulic and Geomorphic Modifications: This impact mechanism is associated with a low risk of take for the majority of fishways because the physical extent of hydraulic and geomorphic effects is expected to be limited.

- Ecosystem Fragmentation: This impact mechanism is associated with a high risk of take because fish ladders pose at least some risk of long-term ecosystem fragmentation in comparison to the natural system baseline.

Additional discussion of the impact submechanisms associated with each of these impact mechanisms and justification for associated risk of take ratings is provided in Section 9.6 (*Risk of Take Associated with Common Impact Mechanisms and Stressors)*. These risk of take ratings apply to species that occur in habitats suitable for this subactivity type. Species-specific risk of take ratings by impact mechanism are provided in Table 9-2 (presented at the end of the narrative portion of Section 9).

9.3 Roughened Channels

The impact mechanisms associated with the creation of roughened channels present several environmental stressors that lead to potential risk of take of HCP species. The degree of risk associated with each of these impact mechanisms varies, but this subactivity type is generally associated with a relatively high risk of take in total. This conclusion is based on the following rationale for each impact mechanism:

- Construction and Maintenance: Roughened channel creation may require extensive in-channel work involving one or more impact submechanisms with the potential for direct injury or mortality. This equates to a high risk of take.

- Water Quality Modifications: Extensive in-channel work requirements and the large wetted area footprint of this type of structure suggest the potential for relatively extensive short-term water quality impacts in comparison to other fish passage subactivity types. This impact mechanism can be associated with a high risk of take in some cases, as many water quality impacts have the potential to cause direct mortality or injury in sensitive species experiencing acute exposure. In many cases, however, a moderate risk of take is more appropriate because stressor exposure is more likely to result in nonlethal responses, and these stressors are typically short term in duration.

- Riparian Vegetation Modifications: This impact mechanism is associated with a moderate risk of take because the physical extent of riparian vegetation modification associated with construction is likely to be relatively extensive in comparison to other fish passage subactivity types. However, these effects are likely to be intermediate term in nature, as this subactivity type lends itself to riparian restoration.

- Aquatic Vegetation Modifications: Where aquatic vegetation is an important component of the riverine landscape, the physical extent of aquatic vegetation modification associated with roughened channel creation is likely to be relatively extensive in comparison to other fish passage subactivity types. Because these effects are expected to be short term to intermediate term in nature, this impact mechanism imposes a moderate risk of take.

- Hydraulic and Geomorphic Modifications: This impact mechanism is associated with a high risk of take for this subactivity type. This conclusion is based on the specific design challenges posed by this subactivity type, which creates the potential for unexpected and potentially adverse hydraulic and geomorphic conditions to develop over time.

- Ecosystem Fragmentation: This impact mechanism is associated with a high risk of take because roughened channel designs pose at least some risk of long-term ecosystem fragmentation in comparison to a natural stream baseline.

Additional discussion of the impact submechanisms associated with each of these impact mechanisms and justification for associated risk of take ratings is provided in Section 9.6 (*Risk of Take Associated with Common Impact Mechanisms and Stressors).* These risk of take ratings apply to species that occur in habitats suitable for this subactivity type. Species-specific risk of take ratings by impact mechanism are provided in Table 9-3 (presented at the end of the narrative portion of Section 9).

9.4 Weirs

The impact mechanisms associated with weirs produce a number of environmental stressors with the potential to impose risk of take of HCP species. The degree of risk associated with each of these impact mechanisms varies. Some mechanisms are expected to produce stressors with relatively low risk of take due to their limited extent and/or short-term nature. In contrast, some submechanisms may result in stressors with the potential to produce direct mortality or injury, or long-term modifications in habitat conditions detrimental to survival, growth, and fitness. These impact mechanisms would be associated with a high risk of take.

The risk of take associated with this subactivity type is summarized by impact mechanism as follows:

- Construction and Maintenance: This impact mechanism is associated with a high risk of take due to the potential for direct injury or mortality from multiple impact submechanisms.

- Water Quality Modifications: This impact mechanism is associated with a high risk of take due to the potential for short-term water quality impacts that can cause direct mortality or injury. In most cases, however, a moderate risk of take is more appropriate.

- Riparian Vegetation Modifications: This impact mechanism is associated with a low risk of take for the majority of weirs because the physical extent of riparian vegetation modification is likely to be limited. However, in certain circumstances (i.e., permanent weirs installed to prevent upstream passage), riparian vegetation effects may be more pronounced, resulting in a high risk of take.

- Aquatic Vegetation Modifications: This impact mechanism is associated with a low risk of take for the majority of fish passage weirs because the physical extent of aquatic vegetation modification is likely to be limited.

- Hydraulic and Geomorphic Modifications: This impact mechanism is associated with a low risk of take for the majority of fish passage weirs because the physical extent of hydraulic and geomorphic effects is expected to be limited.

- Ecosystem Fragmentation: The risk of take associated with this impact mechanism varies depending on the type of weir. Temporary weirs installed for fisheries management purposes are expected to produce only minor and temporary effects associated with a low risk of take. In contrast, permanent weirs intended to promote passage or to restrict passage of undesirable species are associated with a high risk of take because of the broad implications of unintended effects on movement of HCP species and on ecological processes.

Additional discussion of the impact submechanisms associated with each of these impact mechanisms and justification for these risk of take ratings is provided in Section 9.6 (*Risk of Take Associated with Common Impact Mechanisms and Stressors)*. These risk of take ratings apply to species that occur in habitats suitable for this subactivity type. Species-specific risk of take ratings by impact mechanism are provided in Table 9-4 (presented at the end of the narrative portion of Section 9). These ratings reflect the worst-case scenario for effects imposed by permanent weirs intended to manage fish passage.

9.5 Trap and Haul

The majority of trap-and-haul facilities are expected to be associated with a weir or some other type of flow control structure (with rare exceptions for trap-and-haul operations at natural barriers). For the purpose of this analysis, the construction and operational effects of these structures and related risk of take are addressed either earlier in this white paper, or have been addressed in the Flow Control Structures white paper (Herrera 2007b) and are therefore not considered further here. Species-specific risk of take ratings by impact mechanism are provided in Table 9-5 (presented at the end of the narrative portion of Section 9).

9.5.1 Operational Activities

Trap-and-haul operations are associated with a high risk of take because this subactivity type involves the capture, handling, transport, and release of fish. These actions will invariably produce the potential for direct or delayed mortality from stress or injury, even when the most thoughtful precautions are taken. Moreover, the very acts of capture and handling constitute take as defined for the purpose of Section 7 ESA consultations.

The risk of take for nontarget species is generally considered to be low. Some potential for take exists via the introduction of toxic substances from accidental spills during operations. However, this potential is limited if proper BMPs are in place. Therefore, the risk of take for freshwater species that are not typically subject to trap-and-haul operations is expected to be low. Exceptions include those HCP invertebrate species, specifically western ridged mussels, that are dependent on migratory salmonids that are typically the target species for this subactivity type. This invertebrate species would be expected to incur a high risk of take due to the long-term indirect effects of fish passage operations on host-fish species.

9.5.2 Ecosystem Fragmentation

Depending on specific configuration, the trap-and-haul subactivity type can impose a number of unintended effects related to ecosystem fragmentation. Imposing an artificial management regime during a critical phase in the life history of migratory fish species has the potential to create selection pressures that partially disconnect the adaptive capacity of the affected population from the natural environment. Alteration of migratory corridors by modifying release location may lead to decreased survival, fitness, and/or spawning productivity, potentially affecting long-term population viability. These effects would extend indirectly to obligate species (e.g., freshwater mussels) that are dependent on affected host-fish species. Finally, any effects that reduce or modify the upstream transport of allochthonous nutrients may lead to altered food web productivity, an effect with broad consequences for all HCP species occurring in affected habitats. Given the range and breadth of these potential effects, as well as the typical longevity of trap-and-haul operations (which are usually associated with long-lived structures such as dams), ecosystem fragmentation must be associated with a high risk of take.

9.6 Risk of Take Associated with Common Impact Mechanisms and Stressors

This section identifies the estimated risk of take for HCP species associated with the ecological stressors imposed by impact mechanisms common across fish passage subactivity types. The intent of this combined discussion is to maintain parallel organizational structure with Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors*) for ease of reference. Section 9.6.1 (*Common Impact Mechanisms*) provides a general discussion of the risk of take associated with each impact mechanisms by component submechanism, as well as the rationale for the rating selected. Section 9.6.2 (*Common Submechanisms Imposed by Multiple Impact Mechanisms*) provides a similar discussion for common submechanisms that are imposed by multiple impact mechanisms. Again, the intent is to maintain parallel structure with Section 7.6 (*Ecological Effects of Common Impact Mechanisms and Stressors*).

The information presented in this section is also intended to provide supporting context and detail for the risk of take discussion for each subactivity type provided in Sections 9.1 through 9.5, and the species-specific risk of take ratings provided in Tables 9-1 through 9-5 (presented at the end of the narrative portion of Section 9).

9.6.1 Common Impact Mechanisms

The following are common impact mechanisms associated with all fish passage subactivity types (with the exception of trap-and-haul programs):

- Construction and maintenance
- Water quality modifications
- Riparian vegetation modifications
- Aquatic vegetation modifications
- Hydraulic and geomorphic modifications
- Ecosystem fragmentation.

The risk of take associated with these common impact mechanisms is discussed in the following sections. As noted previously, the trap-and-haul subactivity type is somewhat unusual in that it does not require the creation of any structures but does involve annual operational activities. Because trap-and-haul operations have fewer impact submechanisms in common with the other fish passage subactivity types, only the common discussions of risk of take associated with fish capture and handling and fish passage barrier submechanisms presented in this section are pertinent. The risk of take ratings associated with the unique trap-and-haul impact submechanisms are discussed in Section 9.5 (*Trap and Haul*).

The risk of take ratings presented in the following sections represent the worst-case scenario of construction impacts associated with each subactivity type. When interpreting the ratings for common stressors, the mitigating factors affecting risk of take specific to each subactivity type must be considered, which are described in Sections 9.1 through 9.5.

9.6.1.1 Construction and Maintenance

The construction and maintenance of any type of fish passage related structure will inherently impose ecological stressors of varying severity that pose potential risk of take of HCP species. Risk of take ratings for each construction and maintenance submechanism are presented below.

9.6.1.1.1 Equipment Operation and Materials Placement

The construction of fish passage structures will invariably involve the use of heavy machinery and the placement of structural materials in and around the stream channel. Use of machinery (e.g., excavators) will generate noise and visual and physical disturbance. Underwater noise is potentially the most intense of these stressors and has the greatest potential to cause direct injury or mortality. Although no studies have addressed equipment noise associated specifically with construction of fish passage structures, many studies have addressed noise associated with pile driving, general underwater construction, and underwater tool use (see Section 7.6.1.1 [*Construction and Maintenance*] under Section 7.6 [*Ecological Effects of Common Impact Mechanisms and Stressors*]).

