

## DESIGN GUIDELINES FOR PACIFIC LAMPREY PASSAGE STRUCTURES

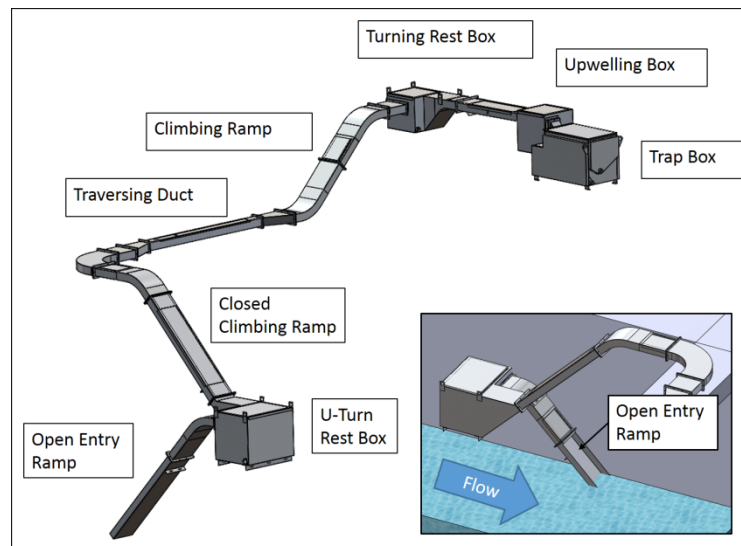
Study Code LMP-P-13-1

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National Marine Fisheries Service,  
Seattle, WA 98112-2097



For

U.S. Army Corps of Engineers  
Portland District

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## **Abstract**

Historically, hydraulic conditions within fishways at Columbia River basin dams were optimized to facilitate the passage of Pacific salmonids (*Oncorhynchus* spp). Declines in other anadromous species, including Pacific lamprey (*Entrophensius tridentatus*), have led to fishway modifications, operational changes, and construction of alternative passage structures such as Lamprey Passage Structures (LPS) in an effort to improve Pacific lamprey passage while minimizing potential impacts on salmonids. Currently, these structures are being considered for implementation at a wide variety of projects from low-head irrigation dams to large mainstem hydroelectric projects. In an effort to assist designers, we compiled design guidelines for use in the development of LPS systems, including hydraulic, structural, and operation considerations. We also present a digital parts library of major LPS structural components to facilitate cost-effective implementation of the systems in other locations.

## Introduction

Lamprey passage structures were developed in response to growing concern over decline of Pacific lamprey in the Columbia River basin and other locations (Close et al. 2002). While Pacific salmon (*Oncorhynchus* spp) decline has been well documented due to the economic impacts resulting from failed migration (Taylor 1999; NOAA 2014), Pacific lamprey were neglected or actively managed against. The hydraulic requirements for salmon are relatively well understood with research aimed at developing engineering criteria for salmonids (Johnson and Perkins 1968; Perkins and Smith 1973; Monk et al. 1989; Clay 1995; NMFS 2011). In contrast, the hydraulic requirements for Pacific lamprey have been less studied and require an understanding of both the swimming modes and capacities of lamprey in relation to the hydraulic, structural, and biological conditions encountered in fishways.

Telemetry and video studies of adult Pacific lamprey indicate that they have difficulty migrating upstream at barriers along the Columbia River (Beck 1995; Moser et al. 2002b; Clabough et al. 2012). Fishway passage efficiency for Pacific lamprey at Bonneville Dam through traditional fishways is often less than 50% (Moser et al. 2002a; Keefer et al. 2013) compared with >90% passage efficiency of salmonids (Caudill et al. 2007). Observations of refuging, milling, and failed passage also highlight the potential hydraulic limits on Pacific lamprey passage in fishways (Moser et al. 2002a, 2002b; Keefer et al. 2010; Johnson et al. 2012). Visual monitoring within fishways revealed that the standard overflow weir presents passage problems which results in milling behavior and failed passage (Beck 1995; Haro & Kynard 1997; Clabough et al. 2012). More recent detailed analyses using tagged lamprey that fishway entrances, the transition area from collection channels to weir-and-pool fish ladders, and serpentine-weir (i.e., vertical slot) sections in flow control sections of upper fish ladders pose the greatest challenges in fishways at Bonneville Dam (Keefer et al. 2013; 2014). In addition to structural considerations, lamprey size and genetics may determine upriver migration distance because adults recorded upstream were larger than average when tagged near the beginning of upstream migration (Keefer et al. 2009b) and size and migration distance have been shown to be associated with specific genetic markers (Hess et al. 2014). Whether the relationship between distance and size is adaptive or results from artificial selection at dams remains an open question.

In rivers and fishways, Pacific lamprey swim using three primary modes: anguilliform swimming in the water column, a saltatory or “burst-and-attach” mode with rapid burst swimming interspersed with attachment to substrates with their oral disc, and climbing while submerged or partially submerged on steep surfaces with sheeting flow using burst-and-attach motions. Saltatory swimming is more common in high velocity and/or turbulent environments and lamprey cannot attach to substrates with very rough or porous surfaces, like metal grating or perforated plate. Similarly, lamprey have difficulty passing areas with gaps or sharp edges such as squared weirs due to a combination of shearing flows and an inability to attach to substrates (Keefer et al. 2010). Lampreys increasingly orient to the bottom and sides of fishway as velocity increases (Beck 1995; Haro and Kynard 1997; Keefer et al. 2010, Kirk et al. 2015a) in many, but not all, locations (Johnson et al. 2013) during passage in the fishways. In addition, when predators are present and the mean velocities allow free swimming, Pacific lamprey shift upward in the water column (Kirk et al. 2015a).

The climbing ability of Pacific lamprey allows them to ascend barriers that would be otherwise impassable. Pacific lamprey can ascend vertical surfaces with sheeting flow and velocities  $\approx 3.7 \text{ m}\cdot\text{s}^{-1}$  ( $\approx 12 \text{ ft}\cdot\text{s}^{-1}$ ) (Kemp et al. 2009) and the lamprey's locomotion is kinematically optimized for maximal efficiency (Zhu et al. 2011). By climbing areas at the margins of flow channels, Pacific lamprey can ascend passage barriers such as the 12 m (39.4 ft) high Willamette Falls on the Willamette River (Clemens et al. 2012). Lamprey Passage Structures (LPS) were designed to exploit this natural climbing behavior and enable Pacific lamprey to bypass difficult sections within fishways (Moser et al. 2005, 2006, 2011). Lamprey ascend LPS systems by climbing on steep slopes ( $45^\circ$ - $60^\circ$ , Reinhardt et al. 2008) with sheeting flow, and via anguilliform swimming in low-slope traversing ducts that connect the sloped sections (Moser et al. 2011). Once lamprey enter an LPS, passage rates have been high ( $>90\%$ ; Moser et al. 2006, 2008, 2011). Interestingly, the rate of use often increases over time, suggesting aging or conditioning of surfaces improves lamprey attraction or guidance (Moser et al. 2009). Success of LPS systems has been highly dependent on location of the LPS entrances and collection efficiency; they have been most effective when placed in areas with high Pacific lamprey densities (Moser et al. 2005, 2006, 2008, 2011).

During anguilliform swimming, the results in laboratory settings estimated the critical swim speed (an estimate of the swim speed that can be maintained without fatiguing) of adult Pacific lamprey at approximately  $0.8 \text{ m}\cdot\text{s}^{-1}$  ( $2.6 \text{ ft}\cdot\text{s}^{-1}$ ) for an average body length (BL) of  $0.66 \text{ m}$  ( $2.17 \text{ ft}$ ) or  $1.3 \text{ BL}\cdot\text{s}^{-1}$  (Mesa et al. 2003). Within an experimental fishway the results were similar, with critical swim speeds around  $0.8 \text{ m}\cdot\text{s}^{-1}$  ( $2.6 \text{ ft}\cdot\text{s}^{-1}$ ) and maximum burst swimming between  $2.5$ - $3.0 \text{ m}\cdot\text{s}^{-1}$  ( $8.2$ - $9.8 \text{ ft}\cdot\text{s}^{-1}$  or  $3.8$ - $4.5 \text{ BL}\cdot\text{s}^{-1}$ ) for Pacific lamprey (Keefer et al. 2010), with passage at the highest velocities requiring saltatory swimming along the substrate.

Lamprey size likely affects swimming capacity. Length of adult Pacific lamprey can vary from  $\approx 0.16 \text{ m}$  to  $>0.80 \text{ m}$  ( $0.52 \text{ ft}$  to  $>2.62 \text{ ft}$ ) (Beamish 1980). In other fishes, smaller fish have lower maximum burst swim speeds and often have passage difficulties at dams designed for salmonids (Haro et al. 2004; Mallen-Cooper and Brand 2007; Barret and Mallen-Cooper 2006). Telemetry results indicate that smaller Pacific lampreys are less successful on average in migrating upstream past dams (Keefer et al. 2009a). The fish trapped for telemetry studies at Bonneville Dam have already entered a fishway and typically have lengths  $> 0.50 \text{ m}$  ( $1.64 \text{ ft}$ ) (Moser et al. 2006, 2008, 2011; Keefer et al. 2013) and there is concern that the current fishways at Bonneville Dam may be excluding smaller lamprey. The mechanism responsible for the association between size, hydraulic conditions, and successful dam passage is an active area of research (Keefer et al. 2013; Kirk et al. 2015b).

