Review of Factors Affecting Larval and Juvenile Lamprey Entrainment and Impingement at Fish Screen Facilities

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Glossary

Ammocoetes	See “larvae”.
Approach velocity	The vector component of velocity that is perpendicular to and upstream of the vertical projection of the screen face is calculated by dividing the maximum screened flow by the effective screen area. An exception to this definition is for end-of-pipe cylindrical screens, where the approach velocity is calculated using the entire effective screen area. Approach velocity should be measured as close to the boundary layer turbulence generated by the screen face as possible (NMFS 2011).
Burst swimming speed	The maximum swimming speed at which a fish can swim for only a very brief amount of time (traditionally defined as < 20 s) before fatiguing.
Diversion	Interception and redirection of surface water.
Entrainment	The unintended diversion of fishes into an unsafe passage route.
Effective screen area	The total submerged screen area, excluding major structural components, but including the screen face material. For rotating drum screens, effective screen area consists only of the submerged area projected onto a vertical plane, excluding major structural components, but including screen face material (NMFS 2011).
Impingement	The injurious contact by a fish with a screen face or bar rack resulting from flow velocity exceeding the swimming capability of the fish (NMFS 2011).
Juvenile lamprey	Life stage of anadromous lampreys (and not resident lampreys). This is the life stage that occurs when eyeless and toothless larvae transform into eyed fish with teeth in preparation for ocean entry and feeding (Clemens 2019).
Larval lamprey	Immature, filter-feeding individuals without eyes or teeth. Most of their lives are spent burrowed in stream sediments, although they can be scoured out by high flows or otherwise choose to leave burrows to emigrate at high flows (Moser et al. 2015; Clemens 2019).
Point of diversion (POD)	The location from which water is diverted using infrastructure.
Porosity	The open area of a mesh, screen, rack or other flow area relative to the entire cross area. (NMFS 2011).
Sustained swimming speed	Speed that a fish can maintain for long periods (>200 minutes) without muscular fatigue.
Sweeping velocity	The vector component of flow velocity that is parallel and adjacent to the screen face, measured as close as physically possible to the boundary layer turbulence generated by the screen face (NMFS 2011).
Thalweg	The stream flow path following the deepest parts of a stream channel (NMFS 2011).
Transformer	Lamprey life stage during which a larva is metamorphosing into a juvenile (Clemens 2019).

1 Introduction

Larval and juvenile lampreys burrow into fine sediment and organic material found in stream substrates. These lamprey life stages often encounter water diversions when they leave these burrows during high flows, due to either the mobilization of the fine sediment where they reside or because high flow conditions provide cues for them to move downstream. Pacific Lamprey (*Entosphenus tridentatus*) and Western River Lamprey (*Lampetra ayersii*) are anadromous and make seaward migrations as juveniles. In addition, larvae of both anadromous and non-anadromous lampreys periodically undertake downstream movements (Dawson et al. 2015). For example, Western Brook Lamprey (*L. richardsoni*) is frequently observed in many of the dewatered irrigation canals in the Yakima River Basin (Lampman and Beals 2019). Larval lampreys are also frequently observed entrained within salmon hatchery rearing and abatement ponds (J. Skalicky, USFWS, unpublished data). These movements can expose larvae and juveniles to injury or mortality from entrainment and impingement.

Lampreys are of conservation concern due to declines in abundance observed for many species where trends have been monitored (CRITFC 2011; Clemens et al. 2021). Threats to lampreys relative to screening, entrainment, and impingement include the trapping or killing of larvae and juveniles when conveyed into water diversions. Using best practices to minimize diversion and permanent removal of lampreys from their river of origin is, therefore, a critical conservation measure (CRITFC 2011; Luzier et al. 2011; Clemens et al. 2017; Clemens et al. 2021).

Potential harm associated with water diversions can be mitigated by fish screens that prevent the entrainment or impingement of lampreys. Screens can be placed at the point of diversion (POD), thereby preventing lampreys and other fishes from being diverted with the water or within the water diversion to direct diverted fishes into a bypass that returns them to the river or stream. In addition to fish screens, structural or functional mechanisms can deter or prevent fishes from encountering the diversion. These could include the design of the water diversion structure, the timing of water diversion, and stimuli that behaviorally deter or attract lampreys.

Although extensive research has been directed towards the development of protective measures for juvenile Pacific salmon (*Oncorhynchus* spp.) at water diversions (NMFS 2011), similar efforts have not been extended to protect larval and juvenile lampreys (Moser et al. 2015). Thus, regulatory screening criteria or guidelines do not currently exist for larval and juvenile lampreys. The size of the openings in fish screens designed to meet salmon-based screening criteria may be insufficient to protect larval and juvenile lampreys from entrainment or impingement, which may lead to injury or death.

The first goal of this paper is to review existing data and literature on entrainment and impingement of larval and juvenile lampreys at screens and provide recommendations for reducing entrainment and impingement. The second goal is to inform proper use of screens in facilities (i.e., aquaculture, lamprey holding, fish traps, etc.) and other situations where either containing or excluding lampreys of a certain size is needed.

2 Screens and Screening Criteria

2.1 Screens

Many types of screens prevent fish from entering canals, turbines, and other types of diversions. Common fish screen configurations include profile bar (vertical bar), perforated plate, woven wire mesh, and interlock (Figure 1). Screens act to reduce the entrainment of fishes by two distinct mechanisms (Weisberg et al. 1987). The first mechanism, physical exclusion, is predicated on the size of the fish being larger than the opening or slot width to which it is exposed, such that the fish cannot physically pass through. The second mechanism is hydrodynamic exclusion, which is facilitated by the diffusion of the flow field immediately surrounding the screen, which can allow sufficiently motile fishes to avoid entrainment even if they are physically small enough to pass through the openings. Given these two mechanisms, the importance of a fish's life stage, morphology, body size, and swimming abilities become relevant. As a fish changes life stage, it also grows, becoming more motile and more likely to be physically excluded. Thus, the larger fish grow, the more likely they are to be physically excluded and to have the swimming abilities to facilitate behavioral avoidance of a diversion (EPRI 2003).

In addition to screen material, many variations in the overall shape and operational parameters of screens are in use. Those briefly reviewed here do not represent an exhaustive list but include the most common fish screen types found in the Pacific Northwest of North America. Brief summaries of primary benefits and potential constraints for screen types are given from the standpoint of fish screening managers to understand that selection of appropriate screen type depends on site-specific physical and hydraulic conditions. Screen selection is based on several application considerations, including water depth, flow, velocity, quality, access (power, transportation, and equipment), debris load, and predation potential.

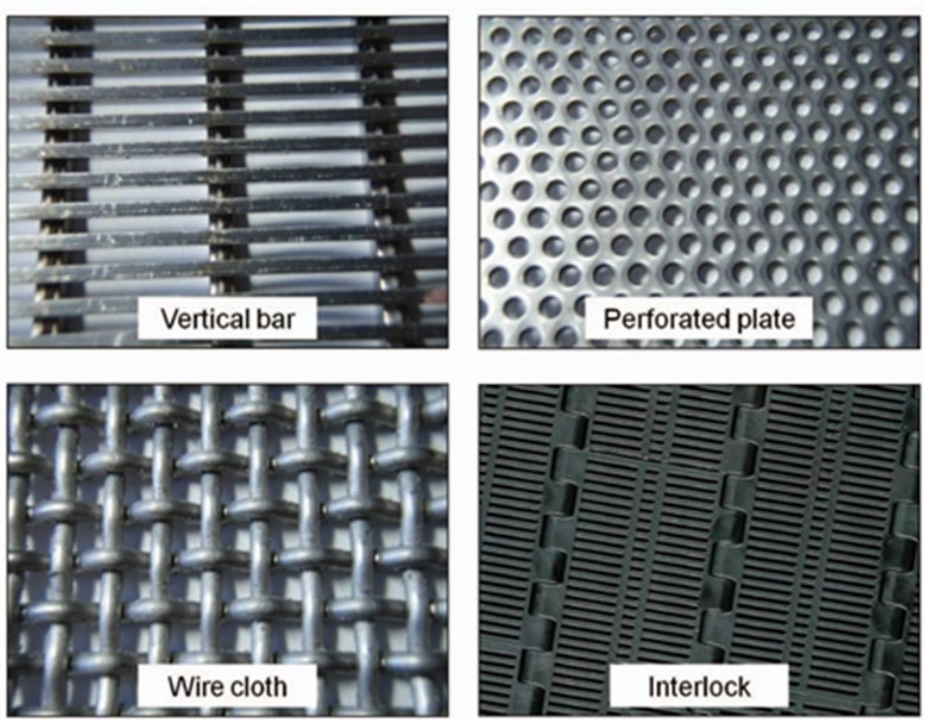

Figure 1. Standard screen materials used to protect fishes. Adapted from Rose and Mesa (2012).