The risk of take associated with this impact submechanism will vary depending on the type of structure and the intensity of construction-related activities. At a minimum, underwater noise and visual and physical disturbance are likely to displace HCP fish species from occupied habitats, and otherwise modify behavior in ways that could affect survival, growth, and fitness. At worst, construction activities that produce intense underwater noise (e.g., installation of steel piles to support a fish ladder chute using an impact hammer) could lead to direct injury or mortality.

Until recently, NOAA Fisheries and USFWS recognized underwater noise levels of 150 dB_{RMS} and 180 dB_{peak} as thresholds for disturbance and injury, respectively, of federally listed salmonid species (Stadler 2007, Teachout 2007). While the disturbance threshold still stands, on April 30, 2007, NOAA Fisheries established the following dual criteria to evaluate the onset of physical injury to fishes exposed to underwater noise from impact hammer pile driving (NMFS 2007b) (exceeding either criterion equals injury):

- SEL: A fish receiving an accumulated Sound Exposure Level (SEL) at or above 187 dB re: one micropascal squared-second during the driving of piles likely results in the onset of physical injury; a simple accumulation method shall be used to sum the energy produced during multiple hammer strikes.

- Peak SPL: A fish receiving a peak sound pressure level (SPL) at or above 208 dB re: one micropascal from a single hammer strike likely results in the onset of physical injury.

While these new criteria accommodate a more comprehensive evaluation of the effects of sound exposure, it is difficult to compare the SEL threshold to established reference values, which are typically reported in dB_{RMS} or dB_{peak} units. In general, pile driving activities with the greatest potential to cause injury involve large diameter steel pilings placed with an impact hammer. Injury and mortality resulting from underwater noise exposure is equated with a high risk of take. Smaller diameter wooden pilings placed with a vibratory hammer present the lowest potential for injury and are likely to result in take only in the form of temporary disturbance and behavioral alteration. This would equate to a moderate risk of take.

The risk of take for HCP invertebrate species associated with underwater noise and visual disturbance is far less certain. Understanding of the sensitivity of invertebrate species to underwater noise and visual disturbance is limited. However, direct physical disturbance will most certainly constitute risk of take. Depending on the nature and severity of the disturbance, the risk of take could range from moderate (e.g., from displacement) to high (e.g., from crushing or other forms of mechanical injury).

9.6.1.1.2 Dewatering and Handling

Temporary dewatering and flow bypass with fish removal and relocation from work areas are common and necessary practices during construction and maintenance of fish passage structures. Even when dewatering is not required for construction and maintenance, exclusion areas are often created around the work sites to contain sediments and other pollutants as well as to reduce the magnitude of stressor exposure. This construction and maintenance activity poses a relatively high risk of take. Well-designed protocols and trained personnel are necessary to avoid high levels of mortality. Even with appropriate protocols and experienced field crews, high levels of mortality can result. For example, NOAA Fisheries evaluated take associated with dewatering and handling in a recent biological opinion. They estimated that cumulative salmonid mortality rates may range as high as 13 percent, even when trained personnel are used, from the combined effects of stranding and electroshock mortality. They assumed an electroshocking related injury rate of 25 percent (NMFS 2006).

Mortality rates may be even higher in areas with complex substrate and bathymetry. During the egg, larval, or juvenile life-history stage of many species, individuals may be too small or too cryptic to collect and relocate effectively (e.g., juvenile salmonids hiding in cobble interstices, river lamprey amocoetes buried in fine substrate, larval or juvenile dace, larvae and juveniles of HCP invertebrate species). Mortality is the expected outcome for any individuals stranded within the exclusion area. Even in the absence of mortality, fish handling and relocation may result in stress and injury, as well as increased competition for forage and refuge in the relocation habitat. Moreover, the act of capture, handling, or forced behavioral modification of an ESA-listed species constitutes harassment, which is considered a form of take. Thus, the permitting of channel and work area dewatering poses a high risk of take of varying levels of severity, depending on habitat and species and life-history stage-specific factors.

In addition to these effects, the act of dewatering the stream and redirecting flow may pose a barrier to fish migration. Delays in migration can lead to adverse effects on spawning fitness, can increase exposure to predation and poaching, and can deny juvenile fish access to rearing habitats during critical periods. These effects constitute a moderate risk of take of HCP species with migratory life-history stages.

9.6.1.1.3 Dredging and Fill

Dredging and fill activities associated with construction would ideally be conducted within a dewatered exclusion area to limit risk of take on HCP species. Should this activity occur in the open channel, however, it presents the potential for high risk of take from two specific stressors, burial and entrainment. The sensitivity to these stressors generally varies by species and life-history stage. However, each HCP species that occurs in freshwater environments where fish passage subactivity types are likely to be implemented has at least one life-history stage with a high likelihood of suffering mortality or injury when exposed to either of these two stressors. Therefore, dredging and fill activities must be associated with a high risk of take.

9.6.1.2 Water Quality Modifications

The installation and operation of fish passage structures can result in water quality modifications through three primary pathways: short-term construction-related effects; riparian vegetation and hydraulic and geomorphic modifications; and ecosystem fragmentation effects, specifically changes in the upstream transport of allochthonous nutrients that alter nutrient cycling. The latter two types of perturbations are intermediate term to long term in nature. The risk of take associated with water quality impact submechanisms are described in the following sections.

9.6.1.2.1 Altered Temperature Regime

Fish passage subactivity types have the potential to alter aquatic temperature regimes through a variety of mechanisms, although generally the extent of these effects would be expected to be quite limited. The predominant mechanisms through which this would occur are through alterations of riparian vegetation, reducing shading, altering ambient air temperatures, and altering groundwater/surface water interactions. Because the extent of riparian vegetation modification associated with the fish passage structures is generally expected to be limited in comparison to other activity types, the magnitude of these effects is similarly expected to be limited. In addition, most riparian vegetation modification associated with fish passage structures is likely to be associated with construction impacts and therefore subject to restoration. This implies that any modest temperature effects would be intermediate term in nature.

Hydraulic and geomorphic modifications can also lead to alterations in temperature regime. Specifically, certain types of weir structures may create impoundments that expand surface area, increasing solar radiation inputs and affecting groundwater and surface water exchange. Ideally, permanent weirs intended to manage fish passage would be designed to minimize hydraulic and geomorphic modifications to the greatest extent possible to limit these temperature-related effects. However, in certain cases, some long-term effects on stream temperatures are possible. This may influence habitat suitability, affecting survival, growth, and fitness of HCP species using the affected habitat.

On this basis, the risk of take from altered temperature regime is expected to range from low to moderate depending on the specific subactivity type and circumstances.

9.6.1.2.2 Elevated Suspended Sediments

Construction of fish passage structures is likely to result in bank and channel disturbance through the use of heavy equipment, materials placement, dredging and fill, and rewatering of exclusion areas. This disturbance is in turn likely to produce a short-term increase in suspended sediment loading to riverine environments downstream of the structure. In certain cases, such as culvert removal or replacement that dewaters upstream impoundments, subsequent geomorphic effects may lead to ongoing bank and channel bed erosion. This is likely to lead to a chronic elevation in suspended sediment load as the channel adjusts to the new hydraulic and hydrologic regime. The effects of elevated suspended sediments vary depending on the magnitude of the stressor and the sensitivity of the species or life-history stage exposed to the stressor.

Nonmotile species or life-history stages exposed to pulses of high concentrations of suspended sediments may suffer direct mortality, injury, or extreme physiological stress, while motile species may be able to avoid these stressors. Stressors of this magnitude would typically be expected during the construction phase and would occur most likely as short-term construction-related impacts. Chronic elevation in suspended sediment levels caused by channel adjustments in downstream reaches would be less likely to reach levels sufficient to cause direct mortality but may affect growth and fitness over the intermediate to long term.

Given the potential for short-term injury or mortality resulting from elevated suspended sediment levels associated with construction, a high risk of take must be assumed for this submechanism for HCP species that occur in riverine habitat types where this activity type is likely to be implemented.

9.6.1.2.3 Altered Dissolved Oxygen

Generally, the direct effects of fish passage subactivity types on dissolved oxygen conditions are not expected to be significant, and the risk of take associated with these effects is insignificant. However, indirect effects on dissolved oxygen conditions may occur as a result of improved ecosystem connectivity and hydraulic and geomorphic modifications. These effects may be more measurable.

In the case of ecosystem connectivity, increased upstream delivery of allochthonous nutrients, particularly large quantities of marine-derived nutrients in the form of salmon carcasses, has the potential to significantly increase ecosystem productivity. This in turn could increase biochemical oxygen demand resulting in decreased dissolved oxygen levels in certain cases. Restoration of fish passage to relatively unimpaired stream systems would generally not be expected to produce these conditions. However, should passage be restored to systems that are in a eutrophic state due to nutrient pollution from other sources, more extensive effects could occur.

Dissolved oxygen depletion as a result of hydraulic and geomorphic modifications would only be expected to occur in certain circumstances. Specifically, fish passage subactivity types that result in dewatering of upstream impoundments (e.g., removing or replacing culverts) can result in the release of a pulse of sequestered nutrients when fine sediments in the impoundment bed are scoured. This is most likely to occur when large wetland areas are created by artificial barriers. A large pulse of nutrients could cause temporary eutrophication that, depending on the nature of the downstream environment, could cause a relatively rapid decrease in dissolved oxygen levels with the potential to adversely affect HCP species.

For example, alteration of flow regime and inundation frequency in saltmarsh and wetland environments has been demonstrated to cause depleted oxygen conditions as organic matter in anoxic soils becomes exposed and available for aerobic decomposition. These combined effects have been demonstrated in saltmarsh ecosystems regulated by tide gates to deplete dissolved oxygen concentrations below levels sufficient to cause fish mortality. Freshwater wetland environments would be expected to experience somewhat similar effects, where the operative physical, biological, and chemical processes are comparable. Even in the absence of mortality, stress from dissolved oxygen depletion in combination with increased water temperatures and poor habitat suitability may lead to decreased survival, growth, and fitness of HCP species occurring within the modified habitat. Due to the short- to intermediate-term nature of these effects in freshwater environments, these effects are equated with a moderate to high risk of take for species occurring in the affected environment. Nonmotile species and life-history stages are most likely to experience high risk of take because they lack the capacity for behavioral avoidance.

9.6.1.2.4 Altered pH

The construction of fish passage structures can in some cases lead to the temporary alteration of pH levels. Many types of fish passage structures are constructed using concrete, a material that produces caustic leachate while curing. Concrete leachate released to surface waters from runoff or curing surfaces “in the wet” can increase pH levels well beyond levels capable of causing injury or mortality of all HCP species. This effect is typically short term in nature and moderates as the concrete cures, and is easily minimized using appropriate BMPs. However, due to the significant level of potential adverse effects, this stressor is equated with a high risk of take.