The key parameters affecting hydraulic conditions in an LPS system are duct slope, surface roughness, and channel shape. Slope describes the ratio of rise per length and determines gravitational influence. Flow depth decreases and velocity increases with increasing slope for a given discharge. Surface roughness describes the height of protrusions into the flow. For example, the material roughness of aluminum is comparable to that of steel or copper and has a roughness value estimated to be  $\epsilon = 0.002 \text{ mm}$  ( $6.6 \text{ e-}6 \text{ ft}$ ) (White 2003). The ratio of roughness to flow depth determines if the flow is hydraulically smooth, in the transitional roughness regime, or fully rough flow (Nezu and Nakagawa 1993). Channel shape affects secondary flows and acts as an additional form of flow resistance similar to roughness, but effects will diminish as the aspect ratio increases (Nezu and Nakagawa 1993). The aspect ratio is the relationship of channel width to flow depth  $\alpha = b/y$ ; in wide channels ( $\alpha > 10$ ), the effects of the walls are

considered negligible (Chow 1959). Increasing the aspect ratio also tends to increase the penetration of the roughness into the flow. The effective roughness of the ductwork will therefore vary with the aspect ratio, itself a function of duct width and discharge, duct material, and the assembly tolerances of the joints.

This document includes a compilation of design criteria used in the construction of several LPS systems now operating at Bonneville and John Day dams in support of future LPS system design and construction. Specifically, we report values for available criteria, evaluate the confidence that each criterion has been optimized, determine the range of acceptable values for each criterion, and identify areas of uncertainty in each criterion. A secondary aim is to develop a greater understanding of hydraulic requirements and modeling criteria including estimates of roughness and drag relative to submergence. Below we provide a brief description of LPS systems currently in place, present criteria, and then discuss specific criteria and important idiosyncrasies of individual systems.

## **Study Sites**

The study sites includes the Bonneville Dam complex and John Day Dam, both on the Columbia River (Figure 1). The LPS fishways we reviewed include an LPS installed in an Auxiliary Water Supply (AWS) channel inaccessible to adult salmonids near the top of the Bradford Island fishway installed in 2003 (Moser et al. 2003, 2011) also described as the Bradford Island Auxiliary Water Supply LPS (BILPS). A similar structure at the Washington Shore Fishway Auxiliary Water Supply LPS (WSLPS) was installed in 2007 (Moser et al 2011). The Cascades Island LPS (CILPS) was installed inside the Cascades Island fishway entrance during winter 2008-2009 (Moser et al. 2008, 2011; Clabough et al. 2010, 2011) and later extended to the forebay in 2013 (Corbett et al. 2014). The Washington Shore Fishway Lamprey Flume (WSF) is a combination structure of two parts. The lamprey are collected and begin to ascend in the Washington Shore Fishway Lamprey Flume using the Washington Shore Ladder Entrance Modification (WSF-WSEM) and then the fish continue up to the 55' deck and to a trap box through the Washington Shore Fishway Lamprey Flume-LPS (WSF-LPS) (Zobott et al. 2013). Finally, the John Day LPS (JDLPS) at the John Day North Fishway Entrance (NFE) was installed in spring of 2013. Pictures of the structures are in Figure 2.

The BILPS was the first LPS system, and was installed in the Bradford Island AWS. This area near the top of the ladder is used for hydraulic control and adult salmonids are excluded but lampreys have access through a picketed lead. Moser et al. (2003) implemented the first LPS at this location because Pacific lampreys were observed to congregate there without upstream access to a fishway exit, and because the experimental structures would not impede salmonid passage. Later, systems were implemented in other areas with lamprey congregations including the WSLPS, CILPS, and WSF. The WSLPS was installed at the Washington Shore AWS (Moser et al. 2011) and the CILPS was installed as part of a series of modifications intended to improve lamprey passage at the Cascades Island Fishway entrance (Clabough et al. 2011).

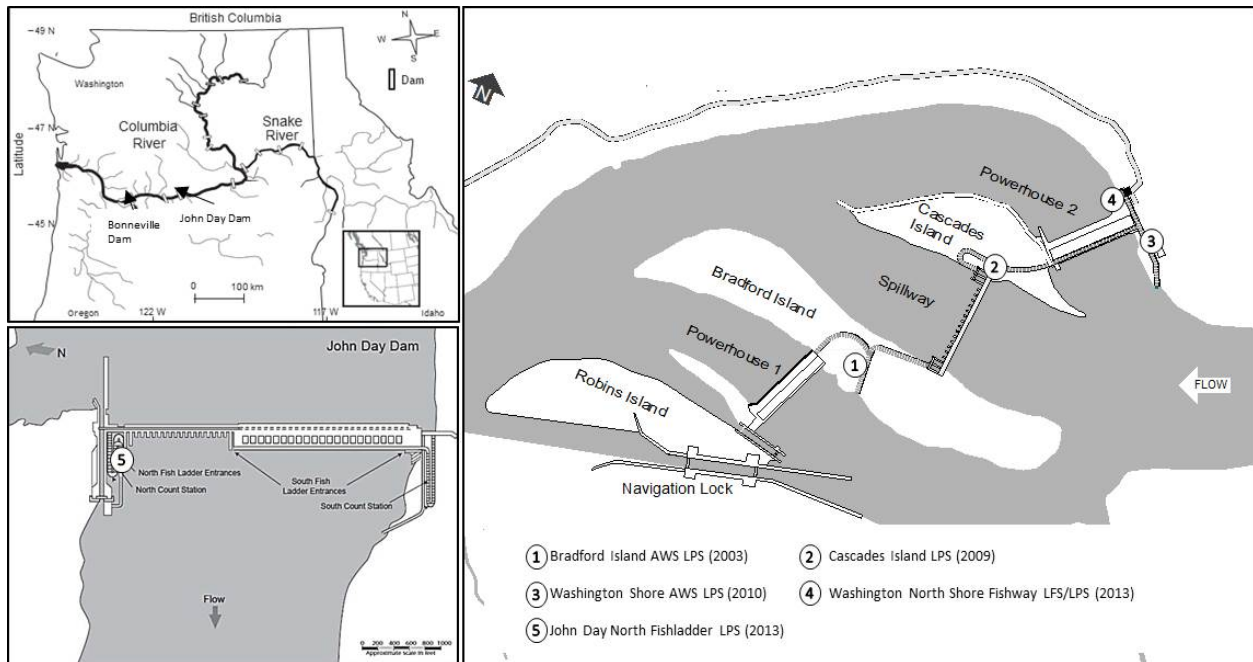


Figure 1. Top Left: Map of the Columbia River and locations of Bonneville and John Day dams. Bottom Left: John Day Dam LPS location. Right: Bonneville Dam Complex with LPS locations.

The first phase of the CILPS installation included a steep and long first ramp, and climbing ducts leading to the deck at forebay elevation. Structural constraints within the existing Cascades Island Fishway required a steeper and longer LPS entrance ramp than previously used at AWS sites. Later modification extended the system to the forebay. The JDLPS was installed in the lower fishway just upstream from the John Day Dam North Fishway Entrance (JDA NFE) in spring of 2013. Adults ascend to the tailrace deck level where they are trapped and transported to the forebay. USACE has begun early planning for an extension to the forebay. Finally, the most complex LPS system installed to date is the upper section of the Washington Shore Lamprey Flume at Bonneville Washington Shore. The WSF-LPS includes a lower WSEM structure with two large lamprey-specific entrances outside one of the Powerhouse 2 fishway entrances (the North Downstream Entrance, NDE). The WSEM entrances are provided with independent auxiliary attraction flow and connect to an above-water LPS leading to a trap box whereas most other LPSs consist of smaller open or closed channel collection ramps located inside fishways.



Figure 2. A) Bradford Island LPS two collector ramps; B) Washington Shore LPS two collector ramps; C) Cascades Island LPS collector ramp; D) Washington Shore Fishway LPS vertical collector, closed tube with baffled opening collector, Lamprey Flume Structure; E) John Day bollard field (foreground) and open ramp LPS collector.

## Results

### *Summary of Design Guidelines*

Design guidelines are based on parameter values used in previous LPS designs and research and are compiled in Table 1 from published and unpublished sources (Moser et al. 2005, 2008, 2011; Reinhardt et al. 2008; Zobott et al. 2013). The best practice to date is also identified in the last column. Various collector designs are compiled in Table 2, and pictures of the different collectors are in Figure 3. Below we discuss LPS component elements, design and siting considerations, and describe hydraulic design (Tables 3 and 4), and operational considerations.

