ASSESSMENT, EVALUATION, AND DEVELOPMENT OF FISH PASSAGE GUIDELINES

by

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DEDICATION

To my wife Anna and son Theodore, thank you for your continual support and patience.

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ABSTRACT

Instream barriers such as dams and diversions have been designed and constructed on America’s rivers for centuries. In recent decades, the negative impacts from instream barriers on freshwater ecosystems have become more well-known and an industry established focusing on mitigating these negative impacts and restoring freshwater ecosystems. A primary focus of practitioners working to restore freshwater ecosystems has been to reconnect aquatic organisms to their original range through the design and implementation of fish ladders, also known as fishways. Fishways provide passage routes for fish past instream barriers, upstream and downstream. Fishway design in the Pacific Northwest United States focused primarily on anadromous salmonids, more commonly known as salmon (genus *Oncorhynchus*), due to cultural, economic, and recreational significance of salmon. Salmon are strong swimmers when compared to many other fish species; therefore, fishways designed and constructed specifically to allow passage of salmon may not provide safe, timely, and effective passage of other fishes.

The purpose of this document is to present a fishway design resource aimed at providing necessary species-specific background and abilities of weaker swimming fishes and evaluate the applicability of existing fishway design criteria when designing fishways for Bull Trout (*Salvelinus confluentus*). The fishway resource focuses on Bull Trout and Pacific Lamprey (*Entosphenus tridentatus*) and will be provided to the United States Fish and Wildlife Service (USFWS) as a draft document for future publishing. An extensive literature review was completed identifying species abilities, background, and comparison to existing design criteria, fishway practitioners were briefed on the project and their opinions related to content and format were solicited, and findings were thoroughly reviewed and discussed by and with USFWS staff. As a result of this project a concise fishway resource has been developed as a draft and template for USFWS staff.

Additionally, an evaluation of the applicability of using anadromous salmonid passage criteria when designing passage facilities for Bull Trout was conducted. Lastly, future research projects were suggested to address data gaps in Bull Trout swimming performance and fishway designs for them.

INTRODUCTION

Dams on the Columbia River in the Pacific Northwest U.S. have been a source of debate prior to the first days of their construction in the 1930s (Billington et al. 2005). Dams cause adverse ecological impacts to freshwater ecosystems and without adequate fish passage facilities can disconnect fish from habitat, isolate populations, and reduce abundance and distribution (Nehlsen et al. 1991; Sheer and Steel 2006; Benson 2009). The Federal Columbia River Power System (FCRPS) comprises 16 dams along the Columbia, Snake, and Clearwater rivers and fish passage facilities are included at all dams except Chief Joseph, Grand Coulee, and Dworshak dams (Figure 1; USACE 2020). Many native and non-native species of fish utilize these fishways with varying degrees of success.

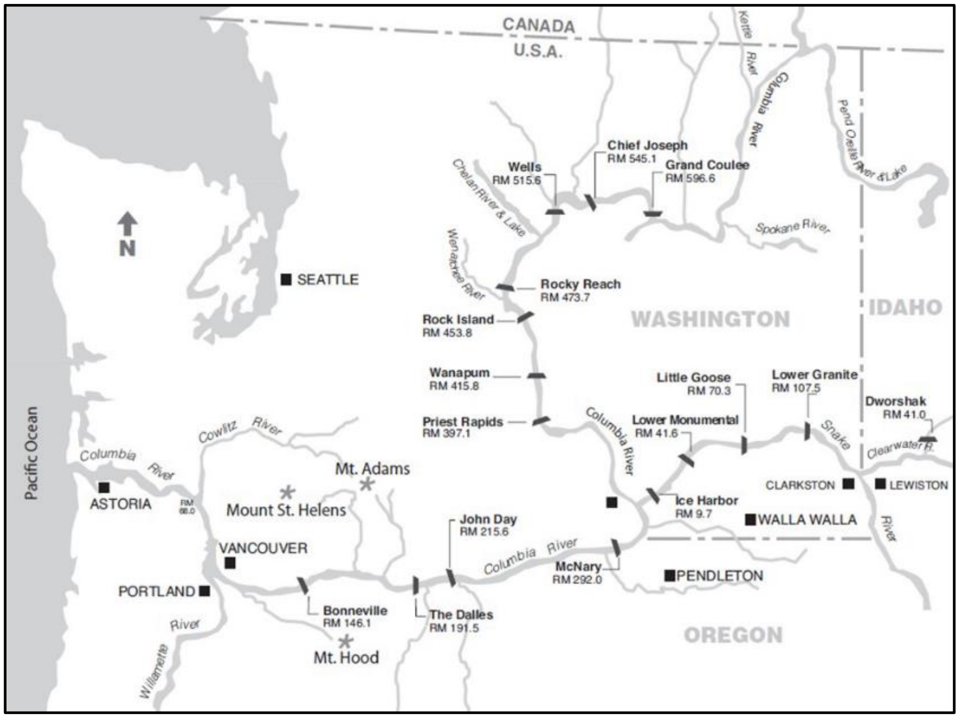

Figure 1. Map of the Federal Columbia River Power System (FCRPS; USACE 2020)

Studies to understand fish abilities and behavior occurred simultaneously with the design and construction of the first fish passage facilities within the FCRPS in the 1930s (Nemenyi 1941; Billington et al. 2005). Anadromous salmonids (genus *Oncorhynchus*) were selected as the design species for the fishways (Nemenyi 1941) due to their cultural, economic, and recreational significance and symbolism to the Pacific Northwest (NRC 1996). The FCRPS fish ladders, also termed fishways or fish passage structures, are concrete structures consisting of a series of pools and weirs or orifices allowing fish more favorable hydraulic conditions to ascend the barrier. The rationale and selection of design criteria for the first fish ladders in the FCRPS is unclear, although values of 1.8 m/s (5.9 ft/s) for velocity and a hydraulic drop of 0.6 m (2 ft) between pools were noted in 1935 by a Scottish water power company (Hydro-Electric Scheme of the Galloway Water Power Company 1935, reviewed in Nemenyi 1941). Studies were conducted at the Bonneville Dam Hydraulics Laboratory throughout the mid-1900s to gain understanding of swimming and leaping abilities of salmon and further develop design criteria (U.S. Army Corps of Engineers 1956; Weaver 1963, reviewed in Katopodis and Gervais 2016; U.S. Army Corps of Engineers 1984).

In recent decades it has become apparent that several fish species within the Columbia River basin are likely unable to ascend fishways designed for salmon in a safe, timely, and effective manner, resulting in efforts aimed at providing passage for a wider variety of species (Keefer et al. 2013b; Ackerman et al. 2019). The approach of designing species-specific fishways was adopted early in the dam building era (Creager and Justin

1927, reviewed in Nemenyi 1941); however, by selecting a strong swimming species such as salmon, weaker swimming fish are less likely to be able to ascend fishways. Two such species of weaker swimming fish are Bull Trout (*Salvelinus confluentus*) and Pacific Lamprey (*Entosphenus tridentatus*). Each species has experienced significant population declines due to both habitat degradation and reduction in connectivity resulting from instream barriers (USFWS 2016; USFWS 2019a). All populations of Bull Trout within the coterminous United States were listed under the Endangered Species Act as a "threatened" by the United States Fish and Wildlife Service (USFWS) in 1999. USFWS staff and partners have set out to develop a species-specific fish passage design resource for Bull Trout and Pacific Lamprey.

The following document provides biological background information on each of the two species, develops a fish passage resource for the two species along with a template for the USFWS, and evaluates the applicability of an existing fish passage guidance document for use when designing fishways specifically for Bull Trout.

The first major portion of this document (Chapter Three), Fish Passage Resource, is the culmination of a collaborative effort made by the USFWS and regional partners in the Pacific Northwest U.S. to provide accurate, concise, and useful guidelines for Bull Trout and Pacific Lamprey passage. In developing the document for Bull Trout and Pacific Lamprey, a synthesis of available information related to each species was completed, practitioner interviews were facilitated, and final product details were evaluated (format, scope, content, etc.). USFWS intends to perform an in-depth review of the document presented herein and publish a final version. The resource format may be used as a template in the future for additional trust resource species. Trust resources are the migratory birds and fish, federally listed threatened and endangered species, inter-jurisdictional fish, wetlands, and certain marine mammals the USFWS is charged by Congress to conserve and protect. The resource will be a living document and is intended to expand and be updated as new information becomes available.

Chapter Three is meant to be a standalone document and is organized into three components: Introduction, Bull Trout Guidelines, and Pacific Lamprey Guidelines. Each of the species-specific components is divided into sections providing biological background information, passage specific parameters and abilities, information related to migration corridors and behavior, design information related to passage at various barriers, and identified research needs and data gaps.

The second major portion of this thesis evaluates the applicability of the 2011 National Marine Fisheries Service (NMFS) Anadromous Salmonid Passage Facility Design (NMFS Criteria) guidelines for use when designing passage features for Bull Trout. The NMFS Criteria are widely used throughout the Pacific Northwest for planning, designing, and assessing fish passage features. The NMFS Criteria cover a variety of topics including design flow range, upstream fish passage systems, exclusion barriers, trapping systems, and others. The NMFS Criteria were written to assist with improving conditions for anadromous salmonids. However, because the criteria focus specifically on the genus *Oncorhynchus*, which does not include Bull Trout, it is unclear if Bull Trout can ascend fishways designed according to the NMFS Criteria in a safe, timely, and effective manner. Chapter Four of this document aims to assess how applicable the NMFS Criteria are for use when planning, designing, constructing Bull Trout passage features; compare swimming performance of Bull Trout to salmon; and provide justification for conclusions.

A summary and discussion follow each of the major portions of this thesis. The remaining work needed for final publishing of the fish passage resource is itemized and described, further studies and research are recommended for validating the conclusions made within Chapter Four, and general comments regarding fish passage design and construction are made.

LITERATURE REVIEW

Introduction

An extensive literature review process was conducted to fulfill the USFWS project requirements during the development of the fish passage resource. Over 200 articles, agency reports, and documents explicitly related to Bull Trout and Pacific Lamprey were reviewed. Additionally, over 100 articles and design resources were reviewed related to fish passage to inform decisions related format, content, and organization of the fish passage resource.

Fish Passage Guidelines

Federal and State agencies within the Pacific Northwest have produced fish passage guidelines throughout the last several decades. One of the first design resources published by a federal agency was the “Fisheries Handbook of Engineering Requirements and Biological Criteria” by Milo Bell and published by the U.S. Army Corps of Engineers in 1973 and revised and republished in 1986 and 1991. The Washington Department of Fish and Wildlife (WDFW) produced “Design of Road Culverts for Fish Passage” in 1999 and a draft “Fishway Guidelines for Washington State” document in 2000. Each were revised and republished under new names in 2013 (Water Crossing Design Guidelines) and 2019 (Fish Passage Inventory, Assessment, and Prioritization Manual).

The National Oceanic and Atmospheric Administration’s (NOAA) National Marine Fisheries Service (NMFS) published the NMFS Criteria in 2011. NMFS Criteria are widely used and referenced throughout the Pacific Northwest for design and assessment of fish passage facilities. A new version of the NMFS guidelines is forthcoming (A. Beavers, NOAA Fisheries, personal communication). Additionally, NMFS published design guidance related to juvenile fish screen design (NMFS 1995, NMFS 1996), both of which were superseded by information contained within NMFS (2011).

The United States Bureau of Reclamation (USBR) has developed several guidelines related to nature-like fishways. USBR (2016) provides considerations related to hydrology, geomorphology, hydraulics, sedimentation, and scour as well as design considerations. USBR (2007a) provides considerations related to hydraulics, material sizing, fish abilities, life cycle costs, as well as a rock ramp design example.

Species-specific fishway design criteria have been a consistent theme in the fish passage industry since the 1920s (Creager and Justin 1927, reviewed in Nemenyi 1941) and recent design documents address the need for species-specific considerations (USBR 2007a; USBR 2007b; NMFS 2011; USFWS 2019b). USBR (2007a) notes consideration of multiple species and multiple life stages as one of the most important concepts when designing fishways. To design fishways for several design species, adequate biological information related to passage (swimming performance, leaping abilities, etc.) must exist for each species (Bell 1991).

Bull Trout

Swim Speed

Bull Trout use subcarangiform (burst and glide) mode of locomotion, like that of other salmonids (Katopodis 1992). Bull Trout burst swim speed is between 1.3 and 2.3 m/s (Mesa et al. 2008). Burst swim speeds are independent of fish size. Burst swim speeds are speeds a specimen can achieve for a short duration, typically less than 20 seconds (Katopodis 1992; Gui et al. 2014). The burst swim speed experiment conducted by Mesa et al. (2008) determined a burst swim speed for Bull Trout achievable for less than 1 – 2 seconds.

Resident and fluvial Bull Trout critical swim speeds vary depending on size and temperature (Mesa et al. 2003a, 2004; Table 1). Critical speeds are achievable for a duration between 20 seconds and 30 minutes (Katopodis and Gervais 2016) and are an indicator of the aerobic capacity of a species (Brett 1964, reviewed in Hammer 1995). Due to a variety of testing procedures for determining critical swim speed and definitions of critical swim speed, comparing critical swim speeds of different species and studies requires careful examination (Geist et al. 2003).

Table 1. Bull Trout critical swim speeds (Mesa et al. 2003a, 2004).

Fork Length (cm)	Temperature (°C)	Mean Critical Velocity (m/s)
32 to 42	11	0.74
11 to 19	11	0.48
14 to 23	15	0.54

Brett (1964, reviewed in Hammer 1995) developed the critical swim speed testing protocols when testing young Sockeye Salmon (*O. nerka*). Critical swim speeds are determined by exposing fish to an initial water velocity in an experimental flume and increasing the velocity by a set increment at an established time step. The critical swimming speed is the water velocity at which a fish reaches exhaustion. The velocity increments and time steps used for salmonids vary widely; therefore, caution should be used when comparing critical swim speeds of different species (Hammer 1995). Moreover, the term "critical swimming speed" is something of a misnomer in that contrary to expectation it is not a water velocity threshold limiting passage.

Each of the studies conducted by Mesa et al. (2003a, 2004, 2008) have resulted in the industry standard values used for Bull Trout swim speeds. Each study reported relatively sparse fish participation and therefore the swim speed values used regionally are based on the abilities of a very small sample size. More research on Bull Trout swimming speeds is needed to provide greater confidence in the validity of these values.

Bull Trout can pass nearly all FCRPS passage facilities, which were designed for passage by anadromous salmonids (Barrows et al. 2016). However, Bull Trout passage efficiency through the FCRPS dams is unknown. Efforts to identify velocities encountered at these dams during times of passage could help enhance understanding of the swimming abilities of the species in a non-laboratory setting.

Leaping Abilities

Identifying vertical barriers goes beyond a calculation of the difference in elevation between the jump and landing pools. Hydraulic, biological, and physiological aspects such as jump pool depth, velocity of water flowing over the jump, landing area at top of the jump, age of the individual, motivation, etc., considered together determine if a barrier exists (M. Barrows, USFWS, personal communication).

Bull Trout jump heights have not been studied specifically. Anecdotal evidence exists indicating that stream resident Bull Trout may be able to jump 0.6 to 0.9 m (2-3 feet) and migratory Bull Trout may be able to jump three times their body length (L. Knotek, Montana Fish, Wildlife and Parks, personal communication) depending on life stage, jump pool depth, and flow rate (USFS and USFWS 2013).

Examples of jump heights that Bull Trout have been known to pass, at unknown and probably varying rates, include a 2.4 m (8 ft.) barrier on Mill Creek and Lostine River, Oregon (P. Sankovich, USFWS, personal communication) and a 0.9 – 1.2 m (3 – 4 ft) barrier at Rainy Dam on the Clearwater River in Montana (L. Knotek, Montana Fish, Wildlife and Parks, personal communication). Passage rates are not known for these obstacles. Future studies could be completed at known vertical passage features to gain understanding of Bull Trout leaping abilities based on the percent, size, age, etc., of Bull Trout passing each vertical passage feature.