9.6.1.2.5 Introduction of Toxic Substances

The primary pathway through which fish passage structures could introduce toxic substances into the aquatic environment is accidental spills from heavy equipment during construction. Depending on the nature and concentration of the contaminant, toxic substance exposure can cause a range of adverse effects on exposed species. In extreme cases, these effects can include direct mortality (e.g., exposure of nonmotile larvae to fuel spills). More commonly, intermittent low-level exposure to a variety of contaminants is likely to cause physiological injury and/or contaminant bioaccumulation, leading to decreased survival, growth, and fitness. This presents a moderate risk of take to species potentially exposed to this stressor.

9.6.1.2.6 Altered Nutrient Cycling

In general, the restoration of fish passage is expected to produce beneficial changes in nutrient cycling that are not associated with risk of take. However, as noted in Section 9.6.1.2.3 (*Altered Dissolved Oxygen)*, a large increase in delivery of allochthonous nutrients to riverine ecosystems that are already in a eutrophic state could result in undesirable conditions.

In contrast, fish passage structures that intentionally or unintentionally limit upstream passage of fish may lead to undesirable effects of a different nature. For example, decreased delivery of marine-derived nutrients to high-gradient stream systems due to downstream barriers to salmon passage is likely to decrease food web productivity, an effect that has been well documented in the literature. Decreased food web productivity will have broad and significant consequences on the survival, growth, and fitness of HCP species that utilize the affected environment. Due to the long-term nature of these effects, this stressor is associated with a high risk of take.

9.6.1.3 Riparian Vegetation Modifications

Removal of riparian vegetation can demonstrably affect the health of aquatic systems through a variety of pathways. However, the physical extent of riparian modification associated with fish passage subactivity types is generally expected to be limited. In most cases, fish passage structures will be placed in areas that are already modified by human activities, and the incremental degradation associated with their construction will be insignificant. Therefore, the degree to which shade, solar exposure, and air temperature regime are affected is likely to be at best insignificant or at worst extremely small. Therefore, the risk of take associated with this impact submechanism is expected to be low. In specific circumstances where more extensive and permanent vegetation modification occurs, a higher risk of take rating may be warranted. Examples of possible exceptions include roughened channel creation and the placement of fishways around natural passage barriers.

The risk of take associated with each riparian impact submechanism is described in further detail below.

9.6.1.3.1 Altered Shade, Solar Exposure, and Ambient Air Temperature Regime

Removal of riparian vegetation can demonstrably affect the temperatures of streams and lower order river environments, producing a range of potential effects on fish and wildlife species. Increased stream temperatures can lead to a variety of unfavorable effects on HCP species occurring in these environment types. However, the physical extent of riparian modification associated with fish passage subactivity types is generally expected to be limited. In most cases, fish passage structures will be placed in areas that are already modified by human activities, and the incremental degradation associated with their construction will be insignificant. Therefore, the degree to which shade, solar exposure, and air temperature regime are affected is likely to be at best insignificant or at worst extremely small. Therefore, the risk of take associated with this impact submechanism is expected to be low. In specific circumstances where more extensive and permanent vegetation modification occurs, a higher risk of take rating may be appropriate.

9.6.1.3.2 Altered Bank and Shoreline Stability

Removal of riparian vegetation associated with the construction of fish passage structures can affect shoreline stability through the reduction in root cohesion and the loss of LWD inputs that affect localized erosion and scour conditions. Bank erosion contributes to increased suspended sediment loading. The risk of take resulting from this stressor varies depending on species-specific sensitivity to increased turbidity (see Section 9.6.1.2.2 [*Elevated Suspended Sediments*]). In general, more motile fish species experience only temporary behavioral alteration and a low risk of take. In contrast, less motile fish life-history stages or sessile invertebrates could experience a moderate to high risk of take from decreased survival due to substrate sedimentation and burial, as well as decreased growth and fitness due to the effects of high turbidity on foraging success.

9.6.1.3.3 Altered Allochthonous Inputs

Riparian vegetation is an important source of nutrient input to the aquatic environment, strongly influencing the productivity of the aquatic food chain. Allochthonous nutrient inputs include sources such as insect-fall, leaf litter and other organic debris, and LWD inputs that contribute both organic material and habitat complexity. The importance of allochthonous inputs to riverine food web productivity decreases along a downstream gradient. However, as rivers grow in size, the contributions of autochthonous production and nutrient cycling to the food web increase. As noted, fish passage subactivity types vary in the extent to which they result in riparian vegetation modifications, but in general the magnitude of this impact mechanism is expected to be low in comparison to other HCP-permitted projects.

Given these limitations, the risk of take associated with altered allochthonous inputs is expected to be low. Further, the effects caused by riparian modifications must be considered against the probable increases in food web productivity that occur as a result of increased fish passage. In many cases, increased delivery of nutrients derived from distant downstream sources (e.g., marine-derived nutrients) would be expected to more than offset the effects of altered allochthonous inputs due to riparian modifications. On this basis, the risk of take associated with this stressor should be considered low.

9.6.1.3.4 Altered Groundwater/Surface Water Interactions

Risk of take associated with this common stressor is discussed in Section 9.6.2.3 (*Altered Groundwater/Surface Water Interactions*) under Section 9.6.2 (*Common Submechanisms Imposed by Multiple Impact Mechanisms*).

9.6.1.3.5 Altered Habitat Complexity

Risk of take associated with this common stressor is discussed in Section 9.6.2.1 (*Altered Habitat Complexity*) under Section 9.6.2 (*Common Submechanisms Imposed by Multiple Impact Mechanisms*).

9.6.1.4 Aquatic Vegetation Modifications

The effects of fish passage structures on aquatic vegetation are generally expected to be limited; however, in specific circumstances, indirect effects due to changes in nutrient cycling may occur. The in-water footprints of most fish passage subactivity types are usually relatively small, meaning that the extent of aquatic vegetation directly affected by construction will be limited. Roughened channels may be an exception, but usually these types of structures are most appropriate in high-gradient or high-velocity reaches where aquatic vegetation growth is naturally limited, or they are cut through existing floodplains and upland environments.

The potential indirect effects of fish passage projects are more likely to influence aquatic vegetation growth. Subactivity types that result in a decrease in upstream transport of allochthonous nutrients may in turn limit habitat productivity and, by extension, aquatic vegetation growth. Alternatively, the increased delivery of allochthonous nutrients derived from marine or other productive downstream sources is likely to have the opposite effect. Given the potential for ill-conceived fish passage projects to increase ecosystem fragmentation, some effects on aquatic vegetation may occur.

9.6.1.4.1 Altered Autochthonous Inputs

The extent to which autochthonous production is affected by fish passage subactivity types is, on balance, expected to be limited. In comparison to the broader effects of ecosystem fragmentation, the loss of food web productivity associated with changes in autochthonous production is expected to be low in most cases. Therefore, the risk of take associated with this submechanism is expected to be low across all subactivity types.

9.6.1.4.2 Altered Habitat Complexity

Risk of take associated with this common stressor is discussed in Section 9.6.2.1 (*Altered Habitat Complexity*) under Section 9.6.2 (*Common Submechanisms Imposed by Multiple Impact Mechanisms*).

9.6.1.5 Hydraulic and Geomorphic Modifications

Hydraulic and geomorphic modifications associated with fish passage structures are expected range considerably depending on specific circumstances. In general, however, these subactivity types are expected to have less extensive effects than activities such as the installation of large flow control structures. Risk of take associated with hydraulic and geomorphic modification impact submechanisms is discussed in the following sections.

9.6.1.5.1 Altered Flow Conditions, Channel Geometry, and Substrate Composition and Stability

Flow regime, channel geometry, and substrate composition and stability are dominant factors determining aquatic habitat structure in riverine environments. The construction and physical presence of fish passage structures can lead to alteration of physical habitat features. Because these structures are typically intended for long-term use, these habitat alterations are essentially permanent and continuous. If the effects are extensive, they can alter the productivity of the affected habitat for spawning, foraging, rearing, refuge, and other uses by HCP species. In a worst-case scenario, these effects in turn are likely to lead to reduced spawning success, as well as reduced survival, growth, and fitness for species and life-history stages dependent on the affected habitat.

In cases where hydraulic and geomorphic modifications are extensive, a broad array of research has demonstrated that detrimental effects on survival, growth, and fitness are likely to occur for many of the HCP species that occur in riverine environments. Using the criteria defined for the purpose of this white paper, effects of this nature equate to a high risk of take.

9.6.1.5.2 Altered Groundwater/Surface Water Interactions

The risk of take associated with this common submechanism is discussed in Section 9.6.2.3 (*Altered Groundwater/Surface Water Interactions*) under Section 9.6.2 (*Common Submechanisms Imposed by Multiple Impact Mechanisms*).

9.6.1.6 Ecosystem Fragmentation

Ecosystem fragmentation refers to the disruption of ecological processes by reducing the connectivity between different components of the ecosystem, or the disruption of ecological processes. The following impact submechanisms have been defined to describe the ecosystem fragmentation effects potentially imposed by fish passage projects:

- Barriers to fish passage

- Modified upstream transport of allochthonous nutrients
- Modified downstream transport of LWD, sediment, and organic material
- Altered lateral and longitudinal connectivity.

The risk of take resulting from ecological stressors imposed by these common submechanisms is described in the following subsections.

9.6.1.6.1 Barriers to Fish Passage, and Modified Upstream Transport of Allochthonous Nutrients

The fish passage activity type by definition is intended to improve fish passage conditions in most cases, the exception being the use of weirs to manage the upstream dispersal of undesirable organisms. However, fish passage projects have the potential to impose a number of barrier conditions that could potentially lead to take of HCP species. Specifically, fish passage structures or operations may fail to provide passage for all species as intended, may place unintended selection pressures on affected populations that limit or alter phenotypic diversity, or may become less effective at passing fish over time if improperly designed for the conditions present or if maintenance is neglected.

For example, culverts retrofitted with baffles or other internal structures to promote fish passage have reduced hydraulic capacity. This may in turn promote a backwater effect that leads to sediment deposition at the upstream end of the structure, creating flow conditions that limit fish passage. Fish passage structures may also limit the upstream movement of certain invertebrate species, or indirectly affect upstream dispersal through direct effects on the migration and productivity of host-fish populations.

More broadly, limitations on fish passage may in turn result in long-term reductions in the abundance of migratory fish reaching areas upstream of the barrier. This may result in decreased food web productivity by reducing the delivery of nutrients derived from allochthonous sources.

Given these potential ecosystem fragmentation effects, fish passage structures are considered to be associated with a high risk of take for HCP fish and invertebrate species that occur in affected environments.

9.6.1.6.2 Modified Downstream Transport of LWD, Organic Material, and Sediment

The risk of take associated with this submechanism varies among subactivity types. For example, culverts have the potential to become significant barriers to the transport of LWD and sediment. Should an improperly designed culvert result in the creation of an upstream impoundment, downstream transport of organic material may also be interrupted, altering nutrient cycling. While ideally designed to be transparent to downstream transport processes, weirs intended to block upstream passage of certain species may also form impoundments that alter the transport of wood, sediment, and organic material. Other types of fish passage structures, such as roughened channels and fish ladders, are generally more transparent (although the artificial structures they are intended to bypass may not be).