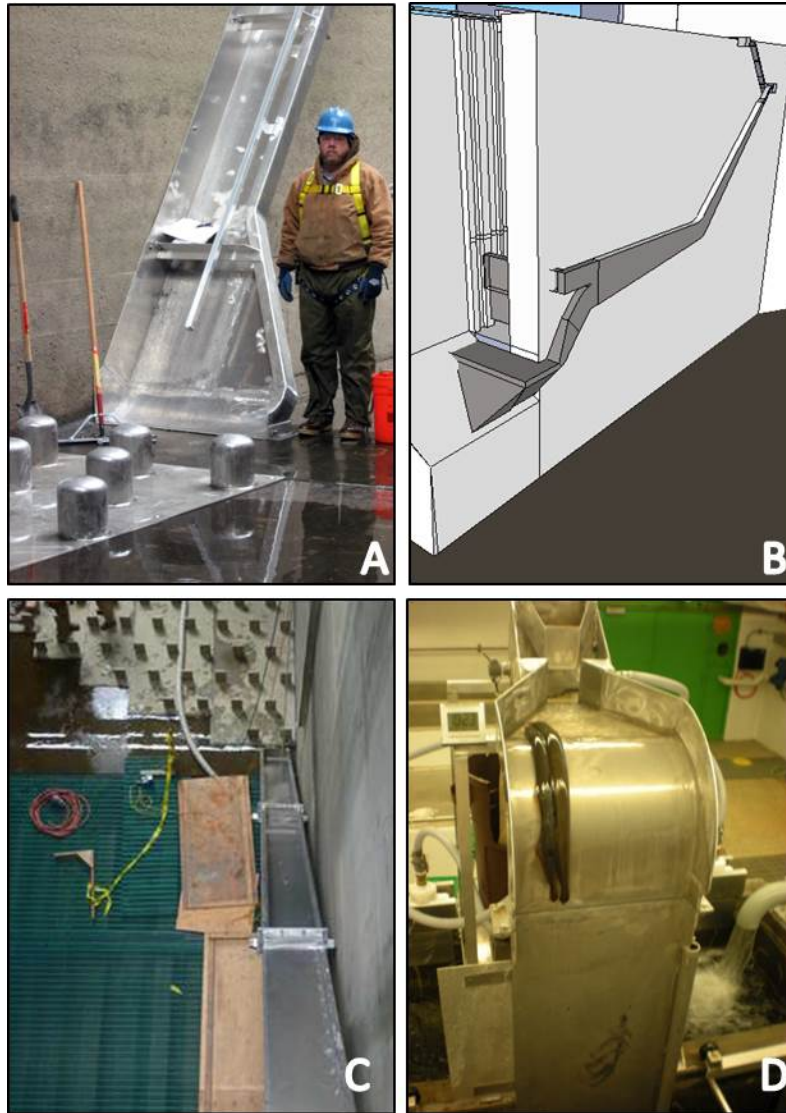


Figure 3. A) Cascades Island LPS bollard field with open ramp collector, ramp wall attached to the fishway wall; B) Schematic of the underwater section of the LFS, collector for the Washington Shore Fishway LPS: vertical collector and closed tube baffled collector; C) John Day LPS bollard field with rectangular bollards and open ramp collector; D) Waterfall collector (Frick 2015, *unpublished data*).

Table 1. Design guidelines for LPS systems

| Structures                                                                 | Bradford Island LPS<br>(BILPS)<br>2003                           | Bradford Island LPS<br>(BILPS)<br>2004-2005                      | Bradford Island LPS<br>(BILPS)<br>2006-2013                      | Washington Shore<br>AWS LPS<br>(WSLPS)<br>2007-2013               | Cascades Island LPS<br>(CILPS)<br>2009-2012                              | Cascades Island LPS<br>(CILPS)<br>2013                                   | Washington Shore<br>Lamprey Flume LPS<br>(WSF-LPS)<br>2013-2014 | Washington Shore<br>Lamprey Flume<br>WSEM<br>(WSF-WSEM)<br>2013-2014                          | John Day North<br>Fishway Entrance<br>LPS<br>(JDLPS)<br>2013-2014       | Best Practice                |
|----------------------------------------------------------------------------|------------------------------------------------------------------|------------------------------------------------------------------|------------------------------------------------------------------|-------------------------------------------------------------------|--------------------------------------------------------------------------|--------------------------------------------------------------------------|-----------------------------------------------------------------|-----------------------------------------------------------------------------------------------|-------------------------------------------------------------------------|------------------------------|
| General Features                                                           |                                                                  |                                                                  |                                                                  |                                                                   |                                                                          |                                                                          |                                                                 |                                                                                               |                                                                         |                              |
| Total Height (ft)                                                          | 25.9                                                             | 25.9                                                             | 25.9                                                             | 30.2                                                              | 88.6                                                                     | 88.6                                                                     | 27.9                                                            | 52.5                                                                                          | 34.8                                                                    | Variable                     |
| Total Length (ft)                                                          | 118.1                                                            | 118.1                                                            | 118.1                                                            | 68.2                                                              | 303.1                                                                    | 532.8                                                                    | 187.0                                                           | 52.5                                                                                          | 29.5                                                                    | Variable                     |
| Max elevation gain<br>between rest boxes<br>(ft)--Excludes initial<br>ramp | 10.5                                                             | 10.5                                                             | 4.6                                                              | 7.5                                                               | 24.6                                                                     | 24.6                                                                     | 12.1                                                            | 59.1                                                                                          | 34.0                                                                    | 11.5                         |
| Entrance Location                                                          | Bradford Island<br>AWS/adjacent<br>to the<br>serpentine<br>weirs | Bradford Island<br>AWS/adjacent<br>to the<br>serpentine<br>weirs | Bradford Island<br>AWS/adjacent<br>to the<br>serpentine<br>weirs | Washington Shore<br>AWS/adjacent<br>to the<br>serpentine<br>weirs | Inside<br>Fishway<br>Entrance/at<br>the end of<br>Bollard field          | Inside<br>Fishway<br>Entrance/at<br>the end of<br>Bollard field          | Washington<br>Shore LFS                                         | Outside<br>Fishway<br>Entrance,<br>vertical face<br>and monolith<br>leading up to<br>fishway. | Inside<br>Fishway<br>Entrance at<br>the end of<br>the bollard<br>field. | Where<br>milling<br>observed |
| Exit Location                                                              | Trap Box at<br>Forebay                                           | Forebay                                                          | Forebay                                                          | Forebay                                                           | Trap Box at<br>Forebay<br>Elevation<br>(2009-2012);<br>Forebay<br>(2013) | Trap Box at<br>Forebay<br>Elevation<br>(2009-2012);<br>Forebay<br>(2013) | Trap Box on<br>Tailrace Deck                                    | WSLPS                                                                                         | Trap Box on<br>Tailrace Deck                                            | Forebay                      |
| Material                                                                   | Aluminum                                                         | Aluminum,<br>PVC                                                 | Aluminum,<br>PVC                                                 | Aluminum,<br>PVC                                                  | Aluminum,<br>PVC                                                         | Aluminum,<br>PVC                                                         | Aluminum                                                        | Epoxy coated<br>Steel,<br>Fiberglass                                                          | Aluminum,<br>PVC                                                        | Low odor<br>material         |
| Discharge (gpm)                                                            | 124                                                              | 124<br>62                                                        | 124                                                              | 124                                                               | 124<br>62                                                                | 124<br>62                                                                | 62                                                              | ---                                                                                           | 62                                                                      | 62                           |
| Mean Annual<br>Passage or Trap &<br>Haul                                   | 5458                                                             | 8366                                                             | 7372                                                             | 5575                                                              | 778                                                                      | 653                                                                      | 545 (partial<br>operation<br>2014)                              | 545 (partial<br>operation<br>2014)                                                            | 1,228 (2014)                                                            | NA                           |

| Structures                         | Bradford Island LPS<br>(BILPS)<br>2003 | Bradford Island LPS<br>(BILPS)<br>2004-2005 | Bradford Island LPS<br>(BILPS)<br>2006-2013 | Washington Shore<br>AWS LPS<br>(WSLPS)<br>2007-2013 | Cascades Island LPS<br>(CILPS)<br>2009-2012 | Cascades Island LPS<br>(CILPS)<br>2013 | Washington Shore<br>Lamprey Flume LPS<br>(WSF-LPS)<br>2013-2014 | Washington Shore<br>Lamprey Flume<br>WSEM<br>(WSF-WSEM)<br>2013-2014 | John Day North<br>Fishway Entrance<br>LPS<br>(JDLPS)<br>2013-2014 | Best Practice |
|------------------------------------|----------------------------------------|---------------------------------------------|---------------------------------------------|-----------------------------------------------------|---------------------------------------------|----------------------------------------|-----------------------------------------------------------------|----------------------------------------------------------------------|-------------------------------------------------------------------|---------------|
| Traversing Duct Design Guidelines  |                                        |                                             |                                             |                                                     |                                             |                                        |                                                                 |                                                                      |                                                                   |               |
| Traversing Slope                   | nearly<br>horizontal                   | nearly<br>horizontal                        | nearly<br>horizontal                        | horizontal                                          | horizontal                                  | horizontal                             | 0.0035                                                          | NA                                                                   | 0.0035                                                            | 0.0035        |
| Mean Velocity<br>Traversing (ft/s) | 1.0                                    | 1.0                                         | 1.0                                         | 1.0                                                 | 1.0                                         | 1.0                                    | 1.3                                                             | 1.6                                                                  | 1.3                                                               | 1.0           |
| Max velocity (ft·s <sup>-1</sup> ) | 1.6                                    | 1.6                                         | 1.6                                         | 1.6                                                 | 1.6                                         | 1.6                                    | 1.6                                                             | 3.0                                                                  | 3.0                                                               | 3.0           |
| Min Duct width (ft)                | 0.7                                    | 0.7                                         | 0.7                                         | 0.7                                                 | 0.7                                         | 0.7                                    | 0.8                                                             | 2.0                                                                  | 1.6                                                               | 0.7           |
| Max Duct width (ft)                | 0.7                                    | 0.7                                         | 0.7                                         | 1.7                                                 | 1.7                                         | 1.7                                    | 1.6                                                             | NA                                                                   | 1.6                                                               | 1.6           |
| Minimum Turning<br>radius (ft)     | NA                                     | NA                                          | NA                                          | 1.6                                                 | 1.6                                         | 1.6                                    | 1.6                                                             | 1.6                                                                  | 1.6                                                               | 1.6           |
| Contraction Angle<br>(°)           | 16                                     | 16                                          | 16                                          | 16                                                  | 16                                          | 16                                     | 25                                                              | NA                                                                   | NA                                                                | 16            |

