Technical White Paper:
Practical Guidelines for Incorporating
Adult Pacific Lamprey Passage at Fishways, Version 2.0
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PACIFIC LAMPREY CONSERVATION INITIATIVE

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Disclaimer:

This document is intended to provide technical guidance for practitioners interested in improving upstream passage conditions for adult Pacific Lamprey. This document does not supersede state or provincial fish passage regulations.

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1 ABSTRACT

Anadromous fishes must migrate between the ocean and spawning grounds in fresh water to complete their life cycles. Many years and much effort has been expended to provide safe passage at human-made barriers for anadromous salmon and steelhead (*Oncorhynchus* spp.) in Pacific Northwest rivers; however, another culturally- and ecologically significant anadromous fish is often overlooked: the Pacific Lamprey (*Entosphenus tridentatus*). The goal of this paper is to provide recommendations for improving passage for upstream-migrating adult Pacific Lamprey in fishways designed for salmon and steelhead. The objectives of this paper include:

- Summarize pertinent information on adult Pacific Lamprey passage capabilities from existing literature; and
- Provide a practical technical reference on how to accommodate passage of adult Pacific Lamprey (new construction and retrofits of existing structures) for persons designing, operating, managing and maintaining fish barriers and fishways.

This paper discusses modifications that can be made to adult salmon and steelhead fishways (hereafter referred to as fishways) to accommodate and improve upstream passage for adult Pacific Lamprey without compromising conditions for salmonids (recognizing that in some cases existing fishways cannot be modified to provide fully unimpaired passage for lamprey). This paper also discusses use of lamprey-specific structures (lamprey passage structures [LPS], tubes, and wetted walls) added to existing facilities to improve passage of adult Pacific Lamprey. Several Case Studies are provided to demonstrate successful passage improvements for lamprey in different circumstances throughout the Pacific Northwest.

This paper relies on existing research and best professional judgment where data are insufficient. Much of the existing research has focused on upstream migrating adult Pacific Lamprey at large dams on the Columbia River. Adult Pacific Lamprey returning to the Columbia River are often larger in general than adults returning to other river systems along the West Coast. Smaller adults may have different swimming abilities, migration timing, maturity rates or other factors that should be considered when applying recommendations from this document. Although much of the research has been at large dams, most structural recommendations can be transferred to fishways at smaller dams. However, other than a brief overview (Appendix B), this document does not provide guidance for passage at small dams/weirs without fishways. Such guidance will be addressed in a separate document. For culvert passage, please see Barriers to Adult Pacific Lamprey at Road Crossings: Guidelines for Evaluating and Providing Passage (Lamprey Technical Workgroup 2020).

This 2022 document is an update to the original 2017 document. Changes include:

- Updated picket weir/ diffuser grating open space/gap recommendations,
- Added new section on trapping lamprey within fishways,
- Conducted editorial review to clarify and tighten language and update citations,
- Addition of 3 new Case Studies (#10-12), and
- Addition of Appendix B- Guidance for Low Head Dams/Weirs.

2 INTRODUCTION

The Lamprey Technical Workgroup (LTW) is a technical advisory committee of the Conservation Agreement for Pacific Lamprey *Entosphenus tridentatus* in the States of Alaska, Washington, Oregon, Idaho, and California. The LTW provides technical support and acts as an advisory group within the Conservation Agreement. The LTW consists of several subgroups that provide technical information for dissemination to various audiences. This paper was developed by the Passage and Engineering Subgroup of the LTW and focuses on upstream passage of Pacific Lamprey (it does not address other native lamprey species).

Pacific Lamprey is an anadromous species of cultural significance to Native American tribes (Close et al. 2002) and of ecological importance to freshwater ecosystems of the Pacific Rim, from California to Alaska and Japan (Renaud 2011; Docker et al. 2015; Clemens and Wang 2021). The abundance of Pacific Lamprey has declined substantially over the past 50+ years in some areas (Moser and Close 2003, Moser and Mesa 2009, Luzier et al. 2011). In recent years, more efforts have been expended to better understand the biology, ecology, distribution, and relative abundance of Pacific Lamprey, and to address factors that impact their local and regional abundance. Since 2000, research in the Columbia River Basin has highlighted the need to understand passage requirements of adult Pacific Lamprey and improve upstream passage so that the species can access spawning grounds upstream. Outmigrating larval and juvenile Pacific Lamprey also experience significant mortalities at various dams and water diversions. Downstream passage and screening requirements for larval and juvenile Pacific Lamprey are therefore also important but are outside the scope of this paper. The goal of this paper is to provide guidance to improve adult Pacific Lamprey upstream passage over obstacles and in fishways originally designed for salmonids (*Oncorhynchus* spp.).

Pacific Lamprey are anguilliform swimmers[1], and this type of swimming is not adapted for passing some of the high-velocity, highly turbulent features common to fishways (e.g., Moser and Mesa 2009, Reid and Goodman 2016). Species selectivity in fishways is a design and management conundrum worldwide (Agostinho et al. 2002, 2007; Mallen-Cooper and Brand 2007; Naughton et al. 2007; Moser et al. 2011; Johnson et al. 2012). Historically in the U.S. Pacific Northwest, fishways were designed and optimized for economically important fish species, namely strong swimming species such as salmon and steelhead *O. mykiss* (e.g. Clay 1995; Keefer et al. 2010; Kirk et al. 2016; Silva et al. 2017; Keefer et al. 2021). Consideration for other fish species was not a design factor when most of these fishways were originally designed and built (Keefer et al. 2010; Katopodis and Williams 2012; Kirk et al. 2016). Many fishways are difficult for Pacific Lamprey to ascend for various reasons, such as high velocity, turbulence, lack of continuous attachment surfaces (such as 90° corners) and exposure to predation.

Due to the difference in swimming behaviors between Pacific Lamprey and salmonids, certain attributes of fishways (i.e., high velocity, lack of attachment surfaces for their sucker mouths) create barriers or impediments to upstream migration (Keefer et al. 2010; Goodman and Reid 2017). Evaluations of lamprey passage at lower Columbia River dams have shown that only ~50 - 89% of upstream migrating adult Pacific Lamprey successfully pass fishways at individual dams (Keefer et al. 2012, 2013a, 2013b). Approximately 50% of lamprey that entered fishways at Bonneville Dam eventually passed (Keefer et

[1] A type of swimming by fishes such as eels, in which most of the body undulates such that over a half a sinusoidal wave is formed (http://www.encyclopedia.com/science/dictionaries-thesauruses-pictures-and-press-releases/anguilliform-swimming).

al. 2013a). The median values for the same metric were ~68% at The Dalles Dam fishways (Keefer et al. 2012), ~51% at John Day Dam (Keefer et al. 2012), and 73% to 89% at McNary Dam (Keefer et al. 2013b). Thus, the cumulative passage efficiency across all of these consecutive dams can be quite low.

The effects of these passage efficiencies of adult Pacific Lamprey in fishways was summarized by Keefer et al. (2010): "*the mismatch between operational criteria in the Columbia River dam fishways and Pacific Lamprey swim performance almost certainly contributes to low dam passage efficiency and often protracted lamprey passage times*." Design criteria for engineered fishways often create structural and water velocity challenges that require repeated attempts and longer passage times for Pacific Lamprey, which may lead to higher energetic costs and physiological exhaustion (Keefer et al. 2010). Adult Pacific Lamprey do not feed during their upstream migration and must rely on stored energy reserves; thus, energy expended by successful migrants negotiating a fishway could result in physiological compromises that negatively affect their reproductive potential, and ultimately population productivity above these fishways (Keefer et al. 2010).

Passage failure may occur from the cumulative effects of passage attempts on lamprey endurance and motivation when considering local (e.g., weir to weir) or large scale (dam to dam) movements, and not necessarily the inability of overcoming a single passage challenge (Mesa et al. 2003; Kirk et al. 2016; Hanchett 2020). Energetic reserves or motivation may be exceeded when lamprey encounter multiple challenges when attempting to pass several dams into the interior Columbia Basin (Kirk et al. 2016; Hanchett 2020). Fewer than 5% of tagged Pacific Lamprey in the Bonneville Dam tailrace passed the lower four Columbia River dams to reach the interior Columbia River Basin, although some of the remaining 95% entered tributaries to the lower Columbia, where they presumably spawned (Keefer et al. 2009b). Some fishways pose a complete barrier for relatively small adult Pacific Lamprey that may have reduced swimming abilities or endurance compared to larger individuals (Keefer et al. 2009a; Kirk et al. 2016).

In addition to high water velocity and turbulence, other factors affect lamprey passage in fishways. These factors include predators, hydraulic cues (Kirk et al. 2015), water temperature, and individual motivation. For example, many lamprey attempting to pass Bonneville Dam turn around and choose not to pass in the low velocity/low turbulence environments of collection channels and transition pools (Keefer et al. 2012). In these areas, lamprey are free-swimming and are not constrained by high velocities, shear flows, and sharp corners. More information on these factors is discussed throughout this document, but the mechanisms of how multiple factors, individually and cumulatively, affect adult Pacific Lamprey passage will require more research (Hanchett 2020).

Passage success for lamprey in fishways can often be improved with structural modifications. To assist those designing, operating, maintaining, and modifying fishways for adult Pacific Lamprey, this document compiles information on the upstream migration of adult Pacific Lamprey, and provides guidelines for how to improve lamprey passage in fishways. These recommendations are based on information from both experimental fishway studies and monitoring passage at operational fishways and are considered "best guidance" based on available information. However, some fishways may present difficulties for lamprey passage that cannot be improved without major structural modifications.

Recommendations for lamprey-specific structures ("lamprey ramps" or lamprey passage structures [LPS]; Moser et al. 2011), tubes (Goodman and Reid 2017), and wetted walls that capitalize on this species' unique ability to climb near vertical and vertical surfaces ("burst-and-attach" locomotion) are discussed briefly, and some Case Study examples are provided (Appendix A). Lamprey Passage Structures are inclined structures with smooth surfaces (typically sheet aluminum) with a thin veil of water passing over them, which allow lamprey to attach and climb over the barrier on which the LPS is positioned (Appendix A, Case Studies 4, 6, and 10). Wetted walls, in short, are vertical ramps (Appendix A, Case Studies 7 and 8). Lamprey-specific structures may be the best alternative to provide passage if fishways present multiple, repeated passage difficulties that require substantial energy expenditures or cause lamprey to cease passage attempts and return to downstream areas (Goodman and Reid 2017, Hanchett 2020). For additional information and specific design criteria for LPS, refer to Zobott et al. (2015); for lamprey-specific passage using tubes, see Goodman and Reid (2017).

3 SUMMARY OF RELEVANT BIOLOGICAL INFORMATION

3.1 Life History

Pacific Lamprey are anadromous: adults spawn in rivers, and their larvae rear in fresh water for up to 10 years before migrating to the ocean as juveniles (Hess et al. 2022). As adults, lamprey return to fresh water from the ocean to spawn; yet unlike salmon, lamprey do not home to natal streams. A detailed description of their life history and threats is provided elsewhere (see Close et al. 2002; Clemens et al. 2010, 2017a). For purposes of this paper, note that the life cycle of Pacific Lamprey requires migration corridors in rivers for both upstream migrating adults and downstream migrating larvae and juveniles, although passage for downstream migration is outside the scope of this paper.

3.2 Swimming Speeds

The swimming speeds of adult Pacific Lamprey are considerably lower (less than half) than the speeds of adult anadromous salmon. Moser and Mesa (2009) summarized existing information on the swimming performance of adult Pacific Lamprey (Table 1). Mean critical swimming speed for Pacific Lamprey was measured at 0.9 m/s (2.8 fps; Mesa et al. 2003), although this is probably a conservative estimate (Moser and Mesa 2009).

To illustrate the problems adult Pacific Lamprey face within fishways, the typical water velocities through a fishway entrance is 2.1 - 3.0 m/s (7.0 - 10.0 fps) and 1.8 - 2.4 m/s (6.0 - 8.0 fps) at submerged orifices (Table 2). These velocities are well above critical swim speeds, 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. Further, these velocities can exceed the ability of Pacific Lamprey to use burst-and-attach locomotion (see Section 3.3 below). These challenges may test both immediate physical abilities (some weaker individuals may be excluded) and longer-term energy costs that could reduce the spawning population. For example, individual Pacific Lamprey may initially enter a fishway and pass several obstacles, but ultimately tire and fall back without successfully passing upstream, thus potentially reducing energy reserves for spawning and reducing upstream population numbers in areas above the fishway.

3.3 Burst-and-Attach Locomotion

In addition to free swimming in the water column, Pacific Lamprey use burst-and-attach locomotion to move forward, allowing them to pass through some areas that have flows in excess of their free-swimming speeds (Reinhardt et al. 2008). Using their sucker mouth to attach to substrate (attaching and resting phase), lamprey hold onto rocks and other smooth, flat surfaces, and then undulate their body to move forward (i.e., "burst"), and quickly re-attach to the substrate (Reinhardt et al. 2008). Adult Pacific Lamprey begin to use burst-and-attach locomotion when velocities reach ~0.60 m/s (2.0 fps; Daigle et al. 2005; Table 1) and in areas of increasing turbulence and velocity (Kirk et al. 2016). Flow velocities in the range of 2.4 - 3.0 m/s (8.2 - 9.8 fps) likely exceed the ability of Pacific Lamprey to use burst-and-attach locomotion and likely represent a complete barrier (Keefer et al. 2010; Kirk et al. 2016). Given large fishways in the Columbia River and encounters with 2.1 - 2.4 m/s (7.0 - 8.0 fps) at each weir orifice, there is concern about depletion of energy reserves for adult Pacific Lamprey that must repeatedly use burst-and-attach locomotion in these fishways (e.g., Kirk et al. 2015, 2017).

3.4 Climbing Behavior

Adult Pacific Lamprey can ascend wetted surfaces that are vertical or at steep angles under certain conditions, using burst-and-attach locomotion (Reinhardt et al. 2008; Kemp et al. 2009). To do this, sufficient water flow must be available for lamprey to aerate their gills, but the lamprey do not need to be completely submerged (Borowiec et al. 2021). In recent years, LPS and wetted walls have been designed, fabricated, and installed in cases where congregations of lamprey were observed, thus allowing them to pass a barrier by climbing (e.g., Moser et al. 2011, Zobott et al. 2015; Moser et al. 2019; Case Studies 4, 6, 7, and 8).

3.5 Lamprey Behavior in Fishways

Several studies have examined Pacific Lamprey behavior in fishways, or laboratory conditions intended to reproduce conditions in existing fishways (e.g., studies referenced in Table 1). The primary study objectives are typically to determine lamprey passage within a specific fishway or specific condition within a fishway. For example, in a laboratory study simulating a specific fishway, Keefer et al. (2010) found that increasing head (and thus increasing velocities) negatively affected passage success and suggested a slot entrance with a head differential of 0.4 m (1.5 ft) may effectively prevent lamprey passage. Goodman and Reid (2017) found that 95% of lampreys failed to pass a single overflow weir with velocities of 1 m/s (3.3 fps) and a 15 cm (6 in) vertical drop between the top of the weir and the pool below in a specific fishway. These studies are two examples that demonstrate several factors (e.g., head, velocity, bursting distance, configuration of a potential passageway) combine to affect lamprey passage conditions and likelihood of passage success. Thus, it is difficult to delineate specific criteria for any one parameter, as there are often multiple variables at play. The following paragraphs provide relevant information from many studies to support the following recommendations for addressing lamprey passage.

Pacific Lamprey are most active at night (Moser et al. 2002a; Daigle et al. 2005; Moser and Mesa 2009; Keefer et al. 2013b; Goodman and Reid 2017), especially within fishways where they encounter hydraulic and environmental complexities (Keefer et al. 2013a). Given the limited role of vision in lamprey navigation and their nocturnal migrations, Kirk et al. (2015) hypothesized that behavioral guidance by lamprey primarily depends on hydraulic cues, and some tactile substrate cues. Lamprey use visual and olfactory cues as well, particularly during the later phase of freshwater migration (Yun et al. 2011, Keefer et al. 2013b). The presence of a dead Pacific Lamprey may act as an alarm cue (Porter et al. 2017), as it does for Sea Lamprey (*Petromyzon marinus*; Bals and Wagner 2012; Byford et al. 2016). Thus, passage of lamprey may be disrupted when a dead lamprey is lodged in a resting box of a LPS. In addition, acoustic cues (e.g., splashing / falling water) may also hold importance in sensing the source and direction of water flow and currents.

Adult Pacific Lamprey locate upstream migration routes by sensing and following water currents (positive rheotaxis). Sufficient flow volume is necessary to attract lamprey to fishway entrances, and the fishway flow must also have sufficient velocity to provide upstream migration cues at the entrance and at each orifice (Moser and Mesa 2009; Keefer et al. 2010; Johnson et al. 2012; Kirk et al. 2015). Thus, it is essential to provide a large, but not excessive, attraction flow to minimize the energy expenditure required by lamprey to enter the fishway (Moser and Mesa 2009; Keefer et al. 2011).

Once in a fishway and provided a choice, adult Pacific Lamprey will preferentially use lower velocity channels with uni-directional flow (Keefer et al. 2011), and areas of lower turbulence (Kirk et al. 2016). Thus, it appears that Pacific Lamprey can select routes that reduce their energy expenditure, as suggested by their extensive exploratory behavior when encountering a difficult passage route (Goodman and Reid 2017). Because of their dependency on hydraulic cues, consistent flow of appropriate velocity is needed to guide lamprey through a fishway. For example, lamprey did not use submerged orifices in transition areas that had no velocity (Moser et al. 2002a; Keefer et al. 2013a). Similarly, in flow transition zones where velocity cues can be near-zero or in turbulent or changing flow patterns that could be confusing, lamprey tend to turn around and exit the fishway and move downstream (Keefer et al. 2010, 2013a; Kirk et al. 2015). Radio-telemetry studies have shown lamprey that fall back seldom attempt to pass upstream again (Keefer et al. 2013a). Some work at the lower Columbia River dams has shown that providing refuge boxes will help retain lamprey in the fishways because the refuge boxes provide cover during daylight hours (Corbett et al. 2013, 2014, 2015; Moser et al. 2021; Appendix A, Case Study 1).

Lamprey typically migrate near the floor and walls of fishways (Keefer et al. 2011; Keefer et al. 2010; Moser and Mesa 2009; Goodman and Reid 2017), especially when confronted with high water velocity or turbulence requiring use of burst-and-attach locomotion (Kirk et al. 2016). However, research at fishways at Bonneville Dam found free-swimming Pacific Lamprey distributed throughout the water column and mid-channel, suggesting that they alter their swimming mode in response to multiple environmental conditions (Kirk et al. 2015). Several factors were hypothesized to influence lamprey distribution and cause them to move away from the floors and walls of the fishway at Bonneville Dam, including reduced velocities within the fishway (making free swimming easier), attraction flows at the entrance in the upper water column, limited turbulence, and presence of the predatory White Sturgeon (*Acipenser transmontanus*) in the lower water column. Under these circumstances, lamprey may employ free-swimming (without tactile substrate cues) to locate the attraction flow, and thereby avoid the sturgeon (Kirk et al. 2015).

Adult Pacific Lamprey appear to readily move through fishways when velocities are <1.2 m/s (3.9 fps; Keefer et al. 2012). However, lamprey switch to burst-and-attach locomotion to deal with difficult passage conditions, such as high velocity and high turbulence. The attachment mode during burst-and-attach locomotion likely provides resting opportunities for the lamprey (Kemp et al. 2009; Kirk et al. 2015). Both extended and repeated bouts of burst-and-attach locomotion through high velocity and highly turbulent areas appears to exert a high physiological cost (Kirk et al. 2016). In circumstances where burst-and-attach locomotion must be used, the presence of continuous surfaces for attachment, (such as rounded corners at entrances/orifices or ramps at steps/sill blocks) is necessary for successful upstream movement.

The critical swimming speed of adult Pacific Lamprey is conservatively hypothesized to be ~0.9 m/s (~3.0 fps; Table 1). However, lamprey were documented to pass through flows of 1.2 m/s (Keefer et al. 2013b). Goodman and Reid (2017) suggested lamprey preferred free-swimming in water velocities < 0.6 m/s (~2.0 fps) near the bottom where velocities were lowest. For the purposes of this document, we assume < 0.9 m/s (~3.0 fps) is an appropriate free-swimming maximum velocity for fish passage designers to use to accommodate Pacific Lamprey in fishways. Above 0.6 - 1.0 m/s (2.0 - 3.3 fps), some adult lamprey switch to burst-and-attach locomotion, but this ability is exceeded at velocities ≥ 2.4 m/s (8.2 fps). It should also be noted that there are large variations in swimming ability within Pacific Lamprey because of relative size, condition, temperature, and even temperament (Moser et al. 2013). Reduced physiological capacity and seasonal changes in water temperature or tailrace conditions may also contribute to seasonal shifts in passage "bottlenecks" (Keefer et al. 2013a) where areas of passage difficulty shift over the migration period, which further complicates understanding passage needs for Pacific Lamprey.

The following sections discuss the different types of fishways, the areas within fishways that are problematic for adult Pacific Lamprey and why, and recommendations to address these problems to improve lamprey passage. These recommendations are based on our limited understanding and may be updated, and in some cases, altered as more research occurs.

4 TYPES OF FISHWAYS

There are several different types of commonly constructed fishways:

1. Pool and weir fishways, including Ice Harbor and half Ice Harbor, which often have both submerged orifices and overflow weirs to connect adjacent pools. Some pool and weir fishways have only submerged orifices or only overflow weirs (Figures 1 and 2).
2. Vertical Slot fishways have a tall, narrow orifice that extends from the floor to the water surface (Figure 3A).
3. Serpentine fishways — an uncommon variant of vertical slot fishways where the slot is an elongated channel — may make lamprey passage more difficult than other types of fishways (Clabough et al. 2009; Keefer et al. 2010; Keefer et al. 2012; Keefer et al. 2014; Figure 4).
4. Pool and chute fishways (a pool-and-weir variant with wide, sometimes full channel, overflow weirs with capability of higher flows (useful for fish attraction) than other fishway types; often include submerged orifices (Figure 5).

This list is limited to the types of fishways these recommendations address. A more exhaustive review of fishway designs is provided by Clay (1995). Generally, fishways consist of a series of sequential pools that gain elevation with each pool. Each pool is separated by some type of weir or constriction (e.g., vertical slots). In many fishways, each weir has an overflow section (surface weir; Figure 1), and often also a submerged orifice at or near the floor level[2] (Figure 2).

[2] In areas where there is insufficient flow the orifices may not be employed, because they would dewater the ladder at lower flows.

TABLE 1. Adult Pacific Lamprey swimming abilities and behaviors documented in fishways.

Parameter	Speed or Behavior Documented	Source
Critical swimming speed[1]	~0.9 (+/- .075) m/s 2.8 fps (+/- 0.25) fps) 1.4 body length per second (bl/s)[2]	Mesa et al. (2003) Moser and Mesa (2009) estimate "conservative" Moser and Mesa (2009) as cited by Reid and Goodman (2016)
Free-swimming abilities	< 1.2 m/s (~3.9 fps) "Lamprey more readily moved through sections where water velocity was ≤1.2 m/s (3.9 fps), below the estimated burst swim speed for adults."	Keefer et al. (2011, 2012)
"Preferred" free-swimming velocities	< 0.6 m/s (~2.0 fps)	Goodman and Reid (2017)
Behaviorally-lamprey change to burst-and-attach locomotion	≥ 0.6 m/s (~2.0 fps); or in areas with increasing turbulence	Daigle et al. (2005); Keefer et al. (2010); Kirk et al. 2015
Burst-and-attach locomotion exceeded	2.5 - 3.0 m/s (8.2 - 9.8 fps)	Keefer et al. (2010); Kirk et al. (2016)
Climbing abilities	Able to climb vertical or near vertical surfaces when smooth, continuous attachment surface is provided with some flow; can climb to move past or around areas with poor passage (e.g. high velocities, sharp corners) or out of "dead end" channels.	Reinhardt et al. (2008); Kemp et al. (2009); Moser et al. (2011, 2019); Frick et al. (2017); Goodman and Reid (2017); Frick and Corbett (2019)
Open Gap in Exclusion Grating, Picket weirs, Diffusers, etc.	Open gap ≤ 1.9 cm (0.75 in) for new migrants entering the Columbia River, as determined at Bonneville Dam. At other locations, reduced gap size (≤ 1.3 cm [0.5 in]) is recommended unless site-specific information supports a wider gap to prevent entry.	Moser et al. (2008); Appendix A, Case Study 10

[1]*Critical swimming speed*: The maximum swimming speed at which a fish can swim for a limited amount of time before fatiguing (traditionally defined as 20 s - 200 minutes). This swimming speed is faster than the sustained swimming speed, but slower than the burst swimming speed. This metric of swim performance is often measured under controlled laboratory conditions, using established procedures (Beamish 1978).

[2]*bl/s = body length per second.* This information was included when available, and can potentially be used to extrapolate swimming abilities of lampreys of varying sizes (e.g. regional size differences or different species).

TABLE 2. Typical velocities found in salmonid fishways and relationship of these fishway conditions to lamprey swimming abilities and likely passage success.

Structure	Velocities	Notes
Entrance	2.1 - 3.0 m/s (~7.0 - 10.0 fps)	Velocities exceeding burst swimming speeds; likely a significant deterrent or barrier for the many upstream migrants, especially without provision of a smooth continuous attachment surface.
Submerged orifice with 0.31 m (1.0 ft) head differential	1.8 - 2.4 m/s (6.0 - 8.0 fps)	Velocities approaching and exceeding lamprey's burst swimming speeds; lamprey may have to resort to burst-and-attach locomotion if smooth continuous attachment surface is available, but may tire with successive, repeated attempts and retreat out of the fishway.
Submerged orifice with 15 cm (6 in) head differential	1.2 - 1.8 m/s (4.0 - 6.0 fps)	Lamprey more readily move using free-swimming through these velocities (especially at the lower end of the range), and would likely rely on burst-and-attach locomotion less frequently.