Modification of downstream transport processes can lead to alteration in habitat complexity, changes in nutrient cycling, and subsequent hydraulic and geomorphic modifications. Each of these perturbations is associated with some risk of take. Given the long-term nature of these effects and the significance of altered ecosystem function, the risk of take associated with this submechanism is considered high for each subactivity type unless otherwise specified in Sections 9.1 through 9.5.

9.6.1.6.3 Altered Lateral and Longitudinal Habitat Connectivity

Culvert removal and replacement projects have the potential to alter lateral and longitudinal habitat connectivity in ways that can be detrimental to HCP species. In many cases, existing culverts have arrested migrating headcuts, and removal or replacement will allow the nickpoint to continue migrating upstream causing channel downcutting. Existing undersized culverts can also cause upstream sediment aggradation that is subject to incision and downcutting when the culvert is removed. Channel downcutting from the migrating headcut can simplify channel geometry and influence the recruitment, transport, and retention of sediments and LWD. This type of channel simplification can affect habitat suitability for HCP species.

Complex channels capture and retain sediment, which promotes the formation of pools and other hydraulically complex features. This hydraulic complexity in turn encourages the sorting and deposition of sediments and organic material in diverse patches, supporting food web productivity and providing spawning and rearing habitat for a diverse array of species. This diversity of habitat patches supports a biologically diverse community. Channel simplification reduces the longitudinal distribution and frequency of these habitat patches across the riverine landscape. This reduction in habitat complexity leads to reduced food web productivity, as well as the reduced availability of habitats suitable for HCP species that occur in these environments. Because these effects are extensive and intermediate term to long term in nature, this submechanism equates to a high risk of take for HCP species.

Channel downcutting associated with headcuts can lead to fragmentation of floodplain and off-channel habitats from the riverine ecosystem. This form of ecosystem fragmentation limits the extent to which river flows interact with the floodplain and terrestrial riparian ecosystem, disconnecting the stream channel from important sources and sinks of organic matter, nutrients, and pollutants. This in turn may limit food web productivity, affecting the survival, growth, and fitness of any species dependent on the riverine environment for rearing. In addition, this loss of connectivity may limit the availability of important habitat types for HCP species. For example, side channel habitats are preferentially selected by various species of salmonids (e.g., sockeye salmon) for spawning. These habitats also provide key winter rearing and storm refuge habitats for coho salmon, steelhead, spring Chinook, native char (bull trout and Dolly Varden), and other species. Floodplain wetlands are also highly productive refuge habitats for a variety of species, such as coho salmon, during high winter flows. The reduction in suitable refuge and foraging habitat area caused by ecosystem fragmentation increases competition for remaining habitat, predation risk, and risk of displacement to habitats unfavorable for rearing. Again, because natural channel recovery is an intermediate-term to long-term process, this submechanism is associated with a high risk of take.

9.6.2 Common Submechanisms Imposed by Multiple Impact Mechanisms

Several submechanisms and their related ecological stressors can be caused by more than one impact mechanism:

- Altered habitat complexity: Caused by modification of hydraulic and geomorphic conditions, riparian vegetation, and aquatic vegetation.
- Burial and entrainment: Caused by dredging and fill, and bank and bed instability caused by modification of hydraulic and geomorphic conditions and riparian vegetation.
- Altered groundwater/surface water interactions: Caused by modification of hydraulic and geomorphic conditions and riparian vegetation.

This section provides a consolidated discussion of the risk of take for HCP species posed by each these common submechanisms.

9.6.2.1 Altered Habitat Complexity

The influence of riparian vegetation and hydraulic and geomorphic processes on riverine habitat complexity is broadly recognized. In certain riverine systems, aquatic vegetation may also play a significant role in habitat complexity. Modifications of riparian vegetation alter habitat complexity in a number of ways, primarily through the loss of undercut banks, root structure, and LWD inputs to the channel. Hydraulic and geomorphic modifications can lead to further alterations in habitat complexity. Changes in flow and sediment transport conditions can lead to channel simplification and reduced availability of valuable habitat features, limiting the productive capacity of the affected habitat.

Submerged aquatic vegetation provides habitat structure in nearshore environments, creating vertical dimension and overhead cover. Alteration of habitat complexity can decrease the availability of suitable rearing habitat for species and life-history stages dependent on the nearshore environment, leading to increased predation risk and increased competition for suitable space, leading to long-term effects on survival, growth, and fitness.

These impact mechanisms present the potential of high risk of take for a broad range of species dependent on riverine aquatic ecosystems through a variety of species-specific stressors. However, the assessment of risk must take into consideration the extent to which habitat modification is expected to occur as the result of a specific fish passage subactivity type. For example, fishways are generally expected to have limited effects on habitat complexity as a whole, which would be more than balanced by increased access to productive habitats. In contrast, weirs constructed to manage fish passage could have more broad-reaching hydraulic and geomorphic effects, influencing habitat complexity both upstream and downstream of the structure.

9.6.2.2 Burial and Entrainment

Burial and entrainment can occur as a result of several impact mechanisms, including: construction-related dredging and fill; bedload mobility induced by hydraulic and geomorphic modifications; and riparian vegetation modifications that result in bank instability and erosion. The risk of take associated with these stressors is rated from moderate to high, depending on the specific circumstances encountered. For example, burial or entrainment during dredging or materials placement would be associated with a high risk of take due to the potential for direct injury or mortality. In contrast, burial or entrainment resulting from short-term to intermediate-term hydraulic and geomorphic modifications would be associated with a moderate risk of take.

9.6.2.3 Altered Groundwater/Surface Water Interactions

Modification of hydraulic, geomorphic, and riparian vegetation through the placement of fish passage structures can influence and alter groundwater and surface water exchange in the project area and downstream. This hyporheic exchange is an important component of ecosystem function (including water quality moderation) in riverine environments. Therefore, this impact mechanism has the potential to affect juvenile and/or adult survival, growth, and fitness, and in some cases the spawning productivity of a range of species. Because this effect is pervasive and essentially permanent, this mechanism is generally equated with a moderate to high risk of take for species exposed to this stressor, depending on species-specific life-history characteristics.

However, when interpreting the risk of take associated with this submechanism, the extent of the riparian and/or hydraulic impact mechanisms it imposes must be considered. Most fish passage subactivity types involve relatively limited additional modification of the environment in comparison to the man-made structures they are intended to bypass. For example, a fishway around a dam will have limited effects through this submechanism in comparison to the effects of the dam itself. In such cases, the additional incremental effect of the structure on groundwater and surface water interactions will be slight, and the risk of take would be considered low. A temporary weir would be expected to have negligible influence on groundwater/surface water interactions; therefore, the risk of take associated with this type of structure would likely be considered insignificant.

In contrast, a structure such as a larger barrier weir may alter these interactions more extensively, leading to effects similar to those of a small dam. In such cases, the long-term nature of these effects would be associated with a higher risk of take. Species with a high risk of take include those with life-history stages that are dependent on hyporheic exchange for its beneficial effects on water temperature and dissolved oxygen levels. For example, most salmonids preferentially spawn in areas with groundwater-induced upwelling, which promotes oxygenation of spawning gravels. Alteration of hyporheic exchange in environments suitable for spawning could potentially affect egg survival and reduce the availability of suitable spawning habitat, resulting in reduced spawning success. Similarly, groundwater inflow can provide important thermal refugia for migrating adult and rearing juvenile salmonids during periods with high water temperatures. A reduction in the amount of thermal refugia may negatively affect survival during these life-history stages. Similar effects would be expected for other coldwater fish species with low thermal tolerance thresholds, such as pygmy whitefish. More generally, hyporheic exchange plays a key role in nutrient cycling and food web productivity in alluvial bed rivers. Projects resulting in significant alteration of hyporheic exchange could adversely affect food web productivity, limiting foraging opportunities for fish and invertebrate species dependent on these types of environments.

Table 9-1. Species- and habitat-specific risk of take for mechanisms of impact associated with culvert removal/replacement/retrofit.

Species	Construction & Maintenance Activities			Water Quality Modifications			Riparian Vegetation Modifications			Aquatic Vegetation Modifications			Hydraulic and Geomorphic Modifications			Ecosystem Fragmentation		
	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine
Chinook salmon	H	N	N	H	N	N	M	N	N	L	N	N	H	N	N	H	N	N
Coho salmon	H	N	N	H	N	N	M	N	N	L	N	N	H	N	N	H	N	N
Chum salmon	H	N	N	H	N	N	M	N	N	L	N	N	H	N	N	H	N	N
Pink salmon	H	N	N	H	N	N	M	N	N	L	N	N	H	N	N	H	N	N
Sockeye salmon	H	N	N	H	N	N	M	N	N	L	N	N	H	N	N	H	N	N
Steelhead	H	N	N	H	N	N	M	N	N	L	N	N	H	N	N	H	N	N
Coastal cutthroat trout	H	N	N	H	N	N	M	N	N	L	N	N	H	N	N	H	N	N
Redband trout	H	N	N	H	N	N	M	N	N	L	N	N	H	N	N	H	N	N
Westslope cutthroat trout	H	N	N	H	N	N	M	N	N	L	N	N	H	N	N	H	N	N
Bull trout	H	N	N	H	N	N	M	N	N	L	N	N	H	N	N	H	N	N
Dolly Varden	H	N	N	H	N	N	M	N	N	L	N	N	H	N	N	H	N	N
Pygmy whitefish	H	N	N	H	N	N	M	N	N	L	N	N	H	N	N	H	N	N
Olympic mudminnow	N	N	N	N	N	N	M	N	N	M	N	N	H	N	N	H	N	N
Lake chub	H	N	N	H	N	N	M	N	N	L	N	N	H	N	N	H	N	N
Leopard dace	H	N	N	H	N	N	M	N	N	L	N	N	H	N	N	H	N	N
Margined sculpin	H	N	N	H	N	N	M	N	N	L	N	N	H	N	N	H	N	N
Mountain sucker	H	N	N	H	N	N	M	N	N	L	N	N	H	N	N	H	N	N
Umatilla dace	H	N	N	H	N	N	M	N	N	L	N	N	H	N	N	H	N	N
Pacific lamprey	H	N	N	H	N	N	M	N	N	L	N	N	H	N	N	H	N	N
River lamprey	H	N	N	H	N	N	M	N	N	L	N	N	H	N	N	H	N	N
Western brook lamprey	H	N	N	H	N	N	M	N	N	L	N	N	H	N	N	H	N	N
Green sturgeon	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
White sturgeon	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N

Table 9-1 (continued). **Species- and habitat-specific risk of take for mechanisms of impact associated with culvert removal/replacement/retrofit.**

Species	Construction & Maintenance Activities			Water Quality Modifications			Riparian Vegetation Modifications			Aquatic Vegetation Modifications			Hydraulic and Geomorphic Modifications			Ecosystem Fragmentation		
	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine
Longfin smelt	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Eulachon	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Pacific sand lance	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Surf smelt	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Pacific herring	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Lingcod	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Pacific cod	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Pacific hake	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Walleye pollock	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Black rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Bocaccio rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Brown rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Canary rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
China rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Copper rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Greenstriped rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Quillback rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Redstripe rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Tiger rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Widow rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Yelloweye rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Yellowtail rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N

Table 9-1 (continued). Species- and habitat-specific risk of take for mechanisms of impact associated with culvert removal/replacement/retrofit.