| Structures                                  | Bradford Island LPS<br>(BILPS)<br>2003                         | Bradford Island LPS<br>(BILPS)<br>2004-2005                    | Bradford Island LPS<br>(BILPS)<br>2006-2013     | Washington Shore<br>AWS LPS<br>(WSLPS)<br>2007-2013 | Cascades Island LPS<br>(CILPS)<br>2009-2012                                       | Cascades Island LPS<br>(CILPS)<br>2013                                            | Washington Shore<br>Lamprey Flume LPS<br>(WSF-LPS)<br>2013-2014 | Washington Shore<br>Lamprey Flume<br>WSEM<br>(WSF-WSEM)<br>2013-2014                                                                  | John Day North<br>Fishway Entrance<br>LPS<br>(JDLPS)<br>2013-2014                              | Best Practice                                                                                                      |
|---------------------------------------------|----------------------------------------------------------------|----------------------------------------------------------------|-------------------------------------------------|-----------------------------------------------------|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|-----------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------|
| Climbing Duct Design Guidelines             |                                                                |                                                                |                                                 |                                                     |                                                                                   |                                                                                   |                                                                 |                                                                                                                                       |                                                                                                |                                                                                                                    |
| Climbing duct width<br>(ft)                 | 1.67                                                           | 1.67                                                           | 1.67                                            | 1.67                                                | 1.67                                                                              | 1.67                                                                              | 1.64                                                            | 2.00                                                                                                                                  | 1.64                                                                                           | 1.64                                                                                                               |
|                                             |                                                                |                                                                | 2.00                                            |                                                     | 2.00                                                                              | 2.00                                                                              |                                                                 |                                                                                                                                       |                                                                                                |                                                                                                                    |
|                                             |                                                                |                                                                |                                                 |                                                     | 4.00                                                                              | 4.00                                                                              |                                                                 |                                                                                                                                       |                                                                                                |                                                                                                                    |
| Ramp Entrance<br>Orientation                | Downstream                                                     | Downstream                                                     | Downstream                                      | Downstream                                          | Downstream                                                                        | Downstream                                                                        | Downstream                                                      | Downstream                                                                                                                            | Downstream                                                                                     | Downstream                                                                                                         |
| Collector design                            | Attached to<br>Fishway wall,<br>open duct<br>ramp<br>collector | Attached to<br>Fishway wall,<br>open duct<br>ramp<br>collector | Attached to<br>both walls,<br>open duct<br>ramp | Attached to<br>both walls,<br>open duct<br>ramp     | At upstream<br>end of<br>bollard field,<br>attached to<br>wall, open<br>duct ramp | At upstream<br>end of<br>bollard field,<br>attached to<br>wall, open<br>duct ramp | WSLFS                                                           | Baffled<br>collector at<br>bottom of<br>fishway<br>structure,<br>submerged<br>vertical<br>collector on<br>fishway<br>entrance<br>wall | At upstream<br>end of<br>bollard field,<br>attached to<br>wall, open<br>duct ramp<br>collector | Where fish<br>observed to<br>aggregate,<br>areas with<br>structural<br>guidance,<br>open duct<br>ramp<br>collector |
| Climbing Slope                              | 1.2                                                            | 1.2                                                            | 1                                               | 1                                                   | 1.64                                                                              | 1.64                                                                              | 1                                                               | 1                                                                                                                                     | 1                                                                                              | 1                                                                                                                  |
|                                             | 0.32                                                           | 0.32                                                           |                                                 |                                                     | 0.81                                                                              | 0.81                                                                              |                                                                 |                                                                                                                                       |                                                                                                |                                                                                                                    |
|                                             | 1                                                              | 1                                                              | 0.32                                            |                                                     | 1                                                                                 | 1                                                                                 |                                                                 |                                                                                                                                       |                                                                                                |                                                                                                                    |
|                                             |                                                                |                                                                |                                                 |                                                     | 0.58                                                                              | 0.58                                                                              |                                                                 |                                                                                                                                       |                                                                                                |                                                                                                                    |
| Mean Velocity<br>Climbing (Range<br>ft-s-1) | 8.9                                                            | 8.9                                                            | unknown                                         | unknown                                             | 8.9                                                                               | 8.9                                                                               | 7.9                                                             | unknown                                                                                                                               | 7.9                                                                                            | 7.9                                                                                                                |
|                                             | 11.8                                                           | 11.8                                                           |                                                 |                                                     | 11.8                                                                              | 11.8                                                                              |                                                                 |                                                                                                                                       |                                                                                                | 11.8                                                                                                               |
| Contraction                                 | at crest                                                       | at crest                                                       | Above water<br>line                             | None                                                | Below Water<br>line                                                               | Below Water<br>line                                                               | None                                                            | None                                                                                                                                  | None                                                                                           | None                                                                                                               |

| Structures                                                 | Bradford Island LPS<br>(BILPS)<br>2003 | Bradford Island LPS<br>(BILPS)<br>2004-2005 | Bradford Island LPS<br>(BILPS)<br>2006-2013 | Washington Shore<br>AWS LPS<br>(WSLPS)<br>2007-2013 | Cascades Island LPS<br>(CILPS)<br>2009-2012 | Cascades Island LPS<br>(CILPS)<br>2013 | Washington Shore<br>Lamprey Flume LPS<br>(WSF-LPS)<br>2013-2014 | Washington Shore<br>Lamprey Flume<br>WSEM<br>(WSF-WSEM)<br>2013-2014 | John Day North<br>Fishway Entrance<br>LPS<br>(JDLPS)<br>2013-2014 | Best Practice                   |
|------------------------------------------------------------|----------------------------------------|---------------------------------------------|---------------------------------------------|-----------------------------------------------------|---------------------------------------------|----------------------------------------|-----------------------------------------------------------------|----------------------------------------------------------------------|-------------------------------------------------------------------|---------------------------------|
| Rest Box Design Guidelines                                 |                                        |                                             |                                             |                                                     |                                             |                                        |                                                                 |                                                                      |                                                                   |                                 |
| Max traversing<br>length w/o rest box<br>(ft)              | 33                                     | 33                                          | 33                                          | 82                                                  | 98                                          | 239                                    | 149                                                             | NA                                                                   | NA                                                                | <656                            |
| Min traversing<br>length into rest box<br>after climb (ft) | 3.6                                    | 3.0                                         | 3.0                                         | 2.0                                                 | 3.0                                         | 3.0                                    | 0.0                                                             | NA                                                                   | 2                                                                 | >3.3                            |
| Min Rest Box<br>Volume (ft <sup>3</sup> )                  | 11.44                                  | 11.44                                       | 11.44                                       | 11.44                                               | 11.44                                       | 11.44                                  | 15.00                                                           | NA                                                                   | 11.44                                                             | 11.30                           |
| Fyke Design Guidelines                                     |                                        |                                             |                                             |                                                     |                                             |                                        |                                                                 |                                                                      |                                                                   |                                 |
| Length (ft)                                                | 1                                      | 1                                           | 1                                           | 1                                                   | 1                                           | 1                                      | 1                                                               | NA                                                                   | 1                                                                 | <0.5 width of<br>Rest Box       |
| Inlet Width (ft)                                           | 0.7                                    | 0.7                                         | 0.7                                         | 1.6                                                 | 1.6                                         | 1.6                                    | 1.6                                                             | NA                                                                   | 1.6                                                               | Match<br>Climbing<br>Duct Width |
| Outlet (ft)                                                | 0.3                                    | 0.3                                         | 0.3                                         | 0.6                                                 | 0.3                                         | 0.3                                    | 0.5                                                             | NA                                                                   | 0.5                                                               | 0.3                             |
| Contraction Angle<br>(°)                                   | 12                                     | 12                                          | 12                                          | 30                                                  | 30                                          | 30                                     | 50                                                              | NA                                                                   | 50                                                                | 12                              |
| Contraction Angle<br>Skew                                  | None                                   | None                                        | None                                        | None                                                | None                                        | None                                   | Positive or<br>Negative                                         | NA                                                                   | Positive or<br>Negative                                           | None                            |