U.S. Forest Service and USFWS staff completed a cooperative project with the Montana Department of Fish, Wildlife and Parks in 2012 to raise the bed elevation below Rainy Dam to allow Bull Trout passage while limiting movement of undesirable species (USFS and USFWS 2013). Fluvial Bull Trout ascend the barrier that ranges from 0.5 m (1.5 ft) at high flows to 0.9 – 1.2 m (3 – 4 ft) at base flows (L. Knotek, Montana Fish, Wildlife and Parks, personal communication).

Pacific Lamprey

Swimming Abilities

Adult Pacific Lamprey can employ two modes of locomotion: anguilliform (swimming without oral disc attachment) and burst-and-attach. Anguilliform locomotion is the primary mode used during movement through open water and low gradient, quiescent channels with low to moderate velocities. Daigle et al. (2005) reported Pacific Lamprey change from anguilliform swimming to burst-and-attach at > 0.6 m/s (~2.0 ft./s). Burst-and-attach is used when hydraulic conditions create velocity or turbulence barriers to anguilliform swimming or when physical barriers are present and climbing via burst-and-attach becomes advantageous.

Burst-and-attach locomotion is accomplished when the lamprey alternates between forming several lateral bends along the longitudinal axis while attached to the surface with its oral disc and straightening the body while briefly releasing suction (Reinhardt et al. 2008). Pacific Lamprey tend to use burst-and-attach locomotion throughout fishways due to the velocities and turbulence present within them. Burst swim speed and burst-and-attach locomotion are exceeded when velocities exceed 2.5 – 3.0 m/s (Keefer et al. 2010, Kirk et al. 2016).

For burst-and-attach locomotion to be effective, smooth surfaces in which the Pacific Lamprey’s oral disc can attach must be present throughout. Surface irregularities should not exceed 2 mm (PLTW 2017). In nature-like fishways, large (4-6” minimum radius), smooth, rounded cobbles and boulders with minimum surface irregularities provide best passage success (Crandall and Wittenbach 2015).

Aluminum ramps and walls are commonly placed within technical fishways as attachment surfaces for Pacific Lamprey when burst-and-attach locomotion is anticipated or expected. For more information regarding Pacific Lamprey passage of technical fishways, see the Fish Passage and Diversions section in the following chapter.

Hanchett and Caudill (2020) studied fatigue during passage and found that Pacific Lamprey showed high individual variability in duration and timing of burst-and-attach locomotion. Fish that failed to ascend spent more time attached and turned around more often. A threshold fatigue was associated with changes in behavior or motivation. The cumulative effects of passage are therefore important to consider when designing or evaluating fishways. Velocities that require high activity levels over a prolonged period may induce fatigue, indicating the need for refuge areas to allow recovery.

Reid and Goodman (2016) noted Pacific Lamprey tend to use lower portions of the water column by swimming within 6 cm of the bottom. Upstream swim speeds of 29.4 ± 11.4 cm/s were reported (originally reported in BL/s, converted to cm/s using a mean body length of 60 cm), after removing the impacts of water velocity.

Climbing Abilities

Pacific Lamprey cannot jump (Goodman and Reid 2017). However, Pacific Lamprey can climb vertical or near vertical surfaces when using burst-and-attach locomotion (Reinhardt et al. 2008).

The maximum vertical distance Pacific Lamprey can ascend has not been studied. Evidence suggests that vertical elements within a fishway should be limited to not more than several meters (Kemp et al. 2009; Frick et al. 2017). Kemp et al. (2009) studied

Pacific Lamprey climbing behavior and found the duration of bouts (active climbing) declined with distance ascended, indicating fatigue is experienced while climbing, suggesting higher vertical elements cause greater fatigue and reduce passage rates.

FISH PASSAGE RESOURCE

Contribution of Authors and Co-Authors

Manuscript in Chapter 3

Author: Travis Denham

Contributions: Synthesized available information, organized information, wrote manuscript.

Co-Author: Kathryn Plymesser Ph.D., PE

Contributions: Helped from conceptual basis, managed progress, proposal to secure funding, and reviewed and revised manuscript.

Co-Author: Janine Castro Ph.D.

Contributions: Intellectual contributions, facilitated partner meetings, provided funding, and reviewed and revised manuscript.

Co-Author: Matt Blank Ph.D., PE

Contributions: Intellectual contributions, provided insight from consulting perspective, and revised and reviewed manuscript.

Co-Author: Alexander Zale Ph.D.

Contributions: Intellectual contributions, provided insight from scientific perspective, and reviewed and revised manuscript.

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U.S. Fish and Wildlife Service

Disclaimer: The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the U.S. Fish and Wildlife Service.

The following chapter is intended to be a standalone document presented to the U.S. Fish and Wildlife Service as a draft fish passage resource.

Introduction

The U.S. Fish and Wildlife Service (USFWS) is charged by Congress to conserve and protect migratory birds and fish, federally listed threatened and endangered species, inter-jurisdictional fish, wetlands, and certain marine mammals. These are known as "trust resources." Among these trust resources are a variety of fish species that have environmental, economic, cultural, recreational, and symbolic importance in the Pacific Northwest (PNW).

Intent

This guidance document is intended to provide passage design guidance on USFWS trust resource fish and aquatic organisms in the Pacific Northwest. The initial version of the document focuses on Bull Trout (*Salvelinus confluentus*) and Pacific Lamprey (*Entosphenus tridentatus*); however, additional trust resources will be added over time. This document was developed to provide guidance to engineers, managers, biologists, stakeholders, and other aquatic restoration practitioners who are funding, designing, reviewing, implementing, or assessing instream structures and features, including fishways, exclusion barriers, road crossing structures, screens, levees, tide gates, infiltration galleries, low-flow passage structures, and irrigation diversions throughout the ranges of these species. These guidelines use best-available science to inform design approaches that improve aquatic connectivity for these trust resources through effective fish passage and screening.

Use of this guidance document is intended to improve conditions for PNW fish that must migrate past barriers upstream, downstream, and laterally into adjacent stream habitats to complete their life cycles and to provide the rationale, guidelines, and definitions needed to design proper fish passage facilities. The document will identify research gaps and data needs related to passage of USFWS trust resources.

The guidance document is intended to be a working document. When new or updated information suggests a different standard provides better fishway passage, simplifies operations, or decreases required maintenance, this document will be updated to reflect the current best practices. Periodic updating of this synthesis document will increase adoption rates of new and improved technology and applications.

Species-Specific Criteria

No consolidated guidelines exist to help designers improve passage and connectivity for USFWS trust species in the PNW. Most current regional fish passage criteria focus on anadromous salmonids, resulting in missed opportunities to improve passage for a wider variety of aquatic organisms. The guidance document initially focuses on two USFWS trust resources of concern, Bull Trout and Pacific Lamprey, but is structured such that other trust resources can be easily added.

Connectivity is a habitat requirement for migratory Bull Trout (USFWS 2010). Physical barriers reducing connectivity are the primary cause of habitat fragmentation, making a compelling case that fish passage is a very high priority for the recovery of Bull Trout. Similarly, the 2019 Pacific Lamprey Assessment indicated that passage barriers and stream and floodplain degradation are principal threats to Pacific Lamprey throughout their range. Therefore, provision of fish passage guidelines for USFWS trust resources will allow project designers to include project-specific elements to improve passage and aquatic connectivity.

The following two sections of this document are devoted to each USFWS trust resource separately and contain the following information: species background, which covers biology and ecology, current and historic range, and migration timing; passage specific parameters and abilities; migration corridors and behaviors; fish passage and diversions; and finally research needs and data gaps. Documents and reports related to management and recovery practices for each species are include in Appendix A.

Bull Trout Guidance

Species Background

Biology and Ecology. Bull Trout are native char found in the coastal and intermountain west of North America. They have unusually large heads and mouths for salmonids (Figure 2; USFWS 2017). Their body coloration can vary tremendously depending on their environment but is often brownish green with lighter spots (often ranging from pale yellow to crimson) running along their dorsa and flanks, with no spots on the dorsal fin, and light colored to white underbellies (USFWS 2017). Leading fin edges are white, as in other chars. Bull Trout tend to be oriented to the bottom quarter of the water column (Al-Chokhachy et al. 2007).

Figure 2. Fluvial Bull Trout from the North Fork Imnaha River. Photograph by Justin R. Cook (Sankovich and Whitesel 2018).

Bull Trout may be migratory, moving throughout large river systems, lakes, and even the ocean in coastal populations, or they may be resident, remaining in the same stream their entire lives (Rieman and McIntyre 1993; Brenkman and Corbett 2005). Resident and migratory forms may be found together, and either form may give rise to offspring exhibiting either resident or migratory behavior (Rieman and McIntyre 1993; Brenkman et al. 2007; Homel et al. 2008; USFWS 2015a).

Migratory Bull Trout are typically larger than resident Bull Trout (U.S. Fish and Wildlife Service 1998). Resident adults range from 15.2 to 30.5 cm (6 to 12 inches) in total length, whereas migratory adults commonly reach 60 cm (24 inches or more (Pratt 1985; Goetz 1989). The largest verified Bull Trout was a 14.5-kg (32-pound) specimen caught in Lake Pend Oreille, Idaho, in 1949 (Simpson and Wallace 1982).

Range. The historical range of Bull Trout includes major river basins in the Pacific Northwest at about 41 to 60 degrees North latitude from its southern limits in the McCloud River in northern California and the Jarbidge River in Nevada to the headwaters of the Yukon River in the Northwest Territories, Canada (Cavender 1978; Bond 1992). To the west, the Bull Trout's range includes Puget Sound, various coastal rivers of British Columbia, Canada, and southeast Alaska (Bond 1992). Bull Trout occur in portions of the Columbia River and its tributaries, including in its headwaters in Montana and Canada. Bull Trout also occur in the Klamath River basin of south-central Oregon. East of the Continental Divide, Bull Trout are found in the headwaters of the Saskatchewan River in Alberta and Montana and in the Mackenzie River system in Alberta and British Columbia, Canada (Cavender 1978; Brewin et al. 1997).

Bull Trout originated in the Columbia River basin. Dispersal to other drainages was accomplished by marine migration and headwater stream capture. Behnke (2002) postulated that dispersal to drainages east of the Continental Divide may have occurred through the North and South Saskatchewan rivers (Hudson Bay drainage) and the Yukon River system. Marine dispersal may have occurred from Puget Sound north to the Fraser, Skeena, and Taku rivers of British Columbia (USFWS 2017).

Six recovery units are necessary to maintain the Bull Trout's distribution, as well as its genetic and phenotypic diversity. The six recovery units are the Coastal, Klamath, Mid-Columbia, Upper Snake, Columbia Headwaters, and Saint Mary recovery units (Figure 4, USFWS 2016a). Each recovery unit is important to ensure the species' resilience to changing environmental conditions. No new local populations have been identified and no local populations have been lost since listing. See USFWS (2017) for information regarding the current population status of Bull Trout in each of the six recovery units.

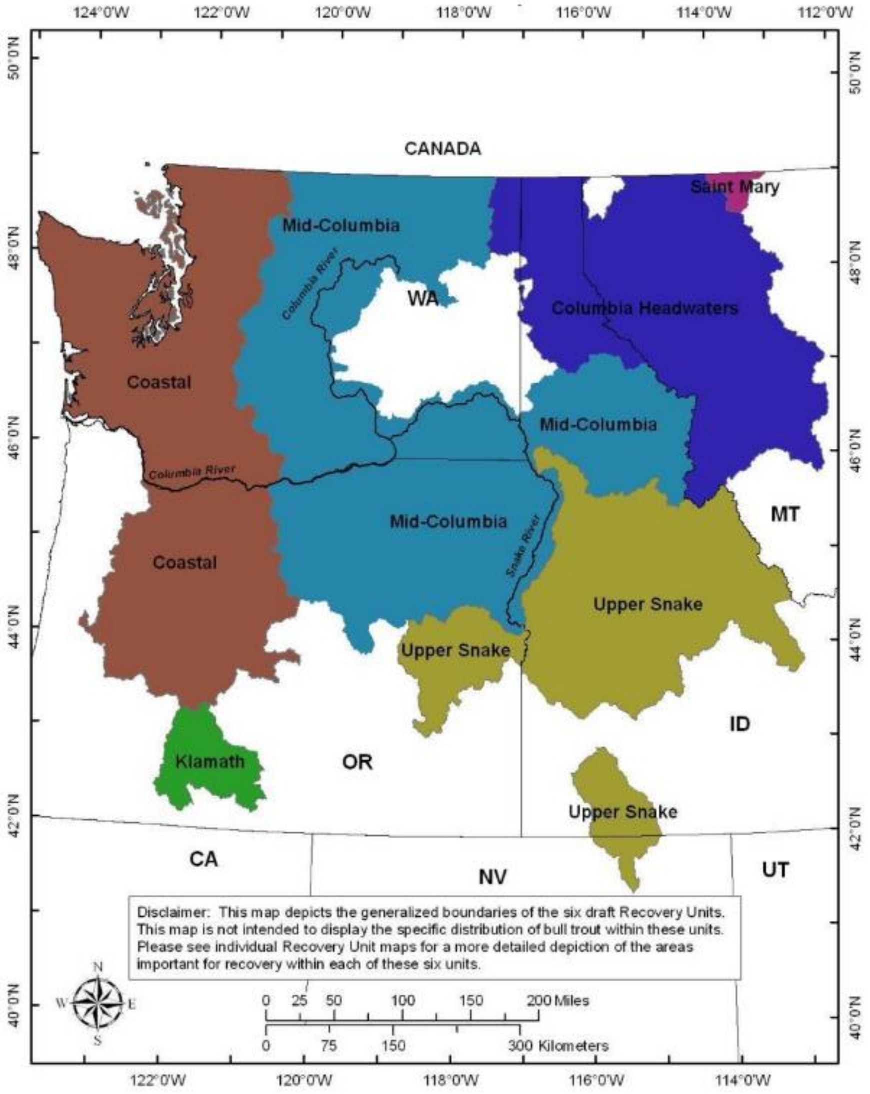

Figure 3. The six Bull Trout recovery units in the coterminous range within the USA (Koski and Whitesel 2012).

<u>Migration Timing.</u> Upstream movement of adult Bull Trout generally occurs during the spring, beginning as early as March in some basins (Barrows et al. 2016).

Additional movement to spawning areas, if needed, occurs from August to November. Juvenile Bull Trout remain in headwater streams for 1-3 years before migrating to a larger river (fluvial life form), lake or reservoir (adfluvial, Hoelscher and Bjornn 1989), or the ocean (anadromous). Resident forms do not migrate. Adult Bull Trout migrate downstream primarily from October through April but can migrate throughout the entire year (Barrows et al. 2016). Outmigration of subadult Bull Trout into the Columbia River is more common in the autumn than in the spring (Barrows et al. 2016). See Table 3.4 in Barrows et al. (2016) for basin-specific outmigration timing of subadult Bull Trout.

Passage Specific Parameters and Abilities

Fish passage facilities throughout the Pacific Northwest tend to be designed for adult anadromous salmonids that can achieve burst swim speeds in excess of 6 m/s (Bell 1991). Whether Bull Trout can efficiently pass such facilities is unclear. Therefore, alternative design parameters must be considered when designing passage facilities for Bull Trout. The following subsections list Bull Trout abilities and requirements for several key passage parameters: swim speeds, jumping abilities, water depth provisions, maximum gradient preferences, and thermal requirements.

Swim Speed.

Bull Trout exhibit subcarangiform (burst and glide) mode of locomotion, like that of other salmonids (Katopodis 1992). Bull Trout burst swim speed is between 1.3 and 2.3 m/s (Mesa et al. 2008). Burst swim speeds are independent of fish size. Burst swim speeds are speeds a specimen can achieve for a short duration, typically less than 20 seconds (Gui et al. 2014). The burst swim speed experiment conducted by

Mesa et al. (2008) determined a burst swim speed for Bull Trout achievable for less than 1 – 2 seconds.