Species	Construction & Maintenance Activities			Water Quality Modifications			Riparian Vegetation Modifications			Aquatic Vegetation Modifications			Hydraulic and Geomorphic Modifications			Ecosystem Fragmentation		
	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine
Olympia oyster	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Northern abalone	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Newcomb's littorine snail	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Giant Columbia River limpet	H	N	N	H	N	N	M	N	N	M	N	N	H	N	N	H	N	N
Great Columbia River spire snail	H	N	N	H	N	N	M	N	N	M	N	N	H	N	N	H	N	N
California floater (mussel)	H	N	N	H	N	N	M	N	N	M	N	N	H	N	N	H	N	N
Western ridged mussel	H	N	N	H	N	N	M	N	N	M	N	N	H	N	N	H	N	N

Risk of Take Ratings: **H** = High, **M** = Moderate; **L** = Low; **I** = Insignificant or Discountable; **N**= No Risk of Take; **?** = Unknown Risk of Take.
Shaded cells indicate environment types in which the species in question does not occur; therefore, there is no risk of take from the impact mechanism in question.

Table 9-2. Species- and habitat-specific risk of take for mechanisms of impact associated with fish ladders/fishways.

Species	Construction & Maintenance Activities			Water Quality Modifications			Riparian Vegetation Modifications			Aquatic Vegetation Modifications			Hydraulic and Geomorphic Modifications			Ecosystem Fragmentation		
	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine
Chinook salmon	H	N	N	H	N	N	H	N	N	L	N	N	L	N	N	H	N	N
Coho salmon	H	N	N	H	N	N	H	N	N	L	N	N	L	N	N	H	N	N
Chum salmon	H	N	N	H	N	N	H	N	N	L	N	N	L	N	N	H	N	N
Pink salmon	H	N	N	H	N	N	H	N	N	L	N	N	L	N	N	H	N	N
Sockeye salmon	H	N	N	H	N	N	H	N	N	L	N	N	L	N	N	H	N	N
Steelhead	H	N	N	H	N	N	H	N	N	L	N	N	L	N	N	H	N	N
Coastal cutthroat trout	H	N	N	H	N	N	H	N	N	L	N	N	L	N	N	H	N	N
Redband trout	H	N	N	H	N	N	H	N	N	L	N	N	L	N	N	H	N	N
Westslope cutthroat trout	H	N	N	H	N	N	H	N	N	L	N	N	L	N	N	H	N	N
Bull trout	H	N	N	H	N	N	H	N	N	L	N	N	L	N	N	H	N	N
Dolly Varden	H	N	N	H	N	N	H	N	N	L	N	N	L	N	N	H	N	N
Pygmy whitefish	H	N	N	H	N	N	H	N	N	L	N	N	L	N	N	H	N	N
Olympic mudminnow	N	N	N	N	N	N	N	N	N	L	N	N	L	N	N	H	N	N
Lake chub	H	N	N	H	N	N	H	N	N	L	N	N	L	N	N	H	N	N
Leopard dace	H	N	N	H	N	N	H	N	N	L	N	N	L	N	N	H	N	N
Margined sculpin	H	N	N	H	N	N	H	N	N	L	N	N	L	N	N	H	N	N
Mountain sucker	H	N	N	H	N	N	H	N	N	L	N	N	L	N	N	H	N	N
Umatilla dace	H	N	N	H	N	N	H	N	N	L	N	N	L	N	N	H	N	N
Pacific lamprey	H	N	N	H	N	N	H	N	N	L	N	N	L	N	N	H	N	N
River lamprey	H	N	N	H	N	N	H	N	N	L	N	N	L	N	N	H	N	N
Western brook lamprey	H	N	N	H	N	N	H	N	N	L	N	N	L	N	N	H	N	N
Green sturgeon	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
White sturgeon	H	N	N	H	N	N	H	N	N	L	N	N	L	N	N	H	N	N

Table 9-2 (continued). Species- and habitat-specific risk of take for mechanisms of impact associated with fish ladders/fishways.

Species	Construction & Maintenance Activities			Water Quality Modifications			Riparian Vegetation Modifications			Aquatic Vegetation Modifications			Hydraulic and Geomorphic Modifications			Ecosystem Fragmentation		
	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine
Longfin smelt	H	N	N	H	N	N	M	N	N	I	N	N	I	N	N	H	N	N
Eulachon	H	N	N	H	N	N	M	N	N	I	N	N	I	N	N	H	N	N
Pacific sand lance	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Surf smelt	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Pacific herring	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Lingcod	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Pacific cod	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Pacific hake	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Walleye pollock	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Black rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Bocaccio rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Brown rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Canary rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
China rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Copper rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Greenstriped rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Quillback rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Redstripe rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Tiger rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Widow rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Yelloweye rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Yellowtail rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Olympia oyster	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N

Table 9-2 (continued). Species- and habitat-specific risk of take for mechanisms of impact associated with fish ladders/fishways.

Species	Construction & Maintenance Activities			Water Quality Modifications			Riparian Vegetation Modifications			Aquatic Vegetation Modifications			Hydraulic and Geomorphic Modifications			Ecosystem Fragmentation		
	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine
Northern abalone	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Newcomb's littorine snail	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Giant Columbia River limpet	H	N	N	H	N	N	H	N	N	L	N	N	L	N	N	H	N	N
Great Columbia River spire snail	H	N	N	H	N	N	H	N	N	L	N	N	L	N	N	H	N	N
California floater (mussel)	H	N	N	H	N	N	H	N	N	L	N	N	L	N	N	H	N	N
Western ridged mussel	H	N	N	H	N	N	H	N	N	L	N	N	L	N	N	H	N	N

Risk of Take Ratings: **H** = High, **M** = Moderate; **L** = Low; **I** = Insignificant or Discountable; **N**= No Risk of Take; **?** = Unknown Risk of Take.
Shaded cells indicate environment types in which the species in question does not occur; therefore, there is no risk of take from the impact mechanism in question.

Table 9-3. Species- and habitat-specific risk of take for mechanisms of impact associated with roughened channels.

Species	Construction & Maintenance Activities			Water Quality Modifications			Riparian Vegetation Modifications			Aquatic Vegetation Modifications			Hydraulic and Geomorphic Modifications			Ecosystem Fragmentation		
	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine
Chinook salmon	H	N	N	H	N	N	H	N	N	M	N	N	H	N	N	H	N	N
Coho salmon	H	N	N	H	N	N	H	N	N	M	N	N	H	N	N	H	N	N
Chum salmon	H	N	N	H	N	N	H	N	N	I	N	N	H	N	N	H	N	N
Pink salmon	H	N	N	H	N	N	H	N	N	I	N	N	H	N	N	H	N	N
Sockeye salmon	H	N	N	H	N	N	H	N	N	M	N	N	H	N	N	H	N	N
Steelhead	H	N	N	H	N	N	H	N	N	M	N	N	H	N	N	H	N	N
Coastal cutthroat trout	H	N	N	H	N	N	H	N	N	M	N	N	H	N	N	H	N	N
Redband trout	H	N	N	H	N	N	H	N	N	M	N	N	H	N	N	H	N	N
Westslope cutthroat trout	H	N	N	H	N	N	H	N	N	M	N	N	H	N	N	H	N	N
Bull trout	H	N	N	H	N	N	H	N	N	M	N	N	H	N	N	H	N	N
Dolly Varden	H	N	N	H	N	N	H	N	N	M	N	N	H	N	N	H	N	N
Pygmy whitefish	H	N	N	H	N	N	H	N	N	M	N	N	H	N	N	H	N	N
Olympic mudminnow	N	N	N	N	N	N	N	N	N	M	N	N	H	N	N	H	N	N
Lake chub	H	N	N	H	N	N	H	N	N	M	N	N	H	N	N	H	N	N
Leopard dace	H	N	N	H	N	N	H	N	N	M	N	N	H	N	N	H	N	N
Margined sculpin	H	N	N	H	N	N	H	N	N	M	N	N	H	N	N	H	N	N
Mountain sucker	H	N	N	H	N	N	H	N	N	M	N	N	H	N	N	H	N	N
Umatilla dace	H	N	N	H	N	N	H	N	N	M	N	N	H	N	N	H	N	N
Pacific lamprey	H	N	N	H	N	N	H	N	N	M	N	N	H	N	N	H	N	N
River lamprey	H	N	N	H	N	N	H	N	N	M	N	N	H	N	N	H	N	N
Western brook lamprey	H	N	N	H	N	N	H	N	N	M	N	N	H	N	N	H	N	N
Green sturgeon	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
White sturgeon	H	N	N	H	N	N	H	N	N	M	N	N	H	N	N	H	N	N

Table 9-3 (continued). **Species- and habitat-specific risk of take for mechanisms of impact associated with roughened channels.**

Species	Construction & Maintenance Activities			Water Quality Modifications			Riparian Vegetation Modifications			Aquatic Vegetation Modifications			Hydraulic and Geomorphic Modifications			Ecosystem Fragmentation		
	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine
Longfin smelt	H	N	N	H	N	N	M	N	N	M	N	N	H	N	N	H	N	N
Eulachon	H	N	N	H	N	N	M	N	N	M	N	N	H	N	N	H	N	N
Pacific sand lance	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Surf smelt	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Pacific herring	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Lingcod	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Pacific cod	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Pacific hake	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Walleye pollock	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Black rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Bocaccio rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Brown rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Canary rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
China rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Copper rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Greenstriped rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Quillback rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Redstripe rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Tiger rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Widow rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Yelloweye rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Yellowtail rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Olympia oyster	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N

Table 9-3 (continued). Species- and habitat-specific risk of take for mechanisms of impact associated with roughened channels.

Species	Construction & Maintenance Activities			Water Quality Modifications			Riparian Vegetation Modifications			Aquatic Vegetation Modifications			Hydraulic and Geomorphic Modifications			Ecosystem Fragmentation		
	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine
Northern abalone	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Newcomb's littorine snail	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Giant Columbia River limpet	H	N	N	H	N	N	H	N	N	M	N	N	H	N	N	H	N	N
Great Columbia River spire snail	H	N	N	H	N	N	H	N	N	M	N	N	H	N	N	H	N	N
California floater (mussel)	H	N	N	H	N	N	H	N	N	M	N	N	H	N	N	H	N	N
Western ridged mussel	H	N	N	H	N	N	H	N	N	M	N	N	H	N	N	H	N	N

Risk of Take Ratings: **H** = High, **M** = Moderate; **L** = Low; **I** = Insignificant or Discountable; **N**= No Risk of Take; **?** = Unknown Risk of Take.
Shaded cells indicate environment types in which the species in question does not occur; therefore, there is no risk of take from the impact mechanism in question.

