Passage Guidelines for Select Native Pacific Northwest Fish

US Fish and Wildlife Service, Region 1

Version 2.0

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Cover art of a stylized salmonid, sturgeon, and lamprey generated by Joe Skalicky using Google Gemini, 2024.

ABSTRACT

This fish passage document summarizes the state-of-the-science and provides guidelines for implementation of nature-based and technical fish passage solutions. Passage needs for Bull Trout (*Salvelinus confluentus*), Pacific Lamprey (*Entosphenus tridentatus*), White Sturgeon (*Acipenser transmontanus*), freshwater sculpin (Family *Cottidae*), and small-bodied (<150 mm) fishes in the Pacific Northwest region of the United States are specifically addressed. These Guidelines include links to useful resources, which should be consulted for more in-depth and detailed information.

To complete their life cycles, most fishes must migrate between habitat types, flow conditions, and thermal regimes, which has become more critical in the face of climate change. The longest migrations are typically for anadromous species, such as Pacific Lamprey (*Entosphenus tridentatus*), that must journey between the ocean and freshwater spawning grounds to complete their life cycles. Additionally, other native aquatic species, such as Western Pearlshell (*Margaritifera falcata*), Western Ridged (*Gonidea angulata*) and Floater (*Anodonta spp.*) mussels, are dependent upon migratory fishes to complete their life cycles by dispersing offspring. On a broader population-level scale, connectivity facilitates the recolonization, range expansion, and migration of native fish species. Preserving and restoring aquatic connectivity will help ensure the long-term viability of fish populations (Olden et al. 2014).

While improving passage at artificial barriers (e.g., dams or weirs) has been a multi-decadal focus for anadromous salmon and steelhead (*Oncorhynchus spp.*) in the Pacific Northwest, comparatively little attention has been given to passage needs for other culturally and ecologically significant fishes. The goal of this document is to fill that gap, which is timely given the growing interest in [Nature-based Solutions] and increasing connectivity in freshwater aquatic systems.

Primary objectives of these Guidelines are to:

1. raise awareness of the different passage needs for species other than Pacific salmon and steelhead;
2. discuss basic passage constraints, such as jump heights, minimum flow depths, and maximum velocities;
3. provide general recommendations to improve passage for a variety of fish life histories; and
4. provide links to additional information and resources.

TABLE OF CONTENTS

INTRODUCTION

The US Fish and Wildlife Service (Service), is charged by Congress to preserve and protect our Federal trust species which include:

> "migratory birds, threatened species, endangered species, interjurisdictional fish, marine mammals, and other species of concern" (Partners for Fish and Wildlife Act of 2006).

Among these trust resources are a variety of fish species which have cultural, ecological, economic, recreational, and symbolic importance to the Pacific Northwest (PNW) region of the United States. Additionally, the Service implements programs that support fish passage improvement, particularly the National Fish Passage Program and the National Fish Habitat Partnership.

Fish passage is the ability of fish to move upstream, downstream and laterally into adjacent side channels, wetlands, floodplains, lakes, ponds, and tributary habitat (Figure 1). This is referred to more broadly as "aquatic connectivity," with the loss of connectivity termed "habitat fragmentation." While provision of fish passage is generally a positive attribute in aquatic systems, it can also result in inadvertent movement of fish into ditches, canals, and irrigation intakes. Additionally, restoring passage can open new pathways for aquatic invasive species. Hence, restoration of fish passage is context dependent and should be thoroughly evaluated prior to project implementation.

The Service defines "fish passage" as the ability of fish and other aquatic species to move volitionally through an aquatic system among all habitats necessary to complete their life cycles; however, the focus of these Guidelines are on fish. In addition, the Service defines "barriers" to passage as anything that either prevents or reduces the ability of aquatic species to freely move to complete their life cycles.

There are three broad categories of barriers:

1) human-caused direct barriers, such as dams, culverts, and levees;
2) human-caused indirect barriers, such as excess sediment, poor water quality, temperature, or flow limiting conditions, and artificial light at night that can be a diel fish barrier; and
3) natural barriers, such as waterfalls, flows that go subsurface, or water chemistry.

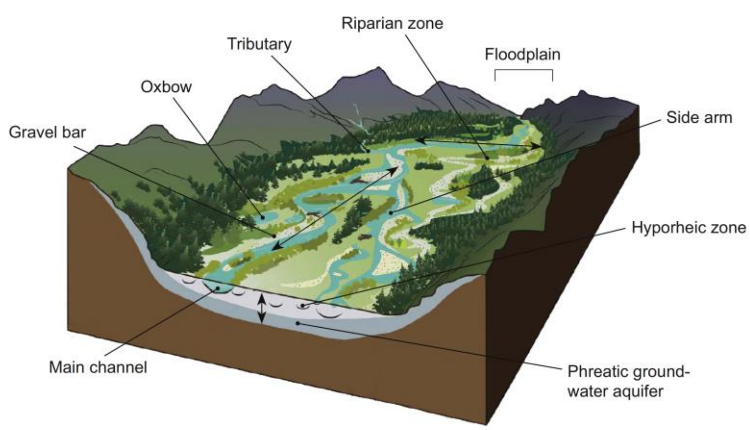

Figure 1 Idealized landscape with multiple habitat types that may be required by aquatic species to complete their life cycles. From Hayes et al. (2018), which is adapted from Hauer et al. (2016).

Only human-caused barriers are addressed in this document. Human-caused barriers (e.g., dams, weirs, irrigation diversions) and lateral constraints (e.g., levees, channelization) that reduce aquatic connectivity can cause habitat fragmentation for migratory fish species. Fragmentation often interrupts the completion of fish life cycles and therefore is identified as a primary threat. Passage restoration is a high priority for native fish conservation and recovery. However, no consolidated approaches exist to help project proponents improve passage and connectivity for the wide spectrum of Service trust species in the PNW. Furthermore, resident small-bodied native fishes, even those that are federally listed under the Endangered Species Act, are often left out of fish passage and screening considerations.

Currently, the National Marine Fisheries Service has the only West Coast-wide fish passage design manual and it is narrowly focused on anadromous salmon and steelhead, which have relatively strong swimming and jumping abilities (NMFS 2022a; Table 1).

Providing passage for anadromous salmonids is clearly important; however, this limited focus on large-bodied, strong swimming fish results in missed opportunities to improve passage and increase survival for a wider variety of weaker swimming and non-jumping native fish. Furthermore, traditionally engineered salmonid-specific fish ladders (for salmon and steelhead) focused on upstream adult passage can inadvertently create partial or complete barriers to other fishes and migration patterns.

At the state level, both the Washington Department of Fish and Wildlife (WDFW) and the Oregon Department of Fish and Wildlife (ODFW) provide design guidance that extends beyond anadromous salmonids, and includes native migratory fish such as trout, lamprey, sturgeon, and suckers:

- WDFW design criteria
- ODFW administrative rules

To ensure compliance with both state and federal criteria and rules, the most conservative design approach should be employed to ensure passage for the widest spectrum of fish and aquatic species.

Terminology and jargon within the fish passage community of practice is extensive. Unfortunately, some common terms have developed multiple meanings and interpretations, particularly between disciplines.

For the purposes of this document:

- “fishway” includes fish ladders, fish passes, and other similar structures used on or around barriers (such as dams or weirs) to provide fish passage.
- “fish screen” includes engineered structures that are intended to either guide or exclude fish into or away from fishways, turbines, canals, ditches, pipelines, and related structures.

Similarly, within the fish passage literature there is considerable variation in both the terminology and metrics used to define a fish swimming performance. As such we use swimming speed definitions from Beamish (1978) as noted in Table 1. The intent of these definitions by Beamish (1978) was to standardize between various studies to allow for more direct comparison, but significant variability remains.

According to Beamish (1978), ‘sustained’ swimming extends for more than 200 minutes, ‘prolonged’ occurs for 20 seconds up to 200 minutes, and ‘burst’ is up to 20 seconds. Further, Beamish (1978) defines ‘cruising’ as a subcategory of ‘sustained’ swimming, and ‘critical’ as a special category of ‘prolonged’ swimming. ‘Critical’ is the maximum velocity fish can maintain for a specified time (Beamish 1978).

Designing passage projects, including barrier removal, habitat reconnection, natural fishways, and engineered structures for a wide range of fish is challenging. Research suggests designing a traditional engineered fishway to effectively accommodate salmonids, lamprey, sturgeon, and other native species may not be feasible (Daigle et al. 2005). Hence the preference for natural fishways and stream simulation (USDA 2008). Stream simulation:

[an ecological approach to providing passage for aquatic organisms at road-stream crossings]().

Engineered fishways with specific hydraulic design parameters, such as jump heights, flow depths, and maximum velocities, should be considered after natural fish passage approaches have been thoroughly evaluated and rejected. When using a hydraulic approach to fish passage, designs usually focus on swimming abilities of a specific fish (Table 1). These design parameters for the target species often result in a lack of adequate passage for other fish species and life stages. For instance, dams on the mainstem Columbia River were constructed with fishways designed to pass only adult anadromous salmonids and thus were not suitable for sturgeon or Pacific lamprey passage without significant retrofits.

Numerous fish recovery plans and status assessments have identified passage barriers as threats. For example, in the Service's Bull Trout Recovery Plan (USFWS 2015), passage is regarded as one of the primary threats to persistence and recovery; however, there is limited information on how to improve passage and reduce habitat fragmentation. The Pacific Lamprey Assessment (USFWS 2019) also identifies passage barriers as the largest threat throughout the range of Pacific Lamprey but provides limited research-based direction on how to counteract this threat. White Sturgeon once moved freely throughout the Columbia River Basin but migrations are now largely restricted between hydropower dams or limited to downstream movements (CBWSPF 2013). Fish passage and screening considerations often fail to include small-bodied (<150 mm) native fishes, even those that are federally listed under the Endangered Species Act, such as Warner Sucker (*Catostomus warnerensis*), Shortnose Sucker (*Chasmistes brevirostris*), Lost River Sucker (*Deltistes luxatus*), Hutton Tui Chub (*Gila bicolor ssp.*) and Lahontan Cutthroat Trout (*Oncorhynchus clarkii henshawi*). Small-bodied fish are also a critical prey resource and some species are hosts for native mussels. To address these limitations, these fish passage guidelines will help project planners, designers, engineers, biologists, and managers include project-specific elements, such as the use of roughness elements, to improve passage and aquatic connectivity.