2.1.1 Drum Screens

Drum screens (Figure A-1) are one of the most common fish screening technologies in the Pacific Northwest. This screen type has been used for over 100 years and is generally favored by water users because of its simplicity. Cylindrical drums vary in size from small modular screens designed to screen a few cubic feet per second (cfs) to extensive facilities incorporating many drums designed to screen thousands of cfs. Older screens utilize woven wire mesh, whereas newer screens usually have perforated plate screen material or profile bar. The drums are commonly set in concrete with rubber seals on the bottom and sides. Side seals are substantiated with foam sealant to minimize fish entrainment through small gaps. Drums rotate so that debris is carried over the drum to be rinsed off by flows (or scraped off by the bottom seal) and washed down the canal or carried out the fish bypass. Drum rotation is powered by a paddlewheel at small sites, whereas more significant sites require electricity and motors.

Primary benefits: Simple, common, established technology and wedge wire mesh slot widths down to 0.5 mm are available.

Potential constraints: Cannot be used as a POD screen due to the need for submergence range compliance. Gaps along edges and the bottom may be challenging to seal. When operating outside of submergence, fishes can pass over the screen. For rotating drum screens, the design submergence must be between 65% and 85% of the drum diameter (NMFS 2011).

2.1.2 Cone Screens

Cone screens (Figure A-2) are less common in the Pacific Northwest than drum screens. Cone screens are primarily used in shallow water bodies, including rivers, streams, and estuaries. They can function partially submerged, and positive brushing action minimizes debris buildup and sedimentation. They have an internal flow baffle to assist in distribution flow evenly across the screen surface. Brushes can be hydraulic, electric, or turbine drive. Power requirements are considered minimal, and solar power options are available for remote sites.

Primary benefits: Shallow water use, solar options, low maintenance, established technology, and wedge wire mesh slot widths down to 0.5 mm are available.

Potential constraints: Power may be required, depending on application and location.

2.1.3 Flat Plate Screens

Flat plate screens (Figure A-3) are also common and function very intuitively. They may be completely vertical or inclined (< 45^{o}). Automatic cleaning is achieved by additional components such as a brush that travels back and forth or an airburst manifold that uses sequential (upstream to downstream) intense bursts of air to mobilize debris, allowing current to remove it. These screens may be located at the POD or in a canal. The screen surface may be perforated plate, profile bar, or woven wire mesh. Plate screens provide a complete seal, and fishes cannot be entrained at these facilities if they are larger than the screen openings.

Primary benefits: Fish-tight, durable

Potential constraints: Requires strong sweeping velocities

2.1.4 Traveling Belt Screens

Traveling belt screens (Figure A-4) are conceptually vertical or slightly inclined conveyor belts with a plastic material that meets compliance standards for fish protection. The belts rotate within steel frames sealed at the sides and bottom, and the screens project safely above the waterline. These screens require electricity. They can be built custom to accommodate a wide range of flows. Debris is kept in front of the screen or, in some cases, is carried up inclined belt screens and collected via scraper bars or spray nozzles into a trough near the top of the screen.

Primary benefits: Can accommodate a wide range of flows,

Potential constraints: Screen material is not as durable as its metal counterparts; many individual parts such as sprockets and pins need replacement relatively frequently.

2.1.5 Horizontal Screens

Horizontal screens (Figure A-5) can be an effective way to screen water when the proper physical conditions are present. Horizontal screen designs are long-established; however, designs that consider fish life protection as a primary goal have been used more recently. They can be designed to screen a wide range of flows up to thousands of cfs. The anadromous passage facility design manual (NMFS 2011) dedicated an entire subsection to specific criteria for horizontal screen operation. When operating most efficiently, the harmonic resonance of the metal screening infrastructure provides the cleaning mechanism, if water flow and velocity are sufficient, and no sediment is falling out of suspension in the water column.

Primary benefits: No external automated cleaning device, reduced maintenance burden (when operating correctly).

Potential constraints: Requires more water for bypass than other screen types; initial construction cost is often expensive.

2.1.6 Coanda Screens

Coanda screens (Figure A-6) are used in the Pacific Northwest and are considered “experimental” (NMFS 2011). Coanda screens are considered a non-vertical fixed plate screen. Coanda Screens are positioned on the downstream face of an intake weir. An ogee-shaped acceleration plate (Figure A-6) delivers the flow at the precise angle and velocity required by the separation area of the screen. Woven wire mesh placed at precise and consistent slot gap tolerance screens away debris and particles. The screened water flowing through the open area collects in a chamber beneath to be distributed to associated pipelines.

Primary benefits: Maintenance-free, no moving parts, slot sizes are commercially available down to 0.2 mm.

Potential constraints: High cost, not fully approved (NMFS 2011).

2.1.7 Pump Screens

Pump or end of pipe screens (Figure A-7) are diverse in appearance, applicability, and functionality. A wide range of commercially available pump screens are designed to move a wide range of water volumes at pumping stations. The diversity of this technology makes succinct description difficult. The appropriateness of a pump screen for a given diversion must be made on a case-by-case basis.

Some pump screen models are self-cleaning, and others are passive. A maintenance protocol should consistently be implemented when a screen is being used.

Primary benefits: A wide range of sizes available and useful for simple water withdrawals.

Potential constraints: Not fully approved (NMFS 2011).

2.1.8 Screens at Mainstem Hydroelectric Facilities

Mainstem intake turbine screens consist of either rotating submerged traveling screens (STS) with 3.18 mm mesh or fixed extended-length vertical bar screens (ESBS) with either 1.75 mm or 3.18 mm openings (Figure A-8). Screens can divert up to 50% of the top vertical intake water volume depending on the facility. Fishes that encounter the screen are pushed upwards with the flow and directed via a flow vane into gatewells (3 per turbine). From the gatewells, fish are eventually flushed through circular backlit orifices (30.5 cm) and then to the primary dewater channel, flumes, dewatering structures, and finally to the juvenile bypass facilities where they can be collected, placed in barges, or returned to the river. Research and refinements since the first STS was tested in 1969 have improved the fish-passage efficiency of the screens and bypass systems.

Primary benefits: ESBSs have a long life and require minimal maintenance. STSs have low impingement rates.

Potential constraints: ESBS openings of 3.18 mm can lead to entrainment and impingement of lampreys. STSs require more maintenance, need to be replaced periodically, and may be damaged by debris.

2.2 Screening Criteria

Current downstream passage criteria developed by NMFS (2011) are focused primarily on protecting juvenile Pacific salmon. Current hydraulic criteria require approach velocities of less than 6 cm/s (0.2 ft/s) for passive intakes and 12 cm/s (0.40 ft/s) for actively cleaned and compliant screens (NMFS 2011). During construction or water drafting activities, 10 cm/s (0.33 ft/s) is allowed at passive screens. Sweeping velocity must be greater than approach velocity, but NMFS (2011) recommends a sweeping velocity-to-approach ratio of at least 2:1. Criteria can be waived only if a site-specific biological rationale exists (e.g., if fry-sized fishes are not present, then hydraulic criteria could be increased to protect the smallest life stage expected to be present).