Resident and fluvial Bull Trout critical swim speeds vary depending on size and temperature (Mesa et al. 2003a, 2004; Table 2). Critical speeds are achievable for a duration between 20 seconds and 30 minutes (Katopodis and Gervais 2016) and are an indicator of the aerobic capacity of a species (Brett 1964, reviewed in Hammer 1995). Due to a variety of testing procedures for determining critical swim speed and definitions of critical swim speed, comparing critical swim speeds of different species and studies requires careful examination (Geist et al. 2003).

Table 2. Bull Trout critical swim speeds (Mesa et al. 2003a, 2004).

Fork Length (cm)	Temperature (°C)	Mean Critical Velocity (m/s)
32 to 42	11	0.74
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Brett (1964, reviewed in Hammer 1995) developed the critical swim speed testing protocols when testing young Sockeye Salmon (*O. nerka*). Critical swim speeds are determined by exposing fish to an initial water velocity in an experimental flume and increasing the velocity by a set increment at an established time step. The critical swimming speed is the water velocity at which a fish reaches exhaustion. The velocity increments and time steps used for salmonids vary widely; therefore, caution should be used when comparing critical swim speeds of different species (Hammer

1995). Moreover, the term “critical swimming speed” is something of a misnomer in that contrary to expectation it is not a water velocity threshold limiting passage.

Each of the studies conducted by Mesa et al. (2003a, 2004, 2008) have resulted in the industry standard values used for Bull Trout swim speeds. Each study reported relatively sparse fish participation and therefore the swim speed values used regionally are based on the abilities of a very small sample size. More research on Bull Trout swimming speeds is needed to provide greater confidence in the validity of these values.

Bull Trout are reportedly able to pass nearly all the Federal Columbia River Power System (FCRPS) passage facilities, which were designed for passage by anadromous salmonids (Barrows et al. 2016). However, Bull Trout passage efficiency through the FCRPS dams is unknown. Efforts to identify velocities encountered at these dams during times of passage could help enhance understanding of the swimming abilities of the species in a non-laboratory setting.

Jump Heights. Identifying vertical barriers goes beyond a calculation of the difference in elevation between the jump and landing pools. Hydraulic, biological, and physiological aspects such as jump pool depth, velocity of water flowing over the jump, landing area at top of the jump, age of the individual, motivation, etc., considered together determine if a leap barrier exists (M. Barrows, USFWS, personal communication).

Bull Trout jump heights have not been studied specifically; therefore, no passage parameter is suggested. Anecdotal evidence exists indicating that stream resident Bull Trout may be able to jump 0.6 to 0.9 m (2-3 feet) and migratory Bull Trout may be able to jump three times their body length (L. Knotek, Montana Fish, Wildlife and Parks, personal communication) depending on life stage, jump pool depth, and flow rate (USFS and USFWS 2013).

Examples of jump heights that Bull Trout have been known to pass, at unknown and probably varying rates, include a 2.4 m (8 ft.) barrier on Mill Creek and Lostine River, Oregon (P. Sankovich, USFWS, personal communication), and a 0.9 – 1.2 m (3 – 4 ft) barrier at Rainy Dam on the Clearwater River in Montana (L. Knotek, Montana Fish, Wildlife and Parks, personal communication). Passage rates are not known for these obstacles. Future studies could be completed at known vertical passage features to gain understanding of Bull Trout leaping abilities based on the percent, size, age, etc., of Bull Trout passing each vertical passage feature.

U.S. Forest Service and USFWS staff completed a cooperative project with the Montana Department of Fish, Wildlife and Parks in 2012 to raise the bed elevation below Rainy Dam to allow Bull Trout passage while limiting movement of undesirable species (USFS and USFWS 2013). Fluvial Bull Trout ascend the barrier that ranges from 0.5 m (1.5 ft) at high flows to 0.9 – 1.2 m (3 – 4 ft) at base flows (L. Knotek, Montana Fish, Wildlife and Parks, personal communication).

Water Depth Provisions. Bull Trout minimum water depth requirements have not been studied specifically.

Minimum water depth requirements for design of fish passage in the Pacific Northwest vary among states. For example, Oregon requires 15.2 cm (6 inches) for juvenile passage and 30.5 cm (12 inches) for adults (Oregon Department of Fish and

Wildlife 2016). Additionally, NMFS (2011) lists minimum depths within culverts of 30.5 cm (1 foot) for adult steelhead, Chinook, Coho, and Sockeye Salmon, 22.9 cm (0.75 feet) for Pink and Chum Salmon, and 15.2 cm (0.5 feet) for juveniles of all species of salmon.

Schaller et al. (2014) used a minimum water depth criterion of 18.3 cm (0.6 feet) to evaluate passage conditions for adult Bull Trout. This criterion was established for both steelhead and large resident trout (Thompson 1972; Reiser and Bjorn 1979). Cutthroat and Brook trout passed test culverts with water depths of 2.0 – 3.5 cm (Burford et al. 2009), well below the requirements mentioned above. The differences between established depth requirements and actual fish abilities indicate that a greater understanding of Bull Trout minimum water depth requirements is needed.

<u>Maximum Gradient.</u> Maximum channel gradient can at times serve as an indicator of a possible velocity barrier because steeper gradients result in increased velocity. For Bull Trout, a gradient that is deemed a barrier and limiting passage is probably a result of high velocity creating the barrier.

No definitive threshold gradient exists; however, some authors have listed gradients assumed to be migration barriers. Rich et al. (2003) identified 20% gradients as apparent fish migration barriers but WDFW (2019) noted Bull Trout can pass gradients as high as 33%. As a result of the varying gradients listed as passable or impassable for Bull Trout, gradients steeper than 18 to 20% should be viewed as limiting migration, and therefore, should be avoided during design. Stream characteristics that can influence a Bull Trout’s ability to pass steep gradients include the absence or presence of resting pools, motivation, and the length of the steep reaches.

Thermal Requirements. Bull Trout require cold water and therefore temperature is a key variable in the survival of Bull Trout; however, no temperature is consistently identified as preventing movement of Bull Trout. Studies comparing Bull Trout location, movement, and temperature indicate movement related to temperature is individual-specific (Howell et al. 2010).

USFWS (2010) listed water temperatures ranging from 2 to 15 °C (36 to 59 °F) as a primary constituent element of Bull Trout critical habitat. Primary constituent elements are essential features to characterize the key components of critical habitat that provide for conservation of Bull Trout (USFWS 2017). For temperatures that exceed the upper end of this range, adequate available thermal refugia are required. The range of water temperatures may vary depending on Bull Trout life-history stage and form; geography; elevation; diurnal and seasonal variation; shading, such as that provided by riparian habitat; streamflow; and local groundwater influence.

Peterson et al. (2015) listed temperatures greater than 18 °C as too warm for Bull Trout within the lower Clark Fork River. Peterson et al. (2015) and Barrows et al. (2016) identify 15 °C as marginal thermal habitat that Bull Trout tend to avoid. As a result, temperatures above 15 °C should be avoided when possible. Additional information related to Bull Trout temperature preferences is listed in the following section.

Migration Corridors and Species Behavior

Information related to migration corridors and species behaviors listed herein describe aquatic environments each species prefers during normal migration, i.e., not in a fish passage feature. The list of preferences is not exhaustive; rather, it is meant to include attributes related to fish passage that may inform decisions related to restoring habitat adjacent to a fish passage project.

Cover. All life history stages of Bull Trout are associated with complex forms of cover, including large wood, undercut banks, boulders, and pools (Fraley and Shepard 1989; Goetz 1989; Hoelscher and Bjornn 1989; Sedell and Everest 1991; Pratt 1992; Thomas 1992; Rich 1996; Sexauer and James 1997; Watson and Hillman 1997). Maintaining Bull Trout habitat requires maintenance of natural stream-channel bed stability and flow patterns (Rieman and McIntyre 1993). Juvenile and adult Bull Trout frequently inhabit side channels, stream margins, and pools with adequate cover (Sexauer and James 1997). These areas are sensitive to activities that directly or indirectly affect stream channel stability and alter natural flow patterns. For example, altered stream flow in the autumn may disrupt Bull Trout during the spawning period, and channel bed instability may decrease survival of eggs and young juveniles in the gravel from winter through spring (Fraley and Shepard 1989; Pratt 1992; Pratt and Huston 1993). Pratt (1992) indicated that increases in fine sediment reduce egg survival and emergence.

Water Depth Preference. Many studies have been conducted relating Bull Trout presence and absence to water depth (Saffel and Scarnecchia 1995; Dunham et al. 2001; Al-Chokhachy and Budy 2007; Anglin et al. 2008; Al-Chokhachy et al. 2010; Barrows et al. 2014; Tennant et al. 2015) and Bull Trout prefer locations that have a variety of depths (USFWS 2017). Anglin et al. (2008) identified depth as a secondary trait of habitat selection for Bull Trout redd sites. Velocity and substrate conditions were prioritized over depth.

Adult and juvenile Bull Trout select the deepest water available (Saffel and Scarnecchia 1995; Al-Chokhachy et al. 2010). Adult Bull Trout tend to select deeper habitats than juveniles; Bull Trout were generally absent from reaches with residual pool depth estimates less than 0.3 m and where the percent undercut banks was less than 16% (Al-Chokhachy et al. 2010).

Turbidity Water Impacts. Bull Trout prefer clean water quality that is free of sediment and contaminants (USFWS 2016a). However, the influences of increased sediment delivery on Bull Trout range from beneficial to detrimental. Elevated turbidity enhances fish cover conditions and reduces piscivorous fish/bird predation rates, thereby possibly improving fish survival for smaller size classes of Bull Trout (USFWS 2017). Elevated turbidities also cause fish physiological stress, reduce fish feeding and growth, and may adversely affect fish survival. High levels of suspended sediment and turbidity for extended periods can result in direct injury or mortality to fish by damaging and clogging gills (gill trauma). The range of effects of increased turbidity on Bull Trout can be beneficial, non-injurious, injurious, or lethal, depending on site conditions, life stage, turbidity levels, and duration of exposure.

Light vs. Darkness. Bull Trout generally tend to be more active in darkness than light (M. Barrows, USFWS, personal communication) but no studies have evaluated this directly. Pearson et al. (2005) and Brandt et al. (2005) found no significant effect of light intensity on successful passage of simulated waterfalls by juvenile salmonids (*O. kisutch* and *S. fontinalis*, respectively).

Substrate. Substrates of sufficient amount, size, and composition are needed to ensure egg and embryo overwinter survival, fry emergence, and age-0 and juvenile survival in spawning and rearing areas. A minimal amount of fine sediment, generally ranging in size from silt to coarse sand, embedded in larger substrates is characteristic of these conditions. The size and amounts of fine sediment suitable to Bull Trout probably varies among systems (USFWS 2017).

Al-Chokhachy et al. (2010) reported little agreement when reviewing previously published Bull Trout habitat studies relating distribution and substrate size. Two primary reasons for the varied results were: confounding effects of water velocity and substrate size, and difficulties observing juvenile Bull Trout in areas of large substrate due to concealment. Bull Trout redds were in areas characterized by high percentages of gravel and cobble substrates (Tennant et al. 2015).

Channel Gradient. The importance of channel gradient varies among the eight different Bull Trout life stages (Schaller et al. 2014). Channel gradient ranged from moderately influential for adult spawning Bull Trout to less influential for fluvial adult upstream migration. Schaller et al. (2014) identified quality of channel gradient related to time of the year.

Gradients related to spawning habitat were assessed in the Walla Walla River basin (USFWS 2012). Redd counts were conducted and compared to channel gradient. Bull Trout preferred moderate gradients, between 2.7% and 7.5%, over mild or steep gradients (Table 3, USFWS 2012).

Table 3. Spawning gradient habitat type (USFWS 2012)

Habitat Type	Gradient %
No Spawning	<1.725 or >7.45
Low Density Spawning	<2.7 and >1.725
High Density Spawning	≥2.7 and <7.45

Peterson et al. (2015) developed a decision support model resulting from 15 years of formal conservation efforts on the lower Clark Fork River. The model was developed to inform conservation decisions related to Bull Trout. Within the decision support model, channel gradient was related to habitat quality (Table 4) and used with other abiotic factors to determine spawning and rearing habitat quality. How the channel gradient values were related to habitat quality is unclear and therefore, careful consideration must be used prior to adopting the listed values.

Table 4. Habitat quality based on channel gradient (Peterson et al. 2015)

Habitat Quality	Channel Gradient (%)
Ideal	<2
Moderate – Ideal	2 – 5
Moderate	5 – 10
Poor	10 – 20
Very poor	>20

Thermal Preference. Cold water temperatures play an important role in determining Bull Trout habitat quality, as these fish are primarily found in cold streams, and spawning habitats are generally characterized by temperatures that drop below 9 °C (48.2 °F) in the autumn (Fraley and Shepard 1989; Pratt 1992; Rieman and McIntyre 1993).

Thermal preferences for Bull Trout appear to differ at different life stages. Spawning areas are often associated with cold-water springs, groundwater infiltration, and the coldest streams in a watershed (Pratt 1992; Rieman and McIntyre 1993). Optimum incubation temperatures for Bull Trout eggs range from 2.2 to 6 °C (36.0 °F to 42.8 °F) whereas optimum water temperatures for rearing range from about 6 to 10 °C (42.8 °F to 50.0 °F) (Goetz 1989; Buchanan and Gregory 1997). In Granite Creek, Idaho juvenile Bull Trout selected the coldest water available in a plunge pool, 6 to 9 °C (46.4 °F to 48.2 °F; Bonneau and Scarnecchia 1996), within a temperature gradient of 6 to 15 °C (46.4 °F to 59.0 °F). In a landscape study relating Bull Trout distribution to maximum water temperatures, Dunham et al. (2003) found that the probability of juvenile Bull Trout occurrence does not become high (i.e., greater than 0.75) until maximum temperatures decline to 11 to 12 °C (51.8 °F to 53.6 °F). Lastly, the ultimate upper incipient lethal temperature for age-0 Bull Trout was determined to be 20.1 °C (69.6 °F; Selong et al. 2001)

Although Bull Trout are found primarily in cold streams, they also use larger, warmer river systems as migratory corridors (Fraley and Shepard 1989; Rieman and McIntyre 1993; Rieman and McIntyre 1995; Buchanan and Gregory 1997). Availability and proximity of cold-water patches and food productivity can influence Bull Trout ability to survive in warmer rivers (Myrick 2002).

Surrogate Species. Chinook Salmon fry have been used, in specific situations, as a surrogate for Bull Trout fry because both use the same types of habitat, are of similar size and have similar swimming abilities (USFWS 2017).

White-spotted Char (*S. leucomaenis*) and Bull Trout are sister taxa of one another (Dunham et al. 2008). Further studies relating their physical abilities and habitat preferences should be completed to understand whether White-spotted Char and Bull Trout are adequate surrogates of one another.

Fish Passage and Diversions

This section of the Bull Trout specific portion of the document is intended to provide information and resources about Bull Trout-specific upstream and downstream passage. Subsections address various types of passage features. Where available, specific considerations and suggestions are provided for the various types of passage features.

Fish Screens.

The NMFS Criteria (2011) screening requirements established for anadromous salmonids were deemed adequate for designing screening facilities for Bull Trout by Zydlewski et al. (2000 and 2002). The applicability of using previously published screening regulations for salmonid fry was assessed in Zydlewski et al. (2000) and Zydlewski and Johnson (2002), which described a single experiment with results published as a report and an article. The study concluded that the screen regulations published by WDFW (Fish and Wildlife 2000; Hydraulic Project Approval Program (HPAP) 2000a; HPAP 2000b) and NMFS (1995) do not need to be modified for Bull Trout fry. The referenced regulations are dated; however, the established criteria were deemed adequate for Bull Trout fry (Table 5).