This document focuses on four Service species of concern -- Bull Trout (*Salvelinus confluentus*), Pacific Lamprey (*Entosphenus tridentatus*), White Sturgeon (*Acipenser transmontanus*), and freshwater sculpin (Family *Cottidae*) -- while also providing more general consideration for small-bodied fishes.

Species	Jumping Ability		Flow Depth	Swimming Speed (m/s)		
	Cited Jumping	Measured/Obs Jump Height (m)	Minimum (m)	Sustained >200 mins	Prolonged < 200 mins but > 20 secs	Burst <20 secs
Chinook Salmon[1]	Y	2.13	0.37	1.04	3.12	6.83
White Sturgeon[1]	N	n/a	1.0	No data	1.23 / 2.26*	No data
Bull Trout[2,5]	Y	<0.5	No data	No data	0.48 / 0.74*	1.3 / 2.3*
Speckled Dace[4]	No data	No data	No data	No data	0.63	1.30
Mottled Sculpin[4]	No data	No data	No data	No data	0.51	1.18
Longnose Dace[4]	No data	No data	No data	No data	0.67	1.15
Redside Shiner[4]	No data	No data	No data	No data	0.55	1.12
Mountain Whitefish[6]	No data	No data	No data	No data	0.43	1.07
Pacific Lamprey[2,7]	Y	<0.5	0.3	No data	0.86	0.86
Riffle Sculpin[1]	N	No data	0.3	No data	0.77	0.77
Warner Sucker[3]	No data	No data	No data	No data	0.37	0.46

Table 1 Published swimming speeds of select PNW fish. From: Matica (2020) and Katopodis and Gervais (2016). Matica 2020[1], Mesa et al. 2008[2], Scheerer and Clements 2013[3], Aedo et al. 2009[4], Mesa and Weiland 2004[5], Katapodis and Gervais 2016[6], LTW 2023[7].

*When two speeds are listed, it indicates "Juvenile / Adult". Swimming speed definitions from Beamish (1978)

This focus does not negate the needs for otherfishes; hence, the document is structured such that other species can be added in the future. The intent is not to provide an exhaustive list of information for all species but rather to provide a broad range of life history strategies and passage considerations. The range of considerations when combined with guidance documents from anadromous salmonids collectively addresses the diversity of species and passage needs that occur within the PNW. The intended audience includes fish passage and habitat engineers, biologists, project managers, and other restoration practitioners who are designing, implementing, and assessing floodplain and channel designs, and structures such as road crossings, fish screens, fishways (e.g., fish ladders), levees, tide gates, and irrigation diversions. Land managers and conservationists may also find these Guidelines useful when considering aquatic management actions.

The geographic focus of this document is the Pacific Northwest (PNW) region of the United States -- Oregon, Washington, and Idaho, and portions of western Montana. While the intent is to include information and examples from throughout the PNW, much of the available data are derived from within the Columbia River Basin.

This document pulls directly from, and relies heavily upon, a number of essential sources, including, but not limited to:

- Considerations for Multi-Species Fish Passage in California: A Literature Review by Zoltan Matica (2020);
- Assessment, Evaluation, and Development of Fish Passage Guidelines by Travis Denham (2021);
- Use of the Mainstem Columbia and Lower Snake Rivers by Migratory Bull Trout. Data Synthesis and Analyses by Barrows et al. (2016);
- Recovery Plan for the Coterminous United States Population of Bull Trout by the US Fish and Wildlife Service (2015);
- Practical guidelines for incorporating adult Pacific Lamprey passage at fishways, Version 2.0 by the Lamprey Technical Workgroup (2022a); and
- Columbia Basin White Sturgeon Planning Framework by CRITFC, WDFW and ODFW (2013).

Please refer to these source documents for additional and more detailed information.

The science, engineering, technology, and practice of fish passage are constantly evolving. When new or updated information addresses passage issues or provides strategies for improved passage, simplified operations, or decreased maintenance, an updated version of this document will be developed and released. If you are aware of new fish passage techniques, approaches, or practices, please email: Vancouver@fws.gov.

GENERAL RECOMMENDATIONS

It is challenging, and at times either not desirable or possible, to design a structure to pass all fish species past a barrier (Daigle et al. 2005). Hence, a stepwise approach that includes an evaluation of Nature-based Solutions to restoring passage is warranted.

According to Woolsey et al. (2007):

> "Restoring riverine connectivity as a nature-based solution (NBS) involves removing these physical barriers, eliminating hypoxic zones, redesigning road stream crossings, and reintroducing natural meanders back into river morphology".

More specifically, a project is considered a Nature-based Solution if it:

- Is an action to protect, sustainably manage, or restore a natural or modified ecosystem;
- Addresses a socioeconomic challenge (e.g., drought, flooding, wildfire);
- Is expected to benefit nature;
- Is expected to benefit people or communities.

From: DOI Nature-based Solutions Roadmap

Following a Nature-based Solution framework, the following stepwise approach is recommended:

1. Remove human-caused barriers to upstream, downstream, and lateral habitats, including dams, weirs, culverts, levees, riprap, and

roads.

2. Reconnect channels to their floodplains, wetlands, side channels, and tributaries. This may include raising channel beds, filling incised channels, placing large and/or small wood, and/or encouraging beaver recolonization.
3. Increase stream crossing structure widths to fully span channels, floodplains, and wetlands.
4. Mimic natural channels through stream crossing structures by using a stream simulation approach (USDA 2008). This should include an unobstructed opening that is wide enough to accommodate water, sediment, wood, and species, and should also account for the predicted effects of climate change. Consider adding additional width to allow for increased channel migration, large wood transport, and less impeded sediment transport processes.
5. Consider nature-based fishways for sites where barriers cannot be fully removed or modified. These include rock ramps and roughened channels, which are typically constructed of natural materials to mimic a variety of hydraulic conditions to provide multi-species passage. However, other engineering solutions may be better based on site conditions, constraints, and species needs.
6. Evaluate the need for an engineered fish passage structure. Review the "Additional Considerations" section at the end of the document.
7. Address human-caused indirect barriers, including excess sediment deposition, poor water quality, temperature or flow limiting conditions, and artificial lighting at night – shield, reduce or eliminate lights that illuminate stream channels and fishways.
8. Monitor project effectiveness over a range of flow and temperature conditions. Direct observation of multiple fish species with varying swimming capabilities moving both up- and downstream through a passage structure, or direct observation of fish exclusion by a screening structure, provides evidence of project effectiveness.
9. Identify areas where seasonal barriers due to insufficient flows or complete stream dewatering (i.e., irrigation diversions) can be remedied through improved infrastructure (i.e., less leaking canals), water rights acquisitions, changing to a non-instream water source, or other methods.

BULL TROUT

Image credit: Joseph R. Tomelleri

Bull Trout (*Salvelinus confluentus*) have some of the most specific habitat requirements of native salmonids in the PNW (Rieman and McIntryre 1993). These requirements are often referred to as "the four Cs" -- Cold, Clean, Complex, and Connected habitat:

- "Cold" refers to low water temperature requirements for spawning and rearing that are often less than 12°C (54°F).
- "Clean" refers to high water quality because Bull Trout are comparatively less tolerant to pollutants than other native and non-native salmonids.
- "Complex" refers to heterogeneous stream habitat needs that include attributes such as deep pools, undercut banks, and large wood.
- "Connected" refers to migratory needs that link spawning and rearing areas to foraging areas and overwintering habitats.

Within the contiguous United States, Bull Trout are currently found within the Columbia River and Snake River basins in Washington, Oregon, Montana, Idaho, and Nevada; the Puget Sound and Olympic Peninsula watersheds in Washington; the Saint Mary basin in Montana; and the Klamath River basin of south-central Oregon. At the time of their coterminous US listing under the ESA in 1999, Bull Trout, although still widely distributed, were in widespread decline (Quigley and Arbelbide 1997).

Behaviors & Life Histories

Bull Trout exhibit both migratory and resident life history strategies (Figure 2). These strategies were likely an evolutionary outcome of the origin of Bull Trout in the Columbia River Basin, followed by dispersal to other drainage systems through marine migration.

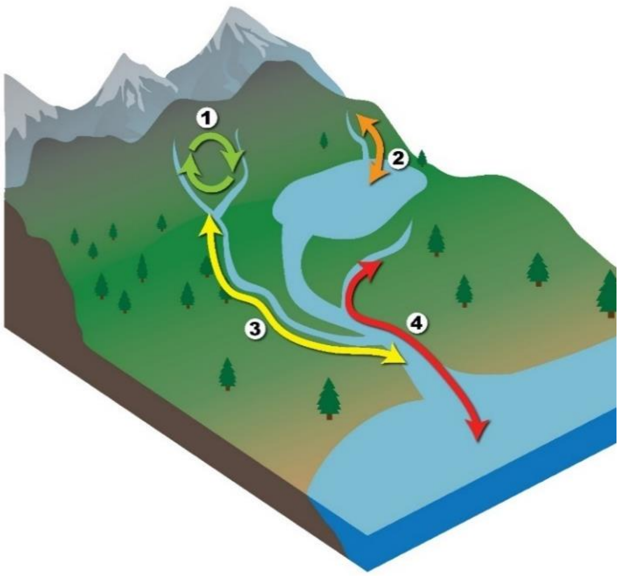

Figure 2 Bull Trout life history diversity. Illustration of typical habitat use by (1) the resident life history form and the three migratory life history forms of Bull Trout: (2) lacustrine or adfluvial, (3) riverine or fluvial, and (4) marine or amphidromous/ anadromous. From: USFWS 2024.