| Structures                  | Bradford Island LPS<br>(BILPS)<br>2003                                                                                           | Bradford Island LPS<br>(BILPS)<br>2004-2005                                                                                      | Bradford Island LPS<br>(BILPS)<br>2006-2013                                                                                 | Washington Shore<br>AWS LPS<br>(WSLPS)<br>2007-2013                | Cascades Island LPS<br>(CILPS)<br>2009-2012                                                  | Cascades Island LPS<br>(CILPS)<br>2013                                                                     | Washington Shore<br>Lamprey Flume LPS<br>(WSF-LPS)<br>2013-2014        | Washington Shore<br>Lamprey Flume<br>WSEM<br>(WSF- WSEM)<br>2013-2014                                      | John Day North<br>Fishway Entrance<br>LPS<br>(JDLPS)<br>2013-2014 | Best Practice                                                  |
|-----------------------------|----------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------|----------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------|----------------------------------------------------------------|
| Exit Duct Design Guidelines |                                                                                                                                  |                                                                                                                                  |                                                                                                                             |                                                                    |                                                                                              |                                                                                                            |                                                                        |                                                                                                            |                                                                   |                                                                |
| Upwelling Box<br>Width (m)  | 2.6                                                                                                                              | 2.6                                                                                                                              | 2.6                                                                                                                         | 2.6                                                                | 2.6                                                                                          | 2.6                                                                                                        | 2.6                                                                    | NA                                                                                                         | 2.6                                                               | 2.6                                                            |
| Exit Design                 | Trap and<br>Haul                                                                                                                 | PVC Chute                                                                                                                        | PVC Chute                                                                                                                   | PVC Chute                                                          | Pond Box to<br>PVC pipe,<br>slight<br>downslope,<br>to PVC chute                             | Pond Box to<br>PVC pipe,<br>slight<br>downslope,<br>to PVC chute                                           | Trap and<br>Haul                                                       | NA                                                                                                         | Trap and<br>Haul                                                  | PVC pipe exit<br>tube                                          |
| Chute Slope (°)             | NA                                                                                                                               | NA                                                                                                                               | 17                                                                                                                          | 51                                                                 | 17                                                                                           | 17                                                                                                         | 60                                                                     | NA                                                                                                         | NA                                                                | 17                                                             |
| Chute Surface               | NA                                                                                                                               | NA                                                                                                                               | Plastic mesh                                                                                                                | Plastic mesh                                                       | PVC                                                                                          | PVC                                                                                                        | Perforated<br>Aluminum                                                 | NA                                                                                                         | Perforated<br>Aluminum                                            | Perforated<br>Aluminum                                         |
| Discharge Flow              | Unknown                                                                                                                          | Unknown                                                                                                                          | Unknown                                                                                                                     |                                                                    |                                                                                              |                                                                                                            |                                                                        |                                                                                                            |                                                                   | 10-12 gpm                                                      |
| Exit Location               | Trap Box                                                                                                                         | Forebay                                                                                                                          | Forebay                                                                                                                     | Forebay                                                            | Forebay                                                                                      | Forebay                                                                                                    | Trap Box                                                               | WSFLPS                                                                                                     | Trap Box                                                          | Forebay,<br>upstream<br>adequately to<br>prevent<br>fallback   |
| Monitoring                  | Twice daily                                                                                                                      | Daily                                                                                                                            | Daily                                                                                                                       | Daily                                                              | Daily                                                                                        | Daily (to<br>check for<br>pond<br>holdovers)                                                               | Twice Daily                                                            | N/A                                                                                                        | Daily                                                             | daily, am                                                      |
| PIT antenna<br>locations    | At top of<br>collection<br>ramp, just<br>downstream<br>from rest<br>box 2 and 3,<br>and just<br>downstream<br>from exit<br>slide | At top of<br>collection<br>ramp, just<br>downstream<br>from rest<br>box 2 and 3,<br>and just<br>downstream<br>from exit<br>slide | At top of<br>collection<br>ramps, just<br>downstream<br>from rest<br>box 3, and<br>just<br>downstream<br>from exit<br>slide | Just<br>downstream<br>from rest<br>box 2 and<br>from exit<br>slide | Just<br>downstream<br>from rest<br>box 3 and<br>just<br>downstream<br>from trap<br>box entry | Just<br>downstream<br>from rest<br>box 3 and<br>just<br>downstream<br>from pond<br>entry and<br>exit slide | Trap box<br>(2015-),<br>Rest Box 2<br>(2014),<br>Rest Box 3<br>(2015-) | Four<br>antennas<br>monitoring<br>upper and<br>lower<br>entrances,<br>junction and<br>upper WSEM<br>(2014) | Trap Box<br>(2014)                                                | Determined<br>by Research<br>and<br>Monitoring<br>Requirements |

| Structures           | Bradford Island LPS<br>(BILPS)<br>2003 | Bradford Island LPS<br>(BILPS)<br>2004-2005 | Bradford Island LPS<br>(BILPS)<br>2006-2013 | Washington Shore<br>AWS LPS<br>(WSLPS)<br>2007-2013 | Cascades Island LPS<br>(CILPS)<br>2009-2012 | Cascades Island LPS<br>(CILPS)<br>2013 | Washington Shore<br>Lamprey Flume LPS<br>(WSF-LPS)<br>2013-2014                   | Washington Shore<br>Lamprey Flume<br>WSEM<br>(WSF-WSEM)<br>2013-2014 | John Day North<br>Fishway Entrance<br>LPS<br>(JDLPS)<br>2013-2014 | Best Practice                                                        |
|----------------------|----------------------------------------|---------------------------------------------|---------------------------------------------|-----------------------------------------------------|---------------------------------------------|----------------------------------------|-----------------------------------------------------------------------------------|----------------------------------------------------------------------|-------------------------------------------------------------------|----------------------------------------------------------------------|
| Water Supply         |                                        |                                             |                                             |                                                     |                                             |                                        |                                                                                   |                                                                      |                                                                   |                                                                      |
| Water Supply Source  | PH1 Forebay                            | PH1 Forebay                                 | PH1 Forebay                                 | Fishway Water                                       | Spillway Forebay                            | Spillway Forebay                       | PH2 Tailrace                                                                      | Forebay                                                              | Fishway AWS channel at tailrace elevation                         | Same as water near entrance ramp                                     |
| Pumping              | Shrouded, 2×3HP Submersible Well Pump  | Shrouded, 2×3HP Submersible Well Pump       | Shrouded, 2×3HP Submersible Well Pump       | Shrouded, 2×3HP Submersible Well Pump               | Shrouded, 2×3HP Submersible Well Pump       | Shrouded, 2×3HP Submersible Well Pump  | Shrouded, 2×3HP Submersible Well Pump                                             | Gravity Supply                                                       | 1×5HP Submersible Well Pump                                       | Minimal vibration pump with shroud that meet NMFS Screening Criteria |
|                      | 4 in Flexible PVC pipe                 | 4 in Flexible PVC pipe                      | 4 in Flexible PVC pipe                      | 4 in Flexible PVC pipe                              | 4in Flexible PVC pipe                       | 4in Flexible PVC pipe                  | 3 in Flexible PVC to Brass and Iron pipe Manifold with Schedule 40 piping on deck | Unknown                                                              | 3 in galvanized pipe with 5.1cm PVC pipe lining                   | PVC or Non-Galvanized metal                                          |
| Water Supply Control | Either 1 or 2 pumps turned on          | Either 1 or 2 pumps turned on               | Either 1 or 2 pumps turned on               | Either 1 or 2 pumps turned on                       | Either 1 or 2 pumps turned on               | Either 1 or 2 pumps turned on          | Dump valve into drain on dam                                                      | Butterfly valve-bubbles at certain discharges                        | Dump valve into storm drain on dam                                | Size pump according to discharge, head height and pipe sizing        |