In addition to hydraulic thresholds, criteria include the porosity (opening area) requirements in the screen material. Screens must have a minimum of 27% open area. Specific criteria for each opening vary depending on the screen material and shape of the openings (Table 1). Many screening systems were built prior to developing the current criteria by NMFS (2011); therefore, older systems may not meet all criteria. For example, many irrigation district facilities have screens with 12 gauge (2.97 mm across, 4.20 mm diagonally) woven wire mesh, which is 1.34 times larger than the current criteria.

Mainstem hydroelectric facilities on the Columbia and Snake rivers have unique fish screening guidelines to protect salmon. Vertical barrier screens must have 1.75 mm (~1/16 in) spacing between bars as in other locations, and the maximum approach velocity is 84 cm/s (2.75 ft/s). Criteria for woven wire and other screen material types are still 3.18 mm (1/8 in).

An assessment of screening criteria for juvenile Pacific Lamprey (NMFS 2011) is needed because larval and juvenile lampreys can be significantly smaller and are weaker swimmers than juvenile Pacific salmon. Laboratory testing revealed that the average burst speed of juvenile Pacific Lamprey was approximately 71 cm/s (Dauble et al. 2006; Mueller et al. 2006). This speed translates to approximately 5.2 body lengths/s, much less than the typical juvenile salmon burst speed of 9-12 body lengths/s. The sustained swim speed of juvenile lamprey ranged from 0 to 46 cm/s with a median of 23 cm/s. Swimming endurance decreased marginally as velocities were increased from 15 to 30 cm/s and then decreased rapidly at velocities more than 46 cm/s (Dauble et al. 2006). For larvae (mean length 120 mm), burst swimming speeds were even lower, and swimming endurance dropped markedly as velocity was increased from 10 to 50 cm/s (Sutphin and Hueth 2010).

An assessment of screening criteria is also helpful because larval and juvenile lampreys exhibit protracted and spatially extensive outmigration (unlike salmon). Lampreys have been observed year-round at mainstem hydropower dams in the Columbia River (Moser et al. 2015). Moreover, they occur in very small tributaries and are exposed to entrainment in irrigation diversions of all sizes (Lampman and Beals 2019). Although lampreys appear to travel primarily in the thalweg and near the bottom (Bracken and Lucas 2013; Moser et al. 2015; Sotola et al. 2018; Lampman and Beals 2019), they can nevertheless be widely distributed throughout the water column, including at the surface and near shore. Using drift nets, Bracken and Lucas (2013) detected that lamprey (*Lampetra* spp.) move primarily at night. They also concluded that juveniles selected areas of higher flow whereas larvae behaved more like passive particles within the river flow. Creative methods that focus on materials and operations that reduce contact with screens will be vital in protecting lampreys.

Table 1. Screen criteria and guidelines required to protect juvenile salmon (from NMFS 2011).

Screen Opening Type	mm	Inch		Parameter
		Fraction	Decimal	
Circular	2.38	3/32	0.094	Diameter
Slotted/Rectangular	1.75	~1/16	0.069	Narrow width
Square	2.38	3/32	0.094	On a side

3 Entrainment and Impingement Studies

Most research on the effects of screening facilities in the Pacific Northwest has focused on Pacific salmon. However, some work to understand the effects of these facilities on lampreys has been conducted over the past two decades. Studies have been conducted in laboratory settings and in the field at screening facilities. This section summarizes existing knowledge, identifies research gaps, and provides guidelines for screening facilities to reduce entrainment and impingement of larval and juvenile lampreys.

3.1 Laboratory Studies

Laboratory studies provide controlled conditions that enable the evaluation of distinct components of passage structures. These studies have focused on both hydraulic conditions and screening material specifications.

3.1.1 Hydraulics

In an evaluation of juvenile lamprey swimming speed and ability, an approach velocity of 46 cm/s (1.5 ft/s) resulted in all lampreys contacting a 3.18 mm (1/8 in) profile bar screen face, and 70% were unable to move away after 1-minute of exposure (Moursund et al. 2000). This approach velocity was lower than the 0.84 cm/s criteria for mainstem Columbia and Snake River facilities. After 12 hours, 98% of the juveniles were permanently impinged against the screen face. At velocities ≤30 cm/s (1.0

ft/s), juveniles contacted the screen but were able to swim away. With prolonged exposure (12 hours), over 50% of the fish could not free themselves from the screen face, even at the lower velocity. To extract themselves from the screen, the lampreys used their tail to push off; but this resulted in some lampreys being impinged when their thin tail became wedged between the screen bars. Permanent impingement becomes a greater mortality risk at higher approach velocities and prolonged exposure.

In tests with larval lampreys, lowering approach velocities in combination with sweeping velocities have resulted in reduced entrainment through screens. An approach velocity of 6 cm/s with a sweeping velocity of 18 cm/s (3:1 ratio) reduced entrainment of larval lampreys for three of four screen types (interlock, woven wire, and profile bar, but not perforated plate) compared to an approach velocity of 12 cm/s (Mesa et al. 2017). At the lower approach velocity, interlock, and profile bar protected fish longer than 40 mm from entrainment and, therefore, may perform better than perforated plate or woven wire mesh. Woven wire screens entrained the highest proportion of fish and protected fish longer than 70 mm.

Maintaining a 3:1 ratio of sweeping velocity to approach velocity may help reduce entrainment of larval lampreys even at higher approach velocities. With an approach velocity of 12 cm/s and sweeping velocity increased to 35 cm/s, perforated plate, profile bar, and interlock all provided protection from entrainment to lampreys longer than 50 mm. In contrast, woven wire screens provided protection only for lampreys longer than 100 mm (Mesa et al. 2017).

Higher approach velocities may decrease protection from impingement, even with a 3:1 ratio of sweeping velocity to approach velocity. An approach velocity of 6 cm/s with a sweeping velocity of 18 cm/s resulted in a reduced impingement rate across all four screen materials compared with an approach velocity of 12 cm/s approach and a sweeping velocity of 35 cm/s (Mesa et al. 2017). Impingement did not affect fish survival; however, the overall size of screens tested was much smaller than many screens encountered in field settings, resulting in a higher incidence of impingement. Impingement times suggested that larval lampreys were not impinged for a long duration at the velocities tested. However, even short-term impingement may result in bruising, loss of mucous, and eventual fungal infection for juvenile lampreys, particularly at high temperatures (Jackson et al. 2019).

In an evaluation of shear stress impacts on lampreys, juveniles did not experience mortality or immediate gross injury when exposed to jet velocity that killed or injured salmon (Moursund et al. 2000). Likewise, when exposed to rapid changes in pressure to simulate passage through a turbine blade area, larval lampreys showed no external injuries or mortalities up to 48 h after the test (Moursund et al. 2002).

In addition, controlled laboratory testing using juvenile Western Brook Lamprey and Pacific Lamprey acclimated to pressure equivalent to a depth of 4.6 m were subjected to rapid (less than 1 s) or sustained decompression (17 min) to a very low pressure using a protocol previously applied to juvenile salmon. No mortality or evidence of barotraumas was observed following rapid decompression, nor up to 120 h after sustained decompression (Colotelo et al. 2012).

3.1.2 Screen Material and Orientation

Entrainment and impingement of larval and juvenile lampreys have been assessed at simulated screens in laboratory environments. Results are variable because of the variety of screening materials and opening sizes and the range of lamprey sizes tested. In an early test utilizing four different screen materials meeting NMFS (2011) criteria (perforated plate, vertical profile bar, horizontal profile bar, and wovern wire)and an approach velocity of 12 cm/s over an 11.5-h period, larval lampreys ranging in total length from 112 to 160 mm were not entrained and did not suffer sustained impingement (Gilmore 2005). However, a much broader range of larval size classes are naturally exposed to screens.