If both surface weirs and submerged orifices are present, lamprey may pass either route. Submerged orifices may be flush with the floor (ideally) or located above the floor (like a window in a wall) and have a step (Figure 2). Other fishways (such as vertical slot and serpentine fishways) have a narrow, vertical slot opening that functions as a passage route from pool to pool. This slot is usually continuous from the water surface to the floor but may have a "step" or sill block at the floor (Figures 3A and 3B).

Lamprey enter fishways via the fishway entrance at the downstream end. A fishway entrance often has several components:

- An attraction jet/flow exiting the entrance to assist fish in locating the fishway. This jet is sometimes enhanced using an auxiliary water supply system (described below). In some fishways, the volume and velocity of added attraction flow is adjustable.
- Auxiliary water supply (AWS) refers to water that is added or manipulated to adjust hydraulic conditions (head or flow) at the fishway entrance. The AWS often increases the volume of water at the fishway entrance to increase attraction and provide sufficient volume relative to other competing flows at the barrier (spill, turbine outflow, etc.). Fishways at smaller dams often do not have AWS.
- Diffuser grating (grating usually associated with the location where auxiliary water is added) to exclude fishes from ascending inappropriate, dead-end, or unsafe routes within the fishway. Diffuser grating is often located immediately above or near the entrance, but water may be added at various locations throughout a fishway.

- Bulkhead isolation slots are adjusted to allow fish access, manage discharge volume and/or head, and isolate a fishway to dewater for maintenance.

Other typical fishway components may include:

Transition Areas are used to link different fishway sections. These areas include collection channels and junction pools and are often located at the upper and lower sections of a fishway to allow for fluctuating forebay and tailrace water levels (Keefer et al. 2012).

Counting Windows: Some fishways have lighted counting windows that allow for the enumeration of fish moving upstream. There is typically a crowding of the fish to one side of the fishway to ensure fish are close enough to the window to be viewed clearly. This crowding is often accomplished with picket leads that guide the fish to the window. There may also be a ramp that guides the fish up into the viewable area of the counting window as most windows are raised off the floor and do not span the entire height of the fishway wall.

Fishway Exits allow fishes to exit a ladder and enter the upstream reservoir or stream and may either be open channel exits or orifices. Typically, a portion of the flow of the fishway enters at the exit, on the upstream end. At projects that have a wide range of reservoir elevations, multiple fishway exits may occur, with each operating at a different reservoir elevation. Such exits require multiple gates and other facilities that can create complex management issues and passage conditions.

5 LAMPREY PASSAGE IN FISHWAYS

High velocity and turbulent areas with limited or insufficient surfaces for lamprey to attach to account for most of the passage impediments to adult Pacific Lamprey. Multiple factors interact within fishways to affect passage success of adult Pacific Lamprey. Areas of combined high velocities and turbulence over long distances (~80 m) are the most difficult for lamprey to pass (Kirk et al. 2015, 2016). The primary hydraulic challenges, which may have cumulative or even synergistic effects on the passage success and physiological condition of adult Pacific Lamprey, were summarized by Keefer et al. (2012):

- Velocities
    - 2.5 - 3.0 m/s (8.2 - 9.8 fps) exceeds burst swimming abilities and likely prevents lamprey passage for most individual lampreys.
    - Lamprey more readily moved by free-swimming in velocities approaching but less than 1.2 m/s (3.9 fps). This velocity is slightly higher than the critical swimming ability of 0.9 m/s thought to be a conservative estimate (Mesa et al. 2003; Moser and Mesa 2009), and higher than the < 0.6 m/s velocities recommended by Goodman and Reid (2017).
- Distance
    - Lamprey encountering difficult passage conditions for extended distances (e.g. a single serpentine weir) are more likely to fail to pass, especially in areas with limited attachment surfaces and resting areas.
    - For large fishways, passage failure may occur from the cumulative effects of multiple passage challenges (hundreds of weirs/pools within a single fishway; and

on the Columbia, up to 9 fishways on large dams) on lamprey endurance and motivation, and not necessarily the inability of overcoming a single passage challenge (Mesa et al. 2003; Kirk et al. 2016; Hanchett 2020).

- Shear flows[3]
  - No quantitative evaluations on Pacific Lamprey currently exist, but these types of flows are problematic because lamprey can be swept downstream as they move into shear flows.
  - Pacific Lamprey do not have the swimming ability to overcome high velocity shear flows, especially if they are positioned perpendicular to the flow and have no attachment areas.
  - Problem sites include weir orifices, sites requiring Pacific Lamprey to employ burst-and-attach locomotion with elevated or recessed steps (non-planar surfaces), some fishway corners, and serpentine weirs.
- Turbulence
  - Often coincides spatially with high velocities and shear flows.
  - Limited quantitative evaluations exist for how turbulence affects Pacific Lamprey passage but hypothesized to be prohibitive for adult Pacific Lamprey attempting to pass dams (Moser et al. 2019).
  - Sites where turbulence can occur include serpentine weir sections, fishway corners and turn pools, some submerged orifices, fishway entrances (especially adjacent to fishways), diffuser areas, and flow disrupters on fishway floors (Moser et al. 2019).

The following sections describe common components of fishways, why these components are problematic for adult lamprey passage, and potential solutions to improve passage efficiency for lamprey. The sections are generally ordered from downstream to upstream. Table 3 provides an overview of recommendations and modifications to fishways to improve passage for adult Pacific Lamprey.

5.1 Attraction Flows and Entrance Conditions

Fishway entrances typically use a submerged orifice, an open channel entrance or both before transitioning into the ladder segments. Substantial volumes of water are used at large fishways to create a relatively extensive, uniform, attraction "jet" at the entrance that can be located by migrant fishese and guide them to the fishway entrance and away from other areas of discharge (spillways, turbines). The flow volume of the attraction jet is typically sized as a percentage of other competing discharges (i.e., spillway flow, turbine discharge, etc.). The large volume of the attraction jet (as distinguished from high velocity flow) is important for both salmonids and lamprey for detecting fishway entrances (Moser and Mesa 2009; Keefer et al. 2010). For example, entrance efficiency of adult Pacific Lamprey at a fishway near the powerhouse at Willamette Falls was higher when all turbines were on, versus when they were off (Moser and Mesa 2009). Similarly, adult Pacific Lamprey did not locate or enter an experimental fishway with near-zero velocities (Keefer et al. 2010).

[3] In this discussion, the term "shearing flow" is used to refer to areas where water velocity changes abruptly in direction or amplitude (e.g., the transition zone between a sheltered, low velocity area --behind a rock or structure, for example--and a much higher velocity flow of water immediately adjacent to that rock or shelter.

Entrance velocities are typically 2.1 - 3.0 m/s (7 - 10 fps; NMFS 2011) and fishway operations target 0.3 - 0.5 m (1.0 - 1.5 ft) head differential (Table 2). These conditions create entrance velocities that meet or exceed the burst swimming speed of Pacific Lamprey (Table 1). Such conditions are challenging for lamprey to overcome, especially if turbulence and or localized higher velocity areas are inadvertently created. However, lamprey may be able to pass through this high velocity jet and enter a fishway using burst speeds over relatively short distances or using burst-and-attach locomotion (Kirk et al. 2016, 2017). In a recent experimental fishway study, the majority of Pacific Lamprey (>80%) were able to pass velocities of 2.4 m/s (8.0 fps) for short distances (≤ 0.6 m [2.0 ft]), but passage success was reduced when the slot length was increased to 1.0 m (3.0 ft; Kirk et al. 2016). A portion of the population (smaller, "weaker" swimmers, or those nearing spawning with reduced energetic capacity) may not be able to successfully pass through the entrance. Thus, there is a need to balance sufficiently large attraction while simultaneously minimizing energy expenditure for lamprey attempting to enter the fishway (Moser and Mesa 2009; Keefer et al. 2010; Johnson et al. 2012).

RECOMMENDATIONS: For existing fishways, reducing velocities through operational changes (Section 5.1.1), and/or physical modifications to the entrance (Sections 5.1.2 and 5.2 - 5.4) may be implemented either individually or in combination, depending on the situation. Operational changes could be done primarily at night (when most lamprey migrate and most salmon are less active), especially if such changes may negatively affect salmonid passage. More than one fix may be needed to substantially improve lamprey passage. The physical modifications may apply to conditions at entrances, orifices, weirs and exits, so each modification is discussed in its own section.

5.1.1 Operational Changes at Entrances

Some operational changes may reduce velocities and head differentials sufficiently at a fishway entrance to improve passage efficiency of adult lamprey while maintaining adequate attraction for them. For example, operational tests at Bonneville Dam fishways, in which velocities and head differentials were reduced at nighttime, increased the entrance efficiency of adult lamprey. These operational changes proved to be a low cost, effective tool that did not impact upstream salmon passage (Daigle et al. 2005; Johnson et al. 2012). Reduced velocities (e.g., ~1.2 m/s [3.9 fps] relative to 1.9 m/s [6.2 fps]) were shown to improve lamprey entrance efficiencies in both experimental fishways and large fishways (Daigle et al. 2005, Johnson et al. 2012). While these modified operations were somewhat beneficial and increased entrance efficiency, these improvements were relative, and did not result in passage success rates similar to those documented for salmonids. Even with these improvements to salmonid fishways, lamprey may experience difficulty in passing these fishways. Thus, some physical modifications (Sections 5.2 - 5.4) or other improvements (either at the entrance or throughout the fishway) should be considered.

RECOMMENDATIONS: Where feasible (i.e., in situations that will not affect competing needs, such as salmonid passage), reduce auxiliary water supply at night to improve lamprey passage while minimizing impacts to migrating salmon. Reducing entrance velocities to below 1.2 m/s (3.9 fps) should maintain sufficient attraction volume for lamprey, while allowing them to swim through the entrance.

5.1.2 Physical Modifications to Entrances

If operational changes are insufficient to allow lamprey entrance, then physical modification of the fishway entrance may be necessary. The fishway entrance may have several components that lack adequate attachment surfaces for lamprey to use burst-and-attach locomotion, including high velocities, entrance orifices with sharp angles and corners, bulkhead slots, and diffuser gratings. When velocities are too high for lamprey to swim through, and no continuous attachment areas are available for burst-and-attach locomotion, lamprey are not able to effectively or efficiently enter the fishway. Problematic features may occur at entrances or other locations within the fishway; recommendations are discussed in the following sections.

The USACE has made modifications to entrances at Bonneville Dam at Cascade Island to benefit lamprey passage (Clabough et al. 2015; Moser et al. 2019). Entrance modifications included installation of a variable width entrance weir, which is designed to improve attraction flows for salmonids in the upper portion of the entrance (which is narrower) and to reduce velocities near the bottom (which is wider) for lamprey passage. Modifications also included placement of bollards along the floor to reduce velocities and elimination of lower bulkheads that may have interfered with lamprey passage (Moser et al. 2019). Subsequent evaluations of lamprey passage comparing passage metrics pre- and post-modification have been mixed: entrance efficiency improved, but more lamprey exited back into the tailrace and had longer travel times after modifications were completed (Clabough et al. 2015).

At the River Mill Dam fishway on the Clackamas River, several important features were included in the entrance design to facilitate lamprey passage (Ackerman et al. 2019; Appendix A, Case Study 3 and 11). Though entrance velocities were estimated at 1.9 m/s, entrance efficiency estimates for Pacific Lamprey ranged from 90 - 92%. The adjustable weirs regulating the entrance head differential were designed to provide flush attachment surfaces through the entrance, ladder corners inside and outside the entrance were rounded with a 0.15 m (0.6 in) radius, and all ladder walls were treated with a grout finish to achieve a smooth surface for attachment.

5.2 Corners / Sharp Angles

Lamprey can be hindered by squared corners or sharp edges (i.e., 90° angles) in areas of high flow velocities where they need to use burst-and-attach locomotion. These sharp angles do not allow lamprey to quickly re-attach to a flat surface after burst swimming. Even seemingly small but abrupt edges that disrupt a continuous flat area can prevent forward movement by lamprey, causing them to fall back downstream in high velocity areas. Examples of these areas include corners at entrances and weir orifices, orifices with steps (orifices not flush with floor; Keefer et al. 2010), overflow weirs, bulkhead slots, and stop log guide slots.

RECOMMENDATIONS: To allow lamprey to use burst-and-attach locomotion, continuous planar areas for attachment are needed as velocities increase above ~1.0 m/s (~3.3 fps). As turbulence increases, continuous planar areas may be needed at velocities <1.0 m/s (3.3 fps). Orifices and slots should be located along a planar surface (e.g., along the floor without a step; Figure 2). For existing fishways with perched orifices (orifices with a step or sill block), the addition of ~3:1 ramps on the downstream side of the orifice provides a route of passage over the step/sill block and provides a continuous attachment along the floor (Figures 3A and 3B). It may be beneficial to also provide a ramp or rounded corners on the upstream side of the orifice to allow the lamprey to maintain attachment through the entire high velocity area. Locating the orifices in the corner of weirs will provide a continuous attachment surface along both the floor and the wall for lamprey (Figure 2).

Rounded corners (8 - 10 cm [~3 - 4 in] radii or greater) at the orifice walls are advised at velocities >1.0 m/s (3.3 fps), on both the up- and down-stream sides of each wall (Figure 2). Improved passage success for adult Pacific Lamprey occurred when bulkheads were rounded with a 20.5 cm (8.4 in) diameter circle (Keefer et al. 2010). Rounding the orifice walls at an existing fishway can either be accomplished by cutting/rounding the wall or installing inserts around the wall (Figure 6) that create a smooth, continuous and rounded surface for lamprey to pass using burst-and-attach locomotion. Rounded corners may not be required where velocities are < 1.0 m/s (3.3 fps). In this case, lamprey are likely to swim in the water column. In some instances, chamfered corners at the orifice walls have been used to improve lamprey passage (Ackerman et al. 2019; Appendix A, Case Study 3); however, no studies have directly tested the ability of lamprey to use chamfered corners relative to rounded corners.

5.3 Bulkhead Slots/Stop Log Guides

Fishways typically have bulkhead gates or stop logs at the entrances and exits to isolate and dewater the fishway for inspection, maintenance/repairs, and other purposes. These features create surface discontinuities that are problematic when lamprey attempt to pass using burst-and-attach locomotion. For example, these gates are held in place with slots, which are built into the sides and bottom of an orifice/entrance to support the gate when closed (Figure 6). When the gates are raised, the slots create a gap in the continuous surface of the orifice wall and can prevent lamprey passage in high velocity areas. Stop log guide gaps may also be in overflow weirs. Some fishways have metal frames to hold bulkheads or stop logs, which can also create non-planar surfaces that prohibit burst-and-attach locomotion (Figure 6).

RECOMMENDATIONS: In some dams in the Columbia River Basin, “inserts” have been added to eliminate the slot or gap when the gates/stop logs are not in place (Figure 6). Care should be taken when designing inserts to ensure that each insert creates a smooth continuous surface with no gaps or abrupt surface changes (bumps) in the transition between the fishway wall and the insert. In new construction, the entrance gate may be designed so there are no slots along floor or lower walls so gates do not need bulkhead slots (Appendix A, Case Study 5 and 6). The River Mill Dam fishway included novel gate designs that ensured adequate attachment surface through both fishway entrance and exit gates (Ackerman et al. 2019).

5.4 Diffuser Grating for Attraction Water Supply

Fishways often add water into the lowermost section to provide attraction into the fishway and away from other non-passage discharges (i.e., spillways, turbines). This additional volume of water is often introduced through floor or wall gratings (diffusers) in the lower part of the fishway, just upstream of the entrance and lower fishway sections (Figures 7A and 7B). Often the gap (open space) within the grating designed to exclude adult salmon is too large to prevent lamprey from passing through the diffuser. Criteria for fishways require the velocity coming through the diffusers to be lower than the prevailing current within the fishway, and can be attractive to lamprey. To create these low velocities through the diffusers, diffuser gratings often cover large areas of fishway floors and walls. This situation can cause the following problems:

- Adult lamprey will potentially be attracted to swim through the grating into the auxiliary water supply because it might appear as a lower velocity route of passage, resulting in their passage delay, injury or death.
- The grating creates a partial or complete passage barrier in high velocity areas where lamprey would otherwise be able to pass using burst-and-attach locomotion because diffuser grating does not provide continuous attachment surfaces (e.g., see Daigle et al. 2005).
- Flow from diffusers may create confusing cues to lamprey and result in increased passage times, fall backs or failed passage (Moser et al. 2008; Keefer et al. 2011, 2012).

In the lower Columbia River (Bonneville and John Day dams), a gap of 1.9 cm (0.75 in) or less was necessary to exclude Pacific Lamprey that recently entered the Columbia River (Moser et al. 2008). Pacific Lamprey were able to compress their body to pass through gaps as narrow as 60% of their body width. The girth of the brachial basket was hypothesized to be the limiting part of their anatomy, as length, weight and body girth was not a good indication. This structure is less flexible than other parts of the body and appears to remain constant in size, even as body mass shrinks over time.

Adult Pacific Lamprey in different drainages outside of the mainstem Columbia River can be smaller (Clemens et al. 2019); thus, the smaller gap size is warranted for exclusion. A smaller gap size is also recommended for other areas such as the interior Columbia Basin tributaries, because adult lamprey shrink over time (Clemens et al. 2009, 2010; Lampman et al. 2016). In these areas, a gap of 1.3 cm (0.5 in) or less is recommended to block passage (Appendix A, Case Study 10). Using perforated plate, grating or bar rack instead of pickets — where hydraulically feasible — may further limit the potential for lamprey to pass into undesirable areas. However, care should be taken to ensure adequate porosity when using perforated plate or bar rack material.

RECOMMENDATIONS: To prevent lamprey from entering diffusers or other undesirable areas at dams, all diffuser gratings should follow these gap recommendations:

- In the mainstem Columbia River:
    - ≤ 1.9 cm (~0.75 in) gap between bars (Moser et al. 2008).
- In other river systems where adult lamprey are generally smaller (e.g., Oregon Coast) or areas where overwintered lamprey occur:
    - ≤ 1.3 cm (~0.5 in) gap between bars (Appendix A, Case Study 10).

Avoid placing grating on fishway floors and the lowermost 0.3 m (1.0 ft) of fishway walls (Figures 7A and 7B). Anecdotal observations suggest that lamprey often attach to the floor or wall/floor interface; thus, the absence of grating will allow lamprey continuous passage along the floor and lower walls and may reduce confusing flow patterns along the floors of fishways. Omitting diffuser gratings from the floors and lower walls of a fishway would also minimize the potential for stranding fishes when dewatering the fishway for maintenance and inspections.

For diffusers located in high velocity areas (≥ 1.0 m/s, 3.3 fps), the following is recommended:

- Wall diffusers should be elevated off the floor by at least 0.3 m (1.0 ft).
- Floor diffusers:
  - Avoid using floor diffusers if possible.
  - If the use of floor diffusers cannot be avoided, diffusers should be located at least 1 m (3.3 ft) upstream and downstream of weir orifices.
  - To provide a continuous attachment surface where existing floor diffuser grating is necessary, a flat metal plate (minimum width of 0.3 m [1.0 ft]) can be used to span diffuser floors and provide attachment areas (Keefer et al. 2010; Figures 7A and 7B). This may be important above and below orifices and entrances where velocities require that lamprey use burst-and-attach locomotion to pass, in areas where there is increased turbulence and confusing hydraulic cues or in areas where the combined distance, turbulence and velocities are such that lamprey may need to attach to rest.

If floor diffusers in new construction cannot be avoided, diffuser grating should not be located in the first 0.3 m (1.0 ft) of the fishway floor next to the wall and the lower 0.3 m (1.0 ft) of the wall. In addition, diffuser grating should not be placed immediately upstream or downstream of localized high velocities (such as a fishway entrance or submerged orifice) where lamprey may need to attach to pass or rest (Figures 7A and 7B).

5.5 Resting Areas/Refuge Boxes

Resting opportunities may be critically important for lamprey traversing a fishway (Daigle et al. 2005; Keefer et al. 2011; Kirk et al. 2016). The lack of resting areas for adult Pacific Lamprey has been found to increase their passage time, and likely their energetic expenditures (Daigle et al. 2005). The USACE has provided refuge boxes in fishways to provide dark, low velocity areas for lamprey to hold and rest during the day, when they normally seek cover and darkness (Corbett et al. 2013, 2014, 2015; Moser et al. 2021; Figure 8; Appendix A, Case Study 1). Monitoring the use of these boxes with PIT tags has shown that a substantial portion of lamprey are seeking out and using these refuges during daylight hours, and that these refuges appear to reduce the number of lamprey that fall back. Additional monitoring is needed to better understand the impact of such refuges on overall passage success (Moser et al. 2021).

RECOMMENDATIONS: The addition of resting areas for lamprey is important for passage, particularly as fishway length, elevation gain or ascent distance increases (Daigle et al. 2005; Keefer et al. 2011). Resting opportunities should be available at regular intervals throughout a fishway. Each resting area for adult Pacific Lamprey in fishways should provide areas of relatively low velocity (≤ 0.9 m/s) and darkness, with natural substrate, such as the refuge boxes developed by Corbett et al. (2013; Figure 8; Appendix A, Case Study 1). These refuge boxes may prove particularly helpful in problematic areas where lamprey have been shown to fall back out of the fishway.

5.6 Attachment Surfaces

The best surfaces for lamprey attachment are “smooth and non-porous,” such as glass and polished metal, although they can and do attach to roughened, wetted concrete (Moser and Mesa 2009). The ideal attachment surface allows the sucker mouth of the lamprey to create a reliable seal. By contrast, thick algal growth can inhibit attachment and climbing on angled surfaces (M.

Moser, pers. comm. 2016). In the Columbia River Basin, aluminum has been used successfully to construct LPSs (Moser et al. 2011). There is some indication that LPS use by lamprey increases as the material ages and a thin biofilm develops on the surface. The cause of increased use is unknown, but it was hypothesized that the aging process reduced presence of repellent olfactory cues that may occur on newly installed aluminum (Moser et al. 2011).

RECOMMENDATIONS: For modifications that require inserts (i.e., bulkhead slots, rounding sharp corners, LPSs), flat plate aluminum may be used to provide a smooth continuous surface for lamprey passage (minimum width of 0.3 m [1.0 ft]). Aging the structure after construction may be beneficial. To create floor ramps for lamprey to pass orifices with steps or sill blocks, concrete could be placed, formed, and smoothed as one option. For any new or modified structure to improve lamprey passage, care should be taken to ensure a smooth, continuous surface with no gaps or abrupt surface changes in the transition areas. Even seemingly small abrupt gaps may inhibit or block successful passage if in an area where burst-and-attach locomotion must be used (i.e., climbing, shear zones, or high velocities). Smoothly painted surfaces, plastics, glass, and concrete can also provide adequate attachment surfaces. Surface irregularities should be minimized and likely not exceed 2 mm (0.08 in), based upon anecdotal observations (M. Moser, pers. comm. 2016). Adams and Reinhardt (2008) found that surfaces with narrowly spaced grooves of 1 mm (0.04 in) width and 3 mm (0.12 in) depth prevented Sea Lamprey from maintaining attachment.

5.7 Collection Channels

Collection channels are common features at large dams and are characterized by relatively non-turbulent flows (although sometimes there are diffusers with upwelling flow; Keefer et al. 2012). Passage studies for Pacific Lamprey conducted at large dams on the Columbia River have found that although lamprey can generally move through these low velocity collection channels (Clabough et al. 2010; Keefer et al. 2012), many will exit these areas and return to the tailrace (fallback). The mechanisms affecting lamprey passage in these areas are not well understood. However, the first submerged weirs inside the fishway at the terminus of the collection channel (determined by the tailwater elevation) may negatively affect passage due to the lack of clear hydraulic cues and/or attraction flow (Keefer et al. 2012). Other factors that may be affecting passage in the collection channels include hydraulic changes associated with multiple fishway openings along the collection channel and the presence of sturgeon.

RECOMMENDATIONS: Insufficient data exists to determine a “best recommendation” for these cases. Assuming the problem with collection channels is associated with hydraulic cues and attraction, new construction should incorporate features to maintain uniform hydraulic flow for lamprey along the floor, while still providing opportunities for resting. The use of refuge boxes in these areas where lamprey have higher rates of fall back may prove useful (see section 5.5 Resting Areas; Figure 8; Appendix A, Case Study 1).

For existing or new construction, alternative routes that bypass the collection channel or portions of it using an LPS or wetted wall (Frick et al. 2017; Frick and Corbett 2019) could also be used if site-specific conditions and behavior indicates these might pass lamprey.

5.8 Junction Pools and Transition Pools

Junction pools are where two or more fishway components join (i.e., where multiple collection channels meet; Keefer et al. 2012). Transition pools are typically used to describe the fishway sections where submerged weirs transition to overflow weirs, and have features common to both fishways (weirs, orifices) and junction pools (reduced velocities, greater depth; Keefer et al. 2012). While some of these areas have been shown to be challenging areas for lamprey passage, the mechanisms of passage failure are not well understood (Keefer et al. 2012). Failed passage within these areas may result from low attraction or confusing hydraulics, velocity barriers, various structural challenges (grating, vertical steps inside submerged orifices, recessed floor segments), and high densities of predatory White Sturgeon (Keefer et al. 2013a; Kirk et al. 2015). As an example of a recent modification for existing fishways, the USACE removed two overflow weirs at John Day Dam (north fishway entrance area) to increase attraction velocities in a transition area in conjunction with several other entrance improvements (Clabough et al. 2015). Subsequent evaluations on passage metrics suggested that the combined modifications provided adequate passage conditions.

The effect of these transition areas on lamprey passage can vary with water level fluctuations within the tailrace, as more or less of the pools are inundated. The following quotation summarizes our understanding of lamprey passage in transition pools: *"Notably, many lamprey that successfully pass through transition pools do so without long passage delays. It is possible that these fish used different routes (i.e., along the walls versus along the fishway floor versus over overflow weirs) than those that turned around in the pools, or that they approached during favorable tailwater or operational conditions, or periods of lower predator density"* (Keefer et al. 2012).