Table 5. Screen criteria evaluated by Zydlewski and Johnson (2002)

Criteria Description (Section)	Criteria Value
Minimum screen face open area	27%
Minimum opening dimensions	Circular openings: 2.4 mm diameter Square openings: 2.4 mm each side Slotted or rectangular: 1.75 mm in narrow direction
Maximum approach velocity	0.12 m/s[1]

1. Velocity measured 7.6 cm in front of the screen

Screen requirements listed in NMFS 2011 are consistent with the regulations listed above except that maximum approach velocity was decreased to 6 cm/s unless equipped with an automatic mechanical screen cleaning system, in which case the maximum approach velocity requirement is 12 cm/s.

Downstream Passage. Bull Trout require passage both upstream and downstream, not only for repeat spawning but also for other reasons important to their survival (foraging, thermal refuge, escape predation, etc.). However, most fish ladders were designed specifically for adult anadromous semelparous salmonids (fishes that spawn once and then die and require only one-way passage upstream). Therefore, dams or other barriers with upstream fish passage facilities may isolate Bull Trout populations if they do not provide a downstream passage route.

Adult Bull Trout migrate downstream primarily from October through April but can migrate at any time during the year (Barrows et al. 2016). Subadult Bull Trout typically disperse downstream from spawning/early rearing areas in the spring through mid-summer. Downstream dispersal slows during mid-summer and then increases again during the autumn and winter months (M. Barrows, USFWS, personal communication). Downstream passage through dam turbines is therefore possible at any time of the year and may be the most likely route for Bull Trout at hydroelectric facilities, which are benthically oriented (Montana Bull Trout Restoration Team 2000; Al-Chokhachy and Budy 2007; USFWS 2007; Barrows et al. 2016).

Feature Specific Notes. State government agencies within the Pacific Northwest have established requirements for a variety of fishway features associated with downstream passage.

The Oregon Department of Fish and Wildlife (ODFW) provides requirements for downstream passage of aquatic organisms within the Oregon Administrative Rules for fish passage (ODFW 2016). The following bullets provide a summary of key requirements for downstream passage set forth by ODFW:

- Water depth over spillways shall be greater than 10 cm (4 inches) during all flows
- Plunging flow moving past an artificial obstruction via spillway, outlet pipes, or some other means that may contain fish shall:
  - At all flows, fall into a receiving pool of sufficient depth, depending on impact velocity and quantity of flow, to ensure that fish and flow shall not impact the stream bottom or other solid features
  - Have a maximum impact velocity into a receiving pool, including vertical and horizontal velocity components, less than 7.6 m/s (25 feet per second)
- Submerged or enclosed conduit or orifice may be used if:
  - Acceptable guidance or collection mechanisms are used and kept free from debris
  - Water depth is greater than 10 cm (4 inches) during all flows

  - Water velocity is greater than 0.6 m/s (2 feet per second) during all flows
  - Water is not pumped
  - Conduits have smooth surfaces and avoid rapid changes in direction to preclude fish impact and injury
  - Conduits are at least 25.4 cm (10 inches) wide

Road-Stream Crossings. No Bull Trout specific road-stream crossing guidelines are known to exist.

When designing a new road-stream crossing or when replacing a road-stream crossing, a stream simulation approach should be employed, aimed at providing passage to all aquatic species. See Water Crossing Design Guidelines (Barnard et al. 2013) and/or USDA Forest Service Stream Simulation Working Group (FSS-SWG) (FSS-SWG 2008) for complete design guidelines of stream simulation road-stream crossings. Key elements of stream simulation design, listed by FSS-SWG (2008) and summarized by Lamprey Technical Workgroup (2020a) are as follows:

- Continuous streambed that simulates natural channel width, depth, gradient, and substrate of adjacent channel (both upstream and downstream).
- Contains diverse water depths and velocities, hiding and resting areas, and moist-edge habitats that support connectivity for multiple aquatic species.
- Accommodates flood discharges and sediment and debris inputs without compromising passage or impairing geomorphic and ecological processes in adjacent reaches.

- Channel inside the crossing structure is at least as wide as bankfull width in a natural reference reach.
- Defined low-flow channel that maintains surface flow at lowest flows (95% exceedance).
- Stream banks maintain hydraulic separation from culvert wall and remain dry at most flows.

Nature-like Bypasses. No Bull Trout specific design criteria for nature-like bypass features exist. However, by intent, nature-like fishways are meant to simulate natural channel environments, providing suitable passage for all aquatic organisms (Katopodis et al. 2001; Calles and Greenberg 2007; Baki et al. 2015; Kirk et al. 2017). Swimming and jumping abilities and effects of fatigue should be considered when designing a nature-like fishway.

Several nature-like fishway design guidelines and research studies have been published in recent decades. The following documents and studies provide background information and design details for nature-like fishways and their components:

- Design of Rock Weirs: Technical Note 24 (NRCS 2000)
- Federal Interagency Nature-like Fishway Passage Design Guidelines for Atlantic Coast Diadromous Fishes (Turek et al. 2016)
- Qualitative Evaluation of Rock Weir Field Performance and Failure Mechanisms (USBR 2007b)
- Rock Ramp Design Guidelines (USBR 2007a)
- Rock Weir Design Guidance (USBR 2016)

- Turbulence Characteristics in a Rock-Ramp-Type Fish Pass (Baki et al. 2015)

Dodd et al. (2017) evaluated the efficacy of a nature-like bypass used by Brown Trout. Similar assessments could be conducted for Bull Trout to better understand fish pass performance and to inform future design guidelines.

Tide Gates. No Bull Trout specific recommendations exist for tide gates. However, aquatic-organism friendly design guidelines for tide gates (Giannico and Souder 2005) account for the need to maximize aquatic organism connectivity. Aquatic-organism friendly tide gates generally are kept open and for long periods of time, create low water velocities and little turbulence, and provide gradual transition between fresh and saltwater, with salinity refugia available for juvenile fish (Giannico and Souder 2005). Bull Trout migration timing, jumping and swimming abilities, and habitat preferences should be considered when designing a tide gate.

Technical Fishways. No Bull Trout specific technical fishway guidelines are known. Technical fishways constructed on streams where upstream passage of Bull Trout is intended are typically designed to the NMFS 2011 design criteria for anadromous salmonids. Bull Trout can pass many of the mainstem Columbia River dams and all four of the lower Snake River dams (Barrows et al. 2016) but passage by a few Bull Trout does not justify the use of design criteria established for anadromous salmonids for Bull Trout passage in general.

The Thompson Falls Fish Ladder was designed and constructed specifically for Bull Trout fish passage and in general accordance with NMFS 2011 design criteria for anadromous salmonids. The Thompson Falls Fish Ladder is located at the Thompson

Falls Project on the Clark Fork River in Thompson Falls, Montana. The fishway was designed with operational flexibility and can function in either orifice or overflow weir mode; operation in orifice mode has a higher passage rate. A 0.3 m (1 ft) hydraulic drop was designed for each of the 48 fish ladder pools (Northwestern Energy and GEI Consultants 2018). Only 18 Bull Trout have ascended the fishway during 10 years of operation. An in-depth hydraulic analysis has been conducted and should be consulted by practitioners designing technical fishways for Bull Trout (Northwestern Energy and GEI Consultants 2018). For additional information on the Thompson Falls Fish Ladder see the following resources:

- Website with general information on project and fish counts - http://www.northwesternenergy.com/environment/thompson-falls-project
- Upstream Fish Passage Alternative Evaluation – Final Report for Thompson Falls Dam Fish Ladder (GEI Consultants 2007)
- Fish Ladder Hydraulic Assessment Thompson Falls Hydroelectric Project (Northwestern Energy and GEI Consultants 2018).
- Thompson Falls Hydroelectric Project Baseline Environmental Document (Northwestern Energy et al. 2018).

Research Needs and Data Gaps

This section of the Bull Trout specific portion of the document lists Bull Trout specific research needs and data gaps. This section is intended to provide a designated location where A) practitioners can suggest Bull Trout specific information deemed missing/unavailable from current knowledge, and B) researchers and funders can systematically approach the allocation of research efforts and resources.

Research needs and data gaps identified throughout the literature as well as expert opinion are synthesized and prioritized based on relevance to Bull Trout passage (Table 6). Priority 1 items include research needs and data gaps related exclusively to the physical abilities of the species. Priority 2 items include research needs and data gaps related to habitat preferences, behavioral patterns, and fishway specific information. Priority 3 items include research needs and data gaps related to management and recovery.

Table 6. Bull Trout research needs and data gap prioritization

Priority 1	Further research will be necessary to elucidate the factors that may influence the performance of Bull Trout in laboratory experiments and provide a more complete understanding of Bull Trout burst swim speeds and swimming performance (Mesa et al. 2004).
	Bull Trout minimum water depth requirements for short duration swimming. Does a minimum depth exist at which Bull Trout can no longer achieve burst swim speeds? Does a minimum water depth exist to be used for design and assessment? Does a relationship exist between minimum water depth, water velocity, and Bull Trout burst swim speed?
	Bull trout jumping abilities need to be studied further, including minimum jumping pool depth.
Priority 2	Hydraulic simulations at dams known to pass Bull Trout could be used to indirectly identify swimming abilities.
	Dodd et al. (2017) evaluated the efficacy of a nature-like bypass used by Brown Trout. Similar assessments could be done for Bull Trout to better understand fish pass performance and to inform future design guidelines.
Priority 3	No Priority 3 research needs and data gaps specifically noted.

Pacific Lamprey Guidance

Species Background

Biology and Ecology. Pacific Lamprey are considered a relatively large anadromous and parasitic fish. They have declined in distribution throughout their native range from Mexico to Japan (Close et al. 2002; Wang and Schaller 2015; Clemens et al. 2017). Artificial structures such as dams impede upstream and downstream migration of Pacific Lamprey and are probably one cause of declines (Clemens et al. 2017). This species, like all lamprey species, has a round sucker-like mouth (oral disc), no scales, and multiple gill openings instead of an operculum. The fish is characterized by the presence of three large teeth (cusps) on the supraoral bar and three points on each of the central four lateral tooth plates. Their bodies are elongate, eel-like, cylindrical toward the head, and compressed toward the tail (Moyle 2002). Two dorsal fins arise far back on its body, and fish exhibit sexual dimorphism of the pseudo-anal fin during sexual maturity. Adults fresh from the sea are blue-black to greenish above, silvery to white below. They do not have swim bladders that allow them to maintain neutral buoyancy and must, therefore, swim constantly or hold to objects with their oral disc to maintain their position in the water column (Mesa et al. 2003b). Spawning adults become reddish brown (Morrow 1980) but may vary in color (Figure 4).

Figure 4. Pacific Lamprey moving small stone. Photograph by Jeremy Monroe at Freshwater Illustrate, courtesy of USFWS (Wang and Schaller 2015).

<u>Range.</u> Historically, their range extended from Hokkaido Island, Japan (Yamazaki et al. 2005); around the Pacific Rim including Alaska (Vogt 1988), Canada, Washington, Oregon, and Idaho (Figure 5; Beamish and Northcote 1989; Moyle et al. 1996; USFWS 2004a; Hamilton et al. 2005); and California to Punta Canoas, Baja California, Mexico (Swift et al. 1993; Ruiz-Campos and Gonzalez-Guzman 1996; Ruiz-Campos et al. 2000; Chase 2001; Renaud 2008). In North America, their distribution included major river systems such as the Fraser, Columbia, Klamath-Trinity, Eel, and Sacramento-San Joaquin rivers. Pacific Lamprey are the most widely distributed lamprey species on the west coast of the United States.

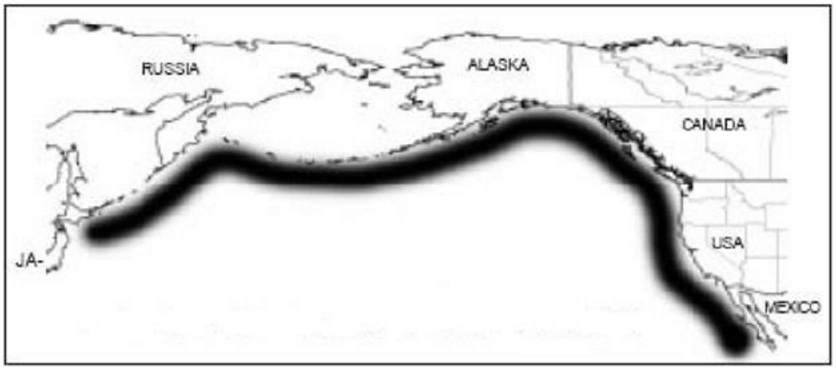

Figure 5. Approximate extent of the range of the Pacific Lamprey. Image from USFWS (2019).

Currently, Pacific Lamprey have been documented in Japan in the Naka River on Honshu Island and other river systems on Hokkaido Island (Yamazaki et al. 2005). Population status in British Columbia is unranked but may be secure (Renaud et al. 2009); status is unknown in Alaska. Anecdotal and empirical information suggests that Pacific Lamprey populations have declined or have been locally extirpated in parts of California, Oregon, Washington, and Idaho (Close 2001; Moser and Close 2003; Luzier et al. 2009; Moyle et al. 2009; Swift and Howard 2009; USFWS 2019). In these states, Pacific Lamprey have declined in their distribution along all coastal streams and large rivers, including the Columbia River basin. They are extirpated in parts of southern California, above dams and other impassable barriers in coastal streams and larger rivers, and in the upper Snake and Columbia rivers. Although historical distribution data is limited, the current distribution data availability has increased in Oregon, Washington, and Idaho with the development of a regional Pacific Lamprey distribution geodatabase (USFWS 2016). The database includes data from targeted lamprey surveys, incidental observations during other surveys, and in-stream work. Whereas these data greatly increase current distribution records, they are not considered exhaustive. Data are continually added to maintain a thorough database of observations and distribution. Data availability has increased in California as well, with a California distribution database populated and maintained by Reid and Goodman (2017).

Migration Timing. Adult Pacific Lamprey enter freshwater and reside there from a few months (Bayer and Seelye 1999, Clemens et al. 2013, Clemens et al. 2016) to a few years prior to spawning (Whyte et al. 1993; Clemens et al. 2013; Clemens et al. 2016; Parker 2018). Timing is influenced by water temperature and streamflow (Keefer et al. 2009a) and freshwater entry generally occurs in spring (April -June; Beamish 1980) with a summer upstream migration (July-September; Luzier et al. 2006) prior to overwintering (October-March; Keefer et al. 2009a) before spawning in the following spring. Both ocean-maturing adults and stream-maturing adults have been observed in the Willamette River and in the Klamath River (Clemens et al. 2013; Parker et al. 2019; Hess et al. 2020). Adults move upstream primarily at night (Moser and Mesa 2009), particularly when faced with difficult migration conditions such as high turbulent flows and predators (Keefer et al. 2013a). In reservoir areas, they migrate during daylight (Keefer et al. 2013a) as well as night. Migratory distance is controlled by body size or condition of the adult, with smaller fish not migrating as far as larger fish (Keefer et al. 2009b). Much of the above information is specific to the Columbia River basin; other areas may differ in terms of timing or other parameters.

Passage Specific Parameters and Abilities

Throughout the Pacific Northwest, fish passage facilities are primarily designed for anadromous salmonids able to achieve burst swim speeds in excess of 6 m/s (Bell 1991). Pacific Lamprey are poor swimmers in comparison to adult salmonids and are often unable to efficiently pass such facilities unless specific design features have been incorporated. Therefore, alternative design parameters must be considered when designing or modifying passage facilities for Pacific Lamprey. The following subsections list Pacific Lamprey abilities and requirements for several key passage parameters: swim speed, climbing abilities, water depth provisions, maximum gradient, and thermal requirements.