A comprehensive test utilizing five different screen materials and a wide size range of larval lampreys (28-153 mm total length) indicated that entrainment rate varied among screen types when approach velocity was held at 12 cm/s over a 1-h period (Rose and Mesa 2012). Screening materials tested included 12-gauge woven wire mesh (3 mm opening), 14-gauge woven wire mesh (2.2 mm), interlock bar screen (1.75 mm), profile bar screen (1.75 mm), and perforated plate (2.38 mm). Openings in 12-gauge woven wire meshes were larger than current (NMFS 2011) criteria but are common because many facilities were constructed prior to 2011. The open area for all screens was ≥27%, and approach velocity was 12 cm/s for all tests. The mean total length of lampreys ranged from 70.9-78.1 mm for each experimental group (five screens and control). Lamprey length was significantly related to odds of entrainment. The interlock, profile bar, and perforated plates had entrainment rates of 25%, 30%, and 18%, respectively, and prevented fish longer than 50-65 mm from entrainment. Both woven wire gauge sizes had higher entrainment rates (67% for the 12-gauge and 63% for the 14-gauge) and only prevented lampreys longer than 90-110 mm from entrainment. Perforated plate, interlock, and profile bar screens protected smaller lampreys and entrained fewer fish than woven wire mesh. Overall, perforated plate resulted in the lowest percentage of entrainment and protected the most significant size range from entrainment.

Pacific Lamprey of all lengths experienced impingement rates of 36-62% on the interlock screen and 13-31% on the woven wire screens (Rose and Mesa 2012). Impingement may have been low on the woven wire screens because high entrainment rates left fewer fish to impinge. Injuries were rare and minor for all screen types, and no delayed mortality was observed. Abrasions were observed on lampreys less than 50 mm in length.

During the development of methods for artificial propagation of Pacific Lamprey (Lampman et al. 2016; Moser et al. 2019; Lampman et al. 2021) and studies at irrigation canals (Lampman and Beals 2019), information has been gained about opening sizes that allow lamprey eggs and larvae to be entrained through screens (Table 2). Although a mesh size of 0.85 mm is sufficient to retain fertilized eggs of Pacific Lamprey, a mesh size of 0.25-0.35 mm is required to retain newly hatched larvae (Lampman et al. 2016; Lampman et al. 2021). However, egg and larva sizes can vary by species. For example, Western Brook Lamprey can be approximately 20% smaller than Pacific Lamprey (R. Lampman, Yakama Nation Fisheries, unpublished data). As a result, it is recommended that the mesh sizes for very early life stages are reduced further to protect resident lamprey species if they are present. As larvae grow, entrainment can be prevented by increasingly larger mesh sizes (Table 2).

Rather than preventing entrainment, in some cases, it may be necessary to understand which mesh sizes that will allow safe passage of juvenile lampreys without resulting in impingement or injury. For example, at juvenile salmon holding raceways on the Columbia River, lampreys should be passed through raceway screens and back to the river instead of being retained and transported with the salmon. Moser and Russon (2009) found that mesh sizes of less than 6.5 mm obstructed juveniles more than 150 mm in length (10 mm wide at the eye). Further laboratory experimentation revealed that 7 mm mesh obstructed most juvenile lampreys and had the highest impingement rates (Moser and Vowles 2011). Nine mm mesh had some obstruction and impingement, but 11 mm allowed juvenile lamprey passage without impingement or injury (Moser and Vowles 2011).

Table 2. Screen opening sizes required to prevent entrainment of Pacific Lamprey eggs and larvae during artificial propagation and irrigation canal field studies.

Life Stage	Total Length (mm)	Screen Opening (mm)	Citation
Embryo	~1	≤0.85	Lampman et al. 2016; Lampman et al. 2021
Larva (newly hatched)	7-10	≤0.35	Lampman et al. 2016; Lampman et al. 2021
Larva (young of the year)	≥13.0	≤0.8	A. Maine, Confederated Tribes of the Umatilla Indian Reservation, unpublished data
Larva (young of the year)	≥15.0	≤1.0	Lampman and Beals 2019
Larva (growing)	≥23.5	≤1.5	A. Maine, Confederated Tribes of the Umatilla Indian Reservation, unpublished data
Larva (growing)	≥32.5	≤2.0	A. Maine, Confederated Tribes of the Umatilla Indian Reservation, unpublished data
Larva (age 1+)	≥40.0	≤2.0	Lampman and Beals 2019
Larva (age 2+)	≥80.0	≤3.0	Lampman and Beals 2019
Transformer & Larva (age 3+)	≥135.0	≤4.0	Lampman and Beals 2019

In addition to screen mesh size, the orientation of screens and the behavior of lampreys should be considered. Larval and juvenile lampreys readily moved through vertically oriented screens, but juveniles were reluctant to move through horizontal and angled separators (Moser and Russon 2008). However, juvenile lampreys showed a conflicting tendency when two types of operations were tested (Moser and Vowles 2011). When exposed to dewatering with horizontal screens, most juvenile lampreys readily moved through those screens. However, when screens were oriented vertically, and juvenile lampreys were exposed to crowding, very few attempted to move through the screens. Only when lampreys were allowed to hold overnight was more movement through the vertical screens observed.

In a laboratory experiment with current criteria (NMFS 2011), the mass and length of larval lampreys were the only significant predictors of fish fate when evaluating two different screen angles (12 and 20 degrees) (Liedtke et al. 2019). Larval lampreys ≥39.5 mm in length or ≥0.16 g in weight had a 95% probability of successfully passing rather than entrained at both screen angles. However, although not statistically significant, bypass rates were higher, rate and duration of impingement were lower, and time in proximity to the screen was shorter at the 12-degree screen angle. This warrants further investigation into screen angles closer to parallel rather than perpendicular to flow.

3.2 Field Studies

Although unable to control conditions to the extent of laboratory studies, field studies have been valuable because of their direct relationship to real-world conditions. Studies to date have focused on the relationship of impingement and entrainment rates to screen material and the size of openings.

3.2.1 Diversion Canals

Consistent with findings from laboratory studies, larval lampreys have been detected downstream of diversion facilities that comply with salmon screen criteria. During annual salvage efforts at the Dryden Diversion on the Wenatchee River (vertical bar spacing = 1.75 mm), lampreys less than 50mm were entrained downstream of the fish screen into the canal (Beals and Lampman 2017a, 2018a). Similarly, in the Yakima River Basin, larval lampreys were found in all diversion canals surveyed downstream of fish screens in 2016-2017 and 2017-2018 (Beals and Lampman 2017b, 2018b). From 2014 to 2018, 25% of lampreys captured in irrigation diversions in the basin have been downstream of screens (Lampman and Beals 2019). In some canals, the overall density and abundance can be higher downstream of screens than upstream. The size of larvae entrained varied with screen type, but overall, smaller lampreys (less than 70 mm) were more common downstream of diversions (Table 3; Lampman and Beals 2019). Consistent with laboratory tests, entrainment varied among screen materials with similar opening sizes.

Other screening systems, such as louvered vertical bars, have been employed to guide salmon past diversions and turbines to bypass channels by creating turbulence fields that salmon avoid as they move downstream. However, little research has documented lamprey guidance by such systems. A system with two louvered screens (louver bar spacing = 25.4 mm (1 in)) at the Tracy Fish Collection Facility in the Sacramento-San Joaquin River Estuary resulted in the entrainment of 94-96% of juvenile lampreys into the canal (Goodman et al. 2017). This suggests that some louvers may be poor at preventing entrainment. However, adding a secondary vertical traveling screen increased guidance efficiency for juvenile lampreys encountering the screen to 100%. This study highlights the need to evaluate more louvered systems and update guidance infrastructure that benefits a broader range of species, including lampreys.

Table 3. Size of lamprey larvae (total length, mm) effectively screened by various screen types and opening sizes (Lampman and Beals 2019).