Migratory Bull Trout are typically larger than resident Bull Trout (USFWS 2015), and move throughout large river systems, lakes, and even the ocean in coastal populations. While resident adults range from 150 to 300 mm (6 to 12 in) total length, migratory adults commonly exceed 600 mm (24 in) (Goetz 1989; Pratt 1985).

Migratory Bull Trout exhibit three different migration patterns:

- Lacustrine or Adfluvial -- between tributaries and lakes or deep reservoirs;
- Riverine or Fluvial -- between tributaries and larger rivers; and
- Marine or Amphidromous/Anadromous -- between tributaries and the ocean.

Bull Trout migrations can be relatively short (a few miles) as occurs with resident populations or quite long (hundreds of miles) for migratory populations. As the name implies, resident fishes remain in the same stream their entire lives (Rieman and McIntyre 1993; Brenkman and Corbett 2005, p. 1077). However, even resident Bull Trout exhibit migratory characteristics on a smaller scale within the same stream or reach (Jokober 1995).

Passage Needs & Observations

Bull Trout, both resident and migratory forms, require upstream and downstream passage, and access to lateral habitats, such as side channels and backwater habitats, for repeat spawning, foraging, overwintering, and temperature refugia.

Natural stream channels and flow paths provide the best passage opportunities, so passage projects that use a stream simulation approach (USDA 2008), and match native streambed materials and morphologies that are found within the reach, are generally the best option. This is particularly true for culvert and bridge projects in smaller stream systems.

Fishways, also known as fish ladders, are designed for migrating fish to provide detour routes past obstructions in a river. Most engineered fishways, especially those on larger rivers within the PNW, were and are designed specifically for anadromous semelparous salmonids (adult fishes that spawn once and then die and require only upstream passage). Subsequently, current engineering design guides tend to focus on upstream passage requirements rather than both upstream and downstream needs. Since Bull Trout require both up and downstream passage year-round, this can result in unintentional, or seasonal, isolation of Bull Trout populations even when fish passage is provided (Schaller et al 2014; Mendel et al 2014).

Downstream passage is vital for Bull Trout given their propensity to migrate both up and downstream in larger river systems throughout their lifespans. Within the large rivers of the Columbia River Basin, downstream passage designs have typically focused on juvenile anadromous salmon and steelhead, which tend to be found near the water's surface. Given that adult Bull Trout generally use deeper habitats than juveniles

(Al-Chokhachy and Budy, 2007), current downstream passage facilities at dams likely provide reduced benefit for Bull Trout, causing them to use less safe passage routes, such as turbines, regulating outlets, or spillways. Hence, safe downstream passage for adult fish should be included in fishway designs when Bull Trout are found in the surrounding watershed.

Fish screens are engineered structures used either to guide or exclude fish depending on the need. In the case of large dams, fish screens are typically used to guide salmon and steelhead into bypass systems. In the case of water diversion into canals, ditches, and pipelines, screens are used to exclude fish from entering. Screens designed and operated to standard criteria (NMFS 2022a) to protect downstream outmigrant juvenile salmonids are generally protective of Bull Trout as well.

It is worth noting that when a “trap and haul” mitigation approach is used in lieu of providing volitional passage, there is a risk of adult Bull Trout preying upon juveniles and other species of concern. Predation will likely be more significant when adults and juveniles occupy the same trap box or holding pool for extended periods of time. This behavior can be exhibited by Bull Trout any time there is a structure that provides a resting area with available prey. Limit the amount of time that fish of disparate sizes are held together to reduce predation risk and include refuge areas that allow smaller fish to escape larger fish. Also consider the potential need to limit resting areas within passageways where predatory fish (including Bull Trout) stage for feeding.

Swimming Performance & Endurance

Bull Trout exhibit burst and sustained swimming modes [(Table 1) (Mesa et al. 2003a; Katopodis 1992)]. In a lab setting inside a swim tube, Mesa et al. (2008) determined that Bull Trout burst swim speed (usually less than 20 s) was independent of fish size, between 1.3 and 2.3 m/s. This does not represent Bull Trout volitional swim speeds in the field. However, in earlier studies, Mesa et al. (2003a, 2004) found that critical swim speed, the maximum velocity that a fish can maintain for a specific time period (usually 20 s), did vary with body size and stream temperature such that fish, on average:

- 320 to 420 mm in length = mean critical velocity of 0.74 m/s at 11°C
- 110 to 190 mm in length = mean critical velocity of 0.48 m/s at 11°C
- 140 to 230 mm in length = mean critical velocity of 0.54 m/s at 15°C (note the difference in temperature which may explain critical velocity variances)

Studies conducted by Mesa et al. (2003a, 2004, 2008) continue to provide Bull Trout swim speed standards; however, each study yielded swim speeds that were based on small sample sizes from laboratory settings, possibly underestimating wild population performance. In addition, studies were conducted at single temperatures and swimming capabilities likely change under different temperature scenarios. Due to the small sample sizes, confidence in swim speeds would be increased through additional research. While Bull Trout vertical jump heights have not been specifically studied, there is anecdotal evidence that adult migratory Bull Trout may be able to jump 0.6 to 0.9 m (2 to 3 feet) (L. Knotek, Montana Fish, Wildlife and Parks, personal communication). This is based on an observation at the Thompson Falls Fish Ladder where an adult Bull Trout jumped out of a holding pool. A 1.2 m (4-foot) high fence was subsequently installed around the holding pool and no further “escapes” have been observed (K. Aceituno, US Fish and Wildlife Service, personal communication). Additional anecdotal observations of Bull Trout jumping heights up to 2.4 m have occurred at Mill Creek Dam, Tucannon Hatchery Weir, in the Lostine River, and at Rainy Dam with unclear levels of success. A few studies in Canada and Montana observed Bull Trout above beaver dams of up to 1.5 m in height (Bustard 2017; Wolf et al *In Press*). Nelson and Nelle (2008) documented Bull Trout jumping Fish Tail Falls in the Entiat River, which is approximately 3 m high.

Lacking Bull Trout-specific metrics, Barrows et al. (2016) found that steelhead may be a reasonable surrogate for similarly-sized Bull Trout for the estimation of passage survival through turbines, spillways or other downstream passage routes. Additionally, juvenile and fry Chinook salmon can reasonably be used as a surrogate for juvenile and fry Bull Trout because they: (1) use the same habitat types, (2) are of similar size, and (3) have comparable swimming abilities (Barrows et al. 2016).

*NOTE: this does not apply to upstream passage.

Upstream migrating Bull Trout (ranging in size between 250 mm to 600 mm) may be able to successfully pass nearly all lower Columbia River upstream fishways, as well as all of the lower Snake River upstream fishways, which were designed for anadromous salmon and steelhead (Barrows et al. 2016). There have also been observations of Bull Trout migrating upstream in a high gradient system with high velocity, turbulent water following dam removal in the Elwha River, Washington (Duda et al. 2021). This provides empirical evidence that Bull Trout, at least migratory forms, exhibit stronger swimming in natural systems than was observed in the Mesa et al. (2003a, 2004, 2008) swim tube and flume studies.

Bull Trout migration through large reservoir systems can pose a unique threat, especially for upstream migrations. As reservoir pools shrink throughout the summer, access to spawning tributaries can become more difficult due to thermal barriers, sediment accumulation at confluences, lack of cover, and low flows. This can be further compounded by human recreational activities, such as small dams for swimming and vehicle access.

While Bull Trout of various sizes (200 mm in length [8 in] and larger) have been documented passing upstream passage facilities via PIT tag detections (PTAGIS database for Snake River Dams), there are very little data on the rates of successful passage. In a rare example at Thompson Falls Dam, only 16 of 24 tagged Bull Trout (67%) fully ascended the fish passage ladder between 2011 and 2018 (NorthWestern 2019).

Data Gaps

- Effectiveness of existing passage facilities and designs for Bull Trout of various sizes, life history strategies, and passage routes (e.g., spill vs. turbine).
- Effect of passage delays at fishways.
- Swimming performance and jump height measured volitionally.
- Effective attraction flows for fishways, which have been established for other salmonids.
- Downstream passage requirements and timing for both adults and juveniles.
- Instream low flow barrier passage.
- Cumulative effects of multiple barriers (e.g., 1 impediment vs. 50 sequential impediments).
- Downstream migration effects from instream picket weirs.

PACIFIC LAMPREY

Image Credit: Joseph R. Tomelleri

Pacific Lamprey (*Entosphenus tridentatus*) are an anadromous semelparous species of significant cultural value to Tribes and First Nations (Close et al. 2002). They are a large fish found in many rivers with unimpeded anadromy and are of ecological importance to freshwater ecosystems along the Pacific Rim, from California in the south, north to Alaska, and across Russia and Japan (Scott and Crossman 1973; Clemens and Wang 2021; Clemens et al. 2010). Pacific Lamprey are parasitic, but only while in the ocean and tidal waters (Clemens and Wang 2021).

Pacific Lamprey populations have steeply declined (Moser and Close 2003; Moser and Mesa 2009; USFWS 2018). In response to this decline, the Pacific Lamprey Conservation Initiative (PLCI) was formed with dozens of signatories and letters of support. PLCI is a collaboration with Tribes and other federal, state, and local agencies to recover Pacific Lamprey. Many documents related to the recovery effort, including Best Management

Guidelines, have been developed by the PLCI Lamprey Technical Workgroup (LTW).