Swim Speed. The suggested swim speeds for Pacific Lamprey are summarized as follows:

- Maximum swim speeds – 2.5 to 3.0 m/s (Keefer et al. 2010; Kirk et al. 2016)
- Anguilliform speed – <1.2 m/s (Keefer et al. 2011; Keefer et al. 2012)
- Sustained swim speeds – 0.9 m/s (Bell 1991)

Justification. Adult Pacific Lamprey can employ two modes of locomotion: anguilliform (swimming without oral disc attachment) and burst-and-attach. Anguilliform locomotion is the primary mode used during movement through open water and low gradient, quiescent channels with low to moderate velocities. Daigle et al. (2005) reported Pacific Lamprey change from anguilliform swimming to burst-and-attach at > 0.6 m/s (~2.0 ft./s). Burst-and-attach is used when hydraulic conditions create velocity or turbulence barriers to anguilliform swimming or when physical barriers are present and climbing via burst-and-attach becomes advantageous (Figure 6). For details regarding climbing behavior, see Climbing Abilities.

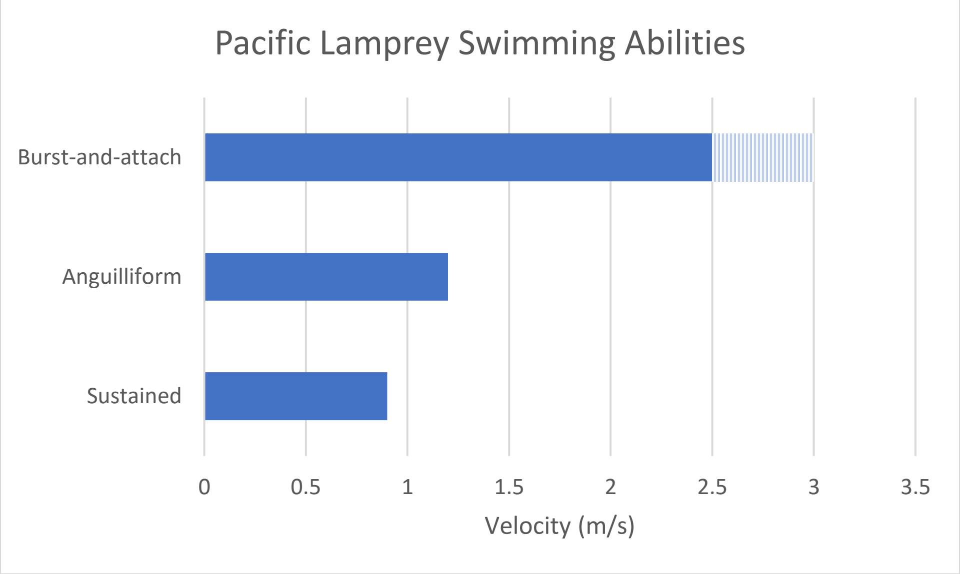

Figure 6. Comparison of Pacific Lamprey swimming abilities.

Burst-and-attach locomotion is accomplished when the lamprey alternates between forming several lateral bends along the longitudinal axis while attached to the surface with its oral disc and straightening the body while briefly releasing suction (Reinhardt et al. 2008). Pacific Lamprey tend to use burst-and-attach locomotion throughout fishways due to the velocities and turbulence present within them. Burst swim speed and burst-and-attach locomotion are exceeded when velocities exceed 2.5 – 3.0 m/s (Keefer et al. 2010, Kirk et al. 2016).

For burst-and-attach locomotion to be effective, smooth surfaces in which the Pacific Lamprey’s oral disc can attach must be present throughout. Surface irregularities should not exceed 2 mm (PLTW 2017). In nature-like fishways, large (4-6” minimum radius), smooth, rounded cobbles and boulders with minimum surface irregularities provide the best passage success (Crandall and Wittenbach 2015).

Aluminum ramps and walls are commonly placed within technical fishways as attachment surfaces for Pacific Lamprey when burst-and-attach locomotion is anticipated or expected. For more information regarding Pacific Lamprey passage of technical fishways, see the Fish Passage and Diversions section below.

Hanchett and Caudill (2020) studied fatigue during passage and found that Pacific Lamprey showed high individual variability in duration and timing of burst-and-attach locomotion. Fish that failed to ascend spent more time attached and turned around more often. A threshold fatigue was associated with changes in behavior or motivation. The cumulative effects of passage are therefore important to consider when designing or evaluating fishways. Velocities that require high activity levels over a prolonged period of time may induce fatigue, indicating the need for refuge areas to allow recovery.

Reid and Goodman (2016) noted Pacific Lamprey tend to use lower portions of the water column by swimming within 6 cm of the bottom. Upstream swim speeds of 29.4 ± 11.4 cm/s were reported (originally reported in BL/s, converted to cm/s using a mean body length of 60 cm), after removing the impacts of water velocity.

Climbing Abilities. The suggested maximum elevation gain between resting areas is 3.5 meters.

Justification. Pacific Lamprey cannot jump (Goodman and Reid 2017). However, Pacific Lamprey can climb vertical or near vertical surfaces when using burst-and-attach locomotion (Figure 7; Reinhardt et al. 2008).

The maximum vertical distance Pacific Lamprey can ascend has not been specifically studied. Evidence suggests that vertical elements within a fishway should be limited to not more than several meters (Kemp et al. 2009; Frick et al. 2017). Kemp et al. (2009) studied Pacific Lamprey climbing behavior and found the duration of bouts (active climbing) declined with distance ascended, indicating fatigue is experienced while climbing, suggesting higher vertical elements cause greater fatigue and reduce passage rates.

Figure 7. Image displaying climbing abilities of Pacific Lamprey. Image from Frick et al. (2017)

Zobott et al. (2015) provide ‘best practice’ values for several variables related to lamprey passage structures (LPS). Variables related to climbing specifically include maximum elevation gain between rest boxes and climbing gradient, where 3.5 meters (11.5 ft.) and 1:1 (horizontal to vertical ratio) are listed as best practices, respectively.

Also see the following documents focusing specifically on climbing behavior:

- Climbing above the competition: Innovative approaches and recommendations for improving Pacific Lamprey passage at fishways (Goodman and Reid 2017)
- Climbing success of adult Pacific Lamprey on a vertical wetted wall (Frick et al. 2017)
- Linking behavior and performance: intermittent locomotion in a climbing fish (Kemp et al. 2009)
- Pacific Lamprey climbing behavior (Reinhardt et al. 2008)

<u>Water Depth Provisions.</u> The suggested maximum water depth is reported as a ratio of water depth to diameter of the specimen for burst-and-attach while climbing vertically. The suggested ratio is < 0.1 y/D, where y is the depth of flow and D is the diameter of the fish. The suggested minimum water depth for Pacific Lamprey using burst-and-attach for swimming is 3 cm (0.1 feet).

<u>Justification.</u> Zobott et al. (2015) modeled relationships between depth of flow, drag force created by flow, and drag force resistance by Pacific Lamprey (and presumed passage success). Zobott et al. (2015) found skin flow (where $y/d < 0.1$) minimized drag force and should be used to maximize passage success in areas where climbing is anticipated. Diameters of adult Pacific Lamprey range from 1.9-4.8 cm (Zobott et al. 2015).

Additionally, Frick et al. (2017) studied climbing abilities of Pacific Lamprey on a vertical wetted aluminum wall. During the experiment, Pacific Lamprey were able to climb the 1.6 m wall using burst-and-attach locomotion in water depths of 2 mm, consistent with the range of y/D recommend by Zobott et al. (2015).

The maximum depth to diameter ratio listed for burst-and-attach climbing assumes sufficient attachment surfaces are provided. In each of the two papers referenced (Zobott et al. 2015; Frick et al. 2017) aluminum sheet metal was used as the attachment surface. When attachment surfaces are less uniform (corrugated metal pipe or native boulders and cobbles) minimum water depths of about 0.1 feet should be provided for adequate passage (Crandall and Wittenbach 2015).

Maximum Gradient. The suggested maximum gradient is 90 degrees and the suggested incline of a ramp is 45 degrees (Zobott et al. 2015).

Justification. Pacific Lamprey can climb vertical wetted walls given adequate attachment surfaces, hydraulic conditions, and motivation. See Climbing Abilities above for more information and details on the climbing abilities of Pacific Lamprey. Climbing walls exceeding 90 degrees have not been assessed and should be avoided.

Zobott et al. (2015) provided best practice values for several variables related to lamprey passage structures (LPS). One such variable is climbing gradient, where 45 degrees is listed as best practice.

Thermal Requirements. The suggested maximum temperature, when temperature control is available, is 20 °C.

Justification. Clemens et al. (2016) reviewed existing information relating Pacific Lamprey movement and temperature. Upstream migration slowed and stopped at water temperatures greater than 20 °C. Pacific Lamprey Technical Workgroup (2017) recommends cooler water be added to fishways, from an upstream cool water source if available, when temperatures reach 20 °C during lamprey upstream migration. A shade cloth or similar material should be used over the fishway to lessen effects of solar radiation.

Migration Corridors and Species Behaviors

Information related to migration corridors and species behaviors listed herein describe aquatic environments each species prefers during normal migration; i.e., not in a fish passage feature. The list of preferences is not exhaustive; rather, it is meant to include attributes related to fish passage that may inform decisions related to restoring habitat adjacent to a fish passage project.

Water Depth Preferences. Adult Pacific Lamprey prefer deep waters during migration through river corridors. Reid and Goodman (2016) noted swimming activity was strongly associated with the bottom (within about 6 cm) in a raceway 55 m long 0.76 m deep.

Spawning depths tend to be between 0.3 m and 4 m (Pletcher 1963; Kan 1975; Gunckel et al. 2006; Luzier et al. 2011). No known studies attempted to assess spawning at depths greater than 4 m.

Water Velocity Preferences. Gunckel et al. (2009) reported that the water velocity associated with Pacific Lamprey redd sites ranged from 0.2 to 1.0 m/s.

Turbid Water Impacts. Turbidity impacts on Pacific Lamprey have not been specifically studied. Reid and Goodman (2016) noted more turbid waters with lower light levels may increase suitable migration windows, increasing Pacific Lamprey activity during the day due to the cover provided by decreased visibility.

Light vs. Darkness. Pacific Lamprey are nocturnal and more active during the night than daytime (Moser et al. 2002a; Reid and Goodman 2016; Goodman and Reid 2017).

Substrate. Substrate requirements are primarily viewed as attachment surfaces for Pacific Lamprey that use burst-and-attach locomotion when ascending a technical fishway. Surface irregularities should not exceed 2 mm (PLTW 2017). In some cases, concrete fishway walls can be cleaned, or smooth aluminum plates can be added over heavily eroded concrete surfaces.

Pacific Lamprey tend to locate redds in similar habitats to that of salmon—below pools at the upstream ends of riffles where upwelling of water occurs (Streif 2008).

Channel Gradient. Pacific Lamprey can ascend vertical wetted walls, but the preferred habitat for activities other than passage are low gradient channels (< 2%) (Gunckel et al. 2009).

Surrogate Species. Byford et al. (2016) noted the well-studied chemical communication system and sensory of Sea Lamprey (*Petromyzon marinus*) may be a useful surrogate for Pacific Lamprey alarm cues, which can be used to guide Pacific Lamprey to fishway intakes and entrances.

The historical spawning distribution of steelhead (anadromous Rainbow Trout, *O. mykiss*) is considered a viable surrogate for lamprey distribution in most cases (USFWS 2019). Chinook Salmon (*O. tshawytscha*) have also been considered a surrogate for lamprey distribution in the Willamette River basin (A. Gray, USFWS, personal communication).

Fish Passage and Diversions

This section of the document is intended to provide Pacific Lamprey-specific upstream and downstream passage information and resources. Subsections have been created based on the varying types of passage features, for which specific considerations and suggestions are provided. A set of generalized recommendations to consider when designing and assessing a passage feature for Pacific Lamprey is provided. The following general recommendations are predominantly from Goodman and Reid (2017).

Preferred Design Features.

- Midwater velocities under 0.6 m/s, preferably with near-bottom velocities approaching zero or under 0.1 m/s. Near-bottom velocities can be reduced by increasing surface roughness, while still providing attachment surfaces.

- Smooth, continuous, wetted surfaces, with shallow flow or spray zones that provide wet climbing attachment surfaces, allowing lampreys to climb around velocity barriers. Wetted climbing surfaces should be free of moss, algae, and detritus.
- Large radius curves at corners (≥ 10 cm), without angular features, to provide a continuous surface for reattaching during climbing.
- Orifices should be flush with the fishway floor and walls and be at least 23 cm wide.
- Extended platform space beyond corners (horizontal or vertical) to avoid conflicting direction of body propulsion. Once an individual's head has passed a curve, the propulsive force vector of the tail and body (upward) is no longer aligned with the head direction, making climbing more difficult. Continue the horizontal platform above a climb for a full body length (ca. 60 cm) allowing the lamprey to align its body before redirecting itself into the subsequent pool.
- In proximity to high velocity areas, the edges of climbing surfaces should incorporate a low fence to keep lampreys from inadvertently falling off. Climbing often involves lateral searching as well as vertical climbing; therefore, the climb path is inherently irregular, with reattachment points off the centerline of movement.
- In consideration of the inherently different approaches that lampreys use to pass physical and velocity barriers compared to other fishes, a dedicated pathway for lampreys is worth considering. Such a route can often be established at relatively

low cost and has the benefit of specifically meeting the needs of lampreys. A separate pathway can also incorporate lamprey-specific monitoring equipment.

- If a separate pathway is established for lampreys, the entry of the main fishway can be adapted to prevent entry by lamprey, thereby avoiding wasted energetic cost expended in attempting to pass or explore the main fishway. This will ultimately reduce the time spent by lampreys searching for a suitable pathway.
- Grating spacing should be < 1.78 cm to preclude lamprey passage or > 2.54 cm to facilitate passage.

Design Features to Avoid.

- Velocities greater than 1.0 m/s in any fishway, including orifices or weir sections.
- Gaps that can entrain and trap lampreys with high velocity near-field flows. These can cause extended attachment times or approach the limits of burst-attach abilities, while increasing energy expenditure. Gaps can also entrain debris, which reduces aperture size and can entangle entrained lampreys, preventing them from passing downstream.
- Sharp corners and edges that break suction and force lampreys off the climbing surface or prevent reattachment, including U-channels (slots) used for retaining weir boards and angular lips on walls.
- Grates or porous surfaces that prevent suction attachment in high velocity areas (where swimming abilities are exceeded).
- High velocity corridors without alternative routes suitable for lamprey passage.

- A fishway can be rendered ineffective for lamprey by a single feature that prevents passage at any point along the pathway. This can be as minor as a single 1 m reach exceeding 1 m/s without attachment points, a U-channel embedded in the wall and bottom in higher velocity areas, or a 2-cm angle-iron lip at the top of a climbing surface—basically any structure or gap that prevents continuous attachment by lamprey in high velocity areas or other areas that require burst-and attach-locomotion.
- Fishway designs should promote through-passage by lampreys by minimizing areas suitable for holding (e.g., complex cover, burrowing substrate, and off-channel refuges). Adult Pacific Lamprey have been observed holding and even over-summering in fishways. Onsite fishway management staff also observe adult Pacific Lamprey emerging from fishway pools annually during late summer fishway dewatering and maintenance. Sometimes individuals do not appear until several days after water levels are lowered and typically in locations where sand and gravels accumulate or where cracks in the concrete exist. Apparently, these individuals are over-summering to spawn the following spring, as they are observed outside of the typical spring migration period.

<u>Fish Screens.</u> The following suggestions were recommended by the Lamprey Technical Workgroup (2020b) to effectively exclude juvenile Pacific Lamprey from irrigation systems and canals:

- Use the smallest mesh opening possible to minimize entrainment of small larvae; however, watch for impingement of larvae.