RECOMMENDATIONS: New construction should ensure that sufficient hydraulic cues exist for lamprey to continue upstream and should incorporate features to maintain uniform hydraulic flow for lamprey along the floor in these pools, while maintaining sufficient resting areas. Placement of refuge boxes as discussed above could provide resting areas (see Section 5.5 Resting areas; Figure 8; Appendix A, Case Study 1). For existing or new construction, alternative routes that bypass these pools using LPS or a wetted wall could be used if site-specific conditions and behavior suggest these might pass lamprey.

5.9 Temperatures in Fishways

Increased water temperatures can affect lamprey migrations and potentially become a barrier. In the Willamette River drainage, warm summertime temperatures (≥20ºC) during July-August have been associated with slowing and stopping lamprey migrations (Lampman 2011; Clemens et al. 2012, 2017b), expediting sexual maturation (Clemens et al. 2009), and in some situations, die-offs (Clemens et al. 2016). At Bonneville Dam, adult Pacific Lamprey tend to migrate earlier in low flow, warm water years, with approximately 80% of the run migrating upstream at ~21 - 23ºC (Keefer et al. 2009b). Similarly, passage of lamprey increased at the Willamette Falls project at ~23ºC (Mesa et al. 2010). Thus, the increased upstream migration of lamprey during warm water temperatures is probably a response by these fish to escape warm temperatures (Lampman 2011; Clemens et al. 2016). Seasonal changes in temperature may also contribute to observed seasonal shifts in passage "bottlenecks" (Keefer et al. 2013a). Thus, whereas warm temperatures may expedite adult lamprey passage, in some cases very warm temperatures have been linked with mortalities. Further research is needed to understand the behavioral propensity to swim and physiological efficiencies at different water temperatures.

RECOMMENDATIONS: In fishways where temperatures reach 20ºC or more when adult lamprey are actively migrating, inputs of cooler water to the fishway from an upstream source (if available) could be considered to appropriately reduce water temperatures. Use of shade cloth or similar material over the fishway can lessen solar radiation effects and reduce warming. Such measures will also benefit migrating salmonids.

5.10 Predation associated with Fishways

Pacific Lamprey are a prey item for many native species (e.g., White Sturgeon [Semakula and Larkin 1968], River Otters [*Lutra canadensis;* Cochran 2009), pinnipeds [Roff and Mate 1984; Stansell et al. 2010; Madson et al. 2017], and Great Blue Herons [*Ardea herodias*; Wolf and Jones 1989]). In some situations, fishways can create conditions or areas that concentrate upstream migrating adult lamprey, making them more susceptible to predators than might occur in natural riverine habitats. These areas include the tailrace areas near fishway entrances, fishway entrances and exits, and within fishways. As previously discussed, high densities of sturgeon at Bonneville Dam may cause lamprey to alter their behaviors or fail to pass (Kirk et al. 2015).

Fishway entrances, exits, and collection channels create localized areas in which predators can ambush lamprey as they attempt to pass. It is well documented that White Sturgeon, seals and sea lions [*Zalophus* and *Eumetopias* spp] prey on lamprey near fishways like those at Bonneville Dam on the Columbia River (Tackley et al. 2008; Madson and Van der Leeuw 2016). River Otters can also hunt within fishways, where there is no cover for lamprey to hide. In certain conditions (e.g., LPS, shallow fishways such as certain areas at Willamette Falls), lamprey may be more easily preyed upon by Great Blue Heron and other avian predators due to the lack of cover on artificial passage structures.

RECOMMENDATIONS:
Reducing the access and opportunities of potential predators should be considered when developing fish passage for lamprey. Some actions that have been used include reducing predator access (e.g., Sea Lion Exclusion Devices) and acoustic deterrent devices and hazing to frighten predators away (Tackley et al. 2008; Madson and Van der Leeuw 2016). However, River Otters are too similar in size to salmon to exclude them from fishways. Installing barriers/fencing to limit overland access into the fishway, covers on LPS, or refuge boxes to provide lamprey protection may reduce predation, but predator removal by trapping may ultimately be necessary if predation is a significant problem. Installation of ropes, wires or flagging may physically deter avian predators. Sprinkler systems may help provide cover from terrestrial predators by breaking up the water’s surface to reduce visibility. In addition, providing natural substrate such as large cobbles and boulders can provide refuge from predators.

5.11 Weir Sections

5.11.1 Overflow Weirs/ Submerged Orifices at Fishways

Many fishways have both overflow weirs and submerged orifices that create localized areas of high velocity and turbulence. Most fishways were designed with 0.3 m (1.0 ft) elevation difference between pools, which results in around 2.1 - 2.4 m/s (7.0 - 8.0 fps) jets through the orifices and overflow weirs. Because of their bottom-oriented behavior, lamprey are more likely to use the submerged orifices; however, they have also been observed using overflow weirs (Keefer et al. 2012). Lamprey primarily appear to pass these areas using burst-and-attach locomotion, and these areas do not appear to be a passage impediment because the areas of high velocity are relatively short (0.3 - 0.6 m (1.0 - 2.0 ft)).

RECOMMENDATIONS: For submerged orifices, continuous planar floor surfaces should be provided for lamprey attachment through the extent of the high velocity area of the orifice (Keefer et al. 2012; ~1.0 m [3.3 ft] upstream and downstream of an orifice or weir) by making orifices flush with the floor and/or flush to the outside fishway wall (Figure 2). If at least one continuous planar surface is provided (e.g., the floors, walls), then rounded corners may not be needed at the orifice walls. For fishways with existing steps at orifices, ramps can be added on the downstream side of the orifice to allow for burst-and-attach locomotion (Figures 2 and 3B). It may be beneficial to also provide a ramp or rounded corners on the upstream side of the orifice to allow the lamprey to maintain attachment through the entire high velocity area. For new construction, all orifices should be flush with the floor (no step), and entrance walls should be rounded (8 - 10 cm [~3 - 4 in] radii; e.g., Ackerman et al. 2019). Chamfered corners have also been used but not specifically evaluated and are thus less preferred than rounded corners.

For overflow weirs, rounding the weir and placing the overflow section against the side wall would allow lamprey to maintain continuous attachment (Figure 1; Ackerman et al. 2019). In addition, customized inserts could be placed into the guide slots to allow lamprey to use burst-and-attach locomotion (Figure 6).

5.11.2 Serpentine Weirs

Serpentine weirs, though uncommon and seldom encountered, can be one of the more difficult structures for lamprey to pass. These weirs have been associated with high rates of failed passage. Few lamprey that failed to pass the serpentine weir sections at Bonneville Dam re-attempted passage (Keefer et al. 2012). Serpentine weirs are characterized by square (90°) corners, grated floor sections, and squared vertical slots that are recessed into fishway walls. These features create high velocity and turbulence that persist over distances that are longer (up to 0.8 m or 2.5 ft) than orifices in other fishways. The hydraulic conditions at serpentine weirs have been hypothesized to be beyond the energetic capacity and motivation of some lamprey to continuously use burst-and-attach locomotion (Keefer et al. 2012; Kirk et al. 2015, 2017).

RECOMMENDATIONS: Avoid installing serpentine weirs in new construction (Figure 4), and instead use vertical slot (Figure 3A) or pool and weir type fishways (Figures 1 and 2). Consistent with other recommendations above, these fishways should limit floor diffuser grating; round corners in areas with high velocities; and vertical slots should extend to the floor or be ramped (no steps or sill blocks). For existing fishways, possibly provide alternative routes (LPS or wetted wall) to bypass serpentine weirs, as was done at the Bonneville Bradford Island and Washington-shore fishways (Moser et al. 2006, 2011; Frick and Corbett 2019).

5.11.3 Differential Between Pools

Differential in elevation between fishway pools for adult salmon and steelhead is typically 0.3 m (1.0 ft; creating 2.1 - 2.4 m/s [7.0 - 8.0 fps]). For lamprey and smaller resident and migratory fishes, fishways can be constructed with 15 cm (6 in) differentials (drop), which reduces head between pools and velocities in the orifices. Whereas reducing the differential between pools helps address passage for a wider range of fish species, increased cost and space is often necessary to construct a 15 cm (6 in) drop between each pool. In existing fishways with 0.3 m (1.0 ft) differentials, operational changes at night may be used to improve lamprey passage by reducing head, which reduces overall velocities and energetic requirements for lamprey to pass through the fishway. Several studies have demonstrated that reducing head at the entrances has improved entrance efficiency (e.g., Daigle et al. 2005; Johnson et al. 2012). In situations where operational changes at existing fishways cannot be accommodated, passage for lamprey may be better addressed with LPS (see Zobott et al. 2015), provided these can be sited in areas where lamprey congregate.

5.11.4 Bollards

Experimentation has been done using bollards along a fishway floor to reduce local velocity and thereby improve passage for lamprey. In an experimental fishway study, Daigle et al. (2005) placed artificial rocks (10.2 cm wide × 10.2 cm high [4 × 4 in]), in rows spaced 0.4 m (1.2 ft) apart and staggered so there was 0.7 m (2.3 ft) in between a rock and the rock immediately downstream. These rocks created velocity refuges where lamprey could rest, and improved passage times. Wooden bollards of the same dimensions (10.2 cm wide × 10.2 cm high [4 × 4 in]) were also tested, and it was found that narrowly spaced bollards (same pattern as above, but only 20 cm [7.9 in] spacing) decreased passage efficiencies under high head conditions (61 cm [2.0 ft]; Daigle et al. 2005; Keefer et al. 2011). However, at lower head conditions, the bollards did not affect lamprey passage regardless of spacing. Adult Pacific Lamprey attempting to move upstream were hindered by narrowly-spaced bollards, which simultaneously created turbulence and imposed constraints on lamprey swimming movements (Keefer et al. 2011).

RECOMMENDATIONS: Install bollards in areas with high head to provide reduced velocities, in rows spaced at least 0.4 m (1.2 ft), with staggered placement (Figure 7A). Bollards may not be necessary in areas where head differentials, and therefore velocities, can be sufficiently reduced.

5.12 Counting Stations and Associated Features

5.12.1 Counting Windows

Initial studies suggested that counting stations may create passage problems for adult Pacific Lamprey (Moser et al. 2002b); however, more recent studies found that lamprey were able to pass the counting window at Bonneville Dam but were not passing due to unfavorable conditions for lamprey passage in the serpentine weir sections immediately upstream of the counting window (Clabough et al. 2012; Keefer et al. 2010). Nearly all lamprey were able to pass counting windows where the target water velocity is ~ 0.5 m/s (1.6 fps) in the water column

(Clabough et al. 2009), which is well below the critical swimming speed of Pacific Lamprey (Table 1).

Counting windows designed for salmon may be inadequate for quantifying lamprey (Clabough et al. 2012) as lamprey can pass below the viewing area where the window does not extend all the way to the floor. They may also be able to pass through overly-wide picket leads and avoid the counting window area entirely. Though not a design consideration, Clabough et al. (2012) found that daytime counts at lower Columbia River dams greatly underestimated adult Pacific Lamprey passage at counting stations and suggests that efforts to estimate lamprey run size from daytime counts should be made with caution because among year variability in the day:night ratio is high. Efforts by the Grant County P.U.D. to improve the reliability of lamprey counts are provided in Appendix A, Case Study 2.

RECOMMENDATIONS: To correct these issues above and improve the accuracy of lamprey counts at these windows, Clabough et al. (2012) made the following recommendations:

- Counting windows should extend all the way to the floor to avoid blind spots where lamprey can pass undetected.
- Counting stations should be located near fishway exits, and upstream from significant passage challenges to reduce milling behaviors, fallback, and repeated attempts — all of which complicate visual counts.
- Infrared light sources should be added to improve night counting (when most lamprey migrate; see also Section 5.12.2 Lighting).
- To eliminate lamprey avoidance of the counting window, spacing of picket leads or grating) should follow the gap guidance as described in above in Section 5.4 Diffuser Grating for Attraction Water Supply.

5.12.2 Lighting

Artificial lights are present at various locations in many fishways and are often needed to see and count fish at counting windows, or necessary for human safety. Changes in light levels can occur anywhere where the fishway transitions from uncovered to covered areas or lighting is needed for human safety. Adult Pacific Lamprey were most active under infrared lighting compared with other types of lights (Daigle et al. 2005). Because of their nocturnal nature and negative phototaxis, Pacific Lamprey could be obstructed by very bright or abruptly changing light conditions (Moser and Mesa 2009). The tests to date have not been comprehensive in terms of light spectra or intensity; thus, effects of any lighting are a reasonable potential concern for passage. However, 1 - 3 lux lights were not a problem for lamprey migration (Daigle et al. 2005).

RECOMMENDATIONS: When artificial lighting is necessary, use lights that are <3 lux or preferably infrared lighting. Also, eliminate or modify areas/overhanging structures that create abrupt changes in lighting of the fishway. If lighting must be present in areas for human safety, use curtains or similar material to darken the fishway. Similarly, refuge boxes can be used to provide darkened areas and refuge in lighted areas and during the day.

5.12.3 Picket Leads

Picket leads are physical barriers used to prevent fish from entering unsafe or non-passage areas in fishways or to narrow the passageway at a counting window to force fish to swim near the window. Picket spacing that was intended to exclude adult salmon may allow smaller fish, including adult lamprey, to pass through the gaps between the pickets and into areas that are potentially harmful or cause passage delays. Lamprey have been documented to seek these areas behind picket leads when spacing is too wide.

RECOMMENDATIONS: The spacing of picket leads (or perforated plates or grating) should follow the gap guidance as described in above in Section 5.4 Diffuser Grating for Attraction Water Supply. Using perforated plate, grating or bar rack instead of pickets — where hydraulically feasible — may further limit the potential for lamprey to pass into undesirable areas. Care should be taken to ensure adequate porosity when using perforated plate or bar rack material.

5.12.4 Collection of Lamprey within Fishways

Some situations may require trapping adult lampreys, for purposes such as trap and haul, translocation, or collection of adults for study purposes. At Bonneville Dam, adult lamprey are collected via LPS that terminate in a holding tank for these purposes. Similarly, adult lamprey are collected at the top of a wetted wall to evaluate wetted wall attraction, use and potential passage (Case Study 7). At the River Mill Fishway on the Clackamas River, a portable lamprey trap is used within the fishway to collect adults for passage studies and conduct a temporary trap and haul program while lamprey passage impediments at the next upstream fishway were under evaluation (Case Study 11).

RECOMMENDATIONS: Trapping lamprey within fishways is a useful tool for collecting adults for passage evaluations, conducting trap and haul operations, and potentially gaining an index for lamprey abundance (when complete counts are not possible). Ideally, collection of lampreys to provide upstream passage via trap and haul should be used in limited circumstances for limited periods of time. The long-term goal should be volitional passage for lamprey to access spawning habitats.

Traps should be placed where lamprey are known to congregate and are able to access the trap. Structures such as orifice blocks or picket weirs can be used to reduce other passage routes and guide lamprey into traps. Traps should have sufficient water flow though the holding box for oxygenation and temperature maintenance. Traps should be checked and emptied at least daily to avoid overcrowding and escapement. A fyke should be incorporated into the trap entrance to prevent escapement from the holding box after entering. If a trap is to be used in a salmonid fishway, special consideration should be made to ensure the design and placement within a fishway does not negatively affect salmonid passage. See Case Studies 7 and 11 for specific examples.

5.13 Dead Ends

Whether boulders, cobble, trees, or other structures in rivers (e.g., see Robinson and Bayer 2005; Clemens and Schreck 2020), log structures in crib dams (e.g., Lampman 2011) or structures within fishways (Keefer et al. 2012), Pacific Lamprey seek out structure to hold and shelter under when they are not actively migrating. Adult lamprey have been found in several fishway features that do not have upstream outlets, particularly those with associated attractive flows (Keefer et al. 2012). For example, lamprey may be attracted to seepages or leaks in infrastructure that may lead them to dead ends, which can contribute to passage delays or failures (Keefer et al. 2012).

At Bonneville Dam, adult Pacific Lamprey were passing through picket leads and accumulating in an area with no passage adjacent to the counting window (Moser et al. 2006). Lamprey were also having difficulty passing the serpentine weir section above the counting window. Instead of modifying the picket leads to prevent lamprey from entering the area, an LPS and a counting mechanism were installed to allow lamprey to bypass the counting station and serpentine weirs and enter the forebay above the dam (Moser et al. 2006, 2011). Subsequently, picket leads were raised off the floor to allow lamprey (but not salmon) easier access to the area (Keefer et al. 2012).

RECOMMENDATIONS: Examine dead ends for lamprey aggregations. If lamprey accumulate in such areas, exclude them from these areas or provide means for egress, such as an LPS or wetted wall. Isolate the areas with picket leads or grating, or permanently dewater the area. Some circumstances may be altered to benefit lamprey passage, such as adding an LPS or wetted wall where lamprey congregate in dead-end areas to allow passage. Such additions have successfully been used at Willamette Falls and Bonneville Dam (Moser et al. 2006; Appendix A, Case Study 6).

5.14 Fishway Exits

Fishway exits can pose challenges to lamprey passage similar to those found at the fishway entrances: specifically, shear flows, sharp corners, and bulkhead slots that may be in areas with high velocities. See recommendations in Sections 5.2 - 5.4 for recommendations to address those problems.

Adult Pacific Lamprey can be swept downstream in conditions where adult salmon would not. Therefore, immediately after exiting a fishway, lamprey should not be subjected to sudden or high velocity currents (such as spillways or turbine intakes) that can carry them back downstream below the dam they just passed.

RECOMMENDATIONS: For existing structures, exits may need to be ramped or rounded on the upstream side to allow lamprey to move to lower velocity areas, and away from areas where spillway and turbine currents or shearing flows could sweep them back below the structures they just passed. To reduce lamprey fallback, new construction should avoid high velocity exit sites or ensure that adequate LPSs or other transitions to low velocity areas allow lamprey to orient and swim upstream easily after exiting the fishway.

TABLE 3. **Summary table of guidelines, recommendations, and key uncertainties for passage of adult Pacific Lamprey in fishways, with associated literature and relevant Case Studies (Appendix A).**

Ladder Component/ ***Problem (in italics)***	**Guideline/Recommendation**	**Key Uncertainties**	**Relevant Literature/Case Studies**
ENTRANCES			
Attraction flows/ Entrance openings *High velocities/ shear velocities with limited attachment surfaces.*	Multiple fixes (implemented individually or in combination) may be needed and include: ● Reduced velocities via operational changes o Reduce auxiliary water supply at the entrance so that water velocity is ≤ 1.0 m/s (3.3 fps), to maintain sufficient attraction volume while allowing lamprey to swim through the entrance. o May be able to only reduce flows at night to avoid negative effects on salmonid passage, which primarily occurs during the day. ● Physical modifications to the entrance in areas of increasing velocities (≥ 1.0 m/s (~3.3 fps)), and or increasing turbulence regardless of velocities: o Provide continuous planar areas for attachment (continuous floor, ramp, or wall). o Provide rounded (8 to 10 cm [~3 to 4 in] radii). Chamfered corners have also been used but not specifically evaluated and are thus less preferred. o Locate orifices (or slots) along the floor without a step/sill (Figure 2). o Locating the orifices in the corner of a weir will provide a continuous attachment surface along both the floor and the wall, which provides more attachment opportunities for lamprey (Figure 2). o If a step is present along the floor, add a ~3:1 ramp on the downstream side. o Install bollards along the floor to reduce velocities (see "Bollards" below) - experimentally done at Bonneville and	Site specific information should determine which fix or suite of fixes is needed. The ~3:1 ratio for ramps and 8 to 10 cm (~3 to 4 in) radii for rounded edges represents best professional judgment. No quantitative studies on this available. It may be beneficial, but unknown at this time, whether providing a ramp or rounded corners on the upstream side of the orifice is necessary to allow the lamprey to maintain attachment until out of the high velocity area.	Daigle et al. (2005); Moser and Mesa (2009); Keefer et al. (2011, 2012); Johnson et al. (2012); Clabough et al. (2015); Kirk et al. (2015); Goodman and Reid (2017); Moser et al. (2019) **Case Studies 3, 5, and 9**

	John Day dams. o Use of a variable width entrance weir to produce sufficient attraction flows high in the water column while reducing flow velocity near the floor at Bonneville and John Day dams (Clabough et al. 2015). o Also see guidance (below) on sharp angles/corners, bulkhead slots/stop logs, and diffuser gratings, all of which can be associated with entrances.		
PHYSICAL MODIFICATIONS			
Sharp Angles/ Corners *lack of attachment surfaces*	Avoid sharp angles or corners (90°) in areas of velocities above 1.0 m/s (3.3 fps), which hinder lamprey from using burst-and-attach locomotion. Rounding (> 8 to 10 cm [~3 to 4 in] radii) the orifice walls or entrance walls is advised on both the up- and downstream sides of each wall (Figure 2). Rounding the orifice walls at an existing fishway can either be accomplished via rounding the wall or installing inserts around the wall (see Figure 1). Chamfered corners have also been used but have not specifically been evaluated and are thus less preferred.	The > 8 to 10 cm (~3 to 4 in) radii for rounded edges represents best professional judgment and not directly supported by specific research.	Keefer et al. (2010); Goodman and Reid (2017) **Case Studies 3 and 5**
Bulkhead slots/ stoplog slots *lack of attachment surfaces*	When bulkhead slots are present and velocity ≥ 1.0 m/s (3.3 fps), eliminate the slot or gap when the gates/stop logs are not in place, to provide a continuous planar surface for attachment (Figure 6). Design inserts to create a smooth continuous surface with no gaps or abrupt surface changes (bumps) in the transition between the fishway wall and the insert. For new construction, the gate bulkhead slot system can be designed so there are no slots along floor or lower walls (0.3 m or 1.0 ft) of entrance.		Keefer et al. (2010); Goodman and Reid (2017) **Case Studies 5 and 6**

Diffuser Grating *lack of attachment surfaces; potentially confusing hydrologic cues*	All diffuser grating should be sized appropriately to prevent lamprey from entering unsafe areas or dead ends. For the mainstem Columbia River, ≤ 1.9 cm (0.75 in) gap between bars is recommended. For other areas, ≤ 1.3 cm (0.5 in) gap is recommended unless site-specific information supports a larger gap to prevent entry (See Section 5.4 Diffuser Grating). ● Wall diffusers located in high velocity areas (≥ 1.0 m/s, 3.3 fps) should be elevated off the floor by at least 0.3 m (1.0 ft). ● Floor diffusers in high velocity areas: o Should be located at least 1 m (3.3 ft) upstream and downstream of weir orifices (Figures 7A and 7B). o To provide a continuous attachment surface where existing floor diffuser grating is necessary, a flat metal plate (minimum width of 0.31 m [1.0 ft]) can be used to span diffuser floors and provide attachment areas (Figures 7A and 7B). o Omitting diffuser gratings from the floors and lower walls of a fishway minimizes the stranding potential when dewatering for maintenance, inspections, etc.	The height at which wall diffusers are recommended (0.3 m or 12 in above the floor) represents best professional judgment and not directly supported by specific research.	Moser et al. (2008); Keefer et al. (2010, 2011, 2012) **Case Studies 9 and 10**
TRANSITIONAL AREAS			
Collection Channels *confusing hydrologic cues*	Assuming the problem with collection channels is associated with hydraulic cues and attraction, new construction should incorporate features to better attain uniform hydraulic flow for lamprey along the floor, while still providing opportunities for resting. The use of refuge boxes in areas in long fishways where lamprey have higher rates of fallback may prove useful (see Section 5.5 Resting Areas, Figure 8). For existing or new construction, alternative routes that bypass the collection channel (or portions of it) using LPSs could also be used if conditions and behavior suggested they might be successful.	The passage problem in these channels and appropriate solutions are site specific and not well understood at this time. Unknown how frequent refuge/ rest areas should be available, but assume more areas are needed more frequently in longer ladders.	Corbett et al. (2013, 2014, 2015); Keefer et al. (2012, 2013a); Kirk et al. (2015) **Case Studies 1, 7, and 8**

Transition Pools/ Junction Pools *confusing hydrologic cues*	New construction should ensure there are sufficient hydraulic cues for fish to continue upstream and incorporate features to better maintain uniform hydraulic flow for lamprey along the floor in these pools, while maintaining sufficient resting areas. Placement of refuge boxes as could provide such resting areas (see Section 5.5 Resting Areas, Figure 8). For existing or new construction, alternative routes that bypass these pools using LPSs could also be used if conditions and behavior suggested they might be successful.	The passage problem in these areas and appropriate solutions are site specific and not well understood.	Keefer et al. (2012, 2013a); Clabough et al. (2015); Kirk et al. (2015) **Case Studies 1, 4, and 7**
WEIR SECTIONS			
Submerged Orifices *Limited attachment surfaces*	Provide continuous planar floor surfaces for lamprey attachment until outside of the high velocity (≥ ~1.0 m (3.3 ft) area of the orifice upstream and downstream of an orifice or weir) ● Make orifices flush with the floor (no steps) and/or flush to the outside fishway wall (Figure 2). If at least one continuous planar surface is provided, (i.e., the floors), then rounded corners may not be needed at remaining edges of the orifice. ● If steps are present, ramps can be added on the downstream side of the orifice to allow for burst-and-attach locomotion (Figures 2, 3A and 3B). ● For new construction, all orifices should be flush with the floor (no step), and entrance walls should be rounded (8 to 10 cm (~3 to 4 in) radii). Chamfered corners have also been used but not specifically evaluated and are thus less preferred.	It may be beneficial, but unknown at this time, whether providing a ramp or rounded corners on the upstream side of the orifice is necessary to allow the lamprey to maintain attachment until out of the high velocity area.	Moser et al. (2002a, 2002b, 2002c); Keefer et al. (2012, 2013a) **Case Studies 2, 3, and 9**
Overflow Weirs *High velocities/ shear velocities with limited attachment surfaces*	For overflow weirs, round the weir and place the overflow section against the side wall to allow lamprey to maintain continuous attachment along the wall (Figure 1). Special inserts may be put in the guide slots (if present) to eliminate the gap and allow lamprey to use burst-and-attach locomotion (Figure 6).		Keefer et al. (2013a)