Table 9-4. Species- and habitat-specific risk of take for mechanisms of impact associated with weirs.

Species	Construction & Maintenance Activities			Water Quality Modifications			Riparian Vegetation Modifications			Aquatic Vegetation Modifications			Hydraulic and Geomorphic Modifications			Ecosystem Fragmentation		
	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine
Chinook salmon	H	N	N	H	N	N	H	N	N	L	N	N	H	N	N	H	N	N
Coho salmon	H	N	N	H	N	N	H	N	N	L	N	N	H	N	N	H	N	N
Chum salmon	H	N	N	H	N	N	H	N	N	L	N	N	H	N	N	H	N	N
Pink salmon	H	N	N	H	N	N	H	N	N	L	N	N	H	N	N	H	N	N
Sockeye salmon	H	N	N	H	N	N	H	N	N	L	N	N	H	N	N	H	N	N
Steelhead	H	N	N	H	N	N	H	N	N	L	N	N	H	N	N	H	N	N
Coastal cutthroat trout	H	N	N	H	N	N	H	N	N	L	N	N	H	N	N	H	N	N
Redband trout	H	N	N	H	N	N	H	N	N	L	N	N	H	N	N	H	N	N
Westslope cutthroat trout	H	N	N	H	N	N	H	N	N	L	N	N	H	N	N	H	N	N
Bull trout	H	N	N	H	N	N	H	N	N	L	N	N	H	N	N	H	N	N
Dolly Varden	H	N	N	H	N	N	H	N	N	L	N	N	H	N	N	H	N	N
Pygmy whitefish	H	N	N	H	N	N	H	N	N	L	N	N	H	N	N	H	N	N
Olympic mudminnow	N	N	N	N	N	N	N	N	N	L	N	N	H	N	N	H	N	N
Lake chub	H	N	N	H	N	N	H	N	N	L	N	N	H	N	N	H	N	N
Leopard dace	H	N	N	H	N	N	H	N	N	L	N	N	H	N	N	H	N	N
Margined sculpin	H	N	N	H	N	N	H	N	N	L	N	N	H	N	N	H	N	N
Mountain sucker	H	N	N	H	N	N	H	N	N	L	N	N	H	N	N	H	N	N
Umatilla dace	H	N	N	H	N	N	H	N	N	L	N	N	H	N	N	H	N	N
Pacific lamprey	H	N	N	H	N	N	H	N	N	L	N	N	H	N	N	H	N	N
River lamprey	H	N	N	H	N	N	H	N	N	L	N	N	H	N	N	H	N	N
Western brook lamprey	H	N	N	H	N	N	H	N	N	L	N	N	H	N	N	H	N	N
Green sturgeon	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
White sturgeon	H	N	N	H	N	N	H	N	N	L	N	N	H	N	N	H	N	N

Table 9-4 (continued). Species- and habitat-specific risk of take for mechanisms of impact associated with weirs.

Species	Construction & Maintenance Activities			Water Quality Modifications			Riparian Vegetation Modifications			Aquatic Vegetation Modifications			Hydraulic and Geomorphic Modifications			Ecosystem Fragmentation		
	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine	Riverine	Marine	Lacustrine
Longfin smelt	H	N	N	H	N	N	M	N	N	I	N	N	H	N	N	H	N	N
Eulachon	H	N	N	H	N	N	M	N	N	I	N	N	H	N	N	H	N	N
Pacific sand lance	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Surf smelt	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Pacific herring	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Lingcod	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Pacific cod	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Pacific hake	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Walleye pollock	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Black rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Bocaccio rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Brown rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Canary rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
China rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Copper rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Greenstriped rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Quillback rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Redstripe rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Tiger rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Widow rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Yelloweye rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Yellowtail rockfish	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Olympia oyster	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N

Table 9-4 (continued). Species- and habitat-specific risk of take for mechanisms of impact associated with weirs.

Species	Construction & Maintenance Activities			Water Quality Modifications			Riparian Vegetation Modifications			Aquatic Vegetation Modifications			Hydraulic and Geomorphic Modifications			Ecosystem Fragmentation		
	Riverine	**Marine**	**Lacustrine**	**Riverine**	**Marine**	**Lacustrine**	**Riverine**	**Marine**	**Lacustrine**	**Riverine**	**Marine**	**Lacustrine**	**Riverine**	**Marine**	**Lacustrine**	**Riverine**	**Marine**	**Lacustrine**
Northern abalone	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Newcomb's littorine snail	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Giant Columbia River limpet	H	N	N	H	N	N	H	N	N	L	N	N	H	N	N	H	N	N
Great Columbia River spire snail	H	N	N	H	N	N	H	N	N	L	N	N	H	N	N	H	N	N
California floater (mussel)	H	N	N	H	N	N	H	N	N	L	N	N	H	N	N	H	N	N
Western ridged mussel	H	N	N	H	N	N	H	N	N	L	N	N	H	N	N	H	N	N

Risk of Take Ratings: **H** = High, **M** = Moderate; **L** = Low; **I** = Insignificant or Discountable; **N**= No Risk of Take; **?** = Unknown Risk of Take.
Shaded cells indicate environment types in which the species in question does not occur; therefore, there is no risk of take from the impact mechanism in question.

Table 9-5. Species- and habitat-specific risk of take for mechanisms of impact associated with trap-and-haul fish passage techniques.

	Operational Activities			Ecosystem Fragmentation		
Species	**Riverine**	**Marine**	**Lacustrine**	**Riverine**	**Marine**	**Lacustrine**
Chinook salmon	H	N	N	H	N	N
Coho salmon	H	N	N	H	N	N
Chum salmon	H	N	N	H	N	N
Pink salmon	H	N	N	H	N	N
Sockeye salmon	H	N	N	H	N	N
Steelhead	H	N	N	H	N	N
Coastal cutthroat trout	H	N	N	H	N	N
Redband trout	H	N	N	H	N	N
Westslope cutthroat trout	H	N	N	H	N	N
Bull trout	H	N	N	H	N	N
Dolly Varden	H	N	N	H	N	N
Pygmy whitefish	H	N	N	H	N	N
Olympic mudminnow	N	N	N	N	N	N
Lake chub	M	N	N	N	N	N
Leopard dace	M	N	N	N	N	N
Margined sculpin	M	N	N	N	N	N
Mountain sucker	H	N	N	H	N	N
Umatilla dace	M	N	N	N	N	N
Pacific lamprey	H	N	N	H	N	N
River lamprey	H	N	N	H	N	N
Western brook lamprey	M	N	N	N	N	N
Green sturgeon	N	N	N	N	N	N
White sturgeon	H	N	N	H	N	N
Longfin smelt	I	N	N	N	N	N
Eulachon	I	N	N	N	N	N
Pacific sand lance	N	N	N	N	N	N
Surf smelt	N	N	N	N	N	N
Pacific herring	N	N	N	N	N	N
Lingcod	N	N	N	N	N	N
Pacific cod	N	N	N	N	N	N
Pacific hake	N	N	N	N	N	N
Walleye pollock	N	N	N	N	N	N
Black rockfish	N	N	N	N	N	N
Bocaccio rockfish	N	N	N	N	N	N

Table 9-5 (continued). Species- and habitat-specific risk of take for mechanisms of impact associated with trap-and-haul fish passage techniques.

	Operational Activities			Ecosystem Fragmentation		
Species	**Riverine**	**Marine**	**Lacustrine**	**Riverine**	**Marine**	**Lacustrine**
Brown rockfish	N	N	N	N	N	N
Canary rockfish	N	N	N	N	N	N
China rockfish	N	N	N	N	N	N
Copper rockfish	N	N	N	N	N	N
Greenstriped rockfish	N	N	N	N	N	N
Quillback rockfish	N	N	N	N	N	N
Redstripe rockfish	N	N	N	N	N	N
Tiger rockfish	N	N	N	N	N	N
Widow rockfish	N	N	N	N	N	N
Yelloweye rockfish	N	N	N	N	N	N
Yellowtail rockfish	N	N	N	N	N	N
Olympia oyster	N	N	N	N	N	N
Northern abalone	N	N	N	N	N	N
Newcomb's littorine snail	N	N	N	N	N	N
Giant Columbia River limpet	N	N	N	H	N	N
Great Columbia River spire snail	N	N	N	H	N	N
California floater (mussel)	N	N	N	H	N	N
Western ridged mussel	H	N	N	H	N	N

Risk of Take Ratings: **H** = High, **M** = Moderate; **L** = Low; **I** = Insignificant or Discountable; **N**= No Risk of Take; **?** = Unknown Risk of Take.
Shaded cells indicate environment types in which the species in question does not occur; therefore, there is no risk of take from the impact mechanism in question.

10.0 Data Gaps

This section summarizes the key data gaps identified during the preparation of this white paper that are relevant to the permitting of fish passage related structures and activities. When viewed generally across all subactivity types, it is clear that key data gaps remain in the following areas:

- Knowledge of the movement patterns of HCP species at different life-history stages relevant to the definition of design flows for fish passage
- Knowledge of the behavioral and physiological limits on the swimming ability of HCP species, sufficient to guide definition of hydraulic design criteria
- Understanding of the situational limits of different design approaches (e.g., stream simulation)

Elaboration on these and other specific types of data gaps as relevant to each fish passage subactivity type is provided in the following sections.

10.1 Culverts

In WAC 220-110-070 as well as in current design guidance documents (e.g., Bates et al. 2003), assumptions are made to define the period of year during which fish passage is required, based on the species that are expected to inhabit a stream. Also, many culverts present only a temporary barrier to fish passage or are barriers to juvenile and resident fish only. However, the significance of such barriers on fish movement in the field has not been thoroughly investigated, particularly where the occurrence and timing of fish movement are poorly understood. Also, there are gaps in knowledge regarding the movement patterns of various salmonid species and life-history stages (particularly of resident and juvenile anadromous salmonids) in small stream channels. Nonsalmonid species are less well understood in many cases. Finally, there are key data gaps relative to the design requirements necessary for structures that maintain performance over time.