- Use perforated plate, Intralox, or profile bar screen materials rather than woven wire screen material (Rose and Mesa 2012).
- Minimize the approach velocity (perpendicular to screen) while maximizing the sweeping velocity (parallel to screen).
- Design fish screens and headgates with the shallowest angle practical (i.e., angle should be as close as possible to parallel to the direction of the flow, not perpendicular; Liedtke et al. 2019)

Laboratory research has been conducted to evaluate NMFS criteria for screen material placed in a vertical configuration to test incidence of impingement and mortality of juvenile Pacific Lamprey at various velocities (Ostrand 2004). The existing NMFS (2011) design criteria for fish screens is established for anadromous salmonids (Table 7).

Table 7. NMFS 2011 screening criteria

Criteria Description (Section)	Criteria Value
Minimum screen face open area (11.7.1.6)	27%
Minimum opening dimensions (11.7.1)	Circular openings: 2.4 mm diameter Square openings: 2.4 mm each side Slotted or rectangular: 1.75 mm in narrow direction
Maximum sweeping velocity (11.6.1.5)	Larger than 1.8 m long: Greater than approach velocity Must not decrease along the length of the screen
Maximum approach velocity (11.6.1.1)	0.12 m/s (active screens)[1] 0.06 m/s (passive screens)[2]

1. Active screens are screens with automated cleaning systems to prevent accumulation of debris
2. Passive screens are screens that must be cleaned manually

Additional research conducted by USGS also evaluated the effectiveness of several common fish screen materials and screen angles to prevent entrainment of larval Pacific Lamprey at irrigation diversions (Rose and Mesa 2012; Liedtke et al. 2019; Mesa et al. 2017). Perforated plate screens offered the best protection for larval lamprey, followed by interlock and vertical bar screening. Wire cloth screens were the least protective and should be replaced with one of the better performing materials.

The body length of larval lamprey also influences entrainment rates; smaller individuals (< 65 mm total length) are more susceptible to pass through the open spaces in screen material (Clemens et al. 2017). Screens with wire cloth allow more entrainment than other types of screen material (Rose and Mesa 2012; Lampman et al. 2014).

Downstream Passage. No Pacific Lamprey specific designs for downstream passage facilities have been suggested, other than those mentioned for fish screens. However, considerations to be mindful of when designing a downstream passage facility exist.

Juvenile outmigrant lamprey and larvae typically travel deeper in the water column (Moser et al. 2015a) (no swim bladder) than salmonids; therefore, the use of spill over hydraulic structures to provide passage for lamprey is probably unsuccessful (Moursund et al. 2003). However, recently constructed surface collectors on the Clackamas River in Oregon have had some success in collecting downstream migrants near the surface (PGE 2018).

Additionally, juvenile lampreys are less likely to be harmed by changes in pressure and shear conditions present during turbine passage than salmonids (Colotelo et al. 2012; reviewed in Moser et al. 2015b). Juvenile Pacific Lamprey move downstream during increasing and/or high flow events and have a lengthy downstream migration (Moser et al. 2015a; Lamprey Technical Workgroup 2020b). The downstream migration timing varies by the location and size of river systems (Clemens et al. 2019).

Road-Stream Crossings. When designing a new road-stream crossing or when replacing a road-stream crossing is feasible, a stream simulation approach should be employed, providing passage to all aquatic species. See Water Crossing Design Guidelines (Barnard et al. 2013) and Stream Simulation (FSS-SWG 2008) for complete design guidelines of stream simulation road-stream crossings. Key elements of stream simulation design, listed by USDA Forest Service Stream Simulation Working Group (2008) and summarized by Lamprey Technical Workgroup (2020a) are as follows:

- Continuous streambed that simulates natural channel width, depth, gradient, and substrate of adjacent channel (both upstream and downstream).
- Contains diverse water depths and velocities, hiding and resting areas, and moist-edge habitats that support connectivity for multiple aquatic species.
- Accommodates flood discharges and sediment and debris inputs without compromising passage or impairing geomorphic and ecological processes in adjacent reaches.
- Channel inside the crossing structure is at least as wide as bankfull width in a natural reference reach.
- Defined low-flow channel that maintains surface flow at lowest flows (95% exceedance).

- Stream banks are rebuilt through structure and remain dry at most flows, maintaining hydraulic separation from the culvert wall.

Nature-like Bypass. No Pacific Lamprey specific design criteria for nature-like bypass features are available in the literature. However, by intent, nature-like fishways are meant to simulate natural channel environments, providing suitable passage for all aquatic organisms (Katopodis et al. 2001; Calles and Greenberg 2007; Baki et al. 2015; Kirk et al. 2017), including all species and life-stages of lampreys. Designers of nature-like fishways should consider the swimming abilities, adequate attachment surfaces, and fatigue of Pacific Lamprey.

Several nature-like design guidelines and research studies have been published during recent decades. The following list of nature-like fishway specific documents and studies provide background information and design details for nature-like fishways and components of nature-like fishways:

- Design of Rock Weirs: Technical Note 24 (NRCS 2000)
- Federal Interagency Nature-like Fishway Passage Design Guidelines for Atlantic Coast Diadromous Fishes (Turek et al. 2016)
- Qualitative Evaluation of Rock Weir Field Performance and Failure Mechanisms (USBR 2007b)
- Rock Ramp Design Guidelines (USBR 2007a)
- Rock Weir Design Guidance (USBR 2016)
- Turbulence Characteristics in a Rock-Ramp-Type Fish Pass (Baki et al. 2015)

Tide Gates. No Pacific Lamprey specific recommendations exist for tide gates. However, aquatic-organism friendly design guidelines for tide gates (Giannico and Souder 2005) account for the need to maximize aquatic organism connectivity. Aquatic-organism friendly tide gates generally are kept open and for long periods of time, create low water velocities and little turbulence, and provide gradual transition between fresh and saltwater, with salinity refugia available for juvenile fish (Giannico and Souder 2005).

Tide gate designs should consider Pacific Lamprey migration timing, climbing and swimming abilities, and habitat preferences. For example, 90-degree corners on the tide gate entrance could limit passage; designs incorporating a smooth rounded entrance should be considered.

Technical Fishways. Many of the general recommendations by Goodman and Reid (2017) apply directly to technical fishways and should be reviewed thoroughly when designing or improving technical fishways for Pacific Lamprey. Additional recommendations for existing technical fishways to improve adult lamprey upstream passage are provided by Rose and Mesa (2012), Keefer et al. (2012), and PLTW (2017):

- Conduct lamprey specific fishway inspections to identify problematic fishway components
- Install lamprey passage structures that bypass the fishways
- Reduce flows within fishways, especially at night when lamprey are more likely to move
- Round off sharp corners to provide for continuous attachment

The construction of a new lamprey passage structure (LPS) should follow the design criteria recommended by Zobott et al. (2015). Zobott et al. (2015) provided guidelines for a variety of LPS system components including traversing ducts, climbing ducts, resting boxes, exit ducts, and collectors. For a more complete list of design criteria see Table 1 of Zobott et al. (2015). Additionally, the PLTW (2017) developed guidelines for incorporating adult Pacific Lamprey passage at fishways.

All the preceding technical fishway suggestions are intended to allow continuous attachment surfaces, provide resting refuges, and ensure hydraulic conditions favorable to adult lamprey.

Numerous studies have assessed the abilities of Pacific Lamprey as they relate to technical fishways. The following list of studies provides practitioners with background information regarding Pacific Lamprey and technical fishways.

- Evaluating swimming behavior and performance of upstream migrating Pacific Lamprey using experimental flumes and accelerometer biotelemetry, 2019 (Hanchett and Caudill 2020)
- Adult Pacific Lamprey passage at the four lower Columbia River dams and lamprey behaviors in relation to nighttime fishway velocity reductions at Bonneville and The Dalles dams and the new UMTJ-LPS at Bonneville Dam – 2019 (Clabough et al. 2019)
- Providing refuges for adult Pacific Lamprey (*Entosphenus tridentatus*) inside fishways (Moser et al. 2019)

- Evaluation of adult Pacific Lamprey upstream passage at Warm Springs National Fish Hatchery, 2018 Annual Report (Barkstedt et al. 2018)
- Climbing above the competition: Innovative approaches and recommendations for improving Pacific Lamprey passage at fishways (Goodman and Reid 2017)
- Climbing success of adult Pacific Lamprey on a vertical wetted wall (Frick et al. 2017)
- Context-dependent responses to turbulence for an anguilliform swimming fish, Pacific Lamprey, during passage of an experimental vertical-slot weir (Kirk et al. 2017)
- Technical white paper: Practical guidelines for incorporating adult Pacific Lamprey passage at fishways (Pacific Lamprey Technical Workgroup 2017)
- Effects of water velocity, turbulence and obstacle length on the swimming capabilities of adult Pacific Lamprey (Kirk et al. 2016)
- Characterization of adult Pacific Lamprey swimming behavior in relation to environmental conditions within large-dam fishways (Kirk et al. 2015)
- 2011 reconnaissance level assessment of fish ladders at The Dalles, John Day and McNary dams for upstream passage of adult Pacific Lamprey (Wills 2014)
- Factors affecting dam passage and upstream distribution of adult Pacific Lamprey in the interior Columbia River basin (Keefer et al. 2013b).
- Fishway passage bottleneck identification and prioritization: a case study of Pacific Lamprey at Bonneville Dam (Keefer et al. 2013c).

- Adult Pacific Lamprey passage: Data synthesis and fishway improvement prioritization tools (Keefer et al. 2012)
- Systematic fishway survey and evaluation for upstream passage of adult Pacific Lamprey at the FCRPS Projects in the mainstem Columbia and Snake rivers (Wills and Anglin 2012)
- The effect of rapid and sustained decompression on barotrauma in juvenile Brook Lamprey and Pacific Lamprey: Implications for passage at hydroelectric facilities (Colotelo et al. 2012)
- Use of night video to enumerate adult Pacific Lamprey passage at hydroelectric dams: Challenges and opportunities to improve escapement estimates (Clabough et al. 2012)
- Behavior of adult Pacific Lamprey in near-field flow and fishway design experiments (Keefer et al. 2011)
- Development of Pacific Lamprey fishways at a hydropower dam (Moser et al. 2011).
- Testing adult Pacific Lamprey performance at structural challenges in fishways (Keefer et al. 2010).
- Passage efficiency of adult Pacific Lampreys at hydropower dams on the lower Columbia River, USA (Moser et al. 2002b)
- Use of an extensive radio receiver network to document Pacific Lamprey (*Lampetra tridentata*) entrance efficiency at fishways in the lower Columbia River, USA (Moser et al. 2002a)

Research Needs and Data Gaps

This section of the Pacific Lamprey specific portion of the document lists Pacific Lamprey specific research needs and data gaps. This section is intended to provide a designated location where A) practitioners can suggest Pacific Lamprey specific information deemed missing/unavailable from current knowledge, and B) researchers and funders can systematically approach the allocation of research efforts and resources.

Research needs and data gaps identified throughout the literature as well as expert opinion are synthesized (Table 8). The information within the table is prioritized based on relevance to Pacific Lamprey passage. Priority 1 items include research needs and data gaps related exclusively to the physical abilities of the species. Priority 2 items include research needs and data gaps related to habitat preferences, behavioral patterns, and fishway specific information. Priority 3 items include research needs and data gaps related to management and recovery.

Table 8. Pacific Lamprey research needs and data gap prioritization

Priority 1	No Priority 1 research needs and data gaps specifically noted.
Priority 2	The integration of eel tiles into fishways needs to be assessed.
	Downstream migrant behavior? How do juveniles move through a reservoir? what distance from the surface or depth? Do any factors "encourage" juveniles to seek the upper water column or pass lower in the reservoir?
	No data exists about the effects of tide gates on upstream and downstream passage.
	Adult upstream migrants – what are attraction cues? Where should entrances be located?
	What specifically about turbulence or other confusing flow patterns within fishways deter upstream migration? How can those areas be addressed?
	Additional methods to retrofit existing fishways to enhance or facilitate passage need to be explored.
	Turbine passage needs further assessment. Different types of turbines are in use. How well do juveniles and larvae survive turbine passage? Studies to date have been in the laboratory and simulated some turbine conditions but not all.

	Although Pacific Lamprey passage at dams may be improved with the use of lamprey specific climbing structures, the effects of such structures on fitness are unknown. Using a genetic algorithm, Zhu et al. (2011) found that vertical climbing in Pacific Lamprey is optimized to conserve energy. However, the actual energetic costs of climbing (as opposed to swimming or holding position in a current) have not been determined (Frick et al. 2017).
	Current values of preferred radii for rounded edges are based on professional judgement. (PLTW 2017). How well do chamfers work relative to rounded edges?
Priority 3	The extent of predation at barrier dams and fishways needs to be assessed. Predation on juveniles in reservoirs—which fish species are the biggest predators? How can we limit that predation if it is significant?
	Clemens et al. (2017) identified four research and monitoring needs: (1) monitoring distribution and occurrence, (2) enumerating relative abundance, (3) understanding limiting factors, and (4) identifying population structure and dynamics through genetic analysis.

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ASSESSMENT AND EVALUATION OF FISH PASSAGE GUIDELINES

Introduction

Background

Fishway design guidelines have been established to provide criteria and rationale for designing fishway facilities for safe, timely, and effective passage of aquatic organisms at artificial and natural barriers. National Marine Fisheries Services (NMFS) plays a supportive and advisory role in managing living marine resources in areas under state jurisdiction (NMFS 2011). NMFS authored the NMFS Criteria to provide practitioners concise recommendations for anadromous salmonids at various passage features. The NMFS Criteria is widely used throughout the Pacific Northwest as a design and assessment tool.

Design Species

The NMFS Criteria were written to assist with improving conditions for anadromous salmonids. The criteria identify salmon and steelhead (hereafter referred to as salmon) as the marine resources of importance and focus specifically on the genus *Oncorhynchus* (NMFS 2011). The NMFS Criteria are generally assumed to be applicable to other species, but evaluations of this assumption are limited. Bull Trout are members of the char subgroup of the family Salmonidae (USFWS 2015a), meaning they are salmonids but not of the genus *Oncorhynchus*. Evaluations of Bull Trout passage rates at facilities designed according to NMFS Criteria are limited and it is unclear if the NMFS

Criteria allow for safe, timely, and effective passage of Bull Trout. The goal of this chapter is to assess the applicability of NMFS Criteria for design of fishways intended to pass Bull Trout in a safe, timely, and effective manner. Bull Trout are listed as threatened under the Endangered Species Act and therefore are a species of special concern in the Pacific Northwest (USFWS 2010). Additionally, barrier passage and connectivity are critical for Bull Trout recovery (USFWS 2008); however, a concise and consistent recommendation for upstream passage parameters for Bull Trout does not exist.

Criteria of Interest

The NMFS Criteria provide design rationale and criteria for aspects of fishway design including design flow range, upstream fish passage systems, exclusion barriers, trapping systems, culverts and road crossings, specifics for Columbia and Snake river fish passage facilities, screen and bypass facilities, infiltration galleries, temporary and interim passage, operation and maintenance, post-construction evaluation, and experimental guidance devices. Adult upstream fish passage systems will be the focus of this assessment.

Adult Upstream Passage Criteria. Chapter Four of the NMFS Criteria details adult upstream fish passage system criteria and guidelines. Only specific components of the adult upstream fish passage system criteria and guidelines will be evaluated. Criteria and guidelines directly related to swimming abilities will be included, such as hydraulic drop and velocity. Criteria and guidelines related to components indirectly related to swimming abilities, such as percent attraction flow, fishway entrance location, staff gauges, etc., will not be addressed because the design basis for these components, and many others, are linked to swimming performance and abilities. Hydraulic drop and transport channel velocity are the NMFS Criteria that will be assessed (Table 9).