Vertical Slot *Limited attachment surfaces*	No specific recommendations, except to follow relevant recommendations provided in elsewhere in this document. Wetted wall LPS have been installed at Prosser Dam to improve upstream passage success and allow lamprey to bypass portions of the salmonid fishway.		**Case Study 7**
Serpentine Weir *High velocities/ shear velocities with limited attachment surfaces;*	In new construction, avoid serpentine weirs (Figure 4); preferentially use vertical slot (Figure 3A) or a pool and weir type ladder (Figures 1 and 2) with the appropriate modifications (rounded corners, sufficient areas of attachment where needed, etc.). For existing fishways, provide alternative routes (such as LPSs, wetted walls, tubes) to bypass serpentine weirs, as was done at the Bonneville Bradford Island and Washington-shore fishways.		Moser et al. (2006, 2011); Clabough et al. (2009); Keefer et al. (2010, 2012, 2014); Kirk et al. (2015); Goodman and Reid (2017)
Pool and Chute *Limited attachment surfaces*	No specific recommendations, except to follow relevant recommendations provided in elsewhere in this document.		**Case Study 3**
Resting Areas *Insufficient resting/ refuge areas*	Provide resting opportunities at regular intervals throughout a fishway, particularly where fishway length, elevation gain or ascent distance is substantial, or in areas where lamprey have been shown to fall back out of the fishway. Each resting area should provide areas of relatively low velocity (e.g., 0.9 m/s or less) and darkness, with natural substrate, such as the refuge boxes (Figure 8).	Unknown how frequent refuge/ rest areas should be available, but assume more areas are needed more frequently in longer ladders.	Daigle et al. (2005); Keefer et al. (2011); Corbett et al. (2013, 2014, 2015); Moser et al. (2021) **Case Study 1**

Dead ends *Unnecessary energy expenditure*	Exclude lamprey from these areas, or provide means for egress (i.e., LPSs). Isolate the areas either via picket leads or grating, or permanently remove access to lamprey (dewater the area).		Moser et al. (2006); Keefer et al. (2012) **Case Studies 4, 5, and 7**
Counting Stations			
Counting Windows	● Counting windows should extend all the way to the floor of the passage route, so there are no blind spots at the floor where lamprey may pass undetected, so that fish are easily viewed. ● Counting stations should be located near fishway exits and upstream from significant passage challenges to reduce milling behaviors, fallback and repeated attempts- all of which complicate visual counts. ● Infrared light sources should be used to improve night counting and reduce behavioral effects when most lamprey migrate. ● Use appropriate spacing for any picket lead or other exclusion grating to ensure lamprey must pass at the counting window.		Clabough et al. (2009, 2012) **Case Study 2**
Lighting	When artificial lighting is necessary, use lights < 3 lux or, preferably, infrared lighting. Also, avoid or eliminate areas/structure that will create sudden changes in fishway light conditions.		Moser et al. (2002c, 2002d); Daigle et al. (2005)
Picket leads	Gap between picket leads (or grating, etc.) should be no greater than 1.9 cm (0.75 in) in the mainstem Columbia River. For other areas, ≤1.3 cm (0.5 in) gap is recommended unless site-specific information supports a larger gap to prevent entry (See Section 5.4 Diffuser Grating). Using perforated plate, grating, or bar rack instead of pickets — where hydraulically feasible — may also further limit the potential for lamprey to pass into undesirable areas. Ensure adequate porosity when using perforated plate or bar rack material.	Gap requirement was based on lamprey sizes at Bonneville Dam in the lower Columbia. Upstream areas or other basins may require reduced gap based on site-specific information on adult lamprey size.	Moser et al. (2008) **Case Study 2**

Traps	Use traps as needed for collection of adult for passage studies, temporary trap and haul programs. Maintain adequate oxygen and temperature and check trap daily. Use mesh funnels to prevent lamprey from escaping the trap after entry. Ensure salmonid passage is not affected.		**Case Studies 7 and 11**
EXITS			
Exit location	For existing structures, exits may need to be ramped or rounded on the upstream side to allow lamprey to gradually move to lower velocity areas and away from areas where spillway or turbine currents or shearing flows could sweep lamprey back downstream and over the structure they just passed. New construction should locate exits away from hazardous areas or ensure adequate LPSs and transition areas to low velocity areas to avoid fallback.		
ATTACHMENT SURFACES			
Attachment surfaces	Ensure a smooth continuous surface (no gaps or abrupt surface changes) at least 0.3 m (1 ft) wide for the entire length of the area with velocities in excess of 1.0 m/s (~3.3 fps). Surface irregularities should not exceed 2 mm (0.08 in). For modifications that require inserts (bulkhead slots, rounding sharp corners, LPSs, etc.), flat plate aluminum (minimum width of 0.3 m [0.1 ft]) may be used to provide a smooth continuous surface for lamprey passage. Aging the structure after construction may be beneficial. To create floor ramps for lamprey to pass orifices with steps or sill blocks, concrete could be placed, formed, and smoothed. Surfaces such as smoothly painted surfaces, plastics, glass, concrete, rubber mats, etc., may also provide adequate attachment surfaces.	Surface must allow the sucker mouth of the lamprey to create a reliable seal. For Sea Lamprey, surfaces with narrowly spaced grooves of 1 mm (0.04 in) width and 3 mm (0.12 in) depth prevented attachment. No studies specific to Pacific Lamprey have been conducted.	Adams and Reinhardt (2008) **Case Studies 2, 6, 7, and 9**

OTHER			
Bollards	If necessary, employ bollards in areas with high head to provide reduced velocities, in rows spaced at least 0.35 m (1.15 ft), with staggered placement (Figure 7A). Bollards may not be necessary in areas where velocities can be reduced to ≤1.0 m/s (3.3 fps).	Use of bollards and benefits not fully understood.	Daigle et al. (2005); Keefer et al. (2011); Clabough et al. (2015); Moser et al. (2019)
Temperature	Ensure fishway temperatures are below 20º C when adult lamprey are actively migrating. Where temperatures exceed 20º C, inputs of cooler water could be added to the fishway to appropriately reduce the water temperatures. Use of shade cloth or similar material over the fishway could also lessen solar radiation effects and reduce warming.	Temperature influences swimming abilities and lamprey passage in fishways, but these effects are poorly understood.	Clemens et al. (2009, 2012, 2016, 2017b); Keefer et al. (2013a)
Predation Issues	Consider the number and size of potential predators on lamprey and incorporate measures to reduce access and opportunities of such predators. Actions may include reducing access of large predators with physical barriers (e.g., Sea Lion Exclusion Devices), use of acoustic deterrents, or hazing. For smaller predators, such as river otter, installing barriers/fencing to limit overland access into the fishway or providing refuge boxes for cover from predation may reduce predator opportunities. Other options include removal of predators by trapping. Installation of ropes, wires, sprinkler systems, or flagging may deter avian predators, such as herons. Providing natural substrate (such as large cobbles and/or boulders) in areas with no cover may also provide refuge from predators.		Tackley et al. (2008); Kirk et al. (2015); Madson and Van der Leeuw (2016); Moser et al. (2021) **Case Study 1**

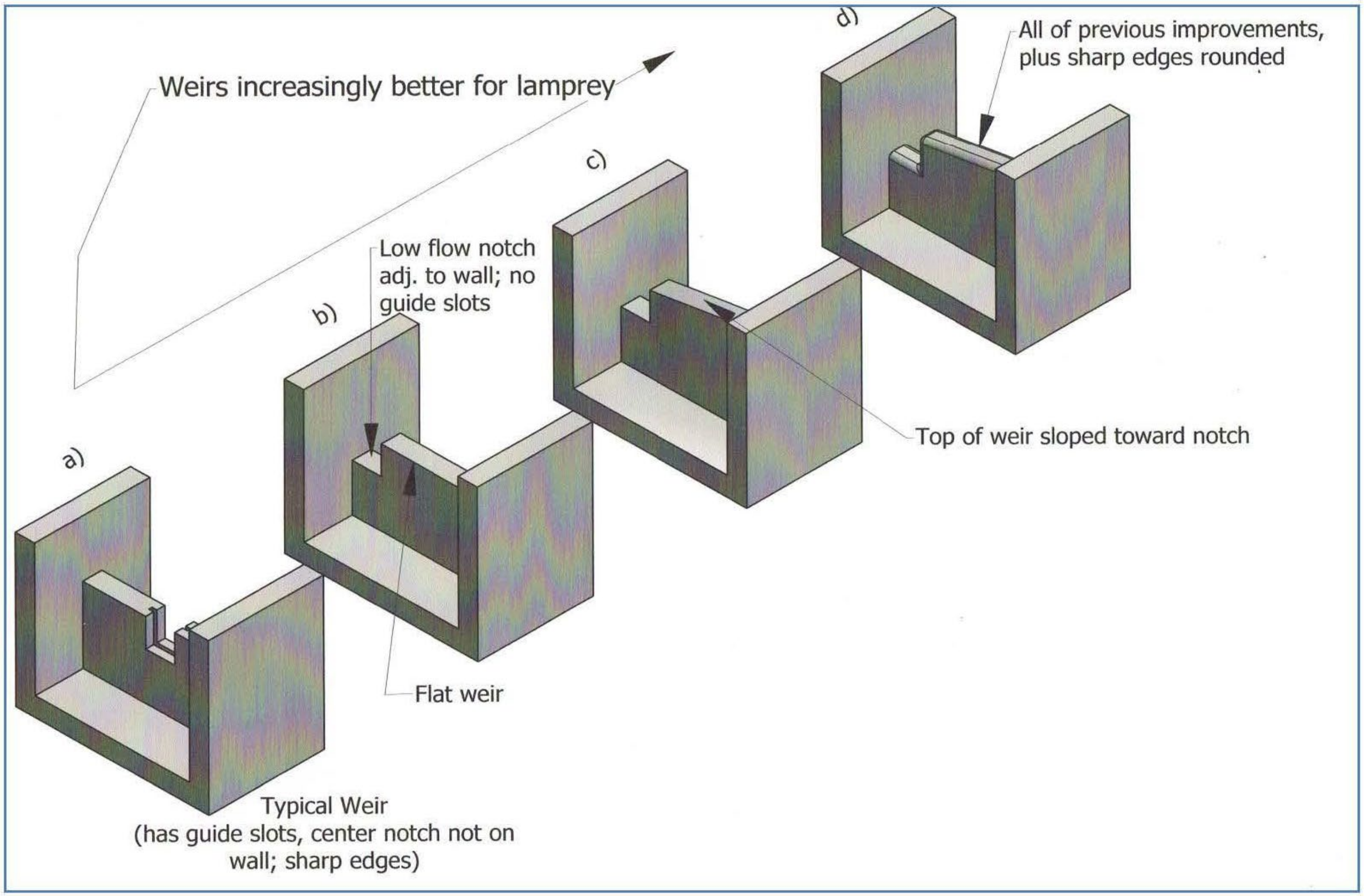


Figure 1. LAMPREY ISSUES WITH OVERFLOW WEIRS AND SUGGESTED IMPROVEMENTS FOR PASSAGE. (a) This type of passage structure is not ideal for lamprey passage because the stoplog guide slots lack a continuous planar surface for lamprey attachment. (b) Overflow weir without stoplog slots, located along the outside wall of a fishway. This configuration is expected to improve lamprey passage because the outside wall provides a continuous planar surface where lamprey should be able to use burst and attach locomotion to pass upstream. (c) This overflow weir improves upon (b) because the tallest part of the wall is gently sloped to provide an area of diminished flow (assuming water does not overtop the entire weir) which can provide improved lamprey passage. (d) This overflow weir improves upon (b) and (c) because the sharp corners have been rounded, thus providing more attachment surfaces for lamprey.

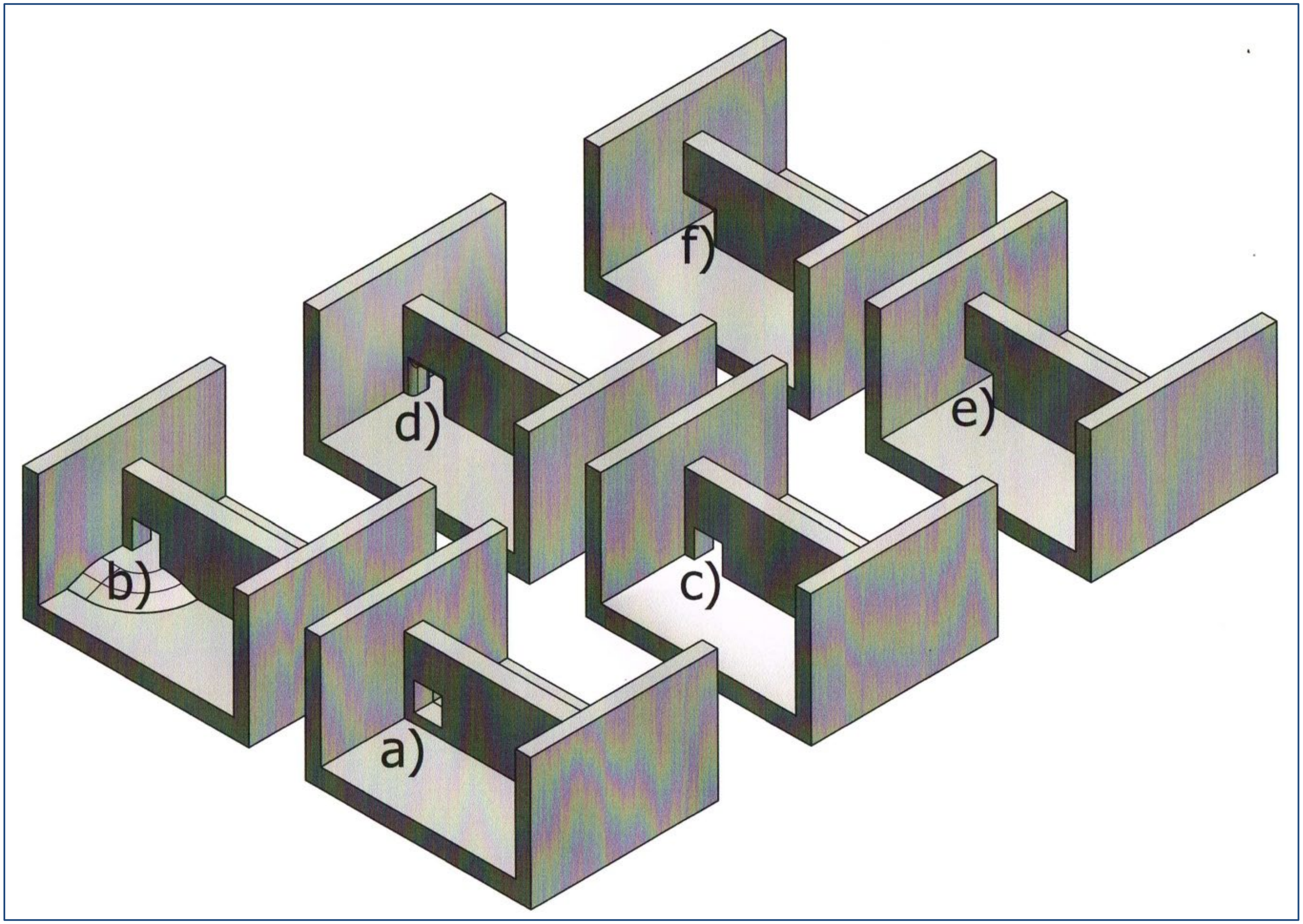


Figure 2. **LAMPREY ISSUES WITH SUBMERGED ORIFICES AND SUGGESTED IMPROVEMENTS FOR PASSAGE. (a) Typical submerged orifice has a step (perched above the floor), offset from the outer wall. This configuration does not provide a continuous planar surface for lamprey attachment. (b) The addition of a ramp on both the upstream and downstream sides of the step can improve lamprey passage by providing a continuous planar surface. Suggest a ~3:1 horizontal: vertical slope. (c) Placing the orifice along the floor of the fishway should eliminate the need for a ramp. (d) The addition of rounded edges (10 cm [~4 inches]) of the orifice walls should provide more opportunities for lamprey attachment. (e) Placing the orifice along the outer wall and along the floor provides two areas with continuous planar areas for lamprey attachment. (f) The addition of rounded edges (10 cm [~4 inches]) on all orifice corners (sides and top) also should provide more opportunities for lamprey attachment.**

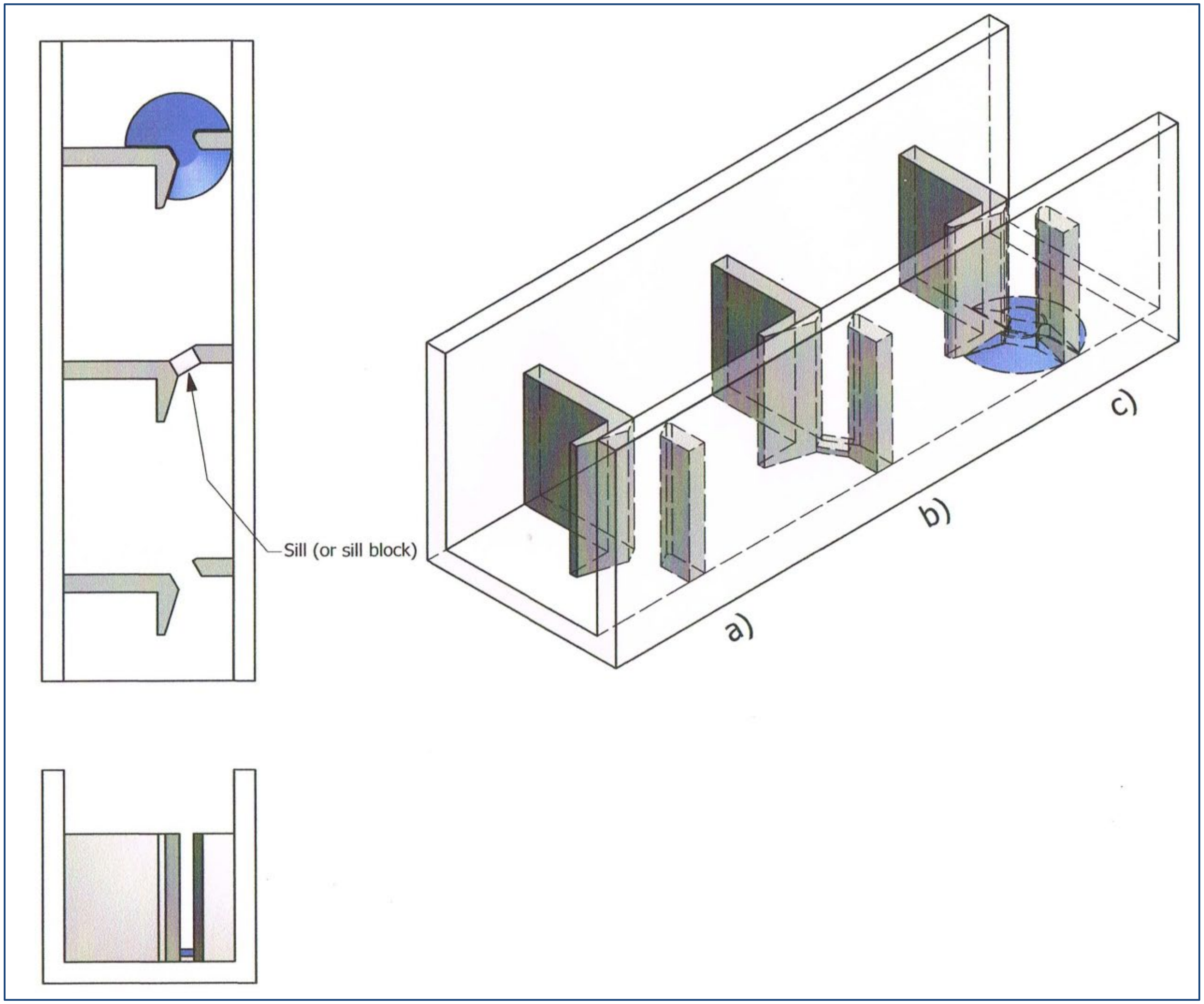


Figure 3A. LAMPREY IMPEDIMENTS AND REMEDIES AT VERTICAL SLOT FISHWAYS. (a) Weir with planar floor in slot with continuous attachment. (b) Some vertical slot fishways have sills (or sill blocks) as shown in weir (b). Sills and sill blocks are not desirable for lamprey passage because these structures disrupt continuous planar surfaces, making it difficult for lamprey to attach. (c) This weir has a ramp (see Figure 3B) over the sill block that should facilitate continuous attachment – and thus passage – by lamprey. The vertical edges of these slots are also rounded with 10 cm (~4 inch) radii to further facilitate attachment and passage by lamprey (the rounded edges are difficult to discern in this figure).

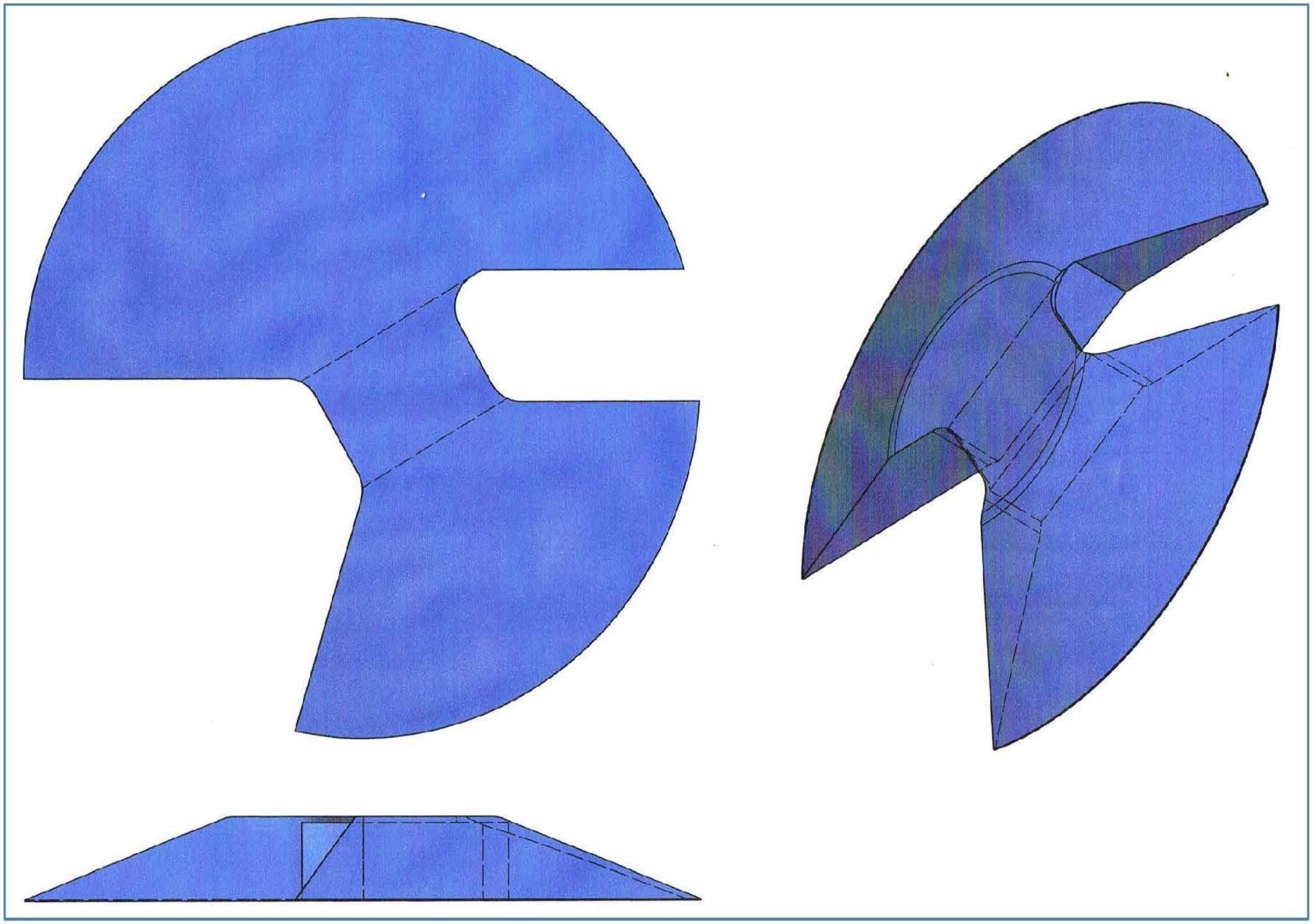


Figure 3B. RAMP FOR SITUATIONS WHERE THERE IS A SILL OR SILL BLOCK. Shown in smaller scale in Figure 3A.