Table 2. Collector design descriptions

| Duct Collector(s)                                  | Bradford Island LPS (BILPS) (2004), Washington Shore AWS LPS (WSLPS) (2007), Cascade Island LPS (CILPS) (2008), John Day LPS (JDLPS) (2013) |                                                      |                               |                                                                                   |                                       |                                                                                                            |
|----------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------|-------------------------------|-----------------------------------------------------------------------------------|---------------------------------------|------------------------------------------------------------------------------------------------------------|
| Description                                        | Duct along fishway wall attaching to side and bottom of fishway                                                                             |                                                      |                               |                                                                                   |                                       |                                                                                                            |
| Pieces                                             | Closed Ramp                                                                                                                                 | Open Ramp                                            | Closed Ramp Baffled Collector | High flow                                                                         | Low Flow                              | Final                                                                                                      |
| Discharge (gpm)                                    | 124                                                                                                                                         | 124                                                  | 124                           | 124                                                                               | 62                                    | 62                                                                                                         |
| Height (ft)                                        | 10                                                                                                                                          | 10                                                   | 10                            | 10                                                                                | 10                                    | 10                                                                                                         |
| Duct Width (ft)                                    | 1                                                                                                                                           | 2                                                    | 1                             | 2                                                                                 | 2                                     | 2                                                                                                          |
| Collector Width (ft)                               | 2                                                                                                                                           | 2                                                    | 2                             | 2                                                                                 | 2                                     | 2                                                                                                          |
| Collector Orientation                              | Upstream/ Downstream                                                                                                                        | Upstream/ Downstream                                 | Upstream/ Downstream          | Downstream                                                                        | Downstream                            | Downstream                                                                                                 |
| Pacific Lamprey Access Point (s)                   | At fishway bottom                                                                                                                           | Along Fishway Wall and Fishway bottom                | At fishway bottom             | Along fishway wall and fishway bottom                                             | Along fishway wall and fishway bottom | Along fishway wall and fishway bottom                                                                      |
| Slope                                              | 0.6                                                                                                                                         | 1                                                    | 0.6                           | 1                                                                                 | 1                                     | 1                                                                                                          |
| Number of Ramps                                    | 1                                                                                                                                           | 1                                                    | 1                             | 1                                                                                 | 1                                     | 2                                                                                                          |
| Combination Collectors                             |                                                                                                                                             | Washington Shore NDE LPS (2009)                      |                               | Washington Shore Entrance Modification (WSEM) (2013)                              |                                       |                                                                                                            |
| Description                                        |                                                                                                                                             | Transition Structure with Collector Ramp             |                               | Transition Structure with additional closed duct and baffled entrance             |                                       |                                                                                                            |
| Pieces                                             |                                                                                                                                             | Transition Structure                                 | Collector Ramp                | Transition Structure with additional closed duct and baffled entrance             |                                       | Closed Duct with Baffled Entrance                                                                          |
| Discharge (gpm)                                    |                                                                                                                                             | 124                                                  | 124                           | Total flow: up to 31000<br>Upper Entrance: 46.6% of flow                          |                                       | Total flow: up to 31000<br>Lower Entrance: 53.4% of flow                                                   |
| Height (ft)                                        |                                                                                                                                             | 26                                                   | 0                             | Entrance 4.5<br>Flow Splitter 4.5-10.5<br>Lower flume 10.5-3<br>Upper flume 3-1.5 |                                       | Entrance 2,<br>Transition piece 2-6.5<br>Flow Splitter 6.5-10.5<br>Lower flume 10.5-3<br>Upper flume 3-1.5 |
| Duct Width (ft)                                    |                                                                                                                                             | 2                                                    | 0                             | 2                                                                                 |                                       | 2                                                                                                          |
| Collector Width (ft)                               |                                                                                                                                             | 2                                                    | 0                             | 11.3                                                                              |                                       | 15                                                                                                         |
| Collector Orientation                              |                                                                                                                                             | Downstream                                           | Downstream                    | Downstream                                                                        |                                       | Downstream                                                                                                 |
| Pacific Lamprey Access Point (s)                   |                                                                                                                                             | In front of fishway on vertical transition structure | Along fishway wall            | In front of fishway on vertical transition structure                              |                                       | On fishway monolith floor in from of fishway entrance                                                      |
| Slope                                              |                                                                                                                                             | Vertical                                             | 1                             | Vertical                                                                          |                                       | Horizontal                                                                                                 |
| Number of Ramps                                    |                                                                                                                                             | 1                                                    | 1                             | 1                                                                                 |                                       | 1                                                                                                          |
| Waterfall Collector (Frick et al. <i>in prep</i> ) |                                                                                                                                             |                                                      |                               |                                                                                   |                                       |                                                                                                            |
| Water Supply type                                  |                                                                                                                                             | Upwelling                                            |                               | Sidewelling                                                                       |                                       | Overflow                                                                                                   |
| Condition                                          |                                                                                                                                             | min                                                  | max                           | min                                                                               | max                                   | min                                                                                                        |
| Discharge (ft <sup>3</sup> /sec)                   |                                                                                                                                             | 0.004                                                | 0.018                         | 0.013                                                                             | 0.061                                 | 0.008                                                                                                      |
| Water depth (in): Wall                             |                                                                                                                                             | 0.1                                                  | 0.1                           | 0.0                                                                               | 0.2                                   | 0.1                                                                                                        |
| Crest                                              |                                                                                                                                             | 0.2                                                  | 0.3                           | 0.2                                                                               | 0.5                                   | 0.2                                                                                                        |
| Depression                                         |                                                                                                                                             | 1.3                                                  | 1.6                           | 1.5                                                                               | 1.9                                   | 1.4                                                                                                        |
| Outfall                                            |                                                                                                                                             | 0.5                                                  | 1.3                           | 0.6                                                                               | 1.8                                   | 0.2                                                                                                        |
| Height (ft)                                        |                                                                                                                                             | 5.3 (water level to crest)                           |                               |                                                                                   |                                       |                                                                                                            |
| Wall width (ft)                                    |                                                                                                                                             | 1.6 (downstream from crest)                          |                               |                                                                                   |                                       |                                                                                                            |
| Outfall width (ft)                                 |                                                                                                                                             | 0.3 (at exit)                                        |                               |                                                                                   |                                       |                                                                                                            |

## Major LPS Components and Parts Library

All of the LPSs are composed of similar structural elements. The three main sub-assemblies of the LPS systems are entrance and climbing ramps, traversing duct sections, and exit/trap sections (Figure 4). Water supply comprises the fourth major component, consisting of the water supply itself (pumps, supply lines) and the interface with the LPS through an upwelling box. These components have been assembled into a digital parts library, which may be used to more rapidly develop new designs (Appendix A).

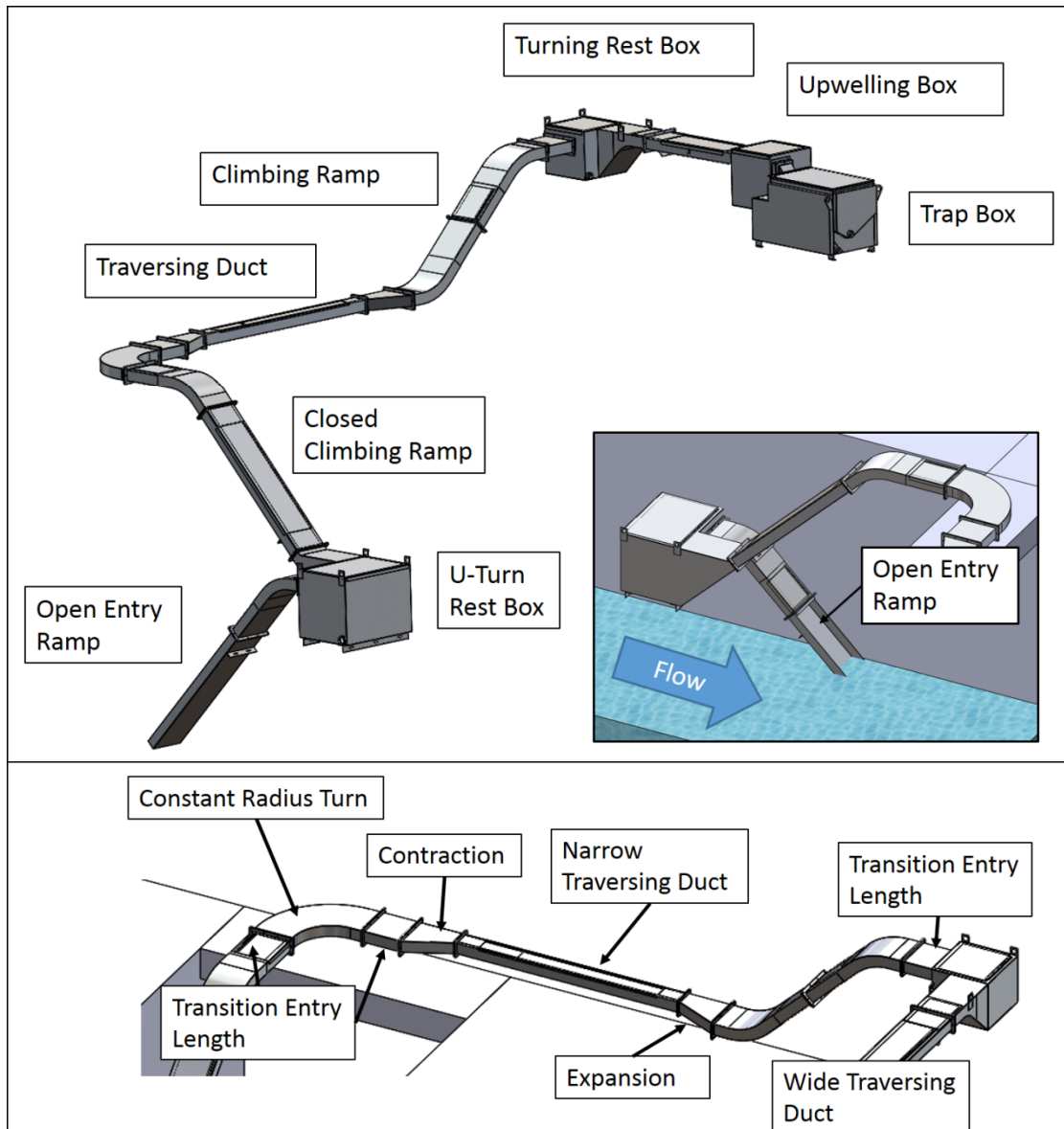


Figure 4. Schematic of a LPS fishway that shows the entry ramp, climbing duct, and traversing section components. Top panel shows a typical orientation with the inset picture describing flow orientation. Bottom panel shows the different cross sections and direction changes of the traversing sections where flow is subcritical.