With regard to the migration requirements of fish, it is known that volitional movement can vary greatly among species, lifestages, habitats, seasons, and years (Gowan et al. 1994; Kahler and Quinn 1998; Kahler et al. 2001). Research on several critical fish passage related topics is currently in progress or has recently been completed. However, it may be difficult to translate this information into meaningful guidance because the research is typically focused on a single species and may not adequately reflect the requirements of a broad range of HCP species; therefore, a number of related uncertainties may remain. The combined effects of culvert length, material selection, and the utility of baffles and similar elements lead to significant uncertainty when applied across a broad range of species. For example, the role of boundary layer turbulence is known to affect the ability of fish to pass through culverts, but the specifics of these effects are poorly understood and considered to be a data gap in an earlier white paper (Kahler and Quinn 1998). Subsequent to Kahler and Quinn’s (1998) review, research on the role of boundary layer turbulence has been studied by examining the swimming performance and behavior of juvenile salmon in test beds (Pearson et al. 2006). Despite this directed research, several additional data gaps on issues relevant to design guidance remain (Bates et al. 2003; Pearson et al. 2006). For example, the flow conditions that constitute an appropriate upper design flow limit for juvenile fish passage are poorly understood for most HCP fish species, as well as other aquatic and semi-aquatic species. The movement of aquatic invertebrates and their passage requirements have received even less study (Vaughan 2002) and are a data gap for the HCP invertebrate species exposed to this activity type.

Current WDFW guidance emphasizes the use of “geomorphic designs” for new and replacement culverts (specifically, structures designed following the no-slope and the stream-simulation options). The intent of these designs is to produce a culvert that allows a broader range of geomorphic processes to function across a broad range of channel types. In the case of the no-slope option, the range of slope and sediment transport conditions over which it can provide effective fish passage remain uncertain. This is particularly true in higher gradient systems and systems with less-mobile bed conditions. It is generally intended for use in low-gradient systems with higher rates of sediment transport.

The development of stream simulation criteria and design procedures is recent. Most of the experience with the method is in mountainous streams. Uncertainties remain about the efficacy of specific criteria and design guidance across a broad range of channel types and hydro-geographic regions. Additional research would fine tune the criteria and guidance, broaden the application, and inform designers of appropriate criteria for unique situations.

Finally, even fish passable culverts may impose ecosystem fragmentation effects on terrestrial and amphibian wildlife species. This may potentially result in indirect ecosystem-level effects on HCP species that are complex and difficult to predict. Even in the absence of complete understanding, it can generally be assumed that designs that promote more natural migration and dispersal behavior are desirable over those that produce barrier conditions. Ongoing research on this subject at the U.S. Forest Service may produce information that will improve guidance in the future (Bates et al. 2008).

10.2 Fish Ladders/Fishways

Additional study of the factors influencing passage of nonsalmonid HCP fish species is necessary to develop improved design criteria. For example, knowledge of juvenile fish jumping ability is necessary to design for the maximum allowable hydraulic jump (i.e., vertical drop) within a fishway. In this regard, recent research on juvenile coho salmon jumping ability has determined that jump heights exceeding 2.5 times the fish length block passage of a high percentage of individuals (Pearson et al. 2005). This information provides useful design guidance for salmonids, but these findings may not apply to nonsalmonid species. For example, recent research has documented low Pacific lamprey passage efficiency through fish ladders in the Columbia River system, but the specific fishway design factors that support or limit successful passage are unclear (Moser et al. 2002).

10.3 Roughened Channels

Roughened channels are outwardly simple structures, but in reality the design parameters required to construct a channel that will function as intended over time are demanding and complex. Improper design may lead to unintended perturbations in hydrologic, geomorphic, and riparian conditions that can cause a number of undesirable indirect effects on HCP species. Definitive design guidance for this type of structure is currently lacking and must be considered a data gap.

10.4 Weirs

Impacts from weirs are in many cases similar to those for small dams, which have been well documented and a topic of research for decades. In general, there are no major data gaps that exist. However, little research on the hyporheic zone has been conducted in highly altered and degraded fluvial systems (Bolton and Shellberg 2001). While the physical effects of weirs on the environment are well understood, there is a lack of information on the impacts from weirs on specific HCP species. When combined with limited understanding of species-specific migration behavior, a lack of knowledge of the physiological and behavioral passage limitations of all potentially affected HCP species presents the likelihood of unforeseen undesirable consequences. This further suggests that definitive guidance is lacking for the design of structures that function as intended across all species.

10.5 Trap and Haul

The effects of alteration of migratory corridors on subject fish species is an area of limited but increasing study. Alteration of migratory corridors may have unintended effects on homing selectivity that are undesirable for long-term evolutionary fitness; therefore, this is an area deserving of further study. Otherwise, there are no significant data gaps with regard to the effects of trap-and-haul programs.

10.6 Discussion of General Data Gaps

Core data gaps have been identified that apply across all fish passage related subactivity types. These include the following:

Effects of disturbance on HCP invertebrate species: Relatively little data are available on the effects of various forms of construction-related disturbance on HCP invertebrate species; specific data gaps include:

- The effects of impulsive and continuous underwater noise
- Survival and fitness following physical disturbance, handling, and relocation-related dispersal (e.g., to what degree does the unintentional dispersal of freshwater mussels limit density-dependent reproductive success).

Passage requirements of nonsalmonid HCP species: Relatively little data are available on the passage requirements of smaller nonsalmonid fish species, such as dace and chub. While Katopodis (1992) has noted that swimming performance tends to be generally similar across species relative to size when grouped by swimming physiology, this may not fully account for the effects of hydraulic complexity in the passage environment. Specifically, research has demonstrated that juvenile salmonids are able to navigate culverts at higher average flow velocities than would be expected from standard swimming performance curves (Kahler and Quinn 1998; Pearson, Southard et al. 2006; Powers and Bates 1997). They do so by exploiting low-velocity zones in the turbulent boundary layer and other areas of hydraulic complexity. The ability of other fish species to similarly exploit these low-velocity zones in many cases is poorly understood. This creates the potential to over- or underestimate the passage requirements of nonsalmonid fish species.

Upstream movement requirements of HCP invertebrate species: The freshwater HCP invertebrate species vary in terms of the mechanisms they use to influence dispersal in flowing water environments appropriate for the fish passage activity type. Unionids mussels, as is well known, rely on host-fish species to disperse their parasitic larvae to upstream environments. However, these species have also been shown to disperse upstream for short distances by crawling along the bottom using their muscular foot and byssal thread attachments (Vaughan 2002). Other HCP invertebrate species, such as the giant Columbia River limpet and great Columbia River spire snail, crawl along hard substrates and are theoretically capable of navigating upstream for short distances. The degree to which fish passage subactivity types may help or hinder these dispersal mechanisms and the ramifications for population health are an area requiring additional study.

11.0 Habitat Protection, Conservation, Mitigation, and Management Strategies

This section discusses measures that could be employed to reduce the effects of fish passage subactivity types addressed in this white paper on the HCP species that are potentially exposed to the impact mechanisms and related stressors they impose. This evaluation employs best professional judgment of the design standards that are commonly used in the Pacific Northwest and elsewhere. These include the Draft Fish Passage Standards developed by NOAA Fisheries (NMFS 2001), draft revisions to these standards currently in development, WDFW culvert design guidelines (Bates et al. 2003), and WDFW fishway design guidelines (Bates 1997).

11.1 Culverts

In circumstances where culverts are required, structures that are designed appropriately for the hydraulic and geomorphic context of the project site can provide a high degree of fish passage and habitat protection. Accordingly, current design guidance directs project proponents in identifying the most appropriate type of structure for their specific circumstances.

Culvert design guidance has continually evolved in recent years as the result of ongoing research on fish passage requirements, as well as a growing understanding of the broader effects of culverts on the aquatic environment. WDFW guidance to date has emphasized the use of three design methods: the no-slope and stream-simulation options, which emphasize the placement and/or natural accumulation of bed material within the culvert to promote a hydraulically complex environment; and the hydraulic design option, which emphasizes the use of hydraulic calculations to design a structure based on the swimming performance of target species. The stream-simulation option is currently the recommended approach to culvert design. The no-slope option is similar in concept, except that this method is limited to lower gradient environments with shorter culvert requirements. These geomorphically oriented designs attempt to accommodate natural fluvial processes to the greatest extent possible, thereby providing passage for a full range of aquatic species.

When properly designed for the hydraulic and geomorphic conditions present in the watershed, these geomorphic designs can provide a high degree of fish passage function with limited effects on ecosystem connectivity. However, any design that fails to incorporate the full range of current and future geomorphic conditions in the watershed may cause unintended effects on habitat conditions, or may ultimately fail to provide fish passage if channel conditions change. For example, a culvert design that fails to recognize the likelihood of migrating headcuts either reaching or being liberated by the structure may not allow the channel to adjust as required. Conversely, a culvert may be designed appropriately for current conditions, but the design may fail to recognize development trends in the watershed that could change local hydrologic and geomorphic conditions.

This speaks to the need for guidance for a predesign hydraulic and geomorphic assessment of current and likely future watershed conditions. This guidance should emphasize assessment of current conditions in the watershed (specifically with regards to channel evolution), and the hydraulic and geomorphic trajectory of the system. The latter should consider likely future land use patterns and their likely effect on hydrologic and geomorphic conditions. This guidance should also cover methods for addressing existing headcut conditions and channel incision, using grade control measures or other forms of habitat and/or channel modification as needed.

Culvert design guidance has evolved in recent years given acknowledgement of the complexities and uncertainties inherent when using the hydraulic design method to provide passage for a broad range of species. This method has become less favored over time because of its demonstrated failure to adequately provide juvenile fish passage, as well as other concerns. This weakness is due in part to limitations and uncertainties in the calculations used, failure to consider the design life of the project in the context of natural variability in channel conditions, and inappropriate criteria used to direct design guidance in the Hydraulic Code. With regard to the former, the hydraulic calculations employed in this method are limited from the standpoint that they may not fully capture the complexity of turbulence and boundary layer velocities within culverts that can aid or hinder fish passage.

Despite these limitations, the hydraulic design option is still employed in specific circumstances where retrofitting of a barrier culvert is required (e.g., when removal or replacement is impractical in the immediate future). In such cases, the use of rigorous hydraulic engineering methods is a desirable approach where fish passage must be considered. However, it must be stressed that the design approach be informed by the best available science on the swimming performance, behavior, and migratory requirements of all species and all life-history stages likely to be affected by the structure in question. As this information is developed, culvert design guidance should be updated accordingly. It is recommended that biological criteria not be included in the Hydraulic Code, however, because the code is updated too infrequently to reflect the most recent science.

Two examples illustrate the weaknesses inherent in the hydraulic design method. First, available data described throughout this white paper indicate that culverts and other fish passage structures need to accommodate the passage of fish species and life-history stages with a broad range of swimming abilities and behavioral requirements. Most research applicable to the retrofitting of culverts has focused on salmonids. However, protection of salmonids may not adequately protect the full range of HCP species. For many other HCPS species, data on swimming performance are too limited to be useful in guiding design, or do not exist at all.

Second, WAC 220-110-070 sets the design discharge criterion as the flow rate that is exceeded no more than 10 percent of the time during the months of active adult and juvenile migration (Bates et al. 2003; Powers and Saunders 2002). If the culvert velocities are less than or equal to the allowable velocity at the high passage design discharge, the WAC criterion is met. If not, the culvert is considered a barrier. However, barrier determinations made by the physical and hydraulic measurements described in the WAC, may not accurately represent the influence a culvert has on the movement of HCP species that are less well understood. Consequently, it is recommended that information be collected on the behavior of nonsalmonid fish species to document the actual effect of culverts on fish movement.