Table 9. Selected NMFS adult upstream passage system criteria

Component (Section)	Criteria
Maximum Hydraulic Drop (4.5.2.1)	0.30 m (1 foot)
Maximum Transport Channel Velocity (4.4.2.1)	0.46 to 1.22 m/s (1.5 to 4 ft./s)

Explicit limitations apply to the criteria and guidelines within the adult upstream fish passage system section. The criteria and guidelines are applicable to “moderately-sized” streams, which in general identifies streams with annual average flows between 152.4 and 1,524 cubic meters per second (500 and 5,000 cubic feet per second). Caution should be used when considering the recommendations herein while designing or assessing upstream passage facilities on streams outside this range of annual average flows.

Comparison and Assessment

The following section presents considerations practitioners must examine when designing upstream fishways and the known swimming and leaping abilities of salmon and Bull Trout.

Considerations

Fish swimming performance depends on numerous factors including fish condition, presence of turbulence, motivation, and duration until fatigue (Powers and

Osborn 1985; Mesa et al. 2003b; Mesa et al. 2008). There are other factors influencing optimization of a fish's swimming performance, but the four mentioned will be briefly described.

Fish Condition. Fish condition and the coefficient of fish condition presented by Powers and Osborn (1985) provide a means of accounting for a specimen's inability to achieve burst swim speeds. Fish conditions applies to anadromous species and estimates how much energy an individual has lost while migrating upstream. Coefficient values of 0.5, 0.75, and 1.0 are applied to the burst swim speed to determine the actual swim speed of a fish at the point of interest (Table 10). By applying a coefficient of fish condition practitioners better predict the species' abilities to pass a potential migration barrier at the point of interest. Values between the coefficients listed can be used when appropriate based on the designer's professional judgement.

Table 10. Summarization of fish condition (Powers and Osborn 1985)

Coefficient of Fish Condition	Fish Condition
0.5[1]	Poor; in the river for a long time; full spawning colors developed and fully mature; very close to spawning
0.75	Good; in the river for a short time; spawning colors apparent but not fully developed; still migrating upstream
1.0	Bright; fresh out of salt water or still a long distance from spawning grounds; spawning colors not yet developed

1. Generally corresponds to the upper limit of critical swim speed.

Turbulence. Turbulence can present several challenges for fish passage. All naturally occurring streams contain varying amounts of turbulence, and in the right situations, fish use turbulence advantageously (Lacey et al. 2012). However, if the intensity, periodicity, orientation, or scale of turbulence within a fishway creates confusing hydraulics, disorientation and false cues can occur (Lacey et al. 2012). Excessive turbulence also entrains air in the upper portions of the water column, which can reduce a fish's ability to create propulsion power reducing achievable speed (Powers and Osborn 1985).

Motivation. A fish must be motivated to pass a barrier. Motivation can come from desire to seek thermal refuge, avoid predation, pursue spawning grounds, or seek foraging grounds. A fish may not be motivated to pass a barrier even when it possess the ability to do so because the individual may be satiated, emaciated, or may have reached adequate spawning grounds (M. Barrow, USFWS, personal communication).

Duration Until Fatigue. The time required to pass a barrier should be considered during design or assessment (Mesa et al. 2003a). The duration to pass a barrier will help inform the design velocity selection. Fishway design should limit or prevent exhaustion of fish during passage by either providing resting areas or be short enough to allow passage at a conservative swim speed. It is important to recall, the duration of passage is the quotient of distance and fish velocity, where fish velocity is the difference between water velocity and swim speed. For example, assume a Bull Trout can maintain a swim speed of 1.5 m/s (swim speed) while passing a 10 m long culvert with an average water velocity of 0.5 m/s. The fish velocity is 1.0 m/s (swim speed minus water velocity) and it would take 10 seconds (length divided by fish velocity) to pass the 10 m long culvert. The 10 second passage duration is within the burst swim speed range (less than 20 seconds; Katopodis and Gervais 2016) and the assumed swim speed is within the range of

Bull Trout burst swim speeds (Mesa et al. 2008). Passage duration and resulting fatigue need to be considered when assessing barriers or selecting length and water velocity of a fishway.

Swimming Performance

Swim speeds are generally divided into three categories; burst, prolonged, and sustained (Wilson and Egginton 1994; Katopodis and Gervais 2016). Burst swim speeds are the highest speeds fish can achieve and occur over a short duration (less than 20 seconds; Katopodis and Gervais 2016). Critical or prolonged swim speeds are categorized by speeds a fish can maintain for 20 seconds to 30 minutes without fatigue (Katopodis and Gervais 2016). Lastly, sustained swim speeds are speeds of lower power output and utilized by fish indefinitely without fatigue. See Katopodis and Gervais (2016) for a more thorough physiological presentation of the differences between the three swim speed categories. Differences exist in the determination and classification of swim speeds, particularly critical swim speed, which is a form of prolonged swimming (Gui et al. 2014). Caution should be used when comparing critical swim speed and aerobic swimming performance between species.

Bull Trout burst swim speed was determined to be between 1.3 and 2.3 m/s by Mesa et al. (2008) and the mean critical swimming speed for adults (32 to 43 cm fork length) was determined by Mesa et al. (2003a, 2004) to be 74 cm/s. Each of the studies conducted by Mesa et al. (2003a, 2004, 2008) have resulted in the industry standard values used for Bull Trout swim speeds. Each study reported relatively sparse fish participation and therefore the swim speed values used regionally are based on the abilities of a very small sample size. For further information and species background see Chapters Two and Three.

The swimming abilities of anadromous salmonids have been summarized by Katopodis and Gervais (2016) and Greene et al. (2017). Burst swim speeds of salmon range from 3.2 – 8.2 m/s (Table 11).

Table 11. Burst speeds of salmon

Common Name	Scientific Name	Burst Speed (m/s)[1]	Leap Height (m)[2]
Chum	*O. keta*	3.2[3] – 4.6	1.0
Coho	*O. kisutch*	6.4	3.0
Chinook	*O. tshawytscha*	6.7	3.1
Steelhead	*O. mykiss*	8.2	4.2

1. Values represent those presented in Table A4 of Greene et al. (2017) unless otherwise noted. Actual experiments and data collection conducted by others.
2. Values represent those presented in Table 3 of Aaserude and Osborn (1985). Values calculated based on bust swim speeds by others and projectile motion equations.
3. Value listed by Aaserude and Osborn (1985).

Leaping Abilities

Leaping abilities must be considered when designing fishways or assessing potential barrier sites (Turek et al. 2016). The NMFS Criteria identify streaming flow as the desirable flow condition, as oppose to plunging flow because plunging flow requires jumping. Leaping abilities are strongly correlated to burst swim speeds (Powers and Osborn 1985). Leaping abilities of salmon range from 1 m to 4.2 m (Table 11) and the predicted jump height of a 0.3 m long Bull Trout specimen is 0.9 m.

Leaping abilities have been determined based on projectile motion equations and assessments by Aaserude and Osborn (1985) and Powers and Osborn (1985). The values presented above for salmon were determined by Aaserude and Osborn (1985) using the following projectile motion equation assuming a leaping angle of 75-degrees and accounted for the fish length, drag forces, buoyant forces, weight of the fish, and propulsion forces while determining the leap height of salmon. See Aaserude and Osborn (1985) for a thorough description of the assumptions and analysis.

$$H_L = \frac{V^2}{2g} + L \tag{1}$$

Where V is the vertical component of fish velocity when it has completely exited the water, H_L is the height of the leap, g is acceleration due to gravity, L is the length of the fish. Fish length is included in predicting the maximum leaping height because it is assumed a fish will create propulsion power until it has completely exited the water (Aaserude and Osborn 1985).

Bull Trout jump heights have not been studied specifically and little definitive information exists related to Bull Trout jumping abilities. Anecdotal evidence exists indicating that stream resident Bull Trout may be able to jump 0.6 to 0.9 m (2-3 feet) and migratory Bull Trout are able to jump three times their body length (L. Knotek, Montana Fish, Wildlife and Parks, personal communication) depending on life stage, jump pool depth, and flow rate (USFS and USFWS 2013). This implies that a 60 cm long migratory Bull Trout could exhibit leap heights exceeding those of Chum Salmon.

The upper value of the reported burst swim speed range of Bull Trout (2.3 m/s) is half of the Chum Salmon burst swim speed (4.6 m/s) reported by Greene et al. (2017), indicating a Chum Salmon should be capable of leaping greater heights than a Bull Trout. Due to the strong association between burst swim speed and leaping ability, the contradicting abilities of migratory Bull Trout and Chum Salmon require further investigation. Additionally, differences exist between reported values of Chum Salmon burst swim speeds. Greene et al. (2017) reports a Chum Salmon burst speed value of 4.6 m/s while USDA (2007) and Aaserude and Osborn (1985) report 3.2 m/s. The calculated leap heights are influenced by the square of the burst velocity, and therefore differences in burst speeds have significant impact on predicted leaping abilities.

Discussion

An analysis similar to that of Powers and Osborn (1985) has been conducted to determine potential burst swim speeds achievable by Bull Trout based on anecdotal leaping abilities. A 60 cm long (total length) fish and a leaping angle of 75-degrees were used for the analysis. The influences of a standing wave (Stuart 1964, reviewed in Powers and Osborn 1985), and drag were neglected.

Based on observations within the Clearwater River, Montana Bull Trout can leap three times their body length (L. Knotek, Montana Fish, Wildlife and Parks, personal communication), resulting in a leap of 1.8 m for a 60 cm fish. Rearranging Equation 1 to solve for fish velocity results in the following:

$$V = \frac{\sqrt{2g(H_L - L)}}{\sin(75)} \tag{2}$$

The resulting burst swim speed from Equation (2) is 5.0 m/s for a 60 cm long Bull Trout. If the fish length is reduced to 30 cm to represent a stream resident adult Bull Trout, the resulting bust swim speed is 3.5 m/s. Each of the two calculated burst swim speeds exceed those determined by Mesa et al. (2008). Based on this simple analysis and comparing the abilities of Bull Trout to Chum Salmon, it is reasonable to assume the

NMFS Criteria range for maximum transport velocity can be used to design a fishway intended to safely, timely, and effectively pass Bull Trout. This is a simplified analysis and should be used to encourage further, more detailed assessments.

Limitations and Challenges

Further research related to Bull Trout swimming performance, burst swim speeds, and leaping abilities is needed to strengthen the opinions herein. The above opinions are made with hesitation, resulting from limited participation by Bull Trout in swim studies conducted by Mesa et al. (2003a, 2004, 2008) and limited leaping ability information.

When site- and species-specific information reveals a low fish condition resulting in marginal swimming performance, the abilities of primary design species should govern the design and justify criteria adjustments. The NMFS Criteria allow for such adjustments to criteria when site-specific biological rationale exists. One such fishway component at an upstream passage facility is the attraction flow. Attraction flows meeting the NMFS Criteria may create adverse hydraulic conditions given the site constraints and fish condition resulting in delay or inefficient passage rates. In this situation, the hydraulic requirement of attraction flow should be altered to prioritize the biological information of the primary design species.

Behavior

Behaviors and traits that characterize a species beyond the physical abilities also play a key role in fishway success. Distinct Bull Trout behaviors and traits that must be considered when designing a fishway include nocturnal movement (M. Barrows, USFWS, personal communication), desire for cover (Al-Chokhachy et al. 2010), and bottom orientation (bottom one-quarter of water column; Al-Chokhachy et al. 2007; GEI Consultants 2007). Being a bottom-oriented species Bull Trout can have difficulty locating fishways designed for salmon. These behaviors and those listed in Chapter Three of this document should be considered when designing a Bull Trout specific fishway.

Final Comments

It is my opinion that by following the guidance and criteria, including provisional modifications set forth by NMFS Criteria, a safe, timely, and effective adult upstream fishway can be designed specifically for adult Bull Trout. I have come to this conclusion based on anecdotal evidence that Bull Trout currently ascend mainstem Columbia River fishways (Barrows et al. 2016) designed to similar standards as the NMFS Criteria, the maximum allowable velocity range can be reduced to a value less than half of the lower burst swim speed range achievable by Bull Trout, Bull Trout are able to achieve burst swim speeds exceeding those reported in published research, and the maximum allowable hydraulic drop is within the leaping abilities of Bull Trout.

The NMFS Criteria covers numerous fishway components not discussed or analyzed within this document. In general, the recommendations for roughened chutes (Section 4.10 of NMFS 2011) for adult salmonids and culverts and other stream crossings (Chapter Seven of NMFS 2011) appear to be applicable for fishway design when the primary design species is Bull Trout. Additionally, the minimum water depth (section 7.5.2.7 of NMFS 2011) and maximum hydraulic drop (section 7.5.2.8 of NMFS 2011) should closely reflect the abilities and swimming performance of Bull Trout. As with all fishway designs, hydraulic modeling paired with consideration of fish condition and resulting swimming performance should be considered when establishing site-specific design parameters.

Screening requirement of previous versions of the NMFS screening criteria have been evaluated for use when designing facilities for Bull Trout. Zydlewski et al. (2000 and 2002) provides details regarding the study, previous criteria, Bull Trout life stages assessed, and conclusions. It was determined the previous NMFS screening criteria adequately protected against entrainment, impingement, injury, and mortality of Bull Trout.

SUMMARY

USFWS Document

Chapter Three of this thesis presents a working document for the USFWS. The document will either be circulated internally within USFWS or published and made available to the public. USFWS staff intends to continually update and refine the document to accurately represent the best available information for each species as well as conduct similar analyses to add additional trust resource species to the fish passage resource. In addition to formatting the document to the style and standards of the USFWS, the following suggested items would add value to the overall product.

Remaining Work Items

The USFWS document currently provides species-specific information for Bull Trout and Pacific Lamprey. Additional species will be added to the document based on the template and structure provided herein. A summary table could be added to the document identifying the known passage parameters and abilities of each species included within the document as additional species are added. The headings within the Passage Specific Parameters and Abilities section could serve as the column headings. Having a summary table would simplify design processes by providing a single location containing the passage specific abilities (swim speeds, jumping abilities, etc.) of each species.

Numerous restoration groups, agencies, and researchers perform work related to recovery of Bull Trout and Pacific Lamprey. An online geographic information system

(GIS) mapping feature associated with the USFWS document, listing names and contact information of individuals and groups conducting work in each core area could streamline a practitioner’s search for information. Such mapping features exist for each species but are either not affiliated with USFWS or not associated with the USFWS fish passage resource.

Validity of NMFS Criteria Assessment

As noted in Chapter Four, successful passage depends on many factors. Further research related to the swimming and leaping abilities of Bull Trout should be completed to strengthen (or disprove) the arguments used to justify the use of the NMFS Criteria when designing an upstream passage facility for adult Bull Trout.

Further research assessing adult Bull Trout upstream passage abilities could be conducted by building upon a study by BioAnalyst, Inc. (2004, 2009) in the mid-Columbia River. Radio-telemetry data was collected over several years and Bull Trout encounters with several mid-Columbia River fishways were documented and monitored. The existing data includes time spent in the tailrace, time spent within the fishway, and likely spawning tributaries (Barrows et al. 2016). Further research could include a 3-Dimensional Computational Fluid Dynamics model of a portion of one fishway, either Wells Dam, Rocky Reach Dam, or Rock Island Dam. Boundary and initial conditions (e.g. flow rate, pool and weir dimensions) for the model could be acquired from the public utility district (Wells Dam operated by Douglas County PUD and Rocky Reach and Rock Island dams operated by Chelan County PUD). The geometry of three pools and two weirs of a pool and weir fishway could be modeled and calibrated using the staff gauges throughout the selected fishway to verify the model is predicting the water surface elevation in the pools and over the weirs correctly. Spot velocity measurements could be used to calibrate and validate the model. With a calibrated model, it would be straightforward to estimate the velocities encountered by Bull Trout at any location in the fishway for a given flow rate. Video footage of the counting station could be used to approximate the length (total length or fork length) of each specimen capable of ascending of the fishway, giving researchers a better understanding of Bull Trout swimming abilities related to length. The time to ascend the fishway data from radio telemetry could also be used to better understand the impacts of fatigue, utilization of resting pools at various flow rates, and swimming performance of Bull Trout.