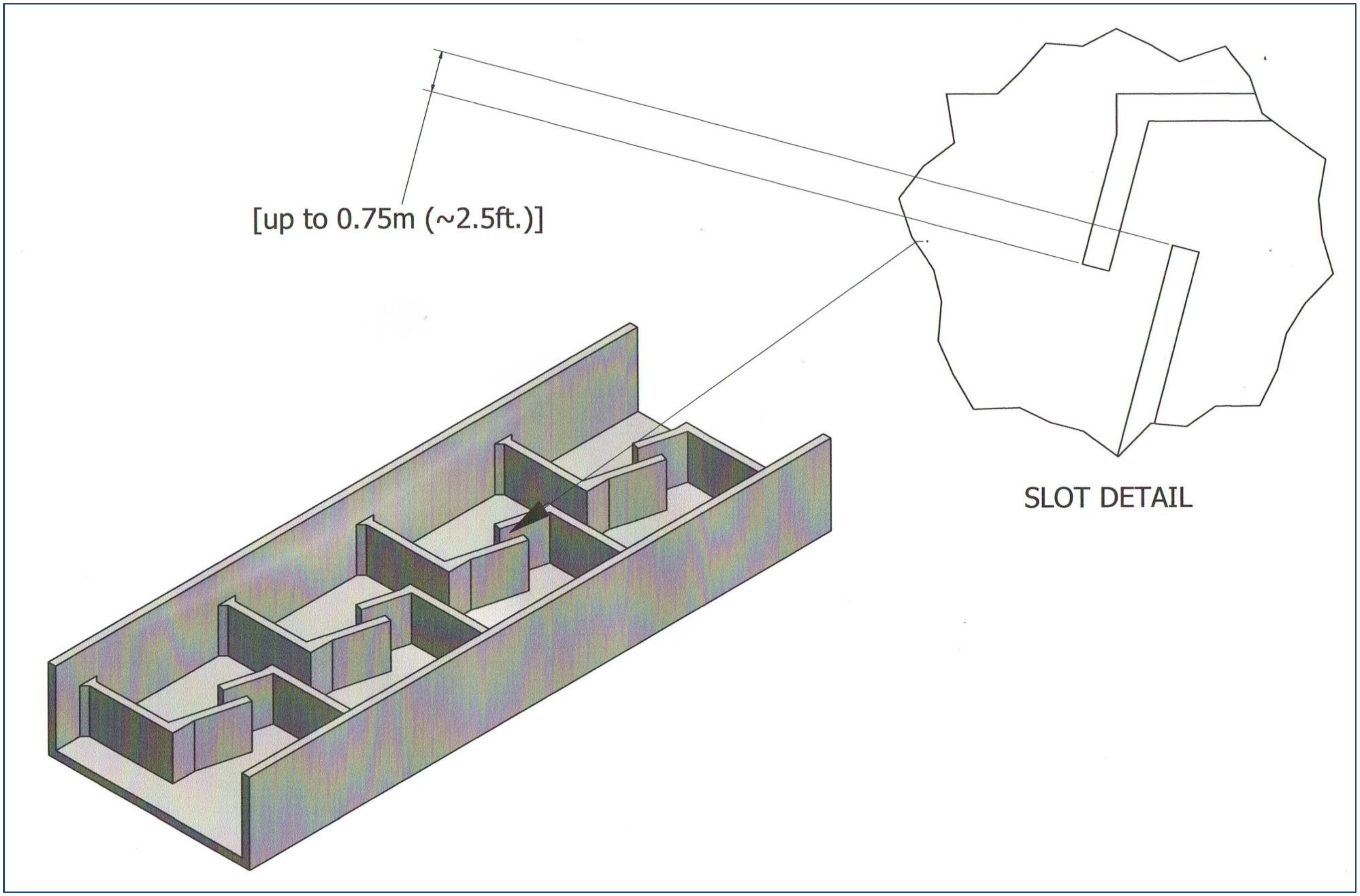


Figure 4. LAMPREY ISSUES AT SERPENTINE WEIRS. Serpentine weirs are problematic for lamprey passage because the slot configuration creates a longer length (up to 0.75 m [2.5 ft.]) of higher velocity flows relative to other types of ladders.

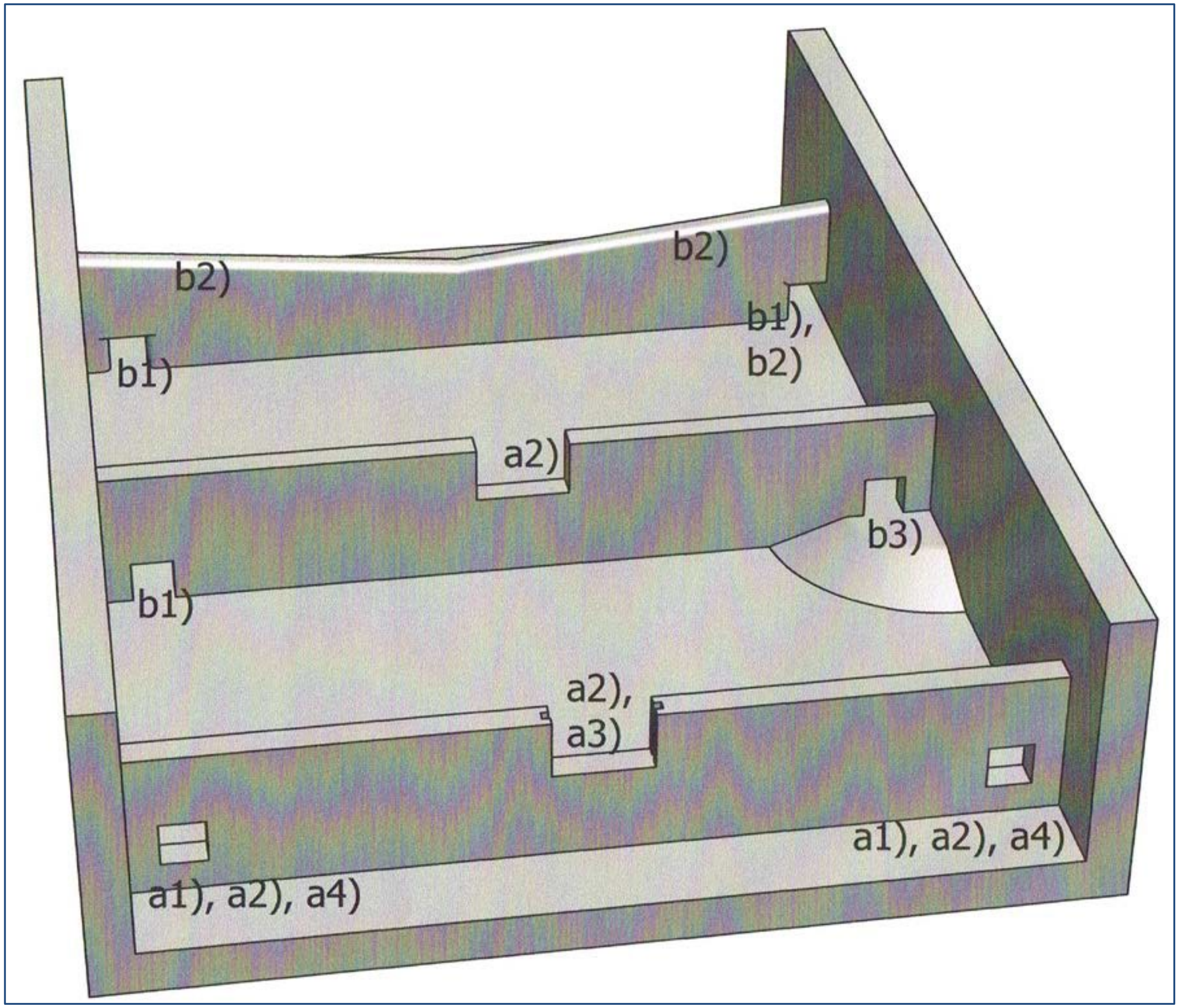


Figure 5. LAMPREY ISSUES AT VARIOUS FISHWAY FEATURES. (a) Typical fishway features are: (a1) Orifices off the floor and walls (not conducive to lamprey attachment). (a2) Weir edges are sharp (difficult for lamprey to attach). (a3) Notch has sharp-edged stoplog slots (difficult for lamprey to attach). (a4) Orifices are square-edged, set apart from the floor and walls. (b) Weir elements modified to provide for lamprey passage. (b1) Orifices lowered to the floor. (b2) Sharp edges radiused (rounded with 10.2 cm [4 inches] radii). (b3) Ramp built up to perched orifices.

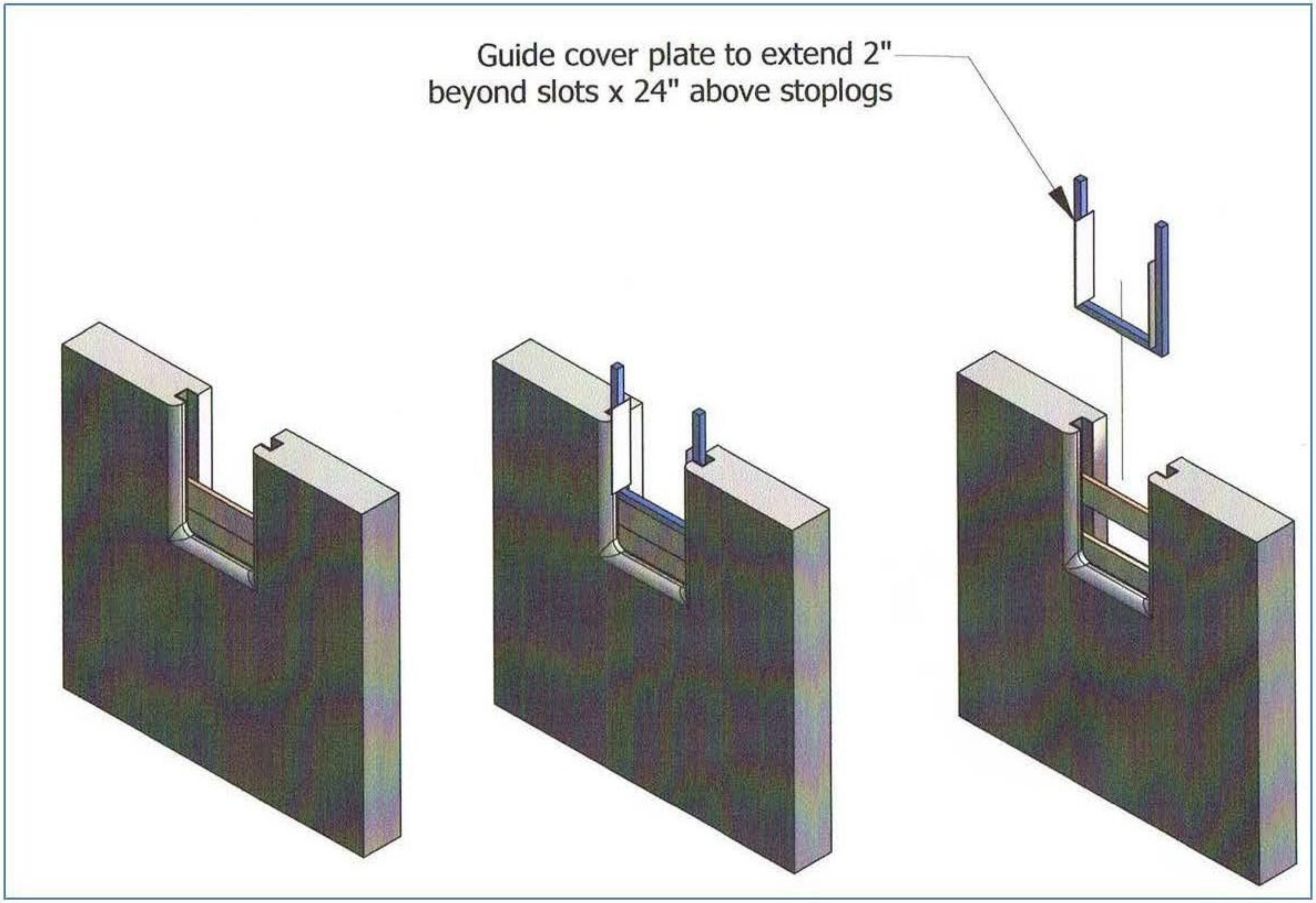


Figure 6. IMPROVED STOPLOG SLOTS (cast-in-place version). (a) Typical weir slots with stoplogs are difficult for lamprey to pass because guide slots prevent utilization of burst and attach locomotion. (b) Weir slot with covers over the guide slots. Slot covers should extend 0.31 m (~12 inches) above the water surface. (c) Exploded view of stoplog slot cover.

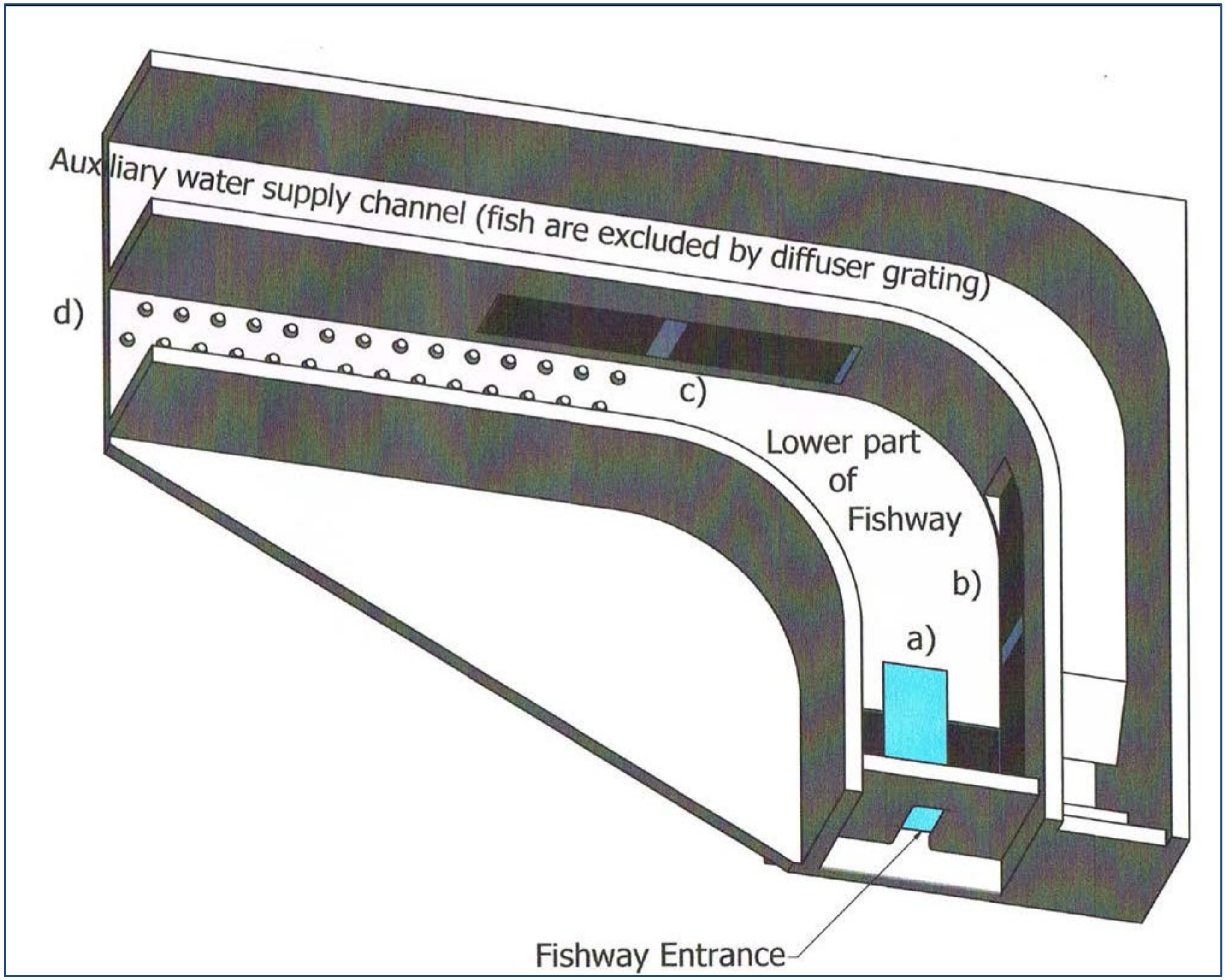


Figure 7A. LAMPREY ISSUES WITH DIFFUSERS. Aerial view of fishway: (a) Bottom diffuser immediately upstream of a gate opening. In this case it is preferred to cover the plate with a sheet of metal so that the lamprey will have something to attach to when they pass through the high velocity of the fish entrance. (b) This wall diffuser is near flush with the floor (minimal attachment opportunity for lamprey along the wall). (c) This wall diffuser is raised 0.31 m (~12 inches) above the floor, thus providing some attachment opportunities for lamprey. (d) A bollard array provides small resting areas for lamprey. Bollards may improve lamprey passage in higher velocity areas.

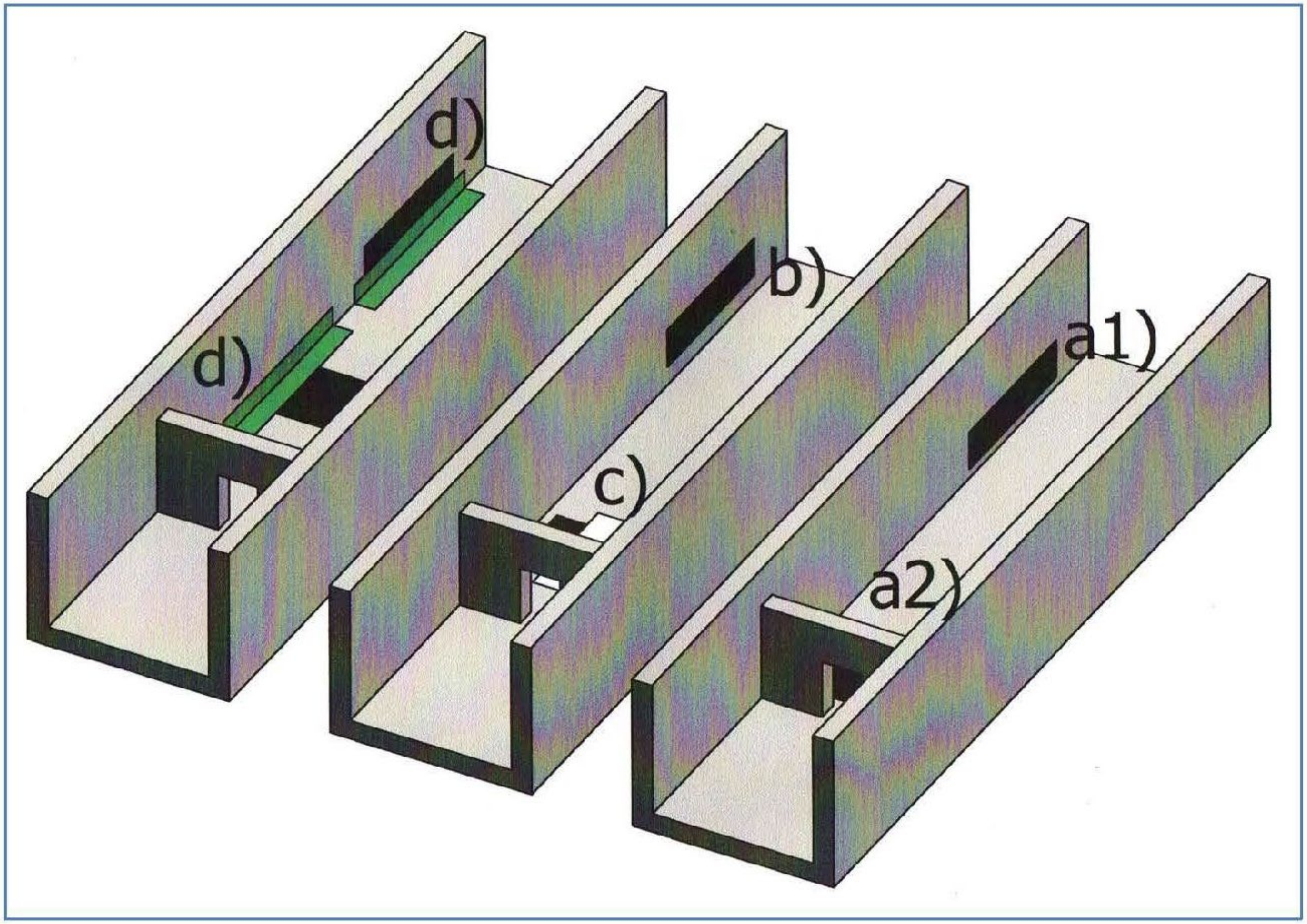
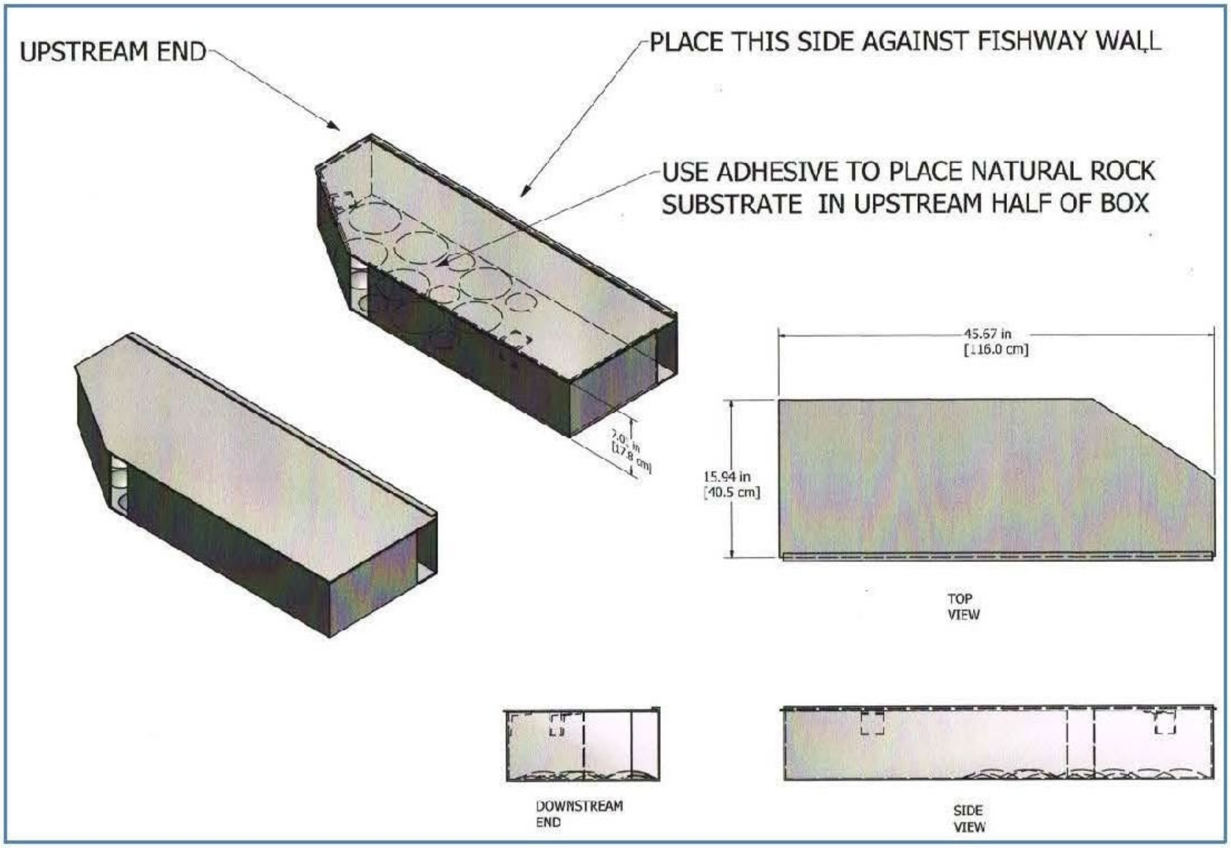


Figure 7B. LAMPREY IMPROVEMENTS AT DIFFUSERS (auxiliary water gratings). (a) Typical situation in fishways with high velocity areas (> 1 m/s [~3 fps]), which is a poor situation for lamprey passage. (a1) Wall diffuser < 0.31 m (~1 ft.) from the floor interrupts attachment opportunities by lamprey in high velocity areas. (a2) Floor diffuser is immediately adjacent to high velocity area (orifice) where attachment opportunities are needed for lamprey. (b) Improved wall diffuser because it is > 0.31 m (~1 ft.) above the floor, thus providing attachment opportunities for lamprey below the diffuser. (c) Place metal sheet over the diffuser when it is < 1 m (~3 ft.) away from high velocity orifice area. Note: In this depiction the diffuser is actually > 1 m (~3 ft.), but the plate is shown nevertheless to illustrate the idea when the diffuser is closer than shown. (d) In high velocity areas (> 1 m/s [~3 fps]) over diffusers, cover the diffuser to 0.31 m (~1 ft.) on the floor and wall to provide a place for lamprey to attach.



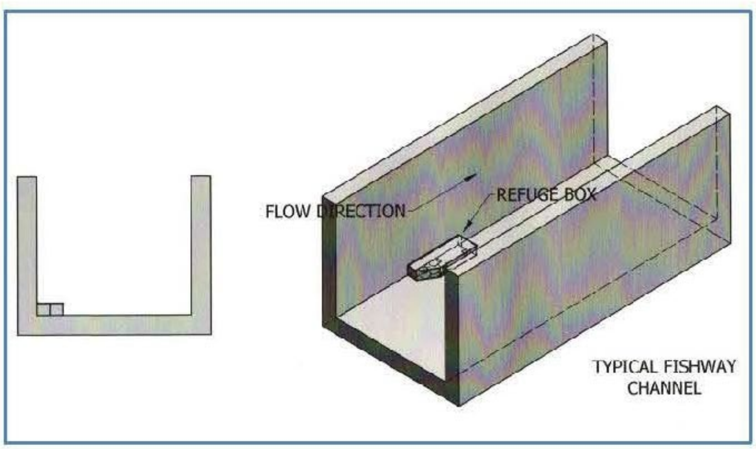


Figure 8. LAMPREY REFUGE BOX (upper) AND TYPICAL PLACEMENT OF REFUGE BOX IN FISHWAY (lower), both as described in Corbett et al. (2013).

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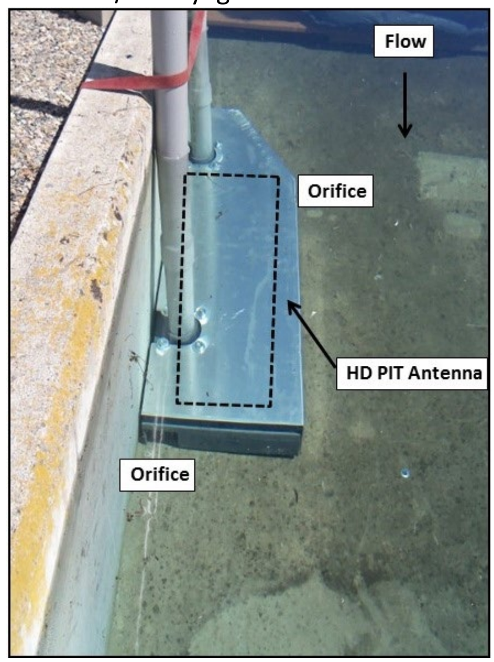
APPENDIX A.
Case Studies of Fishway Modifications to Improve Pacific Lamprey Passage.

LIST OF CASE STUDIES

Refuge Boxes for Pacific Lamprey in Fishway Bonneville Dam, Columbia River

Background

Many fish species are sensitive to unnatural features in fishways and they may delay or abandon migration when confronted with man-made passage structures. In particular, adult lamprey are nocturnal and have been observed to fall back downstream through fishways when exposed to predators and/or daylight. To reduce this fall back, we placed novel "refuges" (Figure 1) within a fishway at a Columbia River hydroelectric dam to improve retention and passage of adult Pacific Lamprey. Lamprey use of the refuges and the effect of refuge use on passage success were assessed using PIT detections and radiotelemetry.