Behaviors & Life Histories

In the larval phase, when Pacific Lamprey are initially the size of human eyelashes, they burrow, feed, and grow as blind, toothless filter feeders in fine sediments in streams and rivers. They can remain as larvae for up to 10 years (Hess et al. 2022) before undergoing a metamorphosis into parasitic juveniles which develop eyes and teeth and emigrate to the ocean (Clemens et al. 2010). Larvae and juveniles tend to move downstream as they age especially during high flow events (Goodman et al. 2015; Moser et al. 2015). Metamorphosis from larva to juvenile occurs gradually over several months, typically starting in summer to fall, with timing with timing varying by elevation, temperature, and latitude (Clemens et al. 2019). Transformation typically completes between winter and spring. Juveniles then move downstream and emigrate to the marine environment (Moser et al. 2015; Clemens et al. 2019).

Marine-phase Pacific Lamprey are estimated to spend up to eight years in the ocean (Hess et al. 2022), feeding as parasites on fishes and occasionally whales (Clemens et al. 2019). After returning to freshwater, Pacific Lamprey cease feeding and migrate to tributaries to spawn (Figure 3). During the following spring, typically one year after entering fresh water, sexually mature Pacific Lamprey spawn and then die in a manner similar to salmon. Some adult lamprey may spawn the same year they enter fresh water, particularly in the southern portion of their range (Clemens et al. 2013). Migration and spawning dates and timing vary with latitude, elevation, and temperature, but are generally earlier in the year in the range's coastal and southern portion (Clemens et al. 2010).

Migrating adult Pacific Lamprey are generally nocturnal (Kirk et al. 2015) and bottom-dwelling (Moursund et al. 2000). Because they are not easily seen, it may be incorrectly assumed that they are not present and thus are potentially at greater risk for negative impacts due to instream management actions, including restoration.

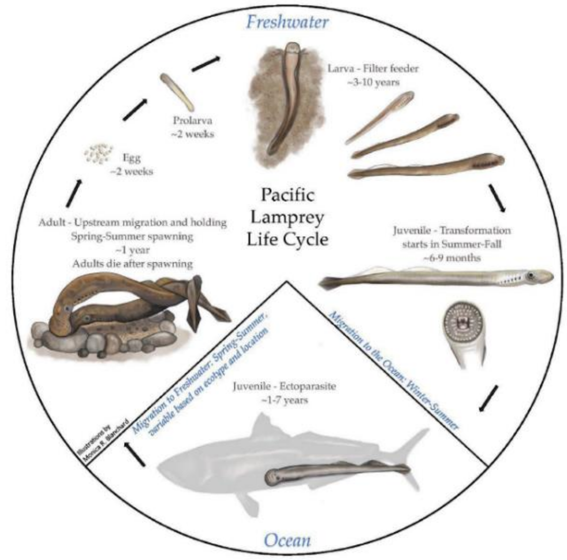

Figure 3 Pacific Lamprey life history. From LTW (2023).

Pacific Lamprey can also navigate through small spaces and, in some cases, ascend wetted, vertical or near-vertical structures, such as waterfalls. This climbing behavior, often referred to as "burst-and-attach locomotion", allows lamprey to move upstream in flow velocities that exceed their free-swimming and jumping abilities (Reinhardt et al. 2008), and has provided unique opportunities for passage solutions (described below). However, sharp corners, edges, and gaps found in many engineered fishways inhibit this specialized climbing behavior. The sharp corners, edges, and gaps force lampreys off the surface and can impede reattachment, especially in higher velocity areas, thereby inhibiting upstream movement.

Passage Needs & Observations

Lamprey, both resident and anadromous, require upstream and downstream passage in mainstem rivers and smaller tributaries, and unimpeded access to lateral habitats, such as floodplains, wetlands, side channels and backwater habitats, to access appropriate habitats for their life history needs. Unimpeded passage is particularly critical for Pacific Lamprey because of their ocean phase and relatively long migrations, often requiring passage through many dams, spanning hundreds of miles.

Lamprey can navigate a wide range of passage conditions and display exploratory behavior when faced with passage barriers (LTW 2022a). Natural stream bottoms and flow paths provide the best passage opportunities, so passage projects that use a stream simulation approach (USDA 2008) and match native streambed materials and morphologies that are found within the reach are generally preferred. This is particularly true for culvert and bridge projects in smaller stream systems, and low-head dam/weir breaching or removal.

In larger river systems with channel spanning structures, such as dams and weirs, engineered fish passage structures (i.e., fishways) are often employed. These fishways are usually designed using the swimming abilities of a targeted fish species. In the Columbia River Basin, fishways are usually designed for adult Pacific Salmon and are often barriers to adult Pacific Lamprey (LTW 2022a). Hence, there is a need to improve the understanding of Pacific Lamprey passage needs.

Pacific Lamprey use their entire body to swim, similar to an eel. This type of swimming is not adapted for passing some of the higher-velocity, highly turbulent features common to engineered salmon fishways (e.g., Moser and Mesa 2009). Since adult lamprey commonly migrate at night, observations of numerous adult lamprey during the day, or lamprey attempting to pass at the surface of a fishway, may be indications of complete or partial barriers to adult passage (Goodman and Reid 2017), which should be further investigated.

Low fishway passage efficiency for Pacific Lamprey has been clearly demonstrated. Passage efficiency at Bonneville Dam on the Columbia River is often less than 50% for lampreys migrating through the fishway (Moser et al. 2002; Keefer et al. 2013) compared with >90% for salmon (Caudill et al. 2007). For the eight dams on the Columbia and lower Snake rivers, Keefer et al. (2021) found that average adult salmon and steelhead passage efficiency was almost 97%. However, increased passage efficiency for Pacific Lamprey is possible and has been achieved at River Mill Dam on the Clackamas River in Oregon. Lamprey passage was accommodated within a newly constructed fishway that resulted in >90% passage efficiency for Pacific Lamprey (Ackerman et al. 2019; LTW 2022a). This passage structure has specific design elements that allow continuous attachment by lamprey through the fishway, including rounded corners at the entrance and other high velocity areas, and reduced turbulence via fishway turns. Existing salmon fishways can be modified to improve passage for Pacific Lamprey by providing smooth, wet, and continuous attachment surfaces in areas of high velocities, and rounded corners (LTW 2022a).

Pacific Lamprey passage structures have been installed within or adjacent to salmonid fishways at a variety of sites, which provide an alternative route for lamprey passage and capitalizes on climbing behaviors (Moser et al. 2011, Zobott et al. 2015; Figure 4). A lamprey passage structure may be warranted in situations when an existing fishway cannot be feasibly modified to provide rounded corners and/or lower velocities. However, these passage structures should only be installed after careful consideration of where passage bottlenecks occur and where lamprey are naturally attracted.

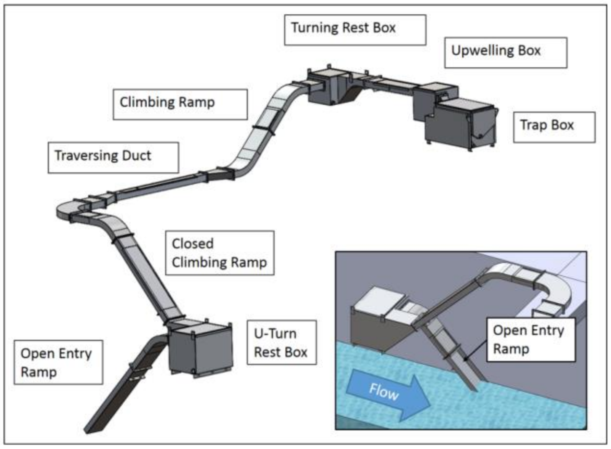

Figure 4 Lamprey Passage Structure. From: Zobott et al. (2015).

For example, a lamprey passage structure was installed at the fishway at Bonneville Dam to allow lamprey to bypass the serpentine sections of the fishway that were shown to be difficult to pass (often less than 50% per Moser et al. 2002; Keefer et al. 2013). Another lamprey-specific passage system was developed at Van Arsdale Dam (Eel River, California) using a 4-inch flexible tube, which is similar in function to an aluminum ramp, that significantly increased lamprey passage success and efficiency compared to the existing fishway passage (Goodman and Reid 2017). As an experimental technology, these tubes are not durable infrastructure and require regular oversight and maintenance.

Other detailed recommendations and examples of implemented upstream passage projects can be found at the [Lamprey Technical Workgroup] website for adult passage (LTW 2022a) and for culverts (LTW 2020).

As described earlier, fish screens are installed at points of diversion to prevent fish entrainment. Screens that are designed and operated to standard criteria (NMFS 2022a) to protect outmigrant juvenile salmonids are also generally protective of larger lamprey (>65 mm total length) but are not protective of larval and smaller juvenile lamprey (Rose and Mesa 2012). Because current screening criteria (NMFS 2022a) are generally ineffective at preventing larval lamprey entrainment (<65 mm), it should be assumed that if suitable lamprey habitat exists in an irrigation ditch or canal, regardless of the presence of a fish screen, that lamprey may be present. Suitable habitat of fine sediments that are regularly saturated or inundated are known to contain high densities and multiple age classes of larval and juvenile lamprey.

A variety of fish screening materials are used for irrigation diversions (e.g., woven or cloth wire, perforated plate, profile bar, and Intralox materials). With entrainment rates nearly twice that of perforated plate, larger mesh woven wire is the least effective in protecting larval lamprey and should be avoided (Rose and Mesa 2012).

Additional guidance on screening can be found in the Lamprey Technical Workgroup's document "Review of Factors Affecting Larval and Juvenile Lamprey Entrainment and Impingement at Fish Screen Facilities" (LTW 2022b), which includes screening types, sizes, and recommendations.

Swimming Performance & Endurance

Adult Pacific Lamprey are typically found near the streambed where water velocities are the lowest. When a smooth surface is available for attachment, lamprey can use burst and attach swimming to move through high velocity zones especially if there is lower turbulence. Excessive turbulence within structures can cause lampreys to be swept downstream if burst-and-attach swimming is attempted. Additionally, burst-and-attach swimming is strenuous and hence is only feasible over relatively short distances. The roles of velocity and turbulence in lamprey swimming behaviors needs to be understood when evaluating fish passage (Kirk et al. 2016).