Screen Type	Screen Opening size (mm)		
	1.75	2.4	3.2
Profile bar	≥50	--	--
Perforated plate	--	≥60	--
Woven wire drum screen	--	≥70	≥100

3.2.2 Mainstem Hydroelectric Facilities

Mainstem hydroelectric facilities on the Columbia and Snake Rivers have unique fish screening guidelines to protect juvenile Pacific salmon. Turbine intake screens are high-velocity screens for which approach velocities are much higher than other screens. Intake screens were retrofitted at many mainstem dams. Fishes also encounter raceway tailscreens at facilities designed to collect and transport Pacific salmon juveniles (Moser et al. 2015).

More juvenile lampreys were permanently impinged on ESBS with 3.18 mm (1/8 in) bar spacing than on STSs with 2.38 mm (3/32 in) bar spacing (Moursund et al. 2002). Horizontal ESBS with 3.18 mm spacing resulted in a higher proportion of lampreys becoming permanently impinged than vertical ESBS with 3.18 mm. Overall, prolonged contact with the ESBS and higher velocities lead to more juveniles being impinged. Reducing the spacing on ESBSs from 3.18 mm to 1.75 mm should be prioritized to avoid the entanglement of lampreys in the woven wire mesh screen material (Moursund et al. 2003a). Submersible traveling screens with 3.18 mm openings were found to be benign. As a result, the U. S. Army Corps of Engineers has changed screen spacing criteria for new screens to minimize impingement risks for lampreys (CRITFC 2018).

At John Day Dam on the mainstem Columbia River, the ESBS at Turbine Unit 7 was modified from 3.18 mm to 2.38 mm (3/32 in) bar spacing to reduce impacts on juvenile fishes. Moursund et al. (2003b) found no lampreys were wedged by their tails in the narrower bar spacing, though many contacted the screen, and one was impinged on the screen face. This study evaluated the existing juvenile bypass system designed to facilitate the downstream passage of juvenile salmon. Of the juvenile lampreys implanted with Passive Integrated Transponder tags, those released in the bypass channel had 97-100% detection rates and demonstrated no problems with downstream passage through the bypass system. However, for individuals released in the forebay and at the upstream extent of the bypass system adjacent to the vertical barrier screen, detection rates were only 0-48%. This suggests that if lampreys entered the bypass system, they successfully passed through the facility. However, guidance to the bypass system was not effective and resulted in lampreys being directed towards the turbines. Moursund et al. (2003b) hypothesized that gaps around the ESBS infrastructure (below and above) and larger holes in the damaged vertical barrier screen were used as pathways that lead to turbine entrainment.

4 Reducing Encounters with Diversions

Additional ways to avoid lampreys passing through or impinging on fish screens is to prevent them from encountering the screens or the POD. Potential methods of accomplishing this include facility design and operation innovations and deterrents to passage based on lamprey behavior.

4.1 Facility Design and Operation

Facility design and operation innovations might include changes to the angle of the canal headgates relative to flow, operations that minimize water diversion when possible, and operations that minimize the amount of sediment (and associated lampreys) moving into the canal. Canal headgate angle and associated hydraulic properties such as approach and sweeping velocities can influence the numbers of entrained lampreys in these screened systems (Lampman and Beals 2019). Overall, smaller canals, which have correspondingly smaller discharges, and canals with inlets near parallel to thalweg flow, lead to fewer entrained lampreys. For example, the Wapato and Sunnyside canals are separated by about 4 km on the Yakima River in Washington, but the Wapato Canal collects considerably less fine sediment and lampreys downstream of the fish screens than the Sunnyside Canal despite diverting a higher volume of water. The Wapato Canal has a low gradient with water flow, oriented towards the fish bypass. In contrast, the Sunnyside Canal has a steeper gradient, and the flow is oriented away from the fish bypass.

Field studies in the Yakima River Basin demonstrated that lamprey abundance and the availability of fine sediment within the canal environment upstream and downstream of the fish screens were strongly correlated (Lampman and Beals 2019). For example, if fine sediment is mainly deposited upstream of fish screens, lampreys were also found predominantly upstream. Reducing fine sediment input at the headgate area may be a potential "long-term" solution, whereas placing effective structures near the fish screens to divert sediment either away from the screens (towards the bypass) or from moving further downstream past the fish screens in the canal are "short-term" solutions that could be implemented relatively quickly. Reducing fine sediment downstream of screens also has operational and economic advantages for irrigation canal operators because dredging is costly.

Alternatively, structures placed downstream of fish screens can be beneficial. They can capture fine sediment that would have otherwise traveled further down the canal, providing the last opportunity for lampreys to remain in the project area and be rescued when the canal is dewatered. However, some structures such as stop logs may increase water velocity and push more fine sediment downstream, which would not help deter lamprey entrainment.

Those options should be pursued if lampreys can be left in the diversions without any risk of desiccation or need to be transferred. Some irrigation canals have been converted to permanent side channels for fishes via sluice gates and associated water blocking structures to allow some of the canals to stay permanently wetted. The upper portion of the Wapato Canal in the Yakima River Basin in Washington now operates as a semi-natural side-channel, eliminating the need to dewater annually except for a few hours at the end of the irrigation season.

4.2 Behavior-Based Deterrents

Because juvenile and larval lampreys exhibit physical and behavioral characteristics that are different from those of salmon and other fishes in the Pacific Northwest, it is possible that behavior-based passage deterrents could potentially be used effectively, including light avoidance, pulsed electrical fields, acoustic deterrents, chemical, and sediment ques, and physical structures that lampreys may avoid (Teague and Clough 2011; Lampman and Beals 2019). Little research has been conducted in these areas to date.

In laboratory tests, Pacific Lamprey exhibited avoidance responses when exposed to pulsing (strobe) and constant white light. Tests were conducted in a swim chamber with a range of light intensities for both strobe (300 flashes per minute) and constant lights (Moursund et al. 2002). When subjected to water velocities that would otherwise allow them to rest on the screen face (0.5 ft/s), the lighting caused juveniles to swim away from the stimulus toward the opposite end of the chamber. In these tests, significantly more lamprey exhibited flight responses when compared to the control group ($P < 0.001$). Larvae have also exhibited light avoidance (Sutphin and Hueth 2010). However, juvenile Pacific Lamprey exhibited habituation to light in 2-h test periods (Moursund et al. 2002) and in as little as 5 min during other laboratory trials (Moser and Russon 2009).

Recent research to assess the potential for the use of light in diverting Sea Lamprey (*Petromyzon marinus*) juveniles has indicated that this method has the potential for guiding downstream migrants and that light intensity is influential (Haro et al. 2020). At low intensity, juvenile Sea Lamprey were attracted to the light source, whereas high-intensity lighting elicited avoidance. Lighting may be helpful in combination with other guidance cues, such as olfactory signals (Johnson et al. 2018).

Field and laboratory studies were also conducted to assess the potential of behavioral deterrents in diverting juvenile Sea Lamprey in tributaries to the Laurentian Great Lakes. Studies using electrical stimuli (pulsed direct current) showed some promise at low water current velocities but were ineffective as velocity increased (Johnson and Miehls 2014). Because juvenile Pacific Lamprey emigrate during periods of high river discharge (Goodman et al. 2015), it is unlikely that electrical stimuli would be effective except in low flow situations. Laboratory testing also revealed that juvenile Sea Lamprey responded to low-frequency sound (50-200 Hz) but could not detect sounds greater than 300 Hz (Mickle et al. 2019).

Temporary fish deterrent or silt curtain structures could also help guide and deflect lampreys and fine sediment away from headgate structures and decrease entrainment into canals. A fish deterrent boom installed upstream of the Sunnyside Diversion in the Yakima River Basin in Washington (Figure 2) in early 2021 likely helped reduce lamprey entrainment. The number of captured lampreys decreased by 72% from 2020 (Beals et al. 2022).