The Washington State Department of Transportation leads a cooperative program to study juvenile salmonid passage through culverts by systematically conducting statistically designed experiments in a full-scale culvert system at the Culvert Test Bed (CTB) at the WDFW Skookumchuck Hatchery near Tenino, Washington (Pearson et al. 2005, 2006). The CTB program is a unique opportunity to provide scientifically sound information that can be used to develop better designs for retrofitted structures (Pearson et al. 2005, 2006). However, WDFW staff have questioned the effectiveness of this program. If this program continues, research should focus on providing relevant understanding of the relationship between hydraulics and behavioral and physiological limitations necessary to develop sound design criteria. In this context, expansion of the program to evaluate the passage requirements of other HCP species may be valuable. As the need for retrofitted culverts declines over time (i.e., barrier culverts are removed or replaced, rather than retrofitted), the program can be retired.

Although not supported by direct citation from scientific literature, general recommendations regarding trash racks and livestock fences associated with culverts are provided in NMFS (2001). According to NMFS (2001), trash racks and livestock fences should not be used near the culvert inlets as accumulated debris may severely restrict fish passage and cause potential injuries to fish. Where fencing cannot be avoided, it should be removed during adult salmon upstream migration periods. 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.

11.2 Fish Ladders/Fishways

Fishways are generally not recommended but may be useful in some applications, such as where excessive drops occur at a culvert outlet (NMFS 2001).

In general, given that fishways are commonly associated with dams, to the extent possible, owners should pursue notching or complete dam removal. The most biologically sound solution to fish passage related impacts from dams is to allow for free and unimpeded upstream and downstream migration at all times of the year.

Based on data and findings from the ongoing monitoring of constructed projects, FishXing (2007) offers the following recommendations with respect to fishway construction:

- Where applicable, design internal weirs with gradual side-slopes. Weirs with gradual side-slopes create a thin sheet of plunging water along the edges. The hydraulics of this thin sheet of water in the receiving pool creates good leaping conditions for smaller fish. Also, place a bevel on the downstream edge of V-notch weirs to create the best conditions for leaping by smaller fish. Placing the bevel on the upstream side may also improve debris passage.

- In a fishway, if the volume of each step-pool is relatively small, it may create excessive turbulence at relatively low flows. Assessing turbulence during the design process involves identifying the highest flow for passage through the step-pools and then sizing the pools to dissipate the energy associated with that flow. Turbulence in step-pools is assessed using the Energy Dissipation Factor (EDF). If the EDF is excessive at the high-passage design flow, either the pool volume should be increased, the drop height reduced, or the proportion of streamflow that bypasses the pools should be increased.

11.3 Roughened Channels

As noted previously, the effects of roughened channel construction are similar to those imposed by channel creation and realignment. Therefore, the habitat protection, conservation, mitigation, and management strategies discussed for channel creation apply also to roughened channel construction, and are addressed in the Channel Modifications white paper (Herrera 2007c).

Based on constructed project monitoring data, FishXing (2007) provides the following recommendations for roughened channels associated with culverts:

- Construction of a roughened channel requires skilled equipment operators and on-site construction guidance from persons familiar with this type of design. Expert construction oversight is needed to avoid the construction of wider and shallower-than-designed roughened channels. These deviations from the design have the potential to create insufficient depth at lower fish migration time flows, possibly hindering fish passage.

- When rock must be used, the use of larger-than-specified rock to construct the bank of a roughened channel results in large voids within the bank rock. This will allow water flow behind the rocks, thus scouring the native bank material. The potential for this issue is greater when donated or “recycled” rock is used to construct the bank of a roughened channel, as it may not meet design specifications. If the problem occurs, it can be addressed with the use of smaller material added in the void areas to prevent water from flowing behind the rocks and scouring the native material.

- In roughened channel projects that extend through/past a culvert, using a continuous slope through the culvert rather than a short, oversteepened section would improve fish passage conditions.

- When designing roughened channel, consider the geomorphic and hydraulic impacts beyond the project area to avoid or minimize the potential for unintended impacts.

- Use an interdisciplinary team of engineers, hydrologists, fisheries biologists, and geomorphologists to identify and address potential problems beyond the project area during the preliminary design phase.

- Poor culvert alignment can increase the risk of debris plugging, scour adjacent banks, and reduce capacity. When extending or installing a culvert, consider the impacts on alignment between the culvert inlet and approaching channel.

- The natural streambed below a lined or hardened channel is typically susceptible to scour and downcutting. Therefore, it is advisable to include a transition area that dissipates energy and reduces velocity before flow enters the natural channel. Addressing this in the initial design phase may avoid the need for subsequent replacement or retrofits.

- Limiting the project length to the right-of-way can make it extremely difficult to satisfy fish passage objectives while maintaining a stable channel. To achieve the project’s objectives, consider extending the project reach beyond the right-of-way. This will require coordination with adjacent property owners as well as stakeholders early in the project design.

11.4 Weirs

Using weirs to provide hydraulic controls in the channel upstream and/or downstream of a culvert can create a continuous low flow path through the culvert and stream reach intended to facilitate fish passage (NMFS 2001). These weirs should be designed to provide instream habitat complexity. To achieve this secondary objective, as well as to greatly improve their hydraulic performance, grade control weirs should be designed as complex structures, rather than simple or single-log structures. Simple or single-log structures are easily undermined and have often been observed in the field posing a barrier to fish after a few months of operation.

Where permanent weirs are desired to manage fish passage, these structures should be designed to limit hydraulic and geomorphic modifications to the greatest extent possible. Specifically, permeability to the downstream transport of water, LWD, sediment, organic material, and fish movement is desirable to limit broader ecological effects.

11.5 Trap and Haul

The principal biological benefits for a trap-and-haul system as for a fishway may be considered similar. These benefits typically include connecting populations, increasing genetic exchange, and increasing access to habitat for multiple lifestages and species. All these benefits can be achieved with trap-and-haul systems. Therefore, given that trap-and-haul systems are typically less expensive than fishways, the former may be more appealing for some applications. However, although initially less expensive than a fishway, a trap-and-haul system has the disadvantage of higher annual maintenance to ensure that the mechanical equipment and systems work properly during the entire fish passage season (Ferguson et al. 2002). Due to these higher maintenance requirements, trap-and-haul systems are likely to cause more environmental disturbance than fishways, thus increasing their chance to affect HCP species (e.g., through water quality impacts).

Trap-and-haul programs present additional disadvantages that render them less desirable than volitional passage. As discussed in Section 7.6.1.1.2 (*Dewatering and Handling*), capture and handling are sources of potential injury and stress that can lead to immediate, delayed, or indirect mortality. In addition, in some cases logistical considerations may require release of transported fish at locations that significantly alter their migratory corridor. This in turn may lead to undesirable effects on survival, fitness, and/or spawning productivity. When imposed over several generations, these combined stressors have the potential to impose selection pressures that may result in undesirable evolutionary consequences.

Trap-and-haul programs are also labor intensive, which translates to burdensome perpetual management costs. This also presents a vulnerability that is somewhat unique in comparison to other fish passage subactivity types. While failure to regularly maintain fish passage structures is likely to lead to a gradual degradation in function, trap-and-haul programs are entirely dependent on annual funding to function. In this light, structures that provide volitional passage are clearly preferable.

Given these inherent limitations, consideration should be given to the preferential construction of fishways over trap-and-haul systems where practicable to reduce the potential for undesirable effects on HCP species and their habitats.

11.6 General Recommendations for All Subactivity Types

The following discussion provides general recommendations for all subactivity types. These general recommendations are provided for construction BMPs and design criteria considerations.

11.6.1 Construction and Maintenance Best Management Practices

The U.S. Environmental Protection Agency (U.S. EPA) has released a recent publication relevant to the management of construction and maintenance related effects on water quality (U.S. EPA 2007). The report summarized BMPs that are relevant to the construction and maintenance of all HPA-permitted activities, including the fish passage subactivity types. The recommended BMPs include:

- Stockpile fertile topsoil for later use for plants
- Use hand equipment rather than heavy equipment
- If using heavy equipment, use wide-track or rubberized tires
- Avoid instream work except as authorized by the local fishery and wildlife authority
- Stay 100 ft away from water when refueling or adding oil
- Avoid using wood treated with creosote or copper compounds
- Protect areas exposed during construction.

Other nonconstruction-related recommendations put forth by U.S. EPA (2007) include:

- Incorporating monitoring and maintenance of structures
- Using adaptive management
- Conducting a watershed assessment to determine project fate and effects
- Focusing on prevention rather than mitigation
- Emphasizing simple, low-tech, and low cost methods.

For activities that require dewatering, impacts can be minimized by performing work during low-flow or dry conditions and by pumping sediment-laden water from the work area to an infiltration treatment site. Disturbed areas within the channel should be stabilized with a layer of sediment corresponding to the ambient bed to prevent an influx of fine sediment once water is reintroduced to the site. Science-based protocols for fish removal and exclusion activities should be adopted to track and report the number and species of fish captured, injured, or killed. Projects should also require slow dewatering and passive fish removal from the dewatered area before initiating active fish-removal protocols. During passive fish removal, fish removal by seining is recommended before resorting to electrofishing, which carries a greater risk of mortality (NMFS 2006). If pumps are used to temporarily divert a stream to facilitate construction, an acceptable fish screen must be used to prevent entrainment or impingement of small fish (NMFS 2001).

Temporary crossings, placed in salmonid streams for water diversion during construction activities, should meet all fish passage guidelines (NMFS 2001) where fish are expected to be present during the construction window.

11.6.2 Design Criteria

Regardless of the structure type, it is apparent from available research that "one-size-fits-all" guidance for the design of fish passage structures will not yield adequate results where the passage of multiple HCP species at multiple life-history stages is a concern. Structure design and specific structural parameters should take into account these biological requirements to ensure long-term success. In this context, fish passage structures that attempt to mimic natural hydraulic and geomorphic complexity are likely to provide the most effective results. Current WDFW guidance emphasizes this approach.

Specific circumstances, such as the retrofitting of existing culverts or the development of fishways, may require engineered solutions based on the swimming abilities of target fish species. Where passage requirements for species of interest are uncertain, factors of safety should be incorporated to the extent practicable. Structure design must also accommodate the hydraulic and geomorphic context of the system in which it is being installed. This will increase the likelihood of successful operation over time, and ideally decrease the need for maintenance.

Consider the following parameters when developing design criteria for retrofitted culverts and fishways:

- For juvenile salmonid passage:
  - Design for the smallest size of fish anticipated to migrate through the structure.
  - Create complex, interconnected low-flow velocity zones within the structure. Incorporation of roughness features (e.g., corrugation, gravel and cobble embedded within concrete, baffles) appears to aid in this objective by creating turbulence that induces low-velocity conditions in the boundary layer.

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