The swimming speeds of adult Pacific Lamprey are considerably lower (<50%) than the swimming speeds of adult salmon (Table 2). According to Moser and Mesa (2009), the mean critical swimming speed for Pacific Lamprey is 0.9 m/s (2.8 fps; Mesa et al. 2003b). For comparison, the mean critical swimming speed of Chinook Salmon is ~5 m/s (Bell 1991; Table 1).

Swim Type:	Swim Speed:
Critical	~0.9 m/s
Free-swimming	<1.2 m/s
Preferred free-swimming	≤0.6 m/s
Burst-and-attach	<2.5-3.0 m/s

Table 2 Adult Pacific Lamprey swimming types and speeds (LTW 2022a).

Some swimming speeds have been published for both larval and juvenile Pacific Lamprey. Sutphin and Hueth (2010) evaluated the swimming performance of Pacific Lamprey larvae in swim tubes. Burst swimming speeds increased with length from 107 to 150 mm TL and ranged from 0.33 to 0.75 m/s. It should be noted that these are large larvae. For juvenile Pacific Lamprey both Moursund at al. (2000) and Mueller et al. (2006) found similar results. For juveniles averaging 142 mm, burst swimming speeds were 0.76 m/s.

To illustrate challenges adult Pacific Lamprey face within fishways, typical water velocities through a fishway entrance are 2.1 - 3.0 m/s and 1.8 - 2.4 m/s at submerged orifices. These velocities are well above critical swim speeds for lamprey, and these conditions can be encountered multiple times in a single fishway, thus representing significant and repeated challenges for adult Pacific Lamprey attempting to pass upstream. Furthermore, these velocities and lack of flow refuges can limit the ability of Pacific Lamprey to use burst-and-attach locomotion and can increase their exposure to predation. These challenges may exclude weaker individuals and could result in longer-term energy costs to other individuals, which may reduce the spawning population (i.e., total numbers and overall productivity). For example, individual Pacific Lamprey may enter a fishway and pass several obstacles but ultimately tire and fallback (Clabough et al. 2010), thus reducing the number of upstream spawners in areas above the fishway.

Detailed lamprey swimming performance and passage recommendations can be found at the Lamprey Technical Workgroup website: "Practical guidelines for incorporating adult Pacific Lamprey passage at fishways, Version 2.0."

Data Gaps

- Swimming performance for larvae 20 – 110 mm in length.
- Swimming performance of the smaller-bodied Pacific Lampreys (e.g., coastal populations) and smaller species of lampreys (e.g. Western Brook Lampreys).
- Evaluation of swimming tubes/chambers used to develop swim performance criteria, which have been shown to significantly underestimate swimming performance outside of the laboratory.
- Lamprey impingement and survival rates for fish screens with openings that are smaller than current National Marine Fisheries Service criteria.
- Better understanding of downstream migration timing and habitat needs of juveniles.
- Downstream dispersal/timing of larvae.

WHITE STURGEON

Image credit: Joseph R. Tomelleri

White Sturgeon (*Acipenser transmontanus*) are ecologically, culturally, and economically important to the Pacific Northwest Region, but their range extends well beyond the PNW. White Sturgeon are found in coastal waters from Ensenada, Mexico, to Alaska (CDFW 2023), but they primarily reside in large freshwater rivers, streams, and estuaries along the Pacific coast from California to British Columbia (ODFW 2011, CDFW 2023). Spawning populations occur in the Sacramento-San Joaquin, Columbia-Snake, and Fraser rivers (Schreier et al. 2013, p. 1273).

Adult White Sturgeon can reach lengths over 6 meters (Scott and Crossman 1973), typically maturing around 15 to 25 years of age, but with significant variation because sturgeon maturation is more a function of size and sex than age (Conte 1988). For such a large-bodied fish, early life stages are much smaller -- eggs are 3.5 to 5.6 mm in diameter, and larval fish emerge from the egg at ~11 mm. This wide range of body sizes, and corresponding swimming abilities, complicates fish passage structure design.

Behaviors & Life Histories

White Sturgeon evolved as a highly mobile species that moved in response to changing river conditions to meet biological requirements to complete its life history (Figure 5). They are freshwater amphidromous (ODFW 2011 page 13), meaning that they migrate between freshwater and the ocean (in both directions), but not for the purpose of breeding. They spawn in freshwater but regularly move between fresh and saltwater to feed.

However, this is not an obligate part of White Sturgeon life cycle as evidenced by landlocked populations segregated by artificial or natural barriers within a river system. These life history traits, combined with blocked access to spawning grounds and habitat degradation, make White Sturgeon populations vulnerable, and very slow to recover from low population sizes. For example, White Sturgeon populations in the Columbia River upstream of Bonneville Dam are functionally isolated from others by the mainstem dams. Thus, each population must depend on conditions within a specific reach to maintain recruitment.

However, individual reaches often do not contain optimal, or sometimes even marginal, conditions for all life stages (Parsley and Beckman 1994).

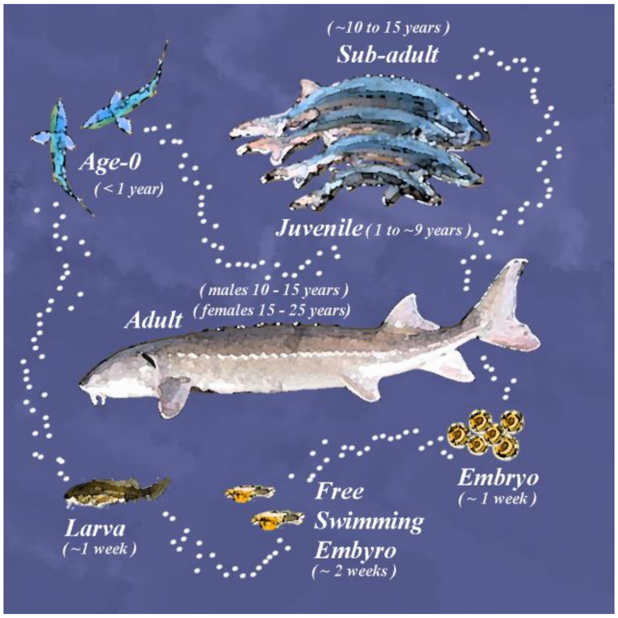

Figure 5 White Sturgeon life history including embryo, free swimming embryo, larva, age-0, juvenile, sub-adult, and adult life stages. From: ODFW 2011

Population Structure

Construction of mainstem dams in the PNW restricted sturgeon movement and reduced recruitment. Populations of sturgeon isolated between major dams, such as those found above Bonneville Dam in the Columbia River, must rely upon the habitat and food resources available within a single river reach. Unfortunately, these highly modified reservoir/river systems generally do not support all life stages. As a result, the once larger single population of Columbia River White Sturgeon is now several fragmented subpopulations, each restricted to a limited reservoir/river reach.

Sturgeon in the lower Columbia River, downstream of Bonneville Dam, have unimpeded access to the ocean and subsequently, that population remains relatively large (CBWSPF 2013). However, recent declines in legal-sized White Sturgeon caught in this reach have been observed (CBB 2023). Legal-sized White Sturgeon fall within a size range of 1.0 to 1.4 m and can be kept by anglers. Even more concerning and problematic are the changes in size structure and declines in productivity; the proportion of juvenile fish in the population (56% in 2021) remains below the conservation status threshold of 60% juveniles (ODFW/WDFW 2024).

Populations in impounded reservoir/river sections upstream from Bonneville Dam have generally declined faster than the population below Bonneville Dam.

Within-drainage population structure is believed to be due to isolation by distance and access along the length of the Columbia-Snake River system and possibly net downstream gene flow (Schreier et al. 2013, p. 1281). It follows that White Sturgeon genetic diversity levels vary regionally, with the highest levels observed in regions with access to estuarine and marine habitat. The lowest levels of genetic diversity are observed in the isolated Kootenai population in Idaho, which is federally ESA-listed as endangered (U.S. Office of the Federal Register 2008).

The within-drainage analysis of population structure for the Columbia-Snake River drainage suggests three populations (Schreier et al. 2013, pp. 1273, 1280–1282):

1) Kootenai River;
2) Lower Columbia River cluster; and
3) Middle Snake cluster at the upstream extent of the Snake River.

Passage Needs & Observations

Traditional engineered fishways have been largely unsuccessful for passing sturgeon (Thiem et al. 2011, Warren and Beckman 1993). Major dam construction that began in the 1930s in the Columbia River has increasingly fragmented the White Sturgeon population. This has also limited their migration to largely downstream movements via entrainment through turbines (Coutant and Whitney 2000; Parsley et al. 2008), over spillways, and through fishways and navigation locks (Parsley et al. 2008). Upstream sturgeon migration is uncommon throughout the Columbia River system that is controlled by hydropower operations (North et al. 1993; Parsley et al. 2008), which results in reduced genetic diversity of impounded populations, particularly in isolated areas with low abundance.

Initial sturgeon passage efforts occurred between 1938 and 1956 with fish elevators at Bonneville Dam. These elevators were somewhat effective, and ~4,500 subadult sturgeon were passed upstream (Warren and Beckman 1993). However, elevators were not as efficient for adult salmon passage, and hence the use of fish elevators was eventually abandoned.

Unfortunately, fish passage systems that optimize salmon passage at the dams are not fully functional for sturgeon passage.

CBWSPF (2013, pg. 68) states:

> "A significant impediment to the consideration of potential passage measures for sturgeon has been their potentially confounding impacts on salmon. Adult passage systems are constructed, calibrated and maintained at each dam to optimize salmonid passage and changes in these systems to attract and pass sturgeon are likely to reduce salmon passage success."