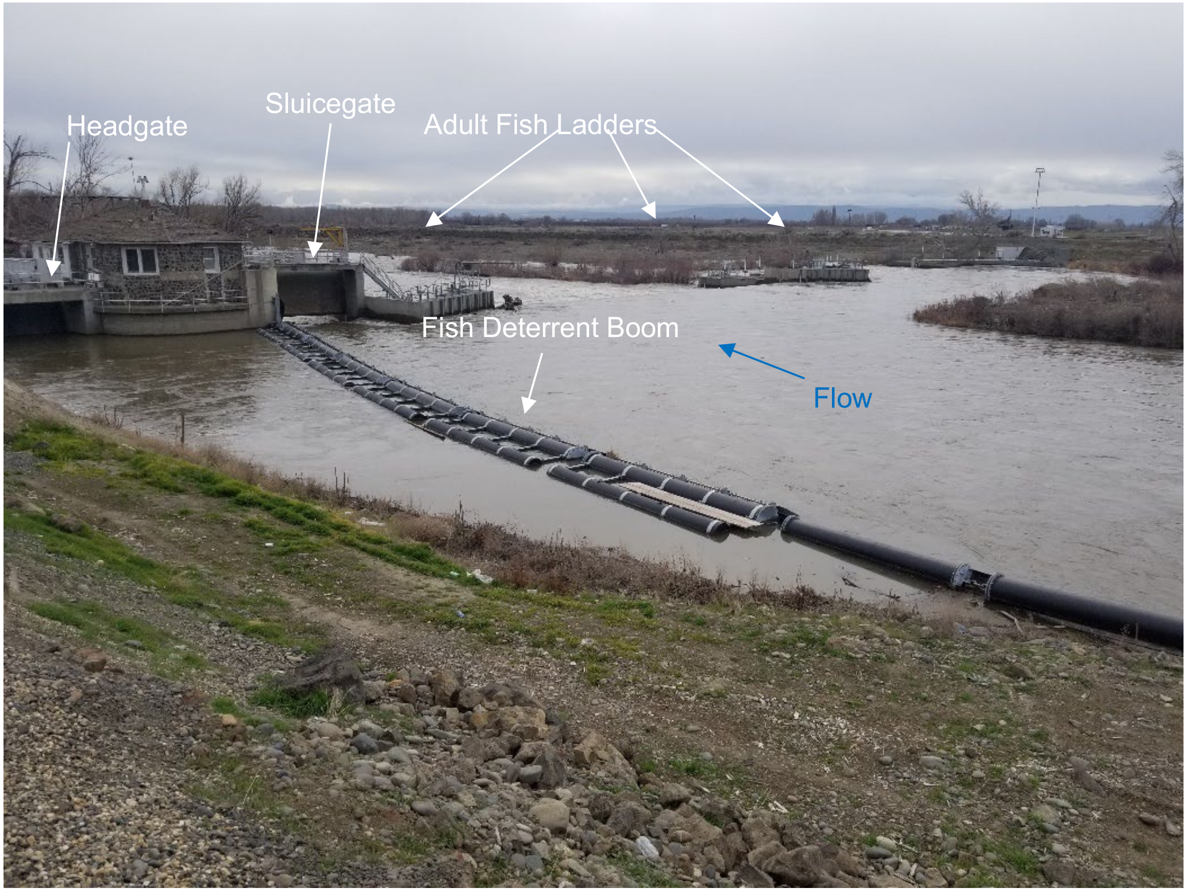

Figure 2. Sunnyside Canal diversion on the Yakima River (Wapato, WA) with a fish deterrent boom installed to deter fish passage into the canal.

5 Summary and Recommendations

5.1 Summary

Although numerous laboratory and field studies have been conducted, much remains to be learned regarding safe passage of larval and juvenile lampreys at water diversions and other screening facilities. Widespread use of screens or guidance methods that have not been designed or tested for lampreys can lead to many lampreys being entrained and potentially permanently lost. This could be a substantial contributing factor to the declines in abundance of many lamprey species.

What is clear is that criteria in place for juvenile Pacific salmon do not always adequately protect lampreys. Fully protecting all lamprey life stages at every facility is not practical; however, some general guidelines for screens and associated hydraulics should be developed. Site-specific considerations for lamprey life stages likely to be encountered would be prudent. For example, low approach velocity and adequate sweeping velocity may be crucial to protecting lampreys as screen opening size at some locations. Facilities more likely to be encountered by larger larvae and juveniles (e.g., far downstream from spawning and rearing areas) may not require the same screen and hydraulic conditions as facilities likely to be encountered by smaller larvae.

Entrainment is a more significant risk than impingement if velocities are low. Impingement is a more significant risk at facilities such as mainstem hydroelectric dams where approach velocities are very high. Smaller openings may be beneficial in reducing entrainment (see Section 6.2.1), and larger percent openings may be beneficial in reducing impingement. Lamprey swimming movement (anguilliform) is different from salmon and exploits gaps (literally and figuratively) in the bypass systems. Lampreys will seek and use even the smallest openings. For example, the seals around the edges of a screen system will allow entrainment if not well maintained.

Active swimming and inclination to travel towards the lower portion of the water column are dissimilar to typical salmon behavior, which may result in decreased passage efficiency through bypass systems at mainstem dams. Other physiological characteristics, such as a lack of scales, paired fins, and swim bladders, may make them more resilient to other components of the hydroelectric infrastructure, such as turbine passage. Lab studies and fish physiology suggest that juvenile lampreys are less likely to be negatively impacted by turbine entrainment (Moursund et al. 2000; Colotelo et al. 2012).

5.2 Recommendations

Despite the critical gaps in the understanding of lamprey passage at screened facilities, enough information has been garnered to allow the development of some general recommendations. Additional recommendations are provided for further research, monitoring, and evaluation needs (see Section 6).

Various fish screen materials are used in irrigation diversions, including woven wire, perforated plate, profile bar, and interlock materials. Based on lab and field studies (Rose and Mesa 2012; Mesa et al. 2017; Lampman and Beals 2019; Liedtke et al. 2019), we recommend, when possible, the following when considering fish screen types for lampreys:

- Minimize the approach velocity while maximizing the sweeping velocity (Rose and Mesa 2012). High sweeping velocity may minimize the number of larval or juvenile lampreys encountering the screens.
- Use the smallest mesh opening possible to minimize entrainment of smaller larvae; however, watch for impingement of larvae and juveniles.
- Use of perforated plate, interlock, or profile bar screen materials rather than woven wire screen material (Mesa et al. 2017).
- Design fish screens and headgates with the shallowest angle practical (i.e., the angle should be as close as possible to parallel to the direction of the flow, not perpendicular (Lampman and Beales 2019; Liedtke et al. 2019).

As older diversion facilities are replaced, we recommend that lamprey species are taken into consideration for the configuration of headgate structures. In addition to the angle and orientation, placing the headgate structure to open in the mid-water column rather than near the bottom may minimize the diversion of fine sediment and, therefore, lampreys. In addition, many diversions have a sluice gate structure close to the headgate. If the sluice gate is opened for extended periods prior to the irrigation season (focusing mainly on high flow events), this could help guide more lampreys rearing immediately upstream of the headgate structure to move downstream away from the risk of diversion entrainment.

6 Research, Monitoring, and Evaluation Needs

Despite extensive research that has been directed towards the development of protective measures and criteria for protecting juvenile Pacific salmon at water diversions (NMFS 2011), more work is needed to facilitate similar protection of larval and juvenile lampreys. Although some general recommendations have been offered (see Section 5.2), critical gaps remain before developing more specific criteria or guidelines becomes feasible. More understanding is needed regarding (1) hydraulics at screen facilities, (2) composition and placement of screens, and (3) behavior of lampreys that could influence the design and operation of screen systems.