Design Elements for Pacific Lamprey

In 2012, two refuges were installed in the upper Washington-shore fishway at Bonneville Dam, one along each wall of the auxiliary water supply channel. The channel width at this location is 9.1 m, so the 7 cm refuge openings (orifices) represented 1.5% of the channel cross-section. These low-velocity, dimly lit refuges were fitted with passive integrated transponder (PIT) antennas to detect PIT-tagged adult Pacific Lamprey that were released downstream from the dam. For each 1.1 × 0.4 × 0.2 m refuge (Figure 2), cobble substrate was cemented to the floor at the upstream end. The long axis of each refuge was oriented parallel with the flow and the orifices were positioned at the upstream and downstream ends (Figure 1).

Design Effectiveness

The refuges were operated and evaluated in 2012-14. Each year lamprey captured in the fishway were marked with a 32-mm half-duplex PIT and released approximately 3 km downstream from the dam: 977 in 2012, 1073 in 2013, and 1198 in 2014. In 2014, 599 of the PIT-tagged lamprey were also implanted with a uniquely-coded radio transmitter. Radiotelemetry data from 2014 were used to assess the relative passage success (at and upstream from Bonneville Dam) of lamprey that used a refuge relative to those that did not.

In each year of study, 12 – 35% of the PIT-tagged lamprey that were detected at the fishway exit had used a refuge. Similarly, 29% of the radio-tagged lamprey detected at the fishway exit had used a refuge. The median time that lamprey resided in the refuges each year was 14.2 - 57.2 h, but the variation among individuals was high, with some lamprey staying in a refuge for weeks at a time. The greatest use of the refuges was during the day: entrance rate peaked at 0300 – 0500 hr and lamprey typically left the refuges at around 2000 hr. Lamprey were clearly attracted to and resided in the refuges, as a much higher percentage of lamprey entered the refuges relative to their footprint on the fishway floor. Moreover, refuge usage was likely underestimated due to the high probability of PIT collisions and known antenna outages. Tagged lamprey were regularly detected in the refuges during the day and for periods in excess of 8 h, suggesting that the refuges functioned to retain lamprey that might otherwise have moved back downstream if they were unable to completely pass the fishway during the night.

The mean percentage of PIT-tagged lamprey detected at sites upstream from Bonneville Dam of those detected exiting the fishway was lower for refuge users (68%) than fish that did not use a refuge (79%). For radio-tagged lamprey, refuge users passed upstream from Bonneville Dam at a slightly lower rate (68.3%, 43/63) than non-users (72.1%, 111/154). Radio-tagged lamprey that used a refuge took longer to pass through the study area (mean= 2d, median=0.9 d) than fish that did not use a refuge (mean=0.6 d, median=0.1 d). A higher percentage of radio-tagged refuge users were last detected in the Bonneville Reservoir after passing over the dam when compared to fish that did not use a refuge. Fewer refuge users than non-users had a last detection upstream from The Dalles Dam, the next dam upstream. It is possible that extended residence times in the refuges resulted in lamprey overwintering in lower portions of the Columbia River drainage. While refuges show promise for improving lamprey retention in fishways, further study is needed to insure that these structures do not negatively affect overall lamprey fitness by delaying migration.

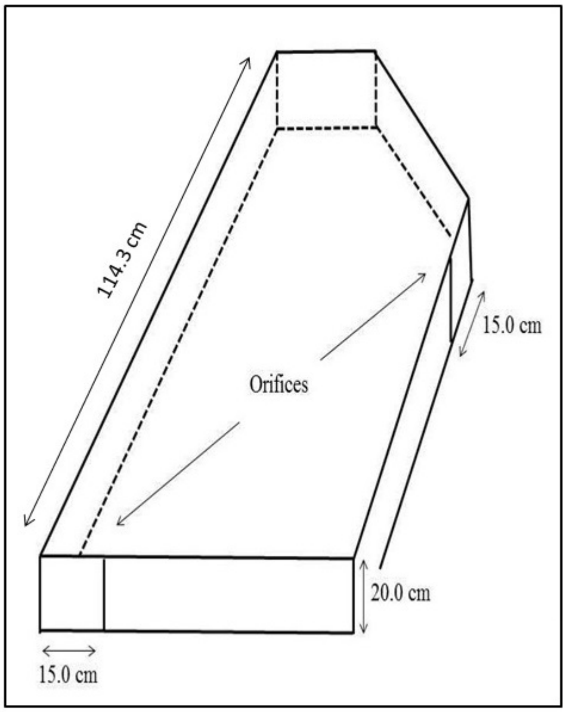


Figure 2. Dimensions of refuge box placed in the auxiliary water supply channel at the Washington-shore fishway at Bonneville Dam.

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Priest Rapids & Wanapum Fishway and Counting Station Modifications -- Grant P.U.D.

Background

Priest Rapids and Wanapum dams, collectively referred to as the Priest Rapids Project were constructed on the mid-Columbia River in the early 1960's. As part of their FERC license requirements, Grant County PUD installed several new structures in the existing fishways at both dams to improve lamprey passage. Improvements were made to the counting station that forced upstream migrating lamprey to pass at this location and improve count accuracy. In addition, flat aluminum plating to provide attachment surfaces around all existing floor diffusers was installed. Grant P.U.D. completed these upgrades in 2010, which were subsequently evaluated using underwater video.

Design Elements for Pacific Lamprey

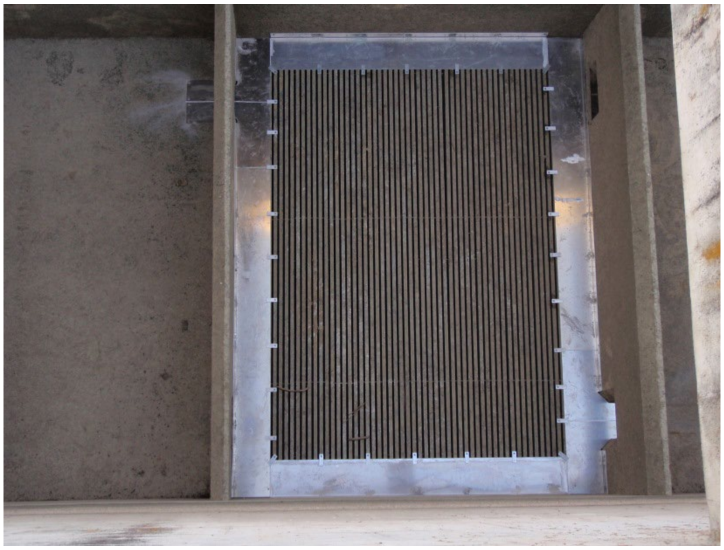
The Priest Rapids and Wanapum fishways are similar in design with both orifice and overflow weir features. Priest Rapids flows range from 12-16 cfs and ascends ~ 74 vertical feet while Wanapum ranges in flow from 12-14 cfs and ascends ~72 vertical feet. The newly installed structures included flat aluminum plating on perimeter of all diffusion grating pools (approximately 16 inches in diameter, Fig.1) and through all weir orifice openings (Fig. 2). The count station was also redesigned to force lamprey to pass through the counting window (Fig. 3), thereby improving accuracy of the adult lamprey counts (previous count stations utilized picketed leads which were easily accessed by adult lamprey). The new count stations includes: a crowder and lamprey ramp angled to guide lamprey to the window (open gap size of 11/16"); a solid ramp leading to the window entrance (approximately 16 inches diameter at ~ 45 degree pitch), and plating (1/4" thickness) at the floor-to-crowder transition to improve guidance.

Design Effectiveness

To evaluate the effectiveness of the lamprey passage modifications, multiple underwater video cameras were installed at strategic locations to collect video imagery of "lamprey events" at these structures. Each event was analyzed according to a behavior protocol; the utility of structures was inferred from summary statistics of behavior criteria.

A total of 23 events were documented at the orifice with aluminum plate. Seven out of 10 lamprey approached the orifice from the immediately downstream and over the diffuser grating. All lamprey swam in the lower half of the orifice, with 95% (18/19) passing on the first attempt, and 100% passing on the second attempt. Most (78%) traveled along the center of the plate and all (95%) attached to the plate at least once. Rare attachments off the plate suggests the plating dimensions are adequate. Plating at the orifice was extensively used, events were of short duration, and all passage attempts were successful.

A total of 123 events were documented at the crowder/counting station; 93 of those events were passage attempts. Of the 93 lamprey that attempted to pass, 94% (87 fish) succeeded. Forty-three percent of those fish use the solid ramp. Plating at the crowder was used by about half of the migrants and search behaviors for count entrance were largely successful. Overall, the crowder guided most lamprey to the chute. Lamprey behavior indicates that plating facilitates passage.



Figures 1-2. Photos of Priest Rapids fish ladder, showing use of flat plating for attachment.

Figure 3. Priest Rapids fishway- approach to counting window and modifications for lamprey.

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River Mill Dam Fish Ladder – Clackamas Hydro Project
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River Mill Dam was completed on the Clackamas River, Oregon in 1911. At the time, the fish ladder included as part of the dam project was considered state-of-the-art. By modern day standards however, the River Mill ladder lacked many of the design elements considered standard even for salmon passage. While passage for steelhead trout and coho salmon was reasonable, the overflow weir style ladder with its short cells, tight turns, and relatively low flow volume posed a challenge to Chinook salmon. No design elements for Pacific Lamprey were included, and the ladder exit with its false weir type design was likely a barrier to lamprey passage. As part of re-licensing the Clackamas Hydro Project, PGE replaced the original ladder, completing the new ladder in late 2006.

Design Elements for Pacific Lamprey

The River Mill ladder was designed to meet all applicable design standards for passage of anadromous salmonids. The ladder is a half Ice Harbor style ladder operated with a flow of approximately 19 cfs and ascends a height of approximately 85 feet. The ladder includes several design characteristics to facilitate the passage of Pacific Lamprey adults. These design elements include:

- Rounded entrance corners (6” radius)
- Flush mounted entrance gates sit within bulkhead slots for smooth attachment (Figure 1)
- ¾” spacing floor diffuser gratings
- 12” solid concrete floor on either side of floor diffuser gratings for lamprey attachment
- A secondary ladder entrance with a head differential of 0.75 ft (lower velocity relative to primary entrance)
- 6” chamfered upstream and downstream edges of weirs and orifices (Fig. 1)
- Continuous attachment along walls adjacent to weirs
- Rounded corners throughout ladder (Fig. 1)
- Adjustable exit weirs have filled bulkhead slots

Figure 1. Photos of Pacific Lamprey passage design elements of the River Mill fish ladder. Rounded entrance and filled entrance gate bulkhead slot (left), chamfered orifice and weir (middle) and rounded ladder corner (right).

Design Effectiveness

Adult Pacific Lamprey passage evaluations of the River Mill fish ladder were conducted in 2013 and again in 2015. In both years, dual tagged (PIT and radio) and PIT tagged fish were released approximately 1km downstream of the dam. Fish receiving tags had previously been captured in a trap in the River Mill ladder. In 2013, dam passage rate estimates were 84% and 96% for dual tagged and PIT tagged fish respectively. When the study was repeated in 2015, the results from 2013 were confirmed with passage rate estimates of 90% and 94% for dual and PIT tagged lamprey. For dual tagged fish, passage rate estimates were derived by dividing the number of fish that successfully passed the dam by those that approached the tailrace. Passage rate estimates of PIT tag fish were estimated by dividing the number that passed the dam by the number released.

Taking a more refined look with radio tag data, the entrance efficiency of the ladder (number entering out of number approaching) was 90-92%, with 94-100% of fish that entered the ladder successfully reaching the forebay. Passage times confirm the efficacy of passage at River Mill. The median time spent from arrival in the tailrace until arrival in the forebay was 1.6 d in 2013 and 2.1 d in 2015 while median passage time through the ladder itself was only 0.9 d and 0.7 d respectively.

Among the two ladder entrances, radio tagged lamprey predominately used the primary ladder entrance despite the higher entrance velocity. For example, in 2015 of 20 successful ladder entries made by radio tagged lamprey 19 of them occurred at the primary entrance. This was driven by the fact that there were far more approaches to the primary entrance. The primary entrance is on the powerhouse side of the dam where the preponderance of attraction flow to the dam exists.

Table 1. River Mill Dam passage rate estimates of PIT and dual tagged Pacific Lamprey in 2013 and 2015.

				Passage Rate	
Year	Tag Type	# Released/In TR[1]	Estimate Passing[2]	Estimate	95% CI
2013	PIT	42	40.3	96%	68-100%
	Dual	37	31.0	84%	69-92%
2015	PIT	51	47.6	94%	86-100%
	Dual	20	18.0	90%	77-100%

1. Number released for PIT tagged fish and number arriving in the tailrace for dual tagged fish.
2. Consider estimate of number passing for PIT tagged fish after accounting for detection efficiency of the PIT antenna array.

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Three Miles Falls Dam
Umatilla River, Oregon

Background

Three Miles Falls Dam is the first major obstacle that pre-spawning adult Pacific Lamprey encounter in the Umatilla River, Oregon. It is fitted with a fish ladder that has been shown to have low passage efficiency for lamprey (Jackson and Moser 2012). The Confederated Tribes of the Umatilla Indian Reservation secured funding from the U.S. Fish and Wildlife Service and Bonneville Power Administration to install a lamprey-specific passage system (LPS) in summer 2009. The LPS design was developed in consultation with a variety of fish and water management agencies and it was positioned next to the existing fishway entrance to minimize effects on other species, while affording the best possible access for lamprey.

Design Elements for Pacific Lamprey

Modular LPS elements were designed and fabricated at the Pasco Research Station (National Marine Fisheries Service) and transported for installation at the dam. The structure was made of aluminum (5052 alloy sheet aluminum and 6061 alloy structural shapes) with all stainless steel fasteners to reduce weight, prevent corrosion, and allow flexibility in design modification and installation. All elements were fabricated using fish-friendly construction (i.e., no rough edges, all corners rounded, no metal burrs, no application of caustic agents, etc.). For installation, each element was custom-fitted on site during low water conditions (Figure 1).


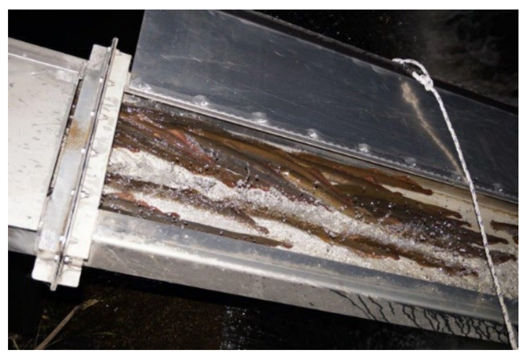

Figure 1. Photos of Three Mile Falls LPS with dual 60° entrance collector ramps that terminate in a large rest box (left). The 45° climbing ramp from the rest box to the exit slide was covered to protect lamprey from predators and reduce algal growth on the ramp (right). This ramp terminated in a horizontal section leading lamprey through an HDX-PIT antenna, into an upwelling box, and down an exit slide to an open trap box in the dam forebay.

Ambient Umatilla River water was pumped to the upwelling box at the structure's terminus to maintain approximately 2 cm depth on the LPS ramps. Lamprey passed through the upwelling box and dropped into a trap box where they could volitionally exit to the dam forebay. A mechanical counter was positioned at the terminus of the exit slide to enumerate lamprey passing into the trap box.

Design Effectiveness

Adult Pacific Lamprey passage evaluations at Three Mile Falls were conducted from 2005 – 2014 using radiotelemetry (Jackson and Moser 2012). In addition, LPS use by HDX-PIT-tagged adult lamprey was assessed from 2009 to 2014 and counts made at the LPS exit were compared to those made at the fishway, along the eastern wall of the dam and via assessment traps (Figure 2). Prior to LPS installation, mean fitted probability of lamprey passage at Three Mile Falls Dam was 25% (Jackson and Moser 2012). After LPS installation, average passage efficiency for radio-tagged lamprey was 44%. In addition, the proportion of lamprey using the LPS relative to other passage routes increased steadily after LPS installation (Figure 2). Planned improvements include the installation of covers on the collector ramps to protect lamprey from otter and bird predation (which has been documented in recent years).

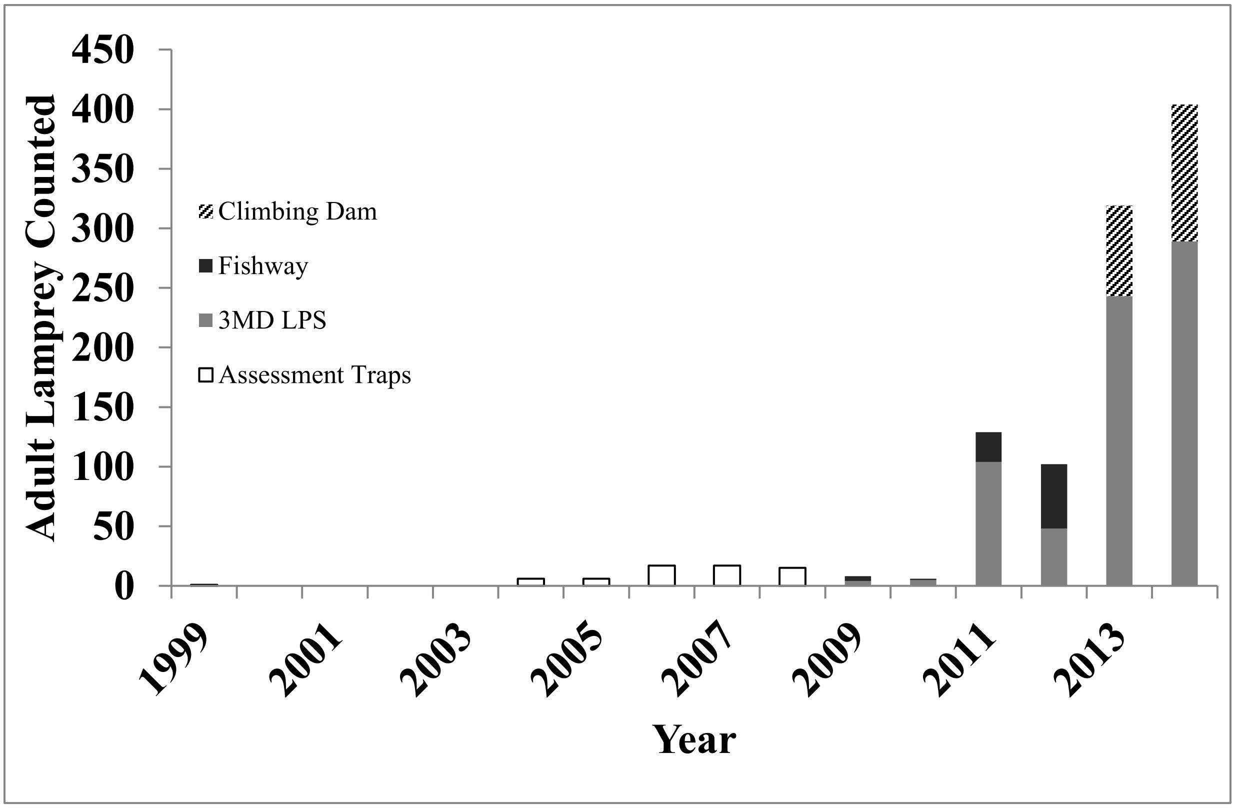

Figure 2. Lamprey counts at the LPS at Three Mile Falls Dam (gray bars) relative to counts at the fishway (solid bars), climbing vertically along the wall on the dam's east side (counting started in 2013, hatched bars), or captures in assessment traps at the fishway entrance (operated 1999-2009, open bars).

Jackson, A.D. and M.L. Moser. 2012. Low-elevation dams are impediments to adult Pacific Lamprey spawning migration in the Umatilla River, Oregon. North American Journal of Fisheries Management 32:548–556.

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Adult Fish Return Channel Fish Ladder
Walterville Hydro Project, McKenzie River, Oregon
Eugene Water & Electric Board

Background

The adult fish return channel (channel) for anadromous fish at the Walterville tailrace barrier is intended to provide a route of passage away from the tailrace and back to the mainstem McKenzie (Figure 1). Prior to construction of the channel, fish were attracted to the outflow from the Walterville tailrace, and observations of salmon holding below the tailrace barrier were of concern. To increase attraction into the channel, modifications were made in 2010 to the entrance of the channel adjacent to the tailrace barrier. These modifications included new construction of a two-step, vertical slot fishway to improve the volume and velocity of water for attraction.

Design Elements for Pacific Lamprey

The new fishway at the channel was designed to meet all applicable design standards for passage of anadromous salmonids. The ladder is operated with a flow of approximately 26 cfs and ascends a height of approximately 2 feet. The ladder includes several design characteristics to facilitate the passage of Pacific Lamprey adults. These design elements include:

- Rounded entrance corners (6” radius)
- Entrance gate designs so there are no bulkhead slots in the lowest 12” (Figure 2-left).
- Rounded step at entrance (6” radius)
- Continuous attachment along walls adjacent to weirs as rounded edges used throughout ladder.

Figure 1. Overhead view of the Walterville Tailrace and Adult Fish Return Channel on the McKenzie River.

Figure 2. Photos of Pacific Lamprey passage design elements. Rounded entrance walls and step, and lack of bulkhead slot in the lower 12”, immediately above the step (left, looking upstream); rounded entrance walls and slot from above (right).

Design Effectiveness

No specific passage studies for Pacific Lamprey have been conducted at this facility to date.

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Willamette Falls Hydro Project- Willamette River, Oregon
Portland General Electric

Background

Willamette Falls is a naturally occurring, horseshoe-shaped, 40 ft high basalt rock formation that marks the upstream boundary of tidal influence on the Willamette River. A concrete cap ranging from 6-20 ft runs the entire 2,950 ft crest of the Falls. During summer low flow conditions, wooden flashboards are installed along the concrete cap to increase river elevation and flow through the PGE Sullivan Powerhouse. In 2007, a flow control structure was constructed at the apex of the Falls to focus flow in a location that provides safe and efficient passage for downstream migrating fish.

In 1880 the first fish ladder was completed at Willamette Falls by blasting stepped pools into the solid rock of the Falls. In 1971, fish passage was again improved when Oregon Department of Fish and Wildlife (ODFW) finished construction of a new fish ladder. Part of the new ladder bisects the original ladder creating a passage barrier at the point of intersection. The new ladder consists of three separate legs that join in a common area referred to as Pool-48. Upstream of Pool-48 is the ODFW fish viewing window where pickets are used to crowd fish in front of the window for enumeration. Upstream of the fish viewing window the ladder exits into the forebay between the Falls and the Sullivan Powerhouse.

Design Elements for Pacific Lamprey

Steps to improve lamprey passage have been taken at a number of areas around the Falls. Improvements were made to the fish ladder leg 1 entrance, construction was completed upstream of the old fishway to provide passage into the forebay, and three lamprey ramps are installed annually with the construction of the flashboards along the cap.

Fish Ladder Leg 1: Original construction of the Willamette Falls fish ladder predated lamprey passage design elements. Modifications were made to the leg one entrance to improve passage for lamprey entering through the “cul de sac” side of Willamette Falls at the Sullivan Powerhouse tailrace. These modifications include:

- Chamfered edges for continuous attachment around entrance corners
- Entrance gate with filled bulkhead slot
- Orifice of entrance modified to reduce water velocity to accommodate Lamprey burst swimming speeds through a wide range of tailrace elevations.
- Continuous attachment points on the floor and walls at the entrance to leg 1.

Old Fishway: The old fishway was abandoned with the construction of the new fish ladder in 1971. This area still receives water from normal river flow into late spring, attracting migrating lamprey to the area. Once in the old fishway there is no available route for upstream passage. Stranded lamprey are observed in this area annually and were previously removed through manual salvage. In 2009 steps were taken to create passage from the terminal end of the old fishway over the cap:

- 12” to 24” fine aggregate concrete curb accommodating changing slope as it traverses 180 linear feet and 8’ of elevation. Rounded edges and smooth aggregate provide attachment points along the length of the structure.
- 8” flow valve providing 2-4cfs depending on forebay elevation
- Adjustable exit gate for changes in forebay elevation
- 8” diameter at top of exit gate
- 3/16” Buna rubber gasket material draped over the face of the exit gate to remove seems created where the two panels bifurcate.
- Fine aggregate smooth concrete step below exit gate with a rounded 90 degree corner to provide continuous attachment surface.

Figure 1. Photos of lamprey curb with flow line open (left) and lamprey exit gate, smooth concrete step, and 8” flow line (right).

Flashboard Lamprey Ramps: Wooden flashboards installed on top of the cap create a passage barrier for lamprey that attempt to ascend the falls during low flow conditions. Passage over the flashboards is provided by annual lamprey ramp construction. Lamprey ramp location is consistent from year to year and was chosen based on lamprey congregation observations. Specific design elements include:

- Smooth epoxy coated section of concrete cap directly below ramp (cleaned annually to remove algal mat to improve lamprey’s ability to “suction” onto surface)
- 4” curb with 12” wide resting pool running the length of the ramp
- 3/16” Rubber mat facing for flashboards and resting curb
- 6” diameter rounded transition at top
- Rope avian Deterrent structure
- “Cattle guard” to reduce debris accumulation
- 1- 6” varying flow depth across top of lamprey ramp
- Fast installation

Design Effectiveness

In 2009, 145 lamprey were captured in the fish ladder or by hand from Willamette Falls, implanted with a radio tag, and released 1.5 miles downstream. Of the 145 tagged fish, 135 fish returned to the vicinity of the Falls. As the percentage of river flow through the powerhouse increased in the summer, use of ladder leg 1 became more prevalent. Overall, fifty seven (42%) of these fish successfully passed the Falls and all did so through the ODFW fish ladder with 68% passing through leg 1. Eighty three percent of fish entering leg 1 (N=39), 70% of fish entering leg 2 (N=7), and 100% of fish entering leg 3 (N=11) passed upstream successfully. Tagging and monitoring efforts completed by the Confederated Tribes of the Warm Springs (CTWS) have found similar passage rates with 28.4% to 45.9% of lamprey released below the Falls successfully passing through the fish ladder (Baker and McVay 2015).