Most fishways in the PNW are designed to attract and accommodate salmon and salmonid-sized and shaped fishes, not the larger sizes of adult sturgeon. Warren and Beckman (1993) state that the typical length of sturgeon that could use existing fish ladders is only in the range of 0.5 to 1.2 m, and that larger sturgeon would have difficulty negotiating the orifices of fishways. Larger fishways to accommodate the size and body structure of these large-bodied fish, along with suitable attractant flows, would improve sturgeon passage (Cooke et al. 2020).

As discussed in previous sections, most fish screening facilities are designed to accommodate out-migrating juvenile salmon. While such screens are likely appropriate for larger juvenile sturgeon, smaller larval and juvenile sturgeon (<93 mm) may suffer entrainment or impingement (Boysen and Hoover 2009).

Kootenai River White Sturgeon

The distinct population segment of White Sturgeon that inhabits the Kootenai River basin has experienced its own unique set of migration and passage issues. Prior to the construction and operation of Libby Dam in the early 1970s, the natural hydrograph of the Kootenai River consisted of a spring freshet (i.e., elevated river flows from rain or meltwater) with high peak flows, followed by a rapid drop in flows into August. Pre-dam fisheries investigations and inventories stated that prior to the construction of Libby Dam, Kootenai sturgeon spawned in the roughly 1.6 km (1 mile) stretch of the Kootenai River downstream of Kootenai Falls (USACE 1971; MFWP 1974). However, after Libby Dam became operational in 1974, peak spring flows were reduced and river conditions were altered. Flow changes that occurred during the Kootenai sturgeon spawning period likely caused sturgeon to reduce the upstream extent of their pre-spawn migrations. This in turn resulted in spawning over less suitable habitat -- sand and silt substrates downstream of Bonners Ferry -- rather than over the rocky substrates upstream of Bonners Ferry to Kootenai Falls.

Changes to Kootenai White Sturgeon migration and spawning in response to altered river flow is an environmental flow barrier -- an example of an indirect human-caused barrier.

Swimming Performance & Endurance

Sturgeon, being large-bodied fish, do not have the same jumping capabilities as adult salmon and have decreased maneuverability (Cooke et al. 2020). Due to their large size, sturgeon require minimum water depths of at least 0.6 m (Matica 2020, from 2012 in-person from A. Seesholtz), while >1.0 m is preferred (CDWR 2007; Webber et al. 2007). For short distances, White Sturgeon can navigate through flow velocities up to 1.8 m/s, but for distances greater than 18 m, maximum flow velocity is approximately 1.2 m/s (USBR and CDWR 2018). Because White Sturgeon are demersal (live and feed near the bed of streams and lakes) and are not known to jump over barriers, passage improvement projects require different design considerations.

Warren and Beckman (1993) reported that some White Sturgeon were able to ascend Columbia River fishways designed for salmon with velocities reported at 2.4 m/s. However, this is not evidence that sturgeon effectively migrated through the system, simply that they entered the fishway. Additionally, sturgeon have difficulty ascending structures with strong velocity gradients and turbulent flows (USFWS 1995). Cooke et al. (2020) concluded:

> "… that fishways intended to be successful for white sturgeon should incorporate rapid-velocity (e.g., 0.84–2.52-m/s) sections, between somewhat slower (e.g., 0.51–0.68-m/s) sections for rest and recovery. This observation (and conclusion) is important in that it aligns with field observations (e.g., Thiem et al. 2011, 2016) and provides evidence that successful fishways require combinations of high flow areas and low flow areas [similar criteria incorporated into the prototype side-baffle fishway designed by Kynard et al. (2011, 2012)]."

Data Gaps

- Improved swimming performance metrics by lifestage.
- Improved swimming performance metrics by lifestage.
- Movement and response to water-operations management actions.
- Screen opening requirements and needs for larval and small juvenile sturgeon.
- Use of tributary habitat (lower portions of tributary rivers to mainstem rivers)
- Spawning and rearing habitat needs.

FRESHWATER SCULPIN

Image credit: Prickly Sculpin by SportfishingReport.com Inc

Freshwater sculpins (Family *Cottidae*) are generally small-bodied benthic fishes commonly found in cool- and cold-water habitats across North America and Eurasia (Berra 2002). They can serve as key indicators of stream health (Matzen and Berge 2008) and play important roles as predators, prey, and competitors within aquatic food webs. Additionally, they inhabit a wide range of habitat types, from fast-flowing lotic systems to lacustrine waters. As benthic dwelling adults, they are plump, lack swim bladders, and have rigid pectoral fins, making them better adapted for anchoring to substrate than for strong swimming (LeMoine and Bodensteiner 2014). Consequently, barriers and habitat fragmentation can significantly impact their movement, with effects varying by species, life history strategy, and location.

Behaviors & Life Histories

Freshwater sculpins can be categorized into two groups based on their larval phase: planktonic or benthic. In western North America, sculpins with benthic larvae include at least 19 species (Goto et al. 2015), though recent genetic analyses by Young et al. (2022) suggest this number may exceed 40. Compared to sculpins with planktonic larvae, those with benthic larvae typically produce fewer, larger eggs, and their larvae disperse more slowly. As adults, these sculpins are also generally less migratory than those with planktonic larvae, and their entire life cycle can be completed within a relatively small area. Although most individuals typically move short distances (i.e., < 100 m) throughout the year, occasional movements of over 500 m have been documented in these species (Breen et al. 2009; Hudy and Shiflet 2009; Deboer et al. 2015). While they are typically less impacted by barriers than species with planktonic larvae, habitat fragmentation remains an important concern (Deboer et. al. 2015).

Sculpin species in western North America with planktonic larvae include coastrange sculpin (Cottus aleuticus) and prickly sculpin (C. asper). Prickly sculpin is the largest freshwater sculpin in North America and can grow up to 23 cm, while coastrange sculpin can reach lengths up to 14.5 cm (Mason and Machidori 1976; Tabor et al. 2007). These saltwater-tolerant fish are often abundant in coastal lowland streams and rivers across the Pacific Northwest and, in many coastal areas (e.g., Vancouver Island and northeast Olympic Peninsula rivers), they are the only sculpin species present. Unlike other Pacific Northwest freshwater sculpins, both species can have a marine planktonic larval phase that likely contributes to their widespread distribution along the west coast from California to Alaska (Tabor et al. 2022; Young et al. 2022).

In lotic systems, coastrange sculpin and prickly sculpin larvae drift downstream to nursery areas such as estuaries, lakes, large low-gradient rivers, or other slow-moving waters. After a few weeks, they transition to a benthic form and often move upstream to occupy the lower reaches of streams and rivers. Because of this upstream migration pattern, both species are particularly vulnerable to barriers (LeMoine and Bodensteiner 2014; Tabor et al. 2017). However, they demonstrate strong migration abilities and can quickly recolonize upstream habitats following barrier removal (Tabor et al. 2020). For example, prickly sculpin can migrate up to 16 km upstream, with individuals observed moving as far as 6 km to recolonize dried habitats, while coastrange sculpin have been observed migrating up to 0.7 km in two weeks. Because they often move long distances over their life span, they are termed "migratory sculpins" (Figure 6; LeMoine and Bodensteiner 2014; Tabor et al. 2017).

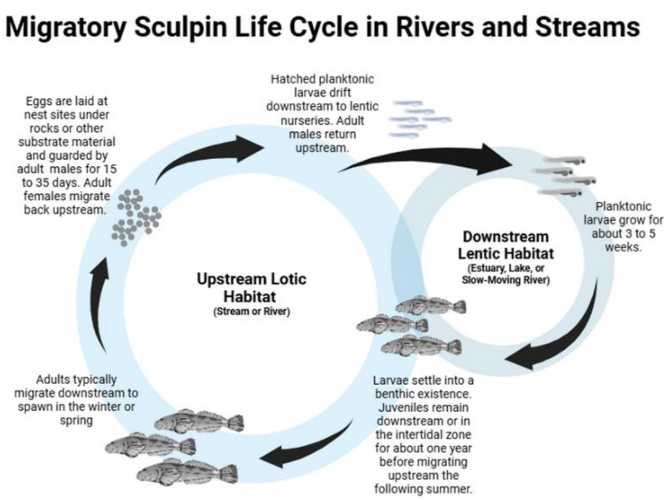

Figure 6 Common Life Cycle of Migratory Sculpins (*Cottus aleuticus* and *C. asper*) living in rivers and streams. Created by Mae Esquibel with BioRender.com. Adult and juvenile *C. aleuticus* graphic from Committee on the Status of Endangered Wildlife in Canada (COSEWIC) (2010)

Coastrange sculpin and prickly sculpin display a variety of life history strategies, including amphidromy (migration between freshwater and marine environments) and potadromy (migration entirely within freshwater). With these two strategies, adults in lotic habitats typically migrate downstream in winter or spring to spawn. Upon hatching, their planktonic larvae drift further downstream to lentic nursery areas and grow for about 30 days before migrating upstream to lotic habitats and assuming a benthic form. After rearing for about a year, adults move upstream to continue the cycle. In lowland coastal streams, both species are commonly amphidromous, with larvae that drift into estuarine and marine environments (Figure 1; Mason and Machidori 1976; Tabor et al. 2022). However, further research is needed to better understand how these life history strategies may vary among different populations and regions, as well as migration patterns and timing across all life stages.

Although ecologically similar, coastrange sculpin and prickly sculpin tend to partition habitat where they co-occur: coastrange sculpin are more commonly associated with faster-moving riffle habitats, while prickly sculpin are more frequently found in slower-moving pool habitats (Mason and Machidori 1976; Tabor et al. 2022). For both species, larger individuals are typically found further upstream, likely because they have had more time to migrate and possess stronger swimming abilities (Tabor et al. 2022).