The geometry of the LPS ductwork controls the hydraulic conditions for passage (Figure 5). All ductwork was 0.15 m (0.49 ft) high. The CILPS, BILPS, and WSLPS traversing duct widths differed slightly, and were either 0.19 m (0.62 ft) or 0.51 m (1.67 ft). The duct widths for the WSF-LPS and the JD LPS fishway were: 0.23 m (0.75 ft) for traversing ducts and 0.50 m (1.64 ft) for climbing duct width (Figure 5). Recommended width depends on discharge and should maintain velocities between  $0.3\text{--}0.5\text{ m}\cdot\text{s}^{-1}$  ( $1.0\text{--}1.6\text{ ft}\cdot\text{s}^{-1}$ ). Climbing duct width likely depends on flow depth and should be 0.5 m (1.64 ft), for flows up to  $7.8\text{ L}\cdot\text{s}^{-1}$  (124 gpm). Wider widths may be necessary to avoid lamprey crowding in systems with high passage rates.

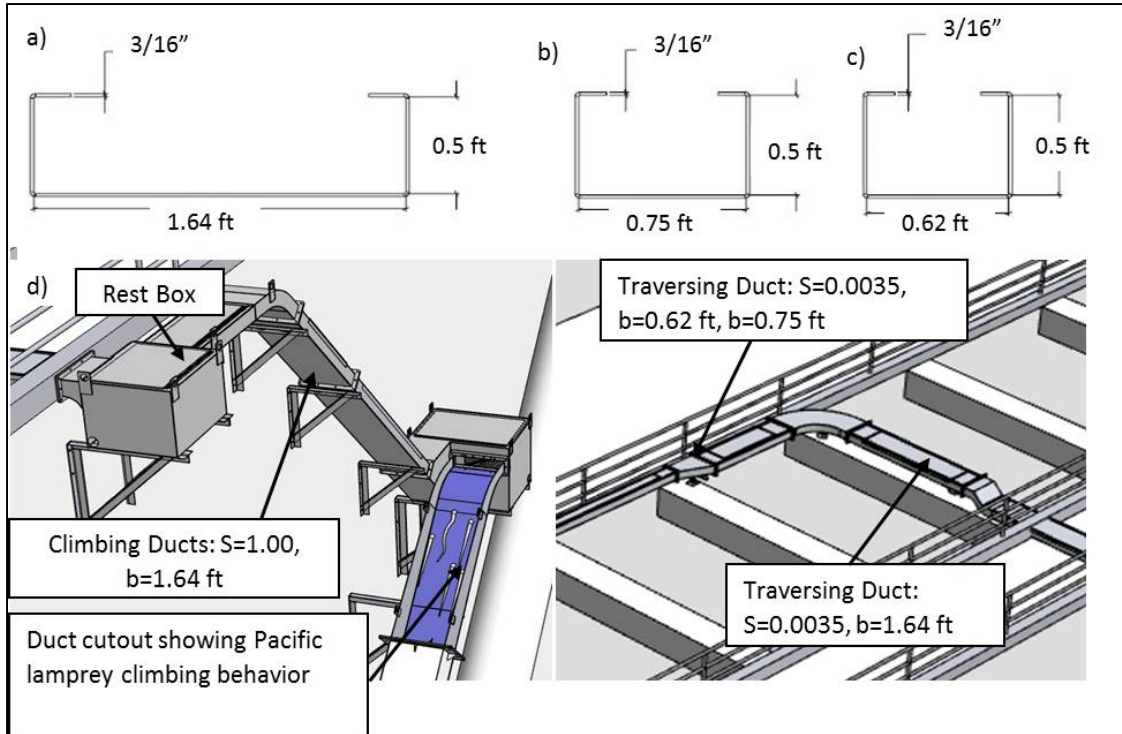


Figure 5. Cross-sectional geometry of typical LPS ductwork, (S) is slope, (b) is width. Interior dimensions used in calculations: a) Climbing duct cross section with Slope = 1; b) Traversing duct cross section with Slope = 0.0035 at Washington Shore Fishway LPS; c) Traversing duct of Cascades Island, Bradford Island, and Washington Shore AWS LPS systems with Slope = 0.0035; d) LPS schematic.

The entry ramps of the climbing section can be either open or closed. The open ramps do not have a cover, are generally attached to a fishway wall, and allow access to the ramp at any point within the water column. The closed duct entry ramps have lids that prevent access to the climbing ramp except at collection points and have generally been used at the bottom or sides of fishways. The climbing duct has supercritical, thin flow that the fish climb, with variable velocities all above the critical swim velocity (Kemp et al. 2009). Ramps should be closed above the typical water level to prevent predation and reduce algal growth, and open at the water surface and below in typical application. Any algae or surface irregularities may inhibit the

lampreys ability to attach and may slow climbing. Long open collection ramp sections may be required to accommodate fluctuating water levels (e.g., Bonneville Dam Cascades Island).

### *Collection and Attraction Structures*

Each LPS built at Bonneville Dam targeted a group of lamprey that were observed to have difficulty entering or passing a fishway. The basic collector is an open ramp against a fishway or AWS wall that extends to the floor. The location of and flow from the structure provide lamprey attraction as does ambient flow in the adjacent fishway or channel.

Several collector designs were evaluated as part of the LPS development, including open ramp, closed ramp, baffled entrance, tube entrance, vertical collector, and waterfall collector. In addition to design, orientation of the collectors with respect to the flow was also evaluated. The most successful LPS to date has been the open ramp collector (Moser et al. 2011).

Waterfall collectors are a potential LPS entrance for space-constrained areas containing high densities of salmonids such as the serpentine weir sections of fish ladders where lamprey exhibit poor passage success. An experimental vertical climbing structure intended as a mechanism of passing lamprey out of a serpentine weir section of a fish ladder into an AWS containing an LPS was tested in the laboratory facility at Bonneville Dam in 2014. Lamprey passage was 100% under all experimental conditions for fish that interacted with the structure (Frick et al. *in preparation*).

### *LPS Traversing Sections, Resting Boxes, and Water Supply*

Within the LPS duct subassemblies there are rest boxes (Figure 5). Rest boxes are structures that have pools of water with low velocities that act as lamprey rest and recovery areas after bouts of climbing, as daytime refuges from light, places for LPS direction changes, and structures that limit down-LPS lamprey movement. The rest boxes and upwelling boxes control fish passage direction with internal fykes (Figure 6). Direction changes of the LPS within climbing sections are almost always made with rest boxes (Figure 7). The exception is a 90° turn within the CILPS structure that was accomplished using a wide traversing section and a constant radius of 0.5 m (1.6 ft) turn that was about 8 m (26 ft) from any other transitions.

Traversing ducts run nearly horizontally, have subcritical flow where the flow is deeper and slower, and have velocities well below the critical swim velocity of lamprey (Table 4;  $<0.5 \text{ m}\cdot\text{s}^{-1}$  [ $1.0 \text{ ft}\cdot\text{s}^{-1}$ ] duct velocity vs.  $0.8 \text{ m}\cdot\text{s}^{-1}$  [ $2.6 \text{ ft}\cdot\text{s}^{-1}$ ] critical swim velocity; Mesa et al. 2003). Typical depths are 0.10 m (4 in) (Moser et al 2011). All traversing ducts should be covered to reduce algal growth and protect lamprey from predation.

Duct width changes occur from the wide duct to the narrow duct (Figure 5d) within the fyke (Figure 6). The contraction has not been well studied. Implemented angles vary from 12° with no skew to 50° with a positive or negative skew. The negative skew has a straight side and only one side contracting the flow. The no skew has a center line which both sides contract equally. Positive or negative skew assumes that the fish swim along a sidewall. Centered skew assumes the fish swim along the centerline. Evidence supports both, although when confronted with hydraulically difficult sections, the fish are observed to move to one side of the duct (Keefer et al. 2011).

LPS systems were largely fabricated from aluminum with some exit components constructed from PVC and some antenna components from HDPE, PVC, and/or fiberglass. The typical material used for LPS was 4.8-mm 5051 H32 Aluminum plate that was then formed with “sharp” interior bends. The typical angle of the climbing duct was  $45^\circ$  (slope = 1), and the angle of the horizontal duct was  $0.2^\circ$  (slope = 0.0035). Small edges or discontinuities can disrupt lamprey climbing. Thus climbing duct junctions were aligned within a tolerance of ( $\pm 1.6$  mm), while the traversing duct alignment was ( $\pm 3.8$  mm). The climbing duct pieces were bolted together with silicone sealant in the interface to maintain a water-tight seal. Excess silicone was wiped out, or trimmed flush if dried.