Although maximizing the ratio between sweeping and approach velocities will benefit downstream migrating lampreys, further information is needed to more completely understand how lamprey entrainment and impingement are affected by hydraulics at screen facilities. This should include comparing hydraulic exclusion among screen types and innovative ways to increase hydraulic exclusion (see Section 6.1).

Small openings in screens will decrease the entrainment of lampreys; however, openings smaller than current criteria have not been evaluated under conditions likely to be encountered by lampreys at screen facilities in the Pacific Northwest. Some screen materials are preferred over others to help reduce entrainment and impingement. However, gaps remain in understanding (1) maximum opening sizes for some size groups of larval and juvenile lampreys, (2) differences in entrainment and impingement among screen types (e.g., horizontal screens vs. Coanda screens), and (3) effects of additional components of some screen systems such as debris removal systems. Placement of screens at shallow angles relative to flow is beneficial to lampreys, but additional work is needed to evaluate further and quantify this relationship. The passage of downstream migrating lampreys at mainstem hydroelectric facilities is poorly understood and should be further assessed (see Section 6.2).

Although little work on how lamprey behavior may affect passage and survival at screen facilities has been conducted, preliminary findings indicate that lamprey reactions to light and sound (or vibration) should be investigated further. Successful behavior-based deterrents that do not adversely affect salmon could reduce the need for lamprey-specific changes to hydraulics and screens in some cases (see Section 6.3).

Although not a focus of this document, other factors are essential to increasing the understanding of lamprey survival at screen facilities. These factors include the development of better tools to aid with evaluations (tags, sampling methods, etc.). A better understanding of how existing salmon collection facilities affect lamprey study results is also warranted.

6.1 Hydraulics

Effects of a screening structure rather than the screen itself may be most important in reducing the entrainment of small fishes (Coutant 2021). Primary mechanisms leading to low entrainment at screens appear to be (1) bow-wave hydraulics at the nose of the screen structure (Figure 3) and (2) fish detection and avoidance of pressure and velocity changes upstream of the structure that aid deflection. A high ratio of sweeping to approach velocity further reduces entrainment. However, site and design specific, further analyses of these physical parameters and hydraulic conditions are warranted.

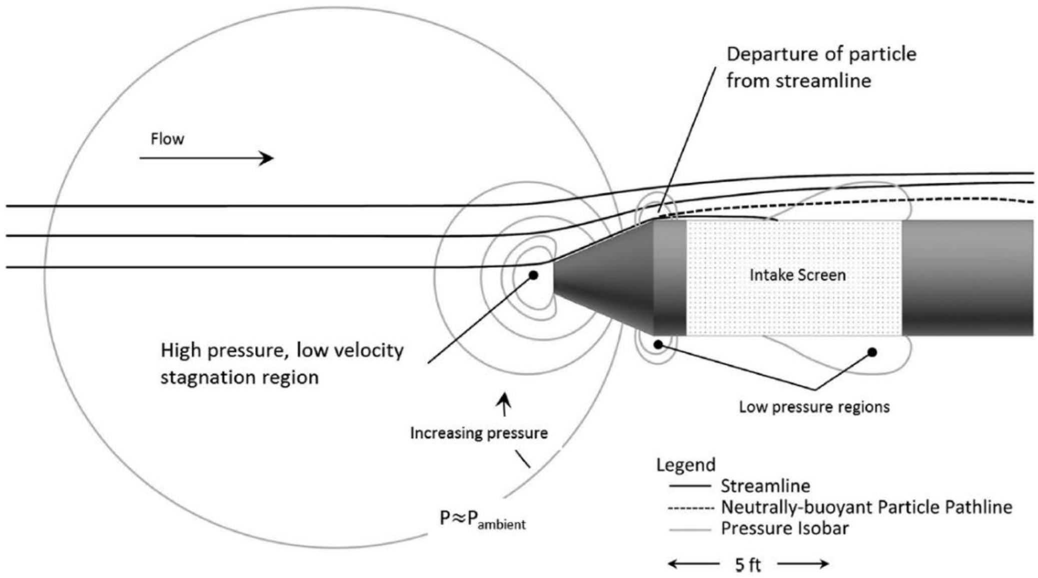

Figure 3. Conceptual view of flow streamlines and altered pressure and velocity around the upstream end of a cylindrical screen structure in a river, illustrating hydraulics of a 'bow wave' that would keep fish from entering a screen either hydraulically or by avoidance of pressure/velocity changes—drawing by B. Mater. Figure used with permission from Coutant (2021).

6.2 Composition and Placement of Screens

6.2.1 Screen Openings Smaller than Current Criteria

The use of screens with openings smaller than required by NMFS (2011) is not common in the Pacific Northwest and has not been evaluated for larval or juvenile lamprey entrainment. However, desalination intakes off the coast of California are required to install screens with 1.0 mm slot openings (State Water Resources Control Board 2019). This is required to prevent the entrainment of eggs and larval fishes. In New York, screens as small as 0.75 mm have been installed at cooling water intakes associated with power plants (ISI Intake Screens 2022, unpublished data). In Chesapeake Bay studies using 0.5 mm and 1.0 mm woven wire mesh cone screens, entrainment rates were reduced by 72% and 58%, respectively, compared to the control condition across all larval fish species and eggs (EPRI 2006). In addition to physical exclusion, hydrodynamic exclusion facilitated the diffusion of the flow field surrounding the woven wire mesh screen to allow sufficiently motile larvae to avoid entrainment, even if they were physically small enough to pass through the slot opening (EPRI 2006).

Smaller screen opening sizes may introduce hydraulic complications at typical screening facilities in the Pacific Northwest. The practicality of using smaller mesh in screens may also be questionable. Although smaller openings provide a better chance of physically preventing entrainment, they may promote faster clogging, leading to an increased impingement risk in unclogged areas. Decreased mesh opening sizes could also result in larger overall screening structures that may increase maintenance needs and decrease the number of sites that could accommodate a screening facility (because of limited stream width, depth, etc.).

6.2.2 Screen Material and Orientation

One need for future evaluation is the impact of horizontal flat plate fish screens on larval and juvenile lampreys. These screens are designed to reduce debris build-up and the incidence of impingement and entrainment of fishes. Mesa et al. (2010) tested the impacts of a small (10 cfs diversion) horizontal screen on juvenile Coho Salmon (*Oncorhynchus kisutch*), and FID (2003) tested a large screen (80 cfs diversion) on juvenile Chinook (*O. tshawytscha*) and steelhead (*O. mykiss*). These studies found that horizontal screens did not severely injure juvenile salmon. However, no studies have evaluated the impacts on lampreys, even though these screens have been utilized in areas with lampreys present. The associated hydraulics could result in efficient passage of lampreys because maintaining low approach velocities was an essential factor in reduced impingement rates (Mesa et al. 2017).

The public utilizes small diversion pump screens at private water rights POD and construction sites for dewatering. These pumps come in various shapes and sizes and pump anywhere from 1-50 cfs. The pump screen is located at the end of the pipe, and the screening material should comply with NMFS (2011) criteria. However, these screening criteria do not restrict the entrainment of small larval lampreys, and the localized suction could result in impingement of various size classes. Evaluating the effects of commonly used pump screens, both at POD and in-water construction could inform the use and recommendations for pump screens that limit lamprey impingement and entrainment. This could include an evaluation of pump placement or orientation to reduce lamprey interactions with the screen.

Because larval and juvenile lampreys have no swim bladders and are generally bottom-oriented, they often approach fish screens at or near the channel bottom (Liedtke et al. 2019). Small crevices or gaps at the bottom of fish screens can be a common pathway for larval lampreys to be entrained or become impinged. Although a direct laboratory test has not been conducted, a solid ledge or plate at the bottom of the fish screens could, in theory, be a potential solution to minimize lamprey interaction with fish screens near the bottom.

6.2.3 Mainstem Hydroelectric Facilities

Further analysis is needed regarding impingement on high-velocity screens at extensive facilities such as mainstem dams, particularly screens with open spaces greater than 1.75 mm (such as STSs and some ESBS's). Further analysis is also needed to evaluate entrainment at these facilities.