Passage Needs & Observations

Barriers constrain the distribution of freshwater sculpin, especially for migratory coastrange sculpin and prickly sculpin. Freshwater sculpins are particularly sensitive to human-caused direct barriers. Due to their small size and poor swimming ability, even small obstructions – like drop structures to create step pools that are intended for habitat improvements – can block movement and restrict access to upstream habitat (Tabor et al. 2017). Furthermore, because sculpin often rely on substrate contact for movement, barriers that create high water velocities, have significant vertical drops, or feature smooth surfaces are particularly problematic. In a study by Lemoine and Bodensteiner (2014), fish ladders with heights greater than 15 cm completely blocked sculpin movement. The authors also noted that while water velocity influences sculpin movement, it may not be the best predictor of passage success (Lemoine and Bodensteiner 2014). Another study found that while coastrange sculpin and prickly sculpin were able to move through some weir baffled culverts, 1) sculpin densities did not differ significantly between streams with baffled and non-baffled culverts and 2) densities were significantly lower in streams with both culvert types compared to reference streams (Favaro et al. 2014). However, because only weir baffled culverts were examined, the effectiveness of other passage aids for coastrange sculpin and prickly sculpin should be further investigated.

Rock ramp fishways offer one potential solution for improving sculpin passage. For example, observations of sculpin using interstitial spaces between rocks and gravel (Phillips and Claire 1966; Thomas 1973) to navigate obstacles led Natsumeda (2007) to recommend installing cobble ramps downstream of barriers to aid their upstream movement. Similarly, Paik et al. (2024) found that mottled sculpin had high passage success using experimental rock ramp fishways with slopes between 2% and 6%. The sculpin in their study used localized areas of reduced water flow created by the heterogeneous arrangement substrate and roughness elements for resting, sheltering, and maintaining their position along the fishway, highlighting the importance of complex substrate in supporting sculpin movement.

Swimming Performance & Endurance

Specific information on swimming performance and endurance of freshwater sculpins is limited. However, sculpins typically have a lower percentage of red muscle mass compared to more endurance-oriented fish (e.g., salmonids), making them better suited for burst swimming rather than endurance swimming (Veillard et al. 2017). Moreover, their use of substrate interstitial spaces for movement (Phillips and Claire 1966; Thomas 1973) suggests that swimming speed criteria may be less important for sculpin than for other fish taxa, provided that appropriately sized and positioned substrate is available.

Data Gaps

- Swimming performance for all life stages.
- Jumping abilities for relevant life stages/species.
- Better understanding of migration patterns and timing for juveniles and adults.
- Downstream dispersal and timing of larvae.
- Design and efficacy of nature-based fishways like rock ramps.

SMALL-BODIED NATIVE FRESHWATER FISHES

Image credit: Umatilla Dace by Joseph R. Tomelleri

We use the term "small-bodied" in reference to native freshwater fishes in their larval, juvenile, or adult life stages that, when compared to their anadromous salmonid counterparts, are significantly smaller in body length (<150 mm). This generally results in reduced swimming speeds, decreased jumping performance, and potentially increased entrainment and impingement rates on fish screens.

This diverse group of fishes includes sculpins, minnows, suckers, stickleback, sand rollers, the smaller non-anadromous lampreys, eulachon, and others. In the State of Oregon alone, there are 79 native freshwater fish species that are not anadromous. Notably, many of these species are important prey resources in the diets of other fishes (Hemingway et al. 2019; Gray et al. 1984; Nigro et al. 1983) and birds (Fitzner and Hanson 1979; Henny et al. 2003) and are a key component of food web nutrient cycling (Schmetterling and McFee 2006). For example, Hemingway et al. (2019) found that Sand Rollers may serve as a buffer against Smallmouth Bass predation for fall Chinook Salmon in Lower Granite Reservoir.

While non-anadromous fishes do not typically have long migrations to and from the ocean, they still need to freely move upstream, downstream, and laterally into floodplains, wetlands, and side channel habitats to complete their life cycles

(ODFW Fish Passage Statutes; WDFW draft fish passage rules; Matica 2020). These lateral and edge habitats are particularly important for smaller-bodied fishes because they provide protected areas to spawn, feed, and rear that are inaccessible to larger predatory fishes. Both lateral and longitudinal aquatic connectivity are crucial for the conservation and perpetuation of fish populations, particularly in the face of habitat fragmentation, degradation, and climate change (Olden et al. 2014).

The broader ecological loss of inadvertently excluding small-bodied fishes when restoring passage and connectivity, as well as screening protection, has not been assessed. For example, Sculpin (*Cottidae species*), Peamouth (*Mylocheilus caurinus*), Dace (*Cyprinidae*), and other native small-bodied fishes, are known to be hosts for many native mussel species (CTUIR 2022). If these host fishes are excluded from suitable habitat due to fragmentation, or their numbers decrease, there is a direct limiting factor to native mussel populations.

Behaviors & Life Histories

The complete range of behaviors and life histories exhibited by this diverse group of fishes is beyond the scope of this document. However, it is worth noting that these fishes still need to migrate to find appropriate habitat and flow types during various life history stages, which is becoming increasingly crucial in the face of climate change (Matica 2020). Additionally, small-bodied native fishes are included in fish passage statutes for both Oregon and Washington. These rules address fish access to spawning, rearing, foraging, and overwintering habitats. Oregon's fish passage policy and rules require that native migratory fish passage is addressed at certain trigger events, such as construction, major maintenance, or abandonment of existing artificial infrastructure.

Passage Needs & Observations

There is very little information on passage requirements of these smaller-bodied fishes (e.g., velocities, jump heights, water depths); however, upstream and downstream passage, along with access to complex lateral habitats, is crucial for many species to complete their life cycle. Natural stream channels and flow paths, along with inundated overbank areas connecting wetlands and floodplains, provide the best passage opportunities. Passage projects that seek to reconnect habitats, at even the lowest flows, and at a high density of access points to lateral habitats are preferred. Effectiveness monitoring that directly observes fish movement in and around passage structures would advance our understanding of passage capabilities and would allow for more comprehensive guidelines in the future (Silva et al. 2018).

If a stream/road crossing is being improved, then a stream simulation approach (USDA 2008) that matches native streambed materials is a good option. The addition of edge complexity and streambanks through the crossing structure will improve passage for many smaller-bodied fishes. The use of structures with diverse flow and velocity pathways is also a reasonable option for improving passage for native, small-bodied fishes, especially when specific swimming abilities are unknown. There is increasing evidence that there is no one-size fits all solution to fish passage (Hershey 2021); hence, diverse flow and velocity conditions may address passage issues for a wider variety of fish species.

Although a few species may have some limited jumping abilities, many, such as sculpins and suckers, have none. A fully inclusive fish passage project should assume that at least some species have no jumping ability and poor swimming ability. Using a stream simulation approach as defined by the US Forest Service "… an approach to designing crossing structures (usually culverts), that creates a structure that is as similar as possible to the natural channel", will provide passage for a spectrum of species in a wide variety of stream types (USDA 2008).

Swimming Performance & Endurance

There are very few publications detailing swimming performance of native, resident small-bodied fish. Within the literature, three publications report swimming performance metrics for seven additional PNW species including: Matica (2022; Riffle Sculpin), Aedo

(2009; Mottled Sculpin, Longnose Dace, Speckled Dace, Redside Shiner), and Scheerer and Clements (2013; Warner Sucker). For these fishes, bursts speed range 0.46 – 1.3 m/s. However, from just these few publications, it is not appropriate to infer passage constraints to the group of small-bodies fishes at large, across their life cycles.

Data Gaps

- Swimming and jumping performance metrics, life stage species wide;
- Migration and movement distances;
- Timing of movements;
- Use of existing fishways and success rates;
- Screening requirements, opening sizes.

ADDITIONAL CONSIDERATIONS

Climate Change

Improved aquatic connectivity will more effectively allow fish to move between different habitat types, expand into new areas, express full life histories, or contract into colder water refugia in response to a changing climate. In addition, providing connectivity between habitats maximizes the ability of species to access areas during disturbance events such as drought, fires, and altered flood regimes expected to be more common into the future and allow recolonization after these events (Franklin et al. 2024; Falke et al. 2015; Gresswell 1999).

Fish passage projects often involve durable infrastructure, such as dams, levees, bridges, culverts, and fishways. Proper design and/or modification of such structures involves understanding and quantifying both current and future hydrological conditions. With climate change, relying on past flow records is no longer adequate for determining the appropriate size or type of structures.

Simplified scaling factors, such as increasing structure widths to 1.5 times the active channel width, are often used as design surrogates when data are lacking; however, these generalized surrogate methods could result in an inappropriately sized structure. To address this concern, all passage projects that include durable infrastructure should also have a robust climate change analysis, including predictions of future flow conditions. In addition to flow conditions, the analysis should also include potential changes in land cover and land use that could lead to changes in sediment loads and the hydrograph, both of which impact structure sizing. Under most climate change scenarios for the PNW, the magnitude and frequency of extreme precipitation events is projected to increase, which could result in higher flow intensity and variability across watersheds (USGCRP 2018).

To address some of these issues, NOAA Fisheries has been working since 2016 to include methods to incorporate future climate change into engineering designs of fish passage facilities and stream crossings. See their document "NOAA Fisheries West Coast Region Guidance to Improve the Resilience of Fish Passage Facilities to Climate Change" (NOAA 2022b). Washington Department of Fish and Wildlife has provided similar guidance in "Incorporating Climate Change into the Design of Water Crossing Structures" (WDFW 2017).

Aquatic Invasive Species

This document emphasizes the need to increase native fish passage; however, there are situations where passage may be undesirable due to a strong potential for the introduction of invasive species. This is of particular concern in areas where a barrier has isolated native species from non-native invasive species.

Because of the site- and species-specific nature of addressing the risk of non-native species introductions, it is recommended that project proponents contact both their state fish and wildlife agency and the US Fish and Wildlife Service for further guidance.