Immediately following dewatering of the old fishway in the spring the area is accessed to open the 8” flow valve and to place the exit gate into operation. It is not uncommon to observe hundreds of lamprey in the channel below the gate when the area is first accessed. After opening the exit gate lamprey are regularly observed ascending the exit gate and during subsequent trips to the area there are very few, if any, lamprey remaining. In 2014, camera monitoring was completed by the CTWS to enumerate fish ascending over the exit gate. This work showed a total of 1,748 lamprey passing the structure with half of the lamprey ascending in the first 24 hours after gate opening (Baker and McVay 2015).

Figure 2. Rubber faced lamprey ramp and resting pool curb (left), debris “cattle guard” (center), and epoxy coated concrete and avian deterrent (right).

Similar to passage at the old fishway, the highest usage of lamprey ramps over the flashboards is observed shortly after the ramps are placed into service. There is very little new recruitment to the ramps under the decreased flow conditions and fish that are in the channels below the ramps vacate the area relatively quickly. Lamprey use at these structures has been observed to vary from year to year indicating that timing of flashboard construction and lamprey distribution affect usage.

Reference:

Baker, C., and C. McVay. 2015. Willamette Falls Lamprey Study. 2014. Annual Report to BPA, Project No. 2008-308-00, Confederate Tribes of Warm Springs Reservation of Oregon. Warm Springs, OR.

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Yakima River Prosser Dam
Vertical Wetted Wall Lamprey Passage Structure

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Jim Simonson, Fishhead Technology
Susan Camp, Bureau of Reclamation Pacific Northwest Region

Background

Prosser Diversion Dam, constructed in 1904 by private interests and now operated by the Bureau of Reclamation, is located at the City of Prosser (river km 75). The facility consists of a concrete weir structure (2.7 m tall, 201 m long), an irrigation and power generating canal on the left bank (Chandler Canal with 1,500 ft^3/s capacity), and three vertical slot fishways (Figure 1). Over the last two decades, the number of adult Pacific Lamprey returning to the Yakima River has been minimal, with counts at Prosser Dam ranging from 0 to 86 individuals per year. Radio telemetry studies of Pacific lamprey from 2012 – 2014 found that overall passage efficiency for lampreys that approached Prosser Dam was 48% (36% during the fall and 53% during the spring). Video counts indicate that Pacific Lampreys use all three fishways, but use of each ladder changes seasonally (Figure 2). This seasonal variation indicates that several passage routes may be needed to provide successful passage for significant numbers of migrants.

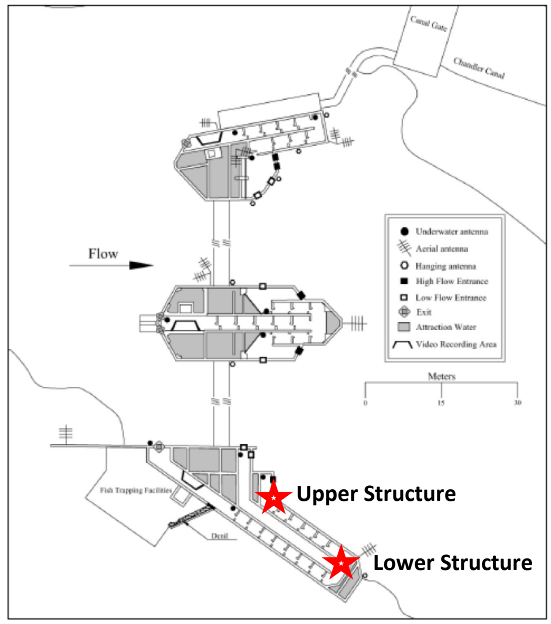

Figure 1 **(above).** *Schematic drawing of the right, center, and left fishways at Prosser Dam. Locations of the two new vertical wetted wall passage structures are also shown (red stars).*

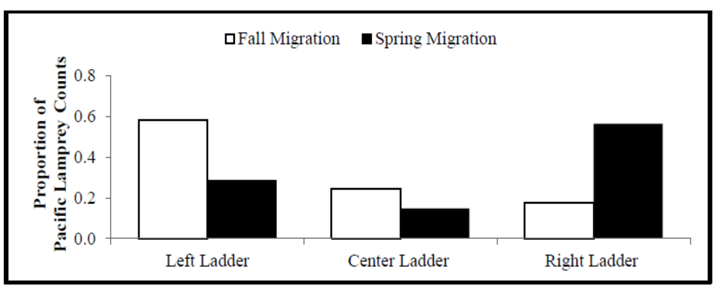

Figure 2 (left). *Proportion of adult Pacific Lamprey video counts by migration season (fall and spring) and ladder location (left, center, and right) at Prosser Dam.*

Vertical Wetted Wall Lamprey Passage Structure

A unique behavior of Pacific Lamprey is their ability to climb vertical walls where water sheets down the surface. As a result of multi-agency collaboration, two vertical wetted wall (VWW) lamprey passage structures (designed by Fishhead Technology) were deployed at Prosser Dam on November 7, 2016, to provide alternative passage options for adult Pacific Lamprey (Photo 1). Each VWW consists of a vertical aluminum sheet that extends into the water with a smooth radius crest that lead to a holding tank with a submersible sump pump (Dayton Model #1XHV7 ½ HP). Flow rate is approximately 60 gpm, with 10 ft of head. The vertical portion is 8-14 ft high, depending on river flow levels. The VWWs were deployed well before the regular lamprey passage season to allow aluminum to "age" to reduce the presence of repellent olfactory cues from construction. Locations for the VWWs at Prosser Dam (Figure 1) were determined based on radio telemetry results, local best knowledge, and

ease of access. Although the VWW is still an experimental device, the primary advantages are: 1) proven way to effectively pass lamprey, 2) cost effectiveness, 3) ease of construction, operation, maintenance, and modification with a modular design, and 4) compatible with current infrastructure with a very small footprint in the water. Once the best locations for the VWW lamprey passage structures are verified, volitional passage can be attained by linking the VWW to other ramp or pipes to reach the forebay of the dam.

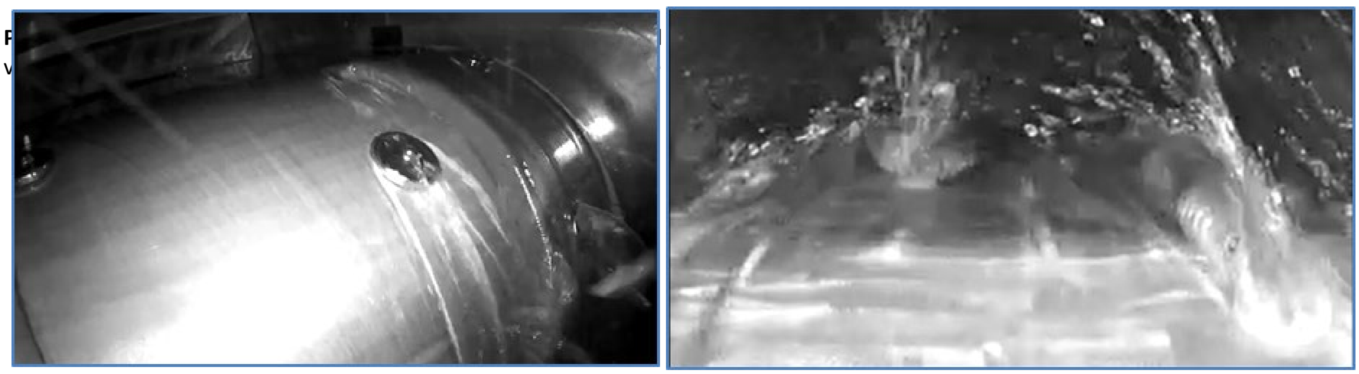

Photo 2. Lamprey successfully passing the radius curve on April 30, 2017 (1st night after the round magnets were added) (left photo). Strategically placed magnets effectively break up the flow and allow lamprey to choose the best path for their passage based on their preferred flow conditions (right photo shows the view from the top with multiple lamprey climbing the center with a flow break created by the magnets).

<u>**Lesson #1A:**</u> The flow rate needs to be balanced effectively to maximize both attraction and ease of access. Too much flow will make the climbing difficult (most lamprey only traveled close to the edges where they encounter reduced flow) and too little flow will limit the attraction and motivation of lamprey to climb. **Resolution ->** use the maximum flow from one pump (~60 gpm in our case) but add small round magnets (2-3" diameter) that break up the laminar flow and produce diverse flow conditions. Variable flows and hydrologic "micro-features" on the VWW effectively created many alternative routes that lamprey used to climb in addition to the edges of the structure (Photo 2). Lamprey were also observed using a "buddy system" in which lamprey upstream acted as a flow buffer for lamprey downstream, aiding their climbing; magnets in essence served this role (without the presence of lamprey).

<u>Lesson #1B</u>: Small distinct ridges on the radius curve made it very difficult for lamprey to maintain their suction. Resolution -> grind down the ridge lines on the radius curve to make it as smooth as possible.

<u>Lesson #2:</u> Many lamprey did not enter the holding tank immediately after climbing to the top of the VWW and a portion of them fell back down the VWW. These fallbacks and delays were likely due to 1) the confusing attractant flows through perforated plates near the entrance to the holding tank and 2) the shape of the tank entrance (a 90 degree bend). **Resolution ->** adding a solid aluminum sheet on the bottom panel near the entrance hole reduced the amount of searching behavior (likely for flow); and reducing the angle of the bend substantially decreased the "wandering" and "holding" behavior at the entrance.

Photo 3. *Lamprey passing through the curved radius with minimal effort after the ridge lines on the radius curve were smoothed out allowing for improved oral disk suction. See Photo 2 (left) for the "before" photo (equally-spaced horizontal ridge lines that are narrower than the lamprey's mouth).*

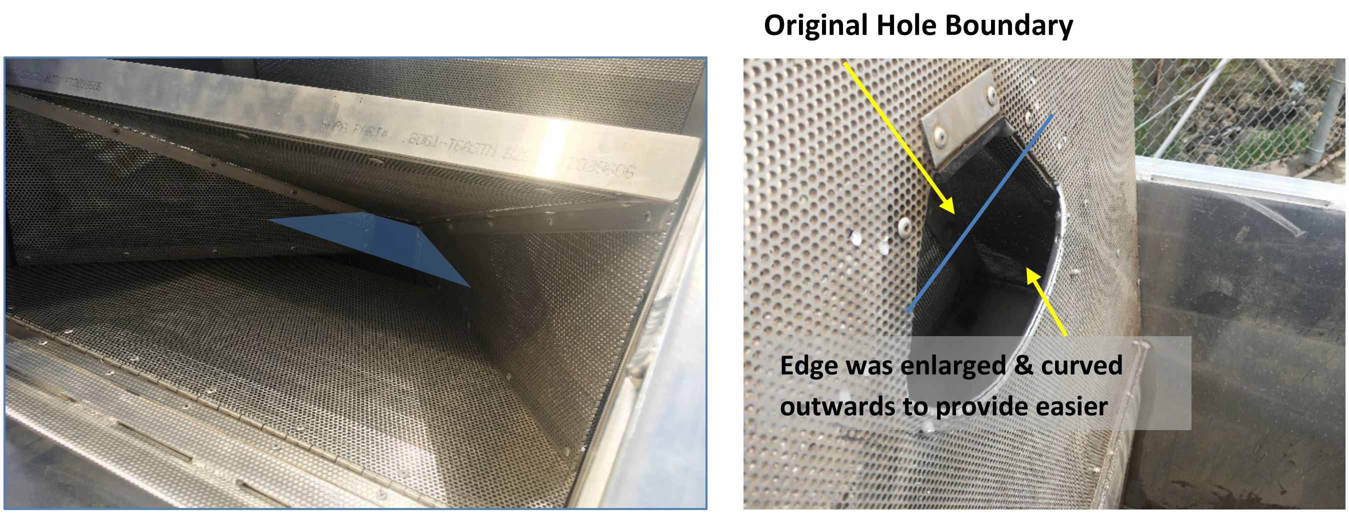

Photo 4. The original hinged fyke design for the entrance was all perforated but a solid plate was added on top of the bottom perforated plate later to reduce the confusion that lamprey seems to encounter from the diffused flow (left photo, blue polygon shows the original hole). Additionally, the hole was enlarged later with a curved round radius to provide easier access for the lamprey (right photo).

<u>Lesson #3</u>: Lamprey can escape the trap box through the entrance hole. **Resolution ->** a few varieties of add-on fyke designs (using frames or funnels) were effective in preventing escapement (with the least amount of resistance to enter the hole). A rubber sheet design was examined but it was not effective in preventing all escapement and also created entrance issues.

<u>Other key design elements to consider</u>:

1. Structure location is critical (all lamprey collected to date are from the Upper Structure and none were captured at the Lower Structure). Interface of fast and slow water at the Upper Structure appears to provide effective attraction; flow near the Lower Structure is predominantly slow water.
2. Most lampreys that climbed the side walls were not successful in reaching the top due to difficulty maintaining suction and transitioning to the frontal wall. Reducing the height of the covered aluminum box section to prevent lamprey from accessing the side walls during high flow events will likely prevent this issue (alternatively, a ledge can be added to the bottom of the side walls to prevent this completely).

3. Attempts by lamprey to climb the VWW have occurred between 8pm-4am (though some holding/resting behavior was observed outside this time range on a few occasions).
4. Video system activation based on motion detection is entirely non-functional with passive infrared sensors (due to the lack of heat sources in cold-blooded lamprey). Motion detection that operates on image or audio (i.e. splashing noise) sensors may provide better results and will be tested. Mechanical counters (preferably with wireless time stamps) are another option for monitoring their use, but the design needs to be configured carefully to ensure accurate counting (and lack of entrance resistance).
5. It is important to note that the spring migrating lamprey have overwintered and may have reduced bioenergetic reserves compared to summer/fall migrants that have not overwintered. The energetic limitations displayed by spring migrants here may be less severe for the summer/fall migrants; however, 100% passage for all migrants should be a goal for all dams.
6. Effectiveness of adult lamprey in attracting other adult lamprey is currently being tested using live adults in PVC traps within the trap box, but results are still inconclusive.

Photo 5. Examples of fyke designs that were successful in funneling lamprey to the trap box (the hinged fyke plate is lifted to show the hole end of the fyke design). An 8.25" diameter funnel with drinking straw extension (left photo). An 8.25" diameter funnel with zip tie extensions (center photo). A metal frame with vexar plastic covering and zip tie extension (right photo); this design was later modified to reduce the sharp angle that lamprey has to turn to enter (reduced it from 135 to 45 degrees). These designs allow lampreys to pass through while preventing those in the trap from escaping. Vexar plastic covering was also glued to the inside of the funnels to prevent lamprey from resting inside the funnel (which prevented other lamprey from accessing the hole).

Design Effectiveness

Initial passage evaluations of the VWW Lamprey Passage Structures were conducted in Spring 2017. The first lamprey was captured on April 19, 2017, and within a month (by May 11, 2017) over 50 wild lampreys were captured in the Upper Structure. The number of lamprey passing through the existing fish ladder during this same period was 123 (VWW proportion was 29%).

Initial video monitoring indicated that only 10-30% of the lampreys accessing the bottom of the VWW were eventually captured at the holding tank. Three key issues were identified as a result of behavior testing and night-time wireless video monitoring (Netgear Arlo cameras): 1) difficulty in climbing up the VWW all the way, especially at and immediately below the radius section, 2) reluctance to pass the entrance hole at the upper terminal, and 3) ability to escape the holding tank. A number of modifications were made based on the following lessons learned, which lead to substantially improved passage rates within the VWW passage structure over the season.

Photo 6. Lamprey struggling to climb the radius curve at the top of the vertical wetted wall prior to the addition of magnets and smoothening of the ridge lines (horizontal equal-spacing lines).

References:

U.S. Bureau of Reclamation. 2016. Project Alternatives Solution Study (PASS) Final Report for Lamprey Passage, Yakima River Diversion Dams. Pacific Northwest Region, Boise, Idaho.

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Wetted Wall for Adult Pacific Lamprey Passage in the Bradford Island Fishway at Bonneville Dam, Columbia River

Background

Lamprey passage structures comprised of ramps and rest boxes have become a method for routing Pacific lamprey around passage obstacles at major hydropower dams in the Columbia River Basin. Pacific lamprey are obstructed in the fishway ladder sections with vertical-slot and serpentine weirs. These areas are not well suited to installation of typical lamprey passage structures due to space constraints and usage of the fishway by other species. A vertical wetted wall design does not require a 3-dimensional structure in the fishway, and is based on experimental structures and field concepts employed in other circumstances.

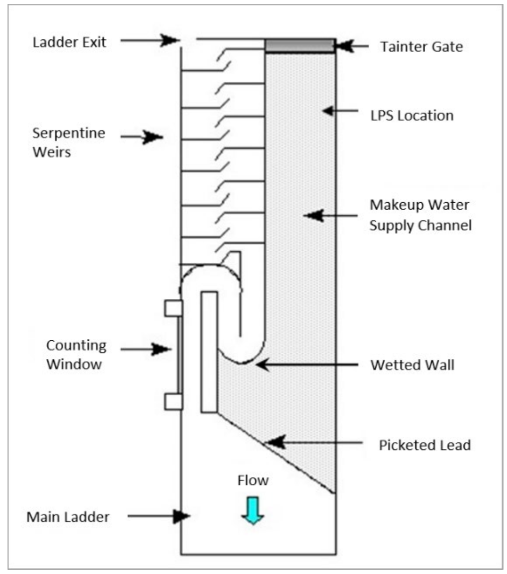

Figure 1. Schematic drawing of serpentine weir and makeup water supply area of the Bradford Island fishway system at Bonneville Dam.

Design Elements for Pacific Lamprey

A prototype structure was installed in the Bradford Island fishway at Bonneville Dam in the winter of 2018. The design takes advantage of Pacific lamprey vertical climbing ability and provides them with a direct route from the serpentine weir section into the adjacent makeup water supply channel, thus providing access to an existing lamprey passage structure (LPS, Figure 1).

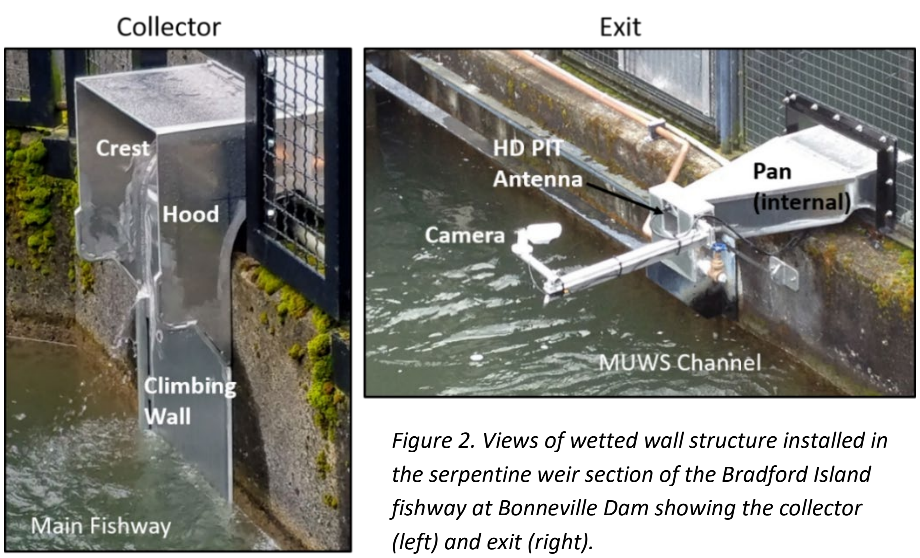

Figure 2. Views of wetted wall structure installed in the serpentine weir section of the Bradford Island fishway at Bonneville Dam showing the collector (left) and exit (right).

The wetted wall was constructed of aluminum. A vertical aluminum collector wall was attached flush to the concrete wall of the fishway (Figure 2, left). The aluminum wall was 24-in wide and covered the vertical height of the fishway from the submerged floor to the top of the concrete wall (exposed to air). The vertical wall was connected seamlessly to a 6-inch-radius crest leading into a shallow pan, which narrowed to 4 inches at the exit. A hood over the collector wall provided shade to the structure and protection from avian predators. Water was supplied to internal reservoirs via a pump located in the makeup water supply channel, with flows set to wet the climbing surface with a continuous sheet of water. Water filled the pan, and flowed from it down over the climbing surface as well as out through the exit. The goal of the sidewelling supply mechanism was to provide smooth flow and a continuous, smooth attachment surface for lamprey from the fishway to the exit of this prototype structure.

Design Effectiveness

Evaluation of the prototype wetted wall structure was based on video monitoring of the climbing surface and water interface in the serpentine weir section, and behavior at the structure exit during the first lamprey migration season, in 2018. The video system was equipped with infrared capability, allowing 24-hour monitoring. For each attachment of a lamprey above the water surface, we noted attachment time, time to the crest of the vertical climbing section of the structure, and time to exit, as well as attempts resulting in falls back into the fishway.

The prototype wetted wall structure was effective at passing lamprey (Figure 3). In its first year of operation (2018), 343 Pacific lamprey passed from the Bradford Island fishway into the adjacent makeup water supply channel via the wetted wall during the 46 days of video monitoring. Expanding our video counts to the duration of the period of operation, the range of lamprey projected to have used the wall during 10 May – 10 September was 1,735 – 3,205, depending on the method of calculation. All but one of the wetted wall passage events occurred at night.

The average time required by Pacific lamprey to navigate this structure was under 2.5 minutes, with a maximum passage time of just over 1 h. The two components of the structure, the vertical wall and upper pan, required similar time for passage, and each allowed lamprey to attach. Linear regression indicated that time to pass was not correlated with either date (R^2 = 0.0000284, P = 0.663) or time of day (R^2 = 0.0114, P = 0.058).

When lamprey found and attached to the wetted wall, they generally climbed it successfully. Fallback behavior occurred 91 times. While 21% of attachment events did not result in passage, 28 of these events (31%) occurred on a single night, seemingly by the same large fish. Fallback observations were often attributed to larger fish (estimated >70 cm). Larger fish seemed to struggle in the crest transition area.

Upon exiting, some lamprey flipped around and attached to the smooth back of the upwelling box before dropping into the makeup water supply channel. The rate of this occurrence was approximately 20% and generally lasted less than 15 seconds. This behavior could be discouraged by attaching a perforated plate or mesh material to this area.

Video was examined for interactions by salmonids. No salmonids were observed interacting with the wetted wall. Lamprey were attracted to the wetted wall when flow was high enough to spray water into the fishway from the hood. Hence, a flow regime with visible flow and some splash should be maintained.

Figure 3. Lamprey attached to the wetted wall and initiating climbing.

In summary, Pacific lamprey found and used the prototype wetted wall structure located in the serpentine weir section of the Bradford Island fishway. This result supported the concept that a vertical wetted wall can be a useful component of systems to improve passage for Pacific lamprey. Such structures can be used to collect lamprey, particularly from constrained areas where they accumulate, and direct them to alternative passage routes. They may also be useful in guiding lamprey over small barriers or into larger passage systems.

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DIFFUSER PLATING AND LAMPREY RAMPS IN FISHWAY
Rocky Reach Hydroelectric Project, Columbia River
Chelan Public Utilities District

Background

Many fish species are sensitive to unnatural features in fishways and they may delay or abandon migration when confronted with man-made structures. Specifically, adult Pacific lamprey experience difficulty passing upstream of diffuser gratings where water is added to the fishway at the Rocky Reach Hydroelectric Project to maintain appropriate water velocity for migrating salmonids. Lamprey also experience difficulty transitioning through perched orifices in the fishway due to sharp 90 degree angles. These grating structures and perched orifices do not provide an adequate, continuous, suction surface for Pacific lamprey to move upstream through the fishway. In 2010-2012, Chelan Public Utilities District, owner and operator of the Rocky Reach Hydroelectric Project (FERC No. 2145), performed significant modifications to the Rocky Reach fishway intended to aid upstream passage for Pacific lamprey, including aluminum plating and ramps. Pacific lamprey use of plating and ramps was evaluated by using PIT detections.

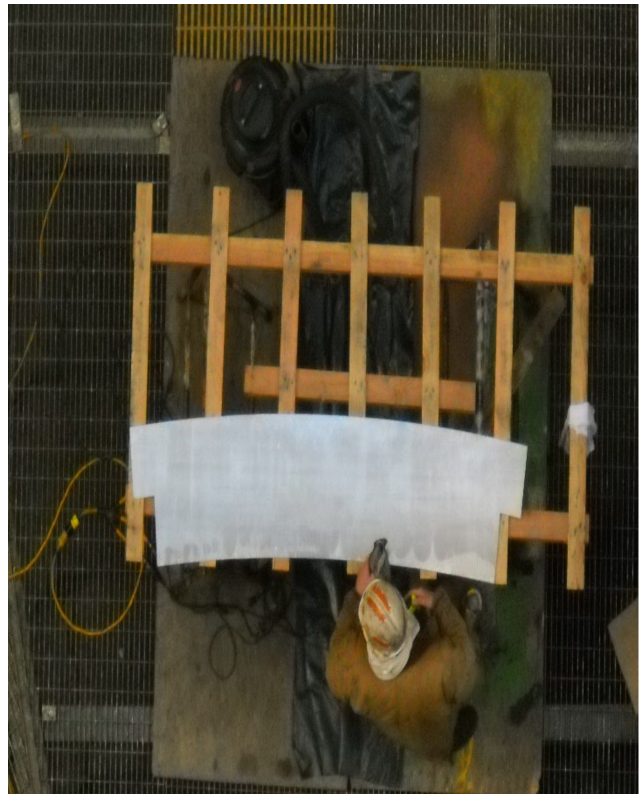

Figure 1. Section of diffuser plating.