Few studies have evaluated turbine passage for lampreys. Lamprey flexibility, lack of a swim bladder, and other physiological features such as a lack of scales and other structures that could be torn (operculum, jaw, etc.) may result in an ability to tolerate high shear velocities and pressure changes than salmon. This could result in higher successful passage through turbines than observed for juvenile salmon, although these results do not consider impact injuries. More studies to evaluate the impacts of turbine passage are warranted. This is important because high proportions of lampreys may be passing through turbines due to low guidance efficiency into bypass systems. If lampreys can pass through turbines safely, it may be advantageous during part of the year (or at night) to lift screens that may be causing more damage than assistance to migrating lampreys while still protecting salmon.

6.3 Lamprey Behavior

Basic information on the timing and emigration routes is needed for larval and juvenile lampreys as they pass through tributaries and mainstem reservoirs. Understanding the seasonality of entrainment in irrigation canals could guide operations to protect both larvae and juveniles. More extensive use of both passive integrated transponders and active radio transmitters is needed to assess the environmental and operational conditions that affect passage timing and route selection and the resulting entrainment risks.

Studies to evaluate how many lampreys are entrained in irrigation canals and settle at points further down irrigation canals are needed during the irrigation season. Although recent research has documented the distribution of larval Pacific Lamprey immediately downstream from irrigation diversion screens after dewatering (Lampman et al. 2020), many more lampreys that move further downstream in the canal may be lost.

Developing behavioral deterrents is a potential avenue for reducing entrainment/impingement risk. Following up on the work of Moursund et al. (2002), further testing is needed to evaluate whether lights could be used to guide lampreys through dangerous areas (Moser et al. 2015). Minimal data exist on the hearing ability of lampreys. The inner ear structure is simple, and lampreys would be considered a hearing generalist, with maximum hearing to no more than several hundred Hz (Potter 2005). Testing is needed to elicit responses of Pacific Lamprey to sound.

Mussen and Cech (2018) assessed the use of vibrations and strobe lights at fish screens to enhance deterrents for estuarine fishes. Vibrating fish screens should also be tested for larval and juvenile lampreys. Lampreys have superficial neuromasts located in grooves on the skin of the head and trunk (similar in function to the lateral line system of other fishes). They may be able to detect and avoid a vibrating screen. Moreover, recent research has indicated the utility of electrical stimuli, chemosensory cues, and lighting to guide juvenile Sea Lamprey (Petromyzon marinus) in field and laboratory studies (Miels et al. 2017; Johnson et al. 2019; Haro et al. 2020). Similar work is needed for Pacific Lamprey larvae and juveniles.

Field studies in the Yakima Basin demonstrated that lamprey abundance and the availability of fine sediment within the canal environment upstream and downstream of the fish screens were strongly correlated (Lampman and Beals 2019). Larval and juvenile lampreys may be migrating alongside the fine sediment, and lampreys may be stopping and burrowing wherever a large amount of fine sediment is deposited. Further research is needed to determine if reducing fine sediment entry into canals reduces lamprey entrainment. The reduction of fine sediment has an operational and economic advantage for irrigation canal operators because it is costly to dredge and remove fine sediment.

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Appendix A. Common Fish Screen Types Found in the Pacific Northwest

Figure A-1. Example of a drum screen facility.

Figure A-2. Example of a cone screen facility (photo from awma Water Control Solutions; awmawatercontrol.com.au).

Figure A-3. Example of a vertical flat plate fish screen facility with a gang brush cleaning system.

Figure A-4. Example of a belt screen facility.

Figure A-5. Example of a horizontal fish screen

Figure A-6. Example of a Coanda screen (photo from Elgin Separation Solutions; https://elginseparationsolutions.com/coanda-screens/)

Figure A-7. Two examples of pump screens. Pump Rite manifold (left) and a Riverscreen (right).

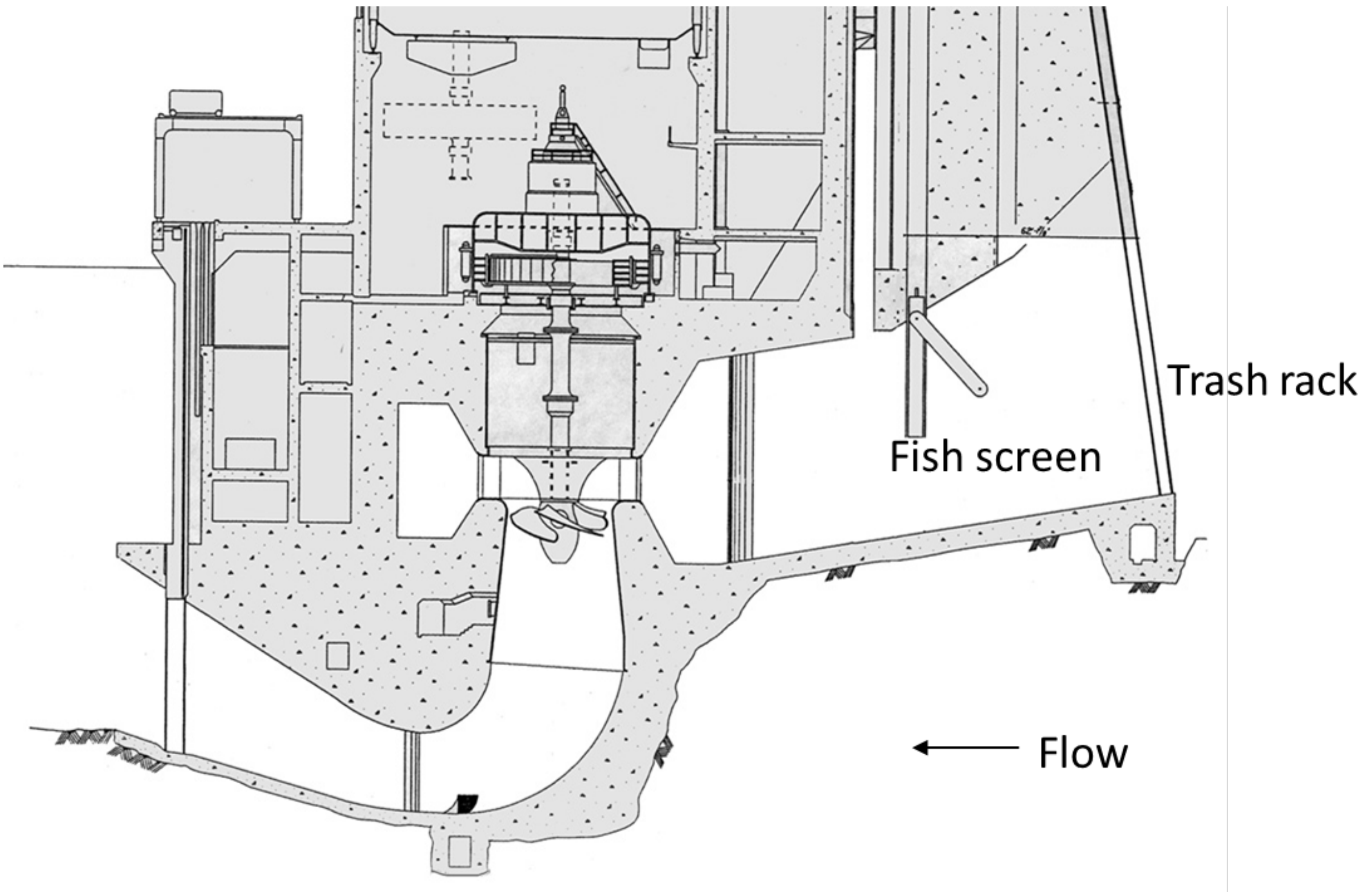

Figure A-8. Schematic cross-section of a turbine unit at a mainstem dam showing placement of a fish screen.