Lateral Connectivity

The Service defines passage as the ability of fish or other aquatic species to move through an aquatic system among all habitats necessary to complete their life cycle. Because large, lateral connectivity projects, often called "floodplain reconnection" and "Stage 0," are a relatively recent aquatic restoration approach, it is worth highlighting some important aspects of these project types (Powers et al. 2019).

Improvements in lateral connectivity restore complexity within the river system while promoting shorter-term stability and creating a more resilient river-wetland corridor (Powers et al. 2018, Wohl et al. 2021). A well-connected floodplain within the river-wetland corridor provides substantial benefits, including feeding, rearing, and flow and temperature refuge, to the species which are the focus of this document. The benefits of floodplain access to fish are well-documented for anadromous species (Katz et al. 2017, Jeffres et al. 2020) and are assumed, by extension, to benefit other native fishes as well. Recent recommendations from the Lamprey Technical Workgroup of the Pacific Lamprey Conservation Initiative suggest "enhancing riparian condition through [riparian] plantings, livestock enclosures, and increased lateral connectivity can benefit lamprey populations" (LTW 2023). It has been hypothesized that White Sturgeon recruitment failure, or severe interannual variability in recruitment, is due to lack of access to floodplain habitat and diverse channel velocities and complexities Coutant 2004).

Fish Passage Performance

For all engineered fishway types, especially those that have durable infrastructure, the authors recommend that passage performance should attempt to meet or exceed 95% for adult Bull Trout, Pacific Lamprey and White Sturgeon. Passage performance for adult small-bodied resident fish should be evaluated based on the biological need of the species involved and all of the habitats needed to robustly complete their life cycles both up- and downstream of the infrastructure. Performance is defined herein as the number of fish that successfully pass a fishway, relative to the number that approached the fishway, expressed as a percentage. Other measures of performance, including hydraulics, attraction flows and entrance efficiency should also be evaluated.

Dewatering

In the PNW, water diversions for irrigation and other consumptive uses are common. Fish screens are engineered structures that preclude adult and juvenile fishes from entering diversion structures, pump intakes, diversion channels, pipes, or penstocks. Screens generally protect the juveniles of larger-bodied fishes from entrainment into irrigation delivery canals and those fish are directed back to the river, often via a bypass channel.

To provide all species of fish in bypass channels safe return to the river when the diversion flows are reduced or stopped, ramping rates published by Washington state (WDFW 2022) are recommended (Table 3). Ramping rates (rate of changes in stage) are a concern because a rapid decrease in flow can strand fish in pools within bypass structures or other areas potentially exposing them to predation, poor water quality, and/or desiccation. Ramping rates apply to hydropower operations as well as diversions. Rapid decreases in flow can result in fish stranding in shallow water or disconnected habitats, and can dewater spawning, rearing, and other habitats.

Season	Day Rates*	Night Rates
Feb 16 to June 15	No Ramping	5 cm/hr
June 16 to Oct 31	2.5 cm/hr	2.5 cm/hr
Nov 1 to Feb 15	5 cm /hr	5 cm/hr

** Day is defined as one hour before sunrise to one hour after sunset*

Table 3 Recommended ramping rates in changes in stage. From: WDFW and WDOE (2022).

Larval Fish Screening

For the PNW, National Marine Fisheries Service develops, updates, and publishes fish screening guidelines (NMFS 2022a) to protect and limit the entrainment and impingent of fry and juvenile anadromous salmon and steelhead on fish screens. Currently, there are no formalized recommendations available to protect native larval fishes in the PNW for which many species are smaller than salmonids. Hence, recommendations provided herein are based on the best available information.

While swimming performance data are broadly lacking, many larval fishes are quite small, and poor swimming performance can be inferred. For example, Largescale Sucker occur in most freshwater bodies west of the Rocky Mountains and from British Columbia (Canada) to Oregon (US) (Scott and Crossman, 1973), and their larvae can be as small as 8 mm in length (Dauble 1986). Larval Mountain Whitefish, a resident salmonid, are notably smaller than other resident and anadromous members of this family. For larvae and early juvenile Mountain Whitefish, Brown (1952) reported a mean tail length of 11.7 mm, and Rajogopal (1975, 1979) a range of 13 to 14 mm upon hatching. Given the inferred swimming performance and size of larval fishes, juvenile salmonid screening criteria (NMFS 2022a) are unlikely to be adequate for larval fishes.

With ten species of native lampreys in the PNW (ODFW lamprey brochure), they are an important group to both protect and to use as a surrogate for other fishes due to their small size. After hatching, larval lampreys are ~10 mm in length (Lampman et al. 2021) and would require a screen opening of ≤0.35 mm (LTW 2022b). The size of the screen opening is not designed to limit passage of larval lamprey through the opening, but rather to limit impingement against the screen by maximizing the resultant "sweeping velocity." While screen manufacturers fabricate screen down to 0.5 mm, (ISI Intake Screens, Hendrick Screen Company, and others), this small gap size may be impractical for many situations, largely due to maintenance and cleaning issues. Testing of small gap screen feasibility is currently planned at a few Service facilities. Until more data are available, we recommend a screen open area (the sum of the area of all the holes, slots, mesh, or perforations on the screen that allow water to flow freely) of at least 27%, and maximum screen size openings as follows:

- Slotted or rectangular 0.75 – 1.00 mm
- Circular or square 1.00 – 1.60 mm

These values are based on:

a) opening sizes to protect larval lamprey (LTW 2022b),
b) current screening used in other parts of the country to protect larval fish and eggs, and
c) commercial availability from screen manufacturers.

Tide Gates

Tide gates are engineered structures that control water inflow/outflow, typically through an embankment or levee system, in coastal and estuarine areas. They are commonly used to reduce the frequent inundation and saturation of infrastructure and arable land due to tidal cycles and storm surges. Similar structures that protect land from larger floods are more appropriately called "floodgates."

Fish passage in and around tide gates are of particular concern due to physical barriers (the gates and berms), velocity barriers (as the gates open and close), and potential temperature and chemical barriers due to strong gradients that tide gates can create. To address some of these concerns, Guidance & Protocols for Estuary Practitioners (2024) was funded by the Oregon Watershed Enhancement Board in collaboration with the Coquille Watershed Association, The Nature Conservancy, and the Tillamook Estuaries Partnership.

The State of Oregon provides design criteria for tide gates in their Oregon Administrative Rules (635-412-0035 parts 4 & 5). These rules identify minimum requirements for tide gate designs and should be consulted when working in Oregon. Similarly, the Washington Department of Fish and Wildlife provides guidance on tide gates in Chapter 10 of their Water Crossings Design Guidelines document.

Information regarding the use of tide gates by fish other than salmonids is generally lacking in the literature. This includes native lamprey species, for which PLCI (2021) reviewed the available literature and found little to no data for lampreys or their use of habitats in estuarine environments.

Engineered Fishway Design

When all other fish passage options have been fully evaluated and an engineered fishway is still necessary, consider the following during structure design:

1. Maintain flow and passage routes for upstream and downstream passage throughout the year.
2. Provide alternate passage routes, such as orifices at various depths, to accommodate different species, behaviors (pelagic vs. benthic swimming), and swimming abilities.
3. Build or modify passage slots and baffles to accommodate the largest fish.
4. Minimize turbulence throughout the fishway.
5. When swimming performance data are available (currently a data gap for many species), maintain velocities at or below threshold for the weakest swimming species to be passed.
6. Create slow-velocity zones to allow smaller and weaker fishes to rest and recover.
7. Keep attraction water velocities between 0.3 m/s and 0.9 m/s. A minimum of 5% of total streamflow should be used as attraction flow (NMFS 2022a, pg. 48).
8. Minimize gaps and recesses (cavities) to aid lamprey passage.
9. Round corners, smooth side surfaces, and provide open pathways to improve lamprey passage efficiency (CRBLTW 2004; Ackerman et al. 2019).
10. Provide alternate passage routes, such as lamprey passage structures (Goodman and Reid 2017; Moser et al. 2019).
11. Check for smooth bottom surfaces to not obstruct lamprey and sturgeon passage.
12. Provide a minimum of 0.75 m wide and >1.0 m high bottom passage to accommodate large sturgeon.
13. Keep water depth >1.0 m for sturgeon passage.

While this document attempts to summarize the literature and provide useful links, significant uncertainties regarding fish passage remain. Projects attempting new and novel approaches to passage should be treated as experiments and closely monitored. On-going, long-term, post-project monitoring is essential to reduce uncertainties and to improve fish passage. The sharing of new information and data derived through these experiments and other studies is strongly encouraged to improve the science, engineering, technology, and practice of fish passage. If you are aware of new fish passage techniques, approaches, or practices, please email: Vancouver@fws.gov.

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RESOURCES

- Considerations for Multi-Species Fish Passage in California: A Literature Review by Zoltan Matica (2020);
- Assessment, Evaluation, and Development of Fish Passage Guidelines by Travis Denham (2021);
- Use of the Mainstem Columbia and Lower Snake Rivers by Migratory Bull Trout. Data Synthesis and Analyses by Barrows et al. (2016);
- Recovery Plan for the Coterminous United States Population of Bull Trout by the US Fish and Wildlife Service (2015);
- Practical guidelines for incorporating adult Pacific Lamprey passage at fishways, Version 2.0 by the Lamprey Technical Workgroup (2022a); and
- Columbia Basin White Sturgeon Planning Framework by CRTFC, WDFW and ODFW (2013)
- WDFW design criteria
- ODFW administrative rules
- USDA 2008 Stream simulation: an

ecological approach to providing passage for aquatic organisms at road-stream crossings.

- "NOAA Fisheries West Coast Region Guidance to Improve the Resilience of Fish Passage Facilities to Climate Change"
- Washington Department of Fish and Wildlife 2017 "Incorporating Climate Change into the Design of Water Crossing Structures"
- "Fish Swimming Performance Database and Analyses" by Katopodis and Gervais (2016).
- "SPOT: Swim Performance Online Tools" by Di Rocco and Gervais (2024)

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