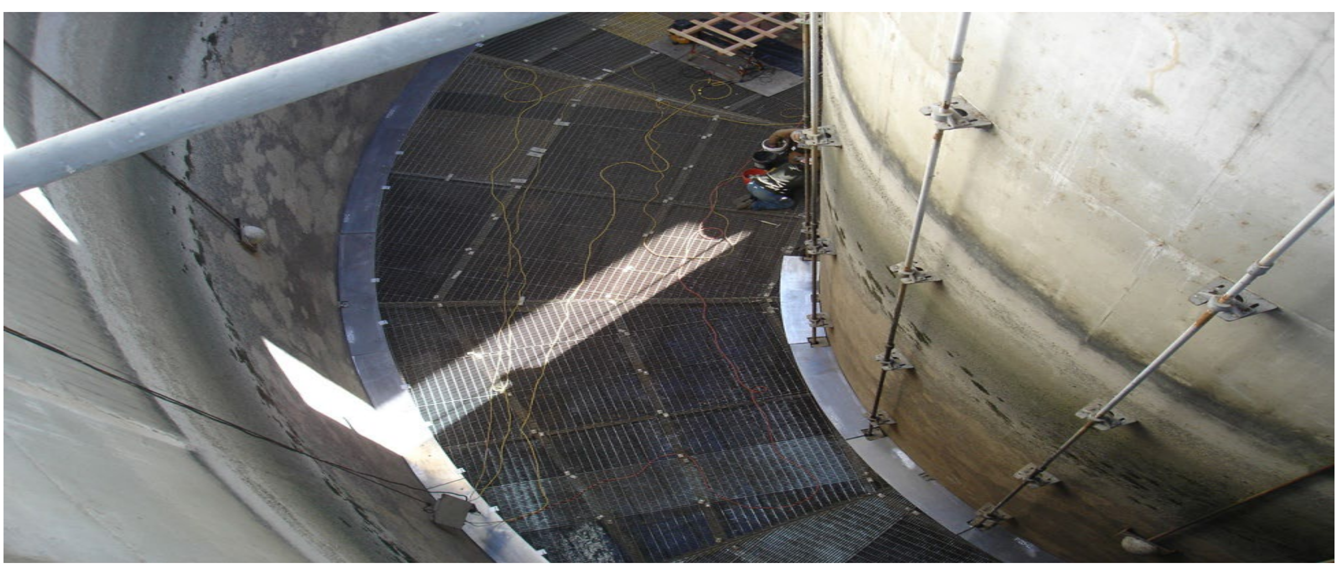

Figure 2. Diffuser plating installed along both walls of the fishway bifurcation channel.

Figure 3. Example of aluminum ramps designed to assist lamprey passage past perched orifices.

Design Elements for Pacific Lamprey - From 2010-2011, Chelan PUD fabricated and installed aluminum ramps and diffuser plating in the existing pool and weir fishway. The ramps were installed at the perched orifices in the upper fishway. Diffuser plating was installed along the fishway walls over the diffusion grating in the bifurcation pool and left powerhouse fishway entrance channel. In 2012, Chelan PUD installed diffuser plating at all weir orifices, extending 24 inches downstream from the orifices in the lower fishway section.

Design Effectiveness - Chelan PUD used FDX PIT technology to evaluate the effectiveness of the lamprey passage modifications completed from 2010-2012 to increase adult lamprey passage rates. Study results from 2016-2018 indicate that modifications made by Chelan PUD for lamprey passage have resulted in significant improvement from pre-modification passage conditions (pre-2011), and that the current fishway provides a higher rate of passage for adult Pacific lamprey. Fishway count conversion rates for lamprey between the downstream Rock Island Dam and Rocky Reach also comport well with the 2016-2018 PIT study results, suggesting high lamprey passage rates at Rocky Reach Dam.

Of the 211 lampreys tagged and released in 2016 and the 300 lampreys released in 2017, 174 (82.5%) and 274 (91.3%) have been detected in either the adult fishway of Rocky Reach Dam or the upstream Wells Dam, or in a mid-Columbia River tributary, respectively. In total, 48 lampreys were detected (94.1%) from the left bank releases below Rocky Reach Dam and 400 (87.0%) from the right bank releases. As of July 15, 2018, the Rocky Reach fishway passage rate for tagged lamprey was 98.8% and 97.7%, for 2016 and 2017 released fish respectively, for a total combined passage rate of 98.1%. Of the year 2016 released fish, 162 of the 164 fish detected in the Rocky Reach fishway were last detected at the fishway exit and two were last detected at the lower weir antennas in the upper fishway. Of the year 2017 released fish, 252 of the 258 fish detected in the Rocky Reach fishway were last detected at the fishway exit.

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Eel Lake Lamprey Passage Structure
Ten Mile Creek Watershed, Lakeside, Oregon

Background

The Eel Lake watershed (Lakeside, Oregon) is situated within the coastal dunes of Oregon. This watershed includes populations of Cutthroat Trout, winter steelhead, ESA-listed Coho Salmon, and Pacific Lamprey. Eel Lake drains into Eel Creek, which runs approximately three miles before entering Tenmile Creek (TMC); TMC then runs another 3.5 miles to the Pacific Ocean. In 1988, a trap was installed at the outlet of Eel Lake to facilitate collection of salmon broodstock for hatchery production. This trap blocked upstream migration of Pacific Lamprey until August of 2018, when a Lamprey Passage Structure (LPS) was installed. The LPS was designed to self-adjust to the changing lake levels so that the flow of water through the LPS would remain constant and facilitate passage of adult Pacific Lamprey.

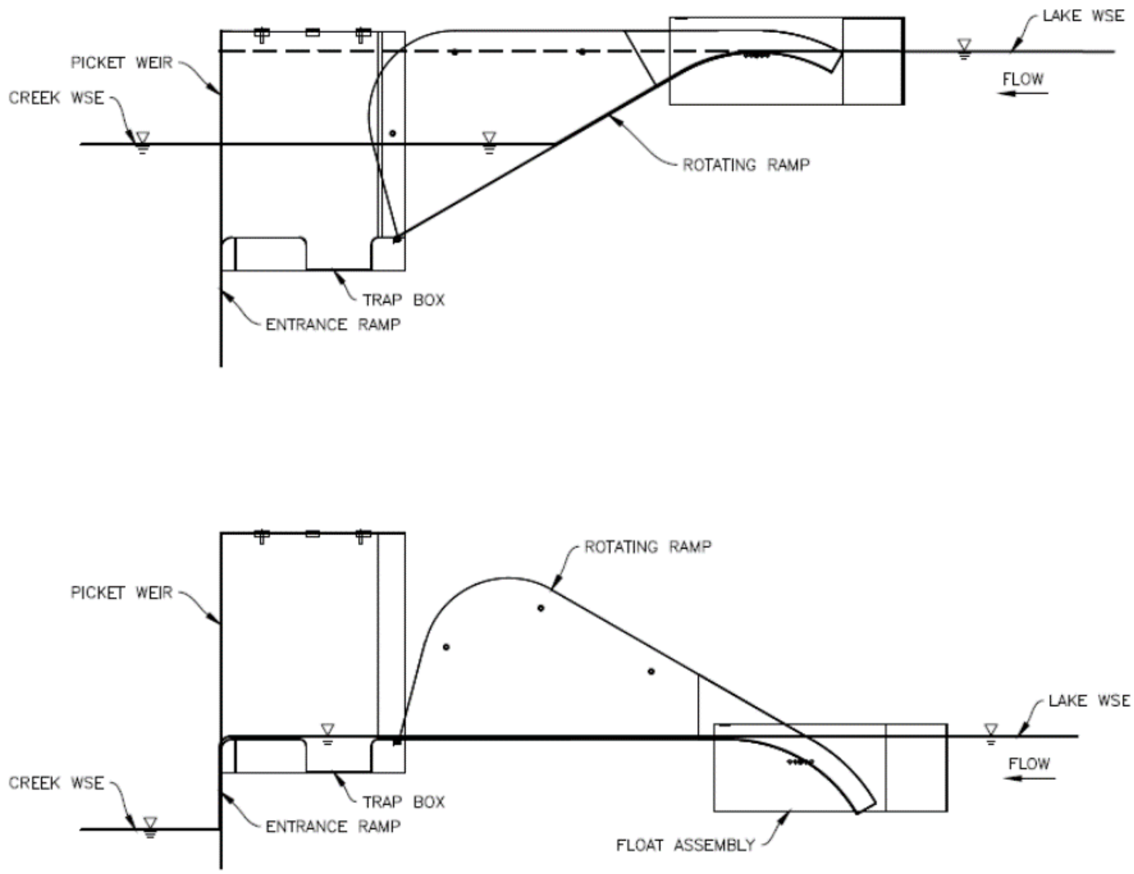

Figure 1. Schematic drawing of the Lamprey Passage Structure (LPS) at the outflow of Eel Lake (Lakeside, Oregon). The top design shows the LPS at high lake levels (pontoon floats at upper end at right), vertical wetted wall entrance downstream, at left. The bottom design shows the LPS at low lake levels, with the same LPS orientation as described. The two designs shows the different configurations of the LPS around the articulating point between the exit and the trap that shows the ramp in elevated (top) and horizontal (bottom) positions.

Considering Lampreys

The Confederated Tribes of the Coos, Lower Umpqua and Siuslaw Indians, Tenmile Lakes Basin Partnership, and the Oregon Department of Fish and Wildlife collaborated to acquire funding, design, fabricate, and install the LPS. The LPS was designed to include a downstream end with a vertical wetted wall for lamprey to enter the LPS, an upper exit that floats in the lake outlet, and a middle portion (ramp) that allows the floating exit to articulate up and down in concert with changing lake levels (Figures 1 and 2). This design automatically adjusts the amount of water that flows through it and over the wetted wall and eliminates the need for electrical pumps to control water flow. The exit at the upper end of the LPS includes float tanks designed to keep the crest of the wetted walls at a constant ~0.75 inches below the surface of the lake. This maintains a constant flow through the LPS and over the vertical wetted wall. The crest of the vertical wetted wall and a few feet above is covered to block sunlight from the lamprey that enter the LPS.

A trap was included in the LPS design (just upstream of the vertical wetted wall, but before the ramp) that enables researchers to capture lamprey for enumeration, measurements, and to take biological samples before placing the lamprey into the lake. The efficacy of the trap was monitored, which led to the revision of the original design to prevent lamprey from escaping. The trap can be configured so that it can either be operational or bypassed. Often, biologists and managers seeking lamprey passage are not necessarily interested in trapping lamprey that will be passed; therefore, the details on trap design and alteration are not included here. The U.S. Fish and Wildlife Service designed and installed a motion activated infrared camera system at the crest of the wetted wall of the LPS to record lamprey passage. This information was available for viewing through the internet and included a daily email summary of passage count totals.

Figure 2. Lamprey Passage Structure showing the vertical wetted wall at the downstream end (left image), and the ramp and exit with floats (right image).

Design Effectiveness

The LPS generally functions as intended: it articulates up and down with the changing lake levels, to self-regulate the amount of water flowing through. Biologists have determined that the LPS needs to be checked and adjusted periodically to ensure that the amount of water flowing through it is sufficient (not too much and not too little) to facilitate lamprey passage, especially during the migration season (March – June). When the amount of water flow is determined to be excessive or lacking, the water in the float tanks occasionally needs to be adjusted. Excessive water flows tend to trigger the LPS camera sensors and cause repeated videos to be captured. This can be mitigated by moving the sensors up to a point that still allows for lamprey to trigger them. Another consideration is the growth of algae on the vertical wetted wall that periodically needs to be cleaned during the active migration season so that lamprey can gain adequate suction with their sucker mouths to ascend the LPS wetted wall and ramp.

After installation of the LPS, low lake levels inhibited operation of the LPS until December of 2018. The first passage of a radio-tagged lamprey was recorded approximately 10 months later in June of 2019. Sucker marks and "tracks" on the LPS vertical wetted wall and ramp (Figure 3) corroborated this passage. Other lamprey have either been collected from the LPS trap or below the LPS and released above the LPS, into Eel Lake.

The trap had weir bars at 0.75 inch spacing associated with it to prevent lamprey from passing and instead be captured in the trap. We tested this spacing by releasing an adult lamprey (1.5-inch body diameter behind the gills) into the LPS. This lamprey was able to squeeze through the weirs and proceed through the LPS ramp and into the lake. The final trap design used 0.5 inch spacing.

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Figure 3. Lamprey sucker marks on wetted wall of the Lamprey Passage

Fish Ladder Trap for Adult Pacific Lamprey

River Mill Fish Ladder, Clackamas River

Background

River Mill Dam is the first passage obstacle Pacific lamprey encounter in the Clackamas River, Oregon. In 2006, PGE replaced a 100-year-old fish ladder with a half Ice Harbor style fish ladder. To facilitate a trap-trap-and-haul program and passage evaluations, a Pacific lamprey fish trap, designed to be installed seasonally, has been in use since 2010 (Figure 1).

Figure 1. Overhead view of River Mill Dam and fish ladder. Location of the lamprey trap is highlighted by the white circle near the top of the ladder.

Design Elements

The trap, when in operation, is positioned along the north wall of the ladder and rests on the lip of the ladder pool weir (Figure 2, Figure 3). Prior to trap deployment an aluminum orifice block with 1 inch tube bars with a center to center spacing of 2 inches, is lowered into bulkhead slots to force lamprey over the pool weir and toward the trap (Figure 6). The aluminum trap is designed so that lamprey passing over the weir along the north wall enter the trap, pass through a fyke, and drop into a holding box towards the rear of the trap. The trap is held in place by two ultra high molecular weight polyethylene (UHMW) strips on each end of the trap and can be lowered or raised into the fishing position via a chain hoist. Once lowered, the trap is secured in place by the UHMW strips sliding between a guide rail and an aluminum plate attached to the ladder cell wall. In addition to securing the trap in place, the aluminum plate provides a smooth attachment surface for Pacific lamprey as they approach the entrance of the trap. The holding box walls are 3/16-inch perforated plate with a 7-inch deep reservoir to prevent dewatering when the trap is raised above the water surface. The approximate volume of the holding box when deployed is 5.8 cubic feet. Captured Pacific lamprey are netted from the holding box through a lockable hatch door on the top of the holding box (Figure 4, Figure 5).

Design Effectiveness

PGE uses this trap to collect Pacific lamprey for its trap-and-haul program and passage evaluations. Since 2015, an average of 455 Pacific lamprey (range: 351 to 749) have been collected using this trap annually. Trap efficiency has not been evaluated to determine collection efficiency or trap retention.

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Figure 2 and 3. Photos of the River Mill Pacific lamprey fish trap while the fish ladder was dewatered.

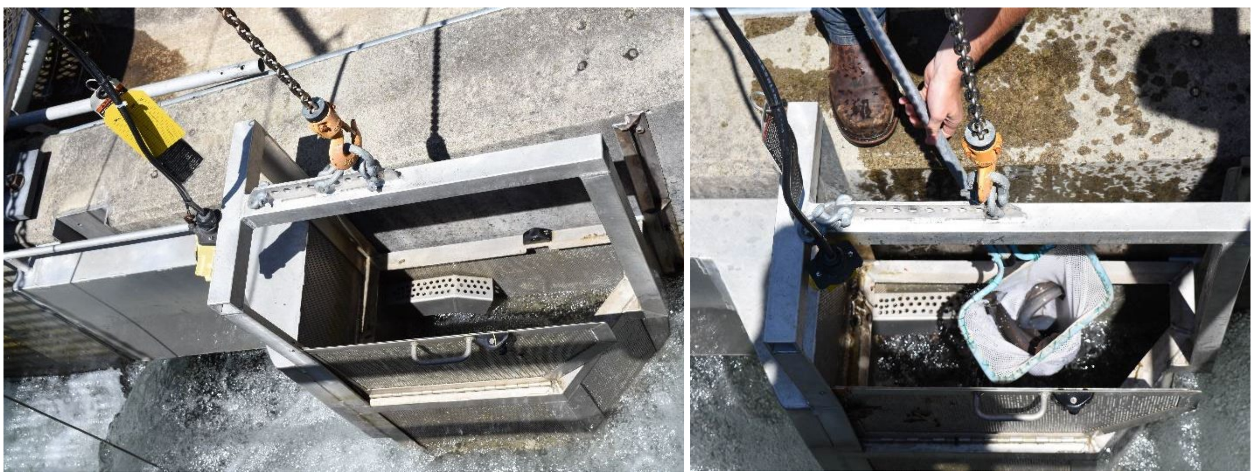

Figure 4 and 5. Photo showing the inside of the holding box of the fish trap where the fyke can been seen in the left photo.

Figure 6. Photo of the orifice block as it is being lowered into bullhead slots.

Pacific Lamprey Compatible Fish Ladder
Three Rivers – Cedar Creek Hatchery
Nestucca Watershed, Oregon

Background

Three Rivers is a Nestucca basin tributary in the Oregon Coast range that supports ESA listed coho, as well as spring and fall chinook, winter steelhead, coastal cutthroat trout, and Pacific and western brook lampreys. The headwaters are owned by US Forest Service and are managed for Late Seral Forest Habitat conditions. The Three Rivers system provides a variety of quality fish habitat types with streambeds rich in spawning gravels, and numerous pools and side channels for rearing. Oregon Department of Fish and Wildlife (ODFW) operates the Cedar Creek hatchery at the confluence of Cedar Creek and Three Rivers. A channel spanning weir on Three Rivers used to manage upstream hatchery fish migration and to facilitate the collection of hatchery brood stock impeded over fourteen miles of spawning and rearing habitat in the Three Rivers system (Figure 1). The barrier was identified on the ODFW Statewide Fish Passage Priority List as one of the top two remaining barriers on Oregon's north coast and a high priority for the Salmon SuperHwy partnership.

Figure 1. Pre Project: the Channel Spanning Weir impeded access to over 14 miles of upstream habitat.

Providing Lamprey Passage

This project removed the picket weir structure and replaced it with a seasonally operated, inflatable Obermeyer weir and new fish ladder. The fish ladder incorporates specific design features (based on differences in body size and movement abilities between lamprey and salmon) to provide continuous year-round passage for species-of-concern such as Pacific lamprey, juvenile salmonids and smaller cutthroat, while detaining adult salmon to allow manual sorting of hatchery fish. Other benefits include improving hatchery management, increasing human safety, improving downstream passage for all species, reducing holding and sorting time for wild fish, and restoring uninterrupted seasonal volitional passage for winter stocks of wild salmonids to over 14 miles of anadromous upstream fish habitat. Volitional run-of-river fish passage will be provided for listed coho and winter steelhead while spring chinook and summer steelhead would be processed through the hatchery fish trap, based on expected timing of use of the Obermeyer weir (primarily up from late April/May to late October/November).

Figure 2. Post Project: Wild fish will have unimpeded access during times when the inflatable replacement weir is

Lamprey Specific Design Features

The US Fish and Wildlife Service worked with ODFW engineers and fish passage biologists to incorporate the most current Pacific lamprey design guidance to the entrance ramp and fishway design to improve adult Pacific lamprey passage. Lamprey specific design features are outlined in this document.

***Rounded Surfaces*— ** As lamprey are demersal and typically move along the floor and walls of fishways, the fishway entrance slot was engineered flush with the floor and oriented to maximize laminar flow. Lamprey can be hindered by sharp edges (e.g. 90° angles) in areas of high velocities where they need to use burst and attach locomotion because sharp angles do not allow them to quickly re-attach to a flat surface after burst swimming. The entrance was designed with rounded edges with six inch minimum radii to allow burst and attach movement (figure 3). The ladder provided continuous attachment points for adult Pacific lamprey to move through the fishway using burst and attachment by ensuring sooth rounded concrete walls, which reduce turbulence (Figure 4).

Figure 3, 4. Fishway entry flush with floor with rounded edges and 6" radius. Fishway walls were rounded for lamprey movement and to reduce turbulence.

***Weir Panel Modifications*— ** The tops of aluminum V-notch weir panels were rounded so lamprey could move over them (Figure 5). Weir panels were also designed with a lower orifice continuous with the floor to allow for demersal movement.

Bulkhead slots, used to insert weir panels, create gaps in the continuous surface of the fishway which could negatively impact lamprey movements. To facilitate uninterrupted movement, the fishway weirs were fabricated so that the bulkhead slot is filled by a solid piece of aluminum that is flush with the fishway walls. The slight gap between the concrete fishway wall and the aluminum will be filled with smooth epoxy to create a continuous surface.

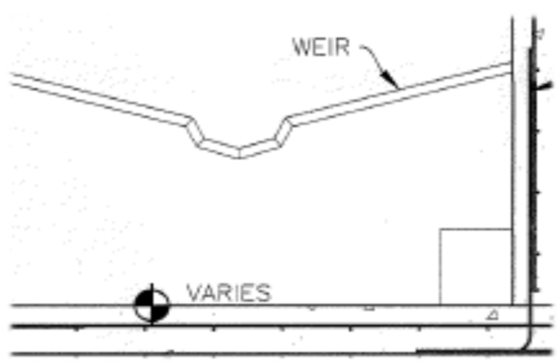

Figure 5. Weir panels with rounded tops and orifices to facilitate lamprey movement.

***1" Picket Spacing*— ** Specifically designed separation weirs were used within the fishway, with a one-inch picket spacing, to allow for juvenile salmonids, small cutthroat and lamprey to use the fishway for volitional upstream passage during trapping periods April through October/November. An additional separator picket assembly will force adults into the fish trap, when in operation, while allowing juveniles, small cutthroat and lamprey to continue up the fishway. A finger weir was added to the fish trap entrance which requires salmon to jump over, effectively precluding lamprey from entering the hatchery trap.

Project Partners

Oregon Department of Fish and Wildlife, U.S. Fish and Wildlife Service, U.S. Forest Service, Resources Legacy Fund Open Rivers, Trout Unlimited

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APPENDIX B – PASSAGE AT LOW HEAD DAMS / WEIRS

Background

To address passage at low head dams (sometimes referred to as weirs), the Lamprey Technical Workgroup will further develop specific guidance and examples. However, the following information is provided to assist those who may be working in these types of situations prior to the completion of that document. Consultation and coordination with PLCI staff of the Passage and Engineering subgroup is also available and recommended. For specific questions or review requests, please email info@pacificlamprey.org.

Low head dams are often associated with irrigation or other diversions on smaller rivers and streams (Figure B-1). Low head dams are typically <5 m but can be higher. Thousands of these dams exist within the native range of Pacific Lamprey. Even a small barrier dam, <1 m can potentially limit adult Pacific Lamprey passage (Jackson and Moser 2012). The purpose of these dams is typically to pond up water to create enough head to convey water into irrigation diversions or to supply hatcheries with a gravity-feed water delivery system; in some instances, the dam is a passage barrier to convey adult salmonids into hatcheries. While many do not have fishways, some low head dams have fish ladders to provide volitional upstream fish passage. When they do, the ladders are designed to pass adult salmonids and may present obstacles to lamprey; common problems for lamprey passage include the lack of continuous attachment surfaces in areas of high velocity (such as 90° corners) and turbulence. For these situations where the fishway can be improved, much of the information on providing passage for lampreys in the parent document is appropriate and useful to retrofit or modify the fishway.

In other instances, different solutions are needed. Low head dams without fishways, or those that dewater at the crest during summer low flow periods require other approaches to remove passage impediments to adult Pacific Lamprey and other native species. See Case Study 12 in Appendix A for one example.

Recommendations

The following recommendations are a generic approach to assess and determine appropriate next steps for lamprey passage. Each dam is unique and passage conditions can vary significantly, depending on seasonal flows and configuration.

Initial Surveys: First, evaluate the presence of Pacific Lamprey above and below the structure using larval lamprey occupancy surveys, eDNA, night-time visual surveys below the structure, or other surveys for adults (e.g. redd surveys upstream and downstream of the barrier). Roughly estimate the amount of habitat available upstream from the barrier.

Hydraulic Conditions: Once Pacific Lamprey presence is determined and passage is warranted, we recommend several assessments to evaluate passage including:

1) physical measurements of velocity over a range of flows that may be encountered during upstream migration,
2) presence of 90° corners or other acute angles that could prevent passage, and
3) other relevant passage metrics at the dam over a range of flows.

Potential Actions: Depending on the results of these studies, further evaluation may be warranted, or dam retrofits could be applied. Such actions could include but are not limited to: rounding corners and smoothing rough concrete to provide a passage route for climbing adults, adding an LPS or wetted wall, improving existing fishway function, and/or ensuring minimum flow requirements to allow passage. If such modifications or dam retrofits are completed, we recommend evaluating passage once modifications are complete, using telemetry or at least conducting visual surveys at night to determine if lamprey are successfully passing the structure.

Another option could be replacement of the dam with a Nature-like fishway (NLFs), which include a wide variety of designs such as step-pools, roughened ramps, rock-arch rapids, rocky riffles, and cross vanes constructed of boulders, cobble, and other natural materials. NFLs create diverse physical and hydraulic conditions providing efficient passage for multiple species including migratory and resident fish (Turek et al. 2016).

We also recommend providing adequate cover below low head dams for adult lamprey to rest and avoid predators. Cover may be necessary to ensure study efforts are not negatively affected by predators. Adequate cover normally includes large boulders with interstitial spaces for lamprey to use and is of adequate size to resist movement during seasonal high flows.

Consultation and coordination with PLCI staff of the Passage and Engineering subgroup is also available and recommended. For specific questions or requests, please email info@pacificlamprey.org.

Figure B-1. Two typical low head dams. The stair step configuration and 90° angles prevent lamprey from climbing the weir on the left. The dam on the right has less 90° angles and the top of the weir is rounded, which at certain flows may allow lamprey to climb the surface. Depending on site-specifics, lamprey may be able to pass upstream of both dams under certain conditions (moderate flows, availability of a wall along the shore, etc.), but those conditions may only exist at very limited times and may not occur when lamprey are migrating.

Literature Cited

Jackson, A.D., and M.L. Moser. 2012. Low-elevation dams are impediments to adult Pacific lamprey spawning migration in the Umatilla River, Oregon. North American Journal of Fisheries Management 32:548-556.

Turek, J., A. Haro, and B. Towler. 2016. Federal Interagency Nature-like Fishway Passage Design Guidelines for Atlantic Coast Diadromous Fishes. Interagency Technical Memorandum. 47 pp.