As noted throughout this document, passage success is dependent upon many factors including swimming performance, fish condition, leaping ability, motivation, ability to locate fishway entrance, ability to navigate turbulence, whether the specimen is adfluvial, anadromous, fluvial, or stream resident, and whether the specimen is adult or juvenile. Thus, simply knowing what Bull Trout can or should do, does not always predict what they will do. To better understand Bull Trout behavior within fishways, in-situ studies coupled with hydraulic modeling should be completed.

Fishway Design General Comments

Adequately designed and constructed upstream adult fishways provide the connectivity required by many species. Fishway designs should accomplish management goals for imperiled, endangered, or threatened species as well as allow passage of all native species. Species-specific design approaches should be based on weaker swimming species to ensure connectivity for all native fishes. Funds and research efforts should be allocated to accurately identify the swimming and leaping abilities of weaker swimming species, increasing the availability of design values for designers and practitioners.

Upstream fishway design should aim to optimize a balance between operational flexibility and maintenance requirements. Two forms of operational flexibility include allowing multiple operational modes and flow dampening features. An example of multiple operational modes is seen at the Thompson Falls Fish Ladder on the Clark Fork River, Montana. The fish ladder can function in either overflow weir or orifice mode, giving operational staff the ability to adjust the mode of operation as the flow rate through the fish ladder changes. Multiple operational modes can be accomplished at nature-like fishways and stream-simulation road-stream crossings by designing multiple channels that become inundated as flows increase creating for multiple passage routes. Flow dampening features include weirs and orifices that remove flow from the fishway during high flow events. This practice is common in the design of technical fishways but can also be used nature-like fishways and stream-simulation road-stream crossings.

The addition of gates, weirs, orifices, and pipes creates additional maintenance requirements. Debris, silt, and sand can clog or damage these components, requiring routine maintenance, such as checking, cleaning, and repairing. The recurring costs of routine maintenance and capital costs of operational flexibility must be accurately accounted for in the pre-design phase to inform early decision making. Agencies, owners, and districts will prioritize the benefits of operational flexibility and the associated maintenance effort and costs differently and therefore the advantages and disadvantages of such features are highly site-specific.

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APPENDICES

APPENDIX A

MANAGEMENT AND RECOVERY DOCUMENTS

Bull Trout Management and Recovery

The following list provides references of management and recovery practices that have been used and/or assessed, to make known the strategies and plans implemented throughout the range of Bull Trout, and to encourage collaborative efforts and consistent transfer of information. The information listed is a summary of the conclusions made by the reference document and is organized from newest to oldest. Some of the bulleted items are document titles, rather than a summary of the information in the document. Titles were used when the intent of the document was to report planning and recovery concepts rather than summarizing results from a research study.

- *Reintroduction:* Clackamas River Bull Trout Reintroduction Project (Barrow et al. 2019)
- *Reintroduction:* Decision Analysis for the Reintroduction of Bull Trout into the lower Pend Oreille River, Washington (Benjamin et al. 2019)
- *Reintroduction:* Wild vs. Stock Populations: Wild fish and captive reared fish from complex habitats exhibited a greater level of boldness and prey acquisition ability, than fish reared in conventional captive environments. Results suggest rearing fish in more complex captive environments can create a more wild-like phenotype than conventional rearing practices. Rearing environment influences boldness and prey acquisition behavior, and brain and lens development of bull trout (Brignon et al. 2018)

- *Management:* Structured Decision Making for Conservation of Bull Trout (Salvelinus Confluentus) in Long Creek, Klamath River Basin, South-Central Oregon (Benjamin et al. 2017)
- *Reintroduction:* Evaluating Tradeoffs in Bull Trout Reintroduction Strategies Using Structured Decision Making (Brignon et al. 2017)
- *Recovery:* Study focuses on the Imnaha River and small isolated populations of Bull Trout. Effective Population Size, Connectivity, and Occupancy of Bull Trout: Tools to Assist in Recovery (Hudson et al. 2017).
- *Recovery:* Willamette River Management: Bull Trout Recovery Action Implementation, Monitoring and Evaluation, and Pacific Lamprey Passage Assessment FY 2016 Progress Report (Hudson 2017)
- *Recovery:* Linking Moral Obligations, Assumption-based Research, and Structural Decision Making to Inform Bull Trout Recovery (Brignon 2016)
- *Management:* Strategic modeling to assist conservation of Bull Trout in the lower Clark Fork River - Management actions that reduced the influence of nonnative trout were predicted to result in the largest comparative improvement in Bull Trout population status for individual patches and at the aggregate level including all patches upstream of Cabinet Gorge Dam. Increasing the capture and transport of out-migrating juvenile Bull Trout from natal patches in Montana to Lake Pend Oreille, Idaho also had a positive effect, but seemingly only at very high transport rates. Strategic modeling to assist conservation of Bull Trout in the lower Clark Fork River (Peterson 2015)

- *Recovery:* Mid-Columbia Recovery Unit Implementation Plan for Bull Trout (USFWS 2015b)
- *Recovery:* Recovery Plan for the Coterminous United States Population of Bull Trout (USFWS 2015a)
- *Recovery:* Bull Trout Recovery Planning Activities FY 2011 and 2012 Progress Report (Koski and Whitesel 2014)
- *Recovery:* Walla Walla River Bull Trout Ten Year Retrospective Analysis and Implications for Recovery Planning (Schaller et al. 2014).
- *Physical Abilities:* Not including periods of rest, Bull Trout swam at median hourly speeds of 0.53 body lengths per second. Understanding fish behavior in the context of their physical environment may help explain population-level responses to hydrologic change. Hydrologic correlates of Bull Trout (*Salvelinus confluentus*) swimming activity in a hydropeaking river (Taylor et al. 2014).
- *Reservoir Levels:* Data concludes that maintaining moderate reservoir elevations during the spawning season and holding the reservoir near this elevation through the incubation period can lower the effect on incubating Bull Trout redds. Impacts of reservoir elevation during the spawning season on the distribution of Bull Trout redds (Barnett et al. 2013).
- *Transport Programs:* Data provides evidence that the upstream transport program is meeting its goal of increasing the number of spawning adults in Bull Trout populations upstream from Clark Fork River dams and highlights the fact that non-transported fish also make an important contribution to the local tributary

populations. Spawning Success of Bull Trout transported above main-stem Clark Fork River dams in Idaho and Montana (DeHaan and Bernall 2013).

- *Management:* Conservation Strategy for Bull Trout on USFS lands in Western Montana (USFS and USFWS 2013).
- *Recovery:* Focuses on a South Fork Walla Wall River, Oregon: Bull Trout population assessment in northeastern Oregon: a template for recovery planning (Budy et al. 2012).
- *Management:* Redd counts can be used to estimate abundance levels and to detect substantial longer-term changes in abundance, particularly for migratory populations. However, the reliability of the counts depends on the skill of the surveyors. An evaluation of redd counts as a measure of Bull Trout population size and trend (Howell and Sankovich 2012).
- *Reintroduction:* An Expert Panel Approach to Assessing Potential Effects of Bull Trout Reintroduction on Federally Listed Salmonids in the Clackamas River, Oregon (Marcot et al. 2012)
- *Recovery:* Bull Trout Recovery: Monitoring and Evaluation Guidance Volume II (USFWS 2012)
- *Transport Programs:* Based on genetic assignments, fish were transported upstream above one or more dams. This protocol has helped re-establish connectivity in a fragmented system, providing increased numbers of spawning adults for numerically depressed populations above the dams. Discusses the utility of genetic data for assisting with upstream passage decisions. Use of genetic

markers to aid in re-establishing migratory connectivity in a fragmented metapopulation of Bull Trout (DeHaan et al. 2011).

- *Management:* Results will help managers identify specific nearshore areas that may require further protection to sustain the unique anadromous life history of Bull Trout. Marine habitat use by anadromous Bull Trout from the Skagit River, Washington (Hayes et al. 2011).
- *Management:* Developed an adaptive management framework to analyze which types of streams should be prioritized for reconnection under a proposed Habitat Conservation Plan. Adaptive management of Bull Trout populations in the Lemhi Basin (Tyre et al. 2011).
- *Recovery:* Lewis River Bull Trout Recovery Monitoring and Evaluation: Patches, Occupancy and Distribution 2006-2007 Progress Report (Hudson et al. 2010).
- *Listing:* Revised Designation of Critical Habitat for Bull Trout in the Coterminous United States (USFWS 2010)
- *Physical Abilities:* Overall, the high degree of upstream movement observed in our study for juvenile and adult westslope cutthroat trout and brook trout during the summer indicates that culvert passage is an important management consideration for stream salmonids during this period. Assessment of trout passage through culverts in a large Montana drainage during summer low flow (Burford et al. 2009).
- *Management:* Respondents (professional biologists) to a survey indicated fish passage, forest management practices, and nonnative species interactions are the primary factors limiting Bull Trout populations, and these issues were identified as

the primary recovery challenges in the foreseeable future. Surveying profession opinion to inform Bull Trout recovery and management decisions (Al-Chokharchy et al. 2008).

- *Recovery:* Bull Trout Recovery: Monitoring and Evaluation Guidance (USFWS 2008).
- *Recovery:* The disparity between redd counts and population estimates for the reproductive population suggests that caution be invoked when choosing the monitoring techniques used to set recovery or monitoring goals for Bull Trout populations. Understanding the significance of redd counts: a comparison between two methods for estimating abundance of and monitoring Bull Trout populations (Al-Chokhachy et al. 2005).
- *Recovery:* Bull Trout Recovery Planning: A review of the science associated with population structure and size (Whitesel et al. 2004).
- *Management:* Study assessing a species presence by field sampling vs. predictive models. Results: Lower probability-of-detection thresholds can be specified with the combined approach (combining field sampling and predictive models), resulting in lower misclassification error rates and improved cost-effectiveness. Combining inferences from models of capture efficiency, detectability, and suitable habitat to classify landscapes for conservation of threatened Bull Trout (Peterson and Dunham 2003).
- *Management:* Study suggests that the risk of outbreeding depression associated with passing adults over dams in the Clark Fork system is minimal compared to the

potential genetic and demographic benefits to populations located above the dams. Fragmentation of riverine systems: the genetic effects of dams on Bull Trout (*Salvelinus confluentus*) in the Clark Fork River system (Neraas and Spruell 2000).

- *Listing:* Listening and Recovery Planning for Bull Trout (Lohr et al. 1999).
- *Habitat:* Land management activities resulting in decreased pool habitat, instream cover, and stream-bed stability may be especially detrimental to Bull Trout. Seasonal and diel changes in habitat use by juvenile (*Salvelinus confluentus*) and cutthroat trout (*Oncorhynchus clarki*) in a mountain stream (Bonneau and Scarnecchia 1998).
- *Habitat:* Even with no further habitat loss, existing fragmentation could contribute to continuing local extinctions aggravated by the expansion of introduced species and the effects of climate change. Distribution, status, and likely future trends of Bull Trout within the Columbia River and Klamath River basins (Rieman et al. 1997).
- *Habitat:* Results support the hypothesis that area of available habitat influences the distribution of disjunct populations of Bull Trout. Occurrence of Bull Trout in naturally fragmented habitat patches of varied size (Rieman and McIntyre 1995).

Pacific Lamprey Management and Recovery

The following list provides references of management and recovery practices that have been used and/or assessed, to make known the strategies and plans implemented throughout the range of Pacific Lamprey, and to encourage collaborative efforts and consistent transfer of information. The information listed is a summary of the conclusions made by the reference document and is organized from newest to oldest. Some of the bulleted items are document titles, rather than a summary of the information concluded in the document. Titles were used when the intent of the document was to report planning and recovery concepts rather than summarizing results from a research study.

Additional management and recovery tools can be found at the Pacific Lamprey Conservation Initiate webpage: Pacific Lamprey Conservation Initiative (fws.gov).

- *Migration:* Adult Pacific Lamprey Migration in the Columbia and Snake Rivers: 2019 Radiotelemetry and Half-Duplex Pit Tag Studies (Keefer et al. 2020).
- *Management:* Best Management Guidelines for Native Lampreys During In-water Work Living Document, Original Version 1.0 (Lamprey Technical Workgroup 2020)
- *Management:* Pacific Lamprey *Entosphenus tridentatus* Assessment (USFWS 2019)
- *Marine Environments:* Three marine factors that may be limiting lamprey abundance include: (1) predation and fisheries bycatch; (2) host availability; and (3) host contaminant loads. Four potential marine-related threats to lamprey include: (1) pollution; (2) climate change; (3) unfavorable oceanographic regimes; and (4) the effects of interactions between climate and regimes. Marine biology of the Pacific Lamprey (*Entosphenus tridentatus*) (Clemens 2019).
- *Management*: Pacific Lamprey 2018 Regional Implementation Plan for the Lower Columbia/Willamette Regional Management Unit Lower Columbia Sub-Unit (USFWS 2018)

- *Management*: Pacific Lamprey recolonization of a Pacific Northwest river following dam removal (Jolley et al. 2017).
- *Management:* Identification of six conservation and restoration actions, including (1) removing passage barriers or providing adequate passage for Pacific Lamprey, (2) modifying diversion screens and facilities to deter impingement and entrainment of larval and juvenile lamprey, (3) restoring and managing river habitats to promote the dynamic equilibria of natural, free-flowing river ecosystems, (4) minimizing losses due to dredging and dewatering, (5) educating citizens about the importance of lamprey, and (6) implementing best management practices to include lamprey in planning and implementation for instream work. Conservation challenges and research needs for Pacific Lamprey in the Columbia River basin (Clemens et al. 2017).
- *Management:* Background on Pacific Lamprey assessment. Conserving Pacific Lamprey through Collaborative Efforts (Wang and Schaller 2015).
- *Background:* Textbook devoted entirely to lampreys. Lamprey: Biology, conservation and control (Docker 2015) –
- *Habitat:* Pacific Lamprey habitat restoration guide (Crandall and Wittenbach 2015)
- *Management:* Results emphasize the importance of natural variation in streamflow regimes and provide insight for management practices that would benefit emigrating lampreys, such as synchronizing dam releases with winter and spring storms to reduce migration time, timing diversions to avoid entrainment

during emigration windows, and ensuring stream flows are sufficient to reach the ocean, thereby avoiding mass stranding events. The punctuated seaward migration of Pacific Lamprey (*Entosphenus tridentatus*): environmental cues and implications for streamflow management (Goodman et al. 2015).

- *Migration:* Seasonal Migration Behaviors and Distribution of Adult Pacific Lampreys in Unimpounded Reaches of the Snake River Basin (McIlraith et al. 2015).
- *Location Specific:* Distribution of Pacific Lamprey *Entosphenus tridentatus* in Watersheds of Puget Sound Based on Smolt Monitoring Data (Hayes et al. 2013).
- *Quantification:* Authors highlight challenges associated with enumerating cryptic and nocturnal species, such as Pacific Lamprey, the potential impact of species-specific behaviors on enumeration efforts, and the importance of appropriate count station location and structure for video monitoring of fish passage. Use of night video to enumerate adult Pacific Lamprey passage at hydroelectric dams: Challenges and opportunities to improve escapement estimates (Clabough et al. 2012).
- *Quantification:* This study identifies how the occurrence of larval Pacific Lampreys can be quantified with statistical rigor in a large river (i.e., larger than fourth order [1:100,000 scale]). The effect of channel management activities on larval lampreys should be considered in efforts to conserve these important species. Occupancy and detection of larval Pacific Lampreys and Lampetra spp. in a large river: the lower Willamette River (Jolley et al. 2012).

- *Management:* Tribal Pacific Lamprey Restoration Plan for the Columbia River Basin (Columbia River Inter-Tribal Fish Commission 2011)
- *Management:* Original assessment: Pacific Lamprey (*Entosphenus tridentatus*) Assessment and Template for Conservation Measures (Luzier et al. 2011).