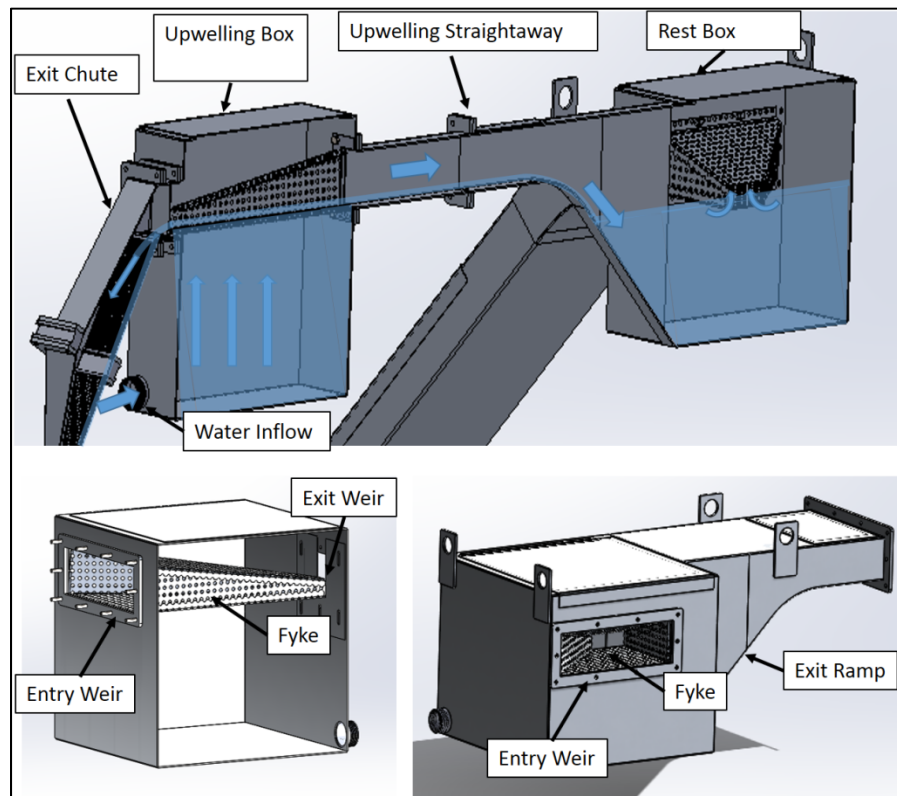


Figure 6. LPS water supply and exit/collection components. Top: Cross-section of the exit assembly: arrows show the flow direction. The upwelling box splits the flow between the LPS and the exit section. Bottom: The internal features of the boxes control fish movement through the system. A rest box has a perforated metal or plastic entry fyke, a pool, and an exit ramp. The upwelling box has a fyke from the entry to the exit with flow rates set by the entry and exit weir shape, size, and relative heights.

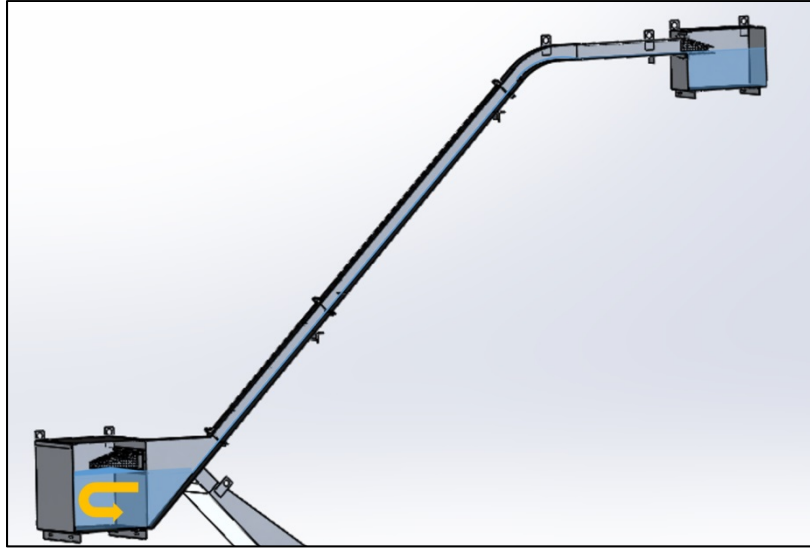


Figure 7. Cross section of the climbing assembly: The climbing section has climbing ducts in straight runs with turns and direction changes occurring in the rest boxes.

All structural materials and LPS parts were made out of aluminum which made onsite modifications easy. It is important to limit galvanic interactions of the structure by limiting the types of metal in contact. Bituminous tape was used between aluminum and concrete interfaces and neoprene washers were used between stainless fasteners and aluminum surfaces for the WSF-LPS and the JD-LPS. The brackets for the WSF-LPS that attached the traversing ductwork were similar to pipe brackets and bolted around the ductwork. The brackets could be moved horizontally and attached to standardized stands. Mounting bracket designs varied between different LPSs, and should be custom fit or designed to allow for several inches of adjustment due to irregular concrete surfaces typical at fishways. Plastic shims were used when necessary to maintain slope. Limit the number and size of the fasteners at each duct union to speed assembly. Silicone sealer effectively sealed any gaps in the interface, and torquing the bolts at each interface is not necessary for structural integrity or a water-tight seal.

Pacific lamprey are sensitive to biological and mechanical residues on the LPS surfaces. For instance, the WSF-LPS had a protective film covering the surfaces during manufacturing that was removed by sanding just prior to installation. There was no further surface treatment prior to use in any system. Every LPS had an increase in use after 1-2 years of seasoning, suggesting the build-up of biofilms and/or leaching of trace manufacturing compounds facilitated use by adult lampreys. The LPS fishway should not be deployed in areas of high predator density such as white sturgeon (*Acipenser transmontanus*; Kirk et al. 2015a) or sea lions to minimize potential for predation. Human contact with the LPS surfaces also deters use. Lastly, any injured or dead lamprey within the structures will likely deter other lampreys from using the structure until it is removed (e.g., Wagner et al. 2011).

## Water Supply

A typical LPS has supply water pumped from the elevation of the entrance (i.e., tailwater or AWS channel) to an upwelling box at the top of the LPS. The USACE has recommended a configuration with two pumps that run continuously to make up the required flow rate for the LPS. For example, two  $4.73 \text{ L}\cdot\text{s}^{-1}$  (75 gpm) pumps with outputs combined through a manifold (with one-way valves) to achieve a target flow rate of  $9.46 \text{ L}\cdot\text{s}^{-1}$  (150 gpm). The rationale is that if one pump fails the LPS will still operate at discharges above  $3.9 \text{ L}\cdot\text{s}^{-1}$  (62 gpm), which is enough discharge to sustain the lamprey already in the LPS while the pump is being repaired. Water supply to the LPS duct is provided through an upwelling box placed at the maximum elevation of the system. The upwelling box splits the LPS supply flow between: 1) the LPS proper; and 2) the exit channel or trap box (Figure 6) where all flow is gravity fed thereafter. Pumps systems are detailed below.

Pumps sizes are selected to exceed the anticipated required flow rate by 20% to 40% and a throttle valve is used to adjust the flow rate down to an optimum level. Dump valves could be used if an acceptable location to dump the excess water is present. We recommend that Variable Frequency Drive (VFD) controllers not be used because of the high frequency interference they add to the power lines, which may disturb RFID antennas commonly in the vicinity of the LPSs.

Submersible well pumps have been used for LPS water supplies. The submersible pumps require a shroud around the pump motor casing. Water is drawn into the annular gap between the shroud and the pump motor casing and provides proper cooling of the pump motor. Minimum flow rates must be maintained around the motor casing when the pump is running as specified by the pump motor manufacturer.

Pump intake screens are also required to meet fish passage facility requirements for juvenile salmon detailed in NMFS (2011). The applicable requirements indicate an approach velocity less than  $0.061 \text{ m}\cdot\text{sec}^{-1}$  ( $0.2 \text{ ft}\cdot\text{sec}^{-1}$ ) and a maximum square screen mesh size of 2 mm (0.08 in) to prevent impingement or entrapment of juvenile salmonids. A typical design combining the pump shroud and the intake screen in a single unit is illustrated in Figure 8.

All LPS fishways to date were designed based on the flow rate of  $3.9 \text{ L}\cdot\text{sec}^{-1}$  to  $7.8 \text{ L}\cdot\text{sec}^{-1}$  (Moser et al. 2011). The operational flow rate may be different because of pump head height, pipe sizing, pump horsepower, duct sizing, and any additional valving employed to control flow in a functional LPS fishway. The typical method is to set the flow depth according to reported values of about 0.10 m (4 in) in the traversing duct or 0.03 m (1.2 in) at the top of the climbing duct; where the traversing duct parameters are: width of 0.23 m, slope of 0.0035, and width of 0.5 m and slope of 1.0 for the climbing duct (Moser et al. 2011).



Figure 8. Pump shroud for submersible pump.

However, flow depths within the climbing section are difficult to measure by hand accurately because of flow velocity and shallow depths. Consequently, we empirically estimated the roughness of a typical LPS fishway and discharge based on flow depth using a refined depth measurement technique (Appendix B) because accurately estimating depth in supercritical flows is challenging. We generated operational curves that relate flow depth to discharge and velocity for the various traversing duct widths and for the climbing duct (Figure 9) based on the determined roughness values from flume experiments (Appendix B). The model is for fully developed flow and would be representative of velocities and depths near the end of a stretch of duct, when the flow has stabilized. Fully developed flow is required to use the charts of flow depth versus velocity in Figure 9. Guidelines for flow measurement conditions for fully developed flow are as follows: The depth measurement should be done in a narrow traversing duct section, at the end of a straightaway between 6-12 m (20-40 ft) from any direction change or cross section change, or when the ratio of entrance length to overall length ( $L_e/L$ ) is  $< 60\%$  (Appendix B). One alternative to careful measurement of depth using the method above is to use a flowmeter on the water supply line into the upwelling box.

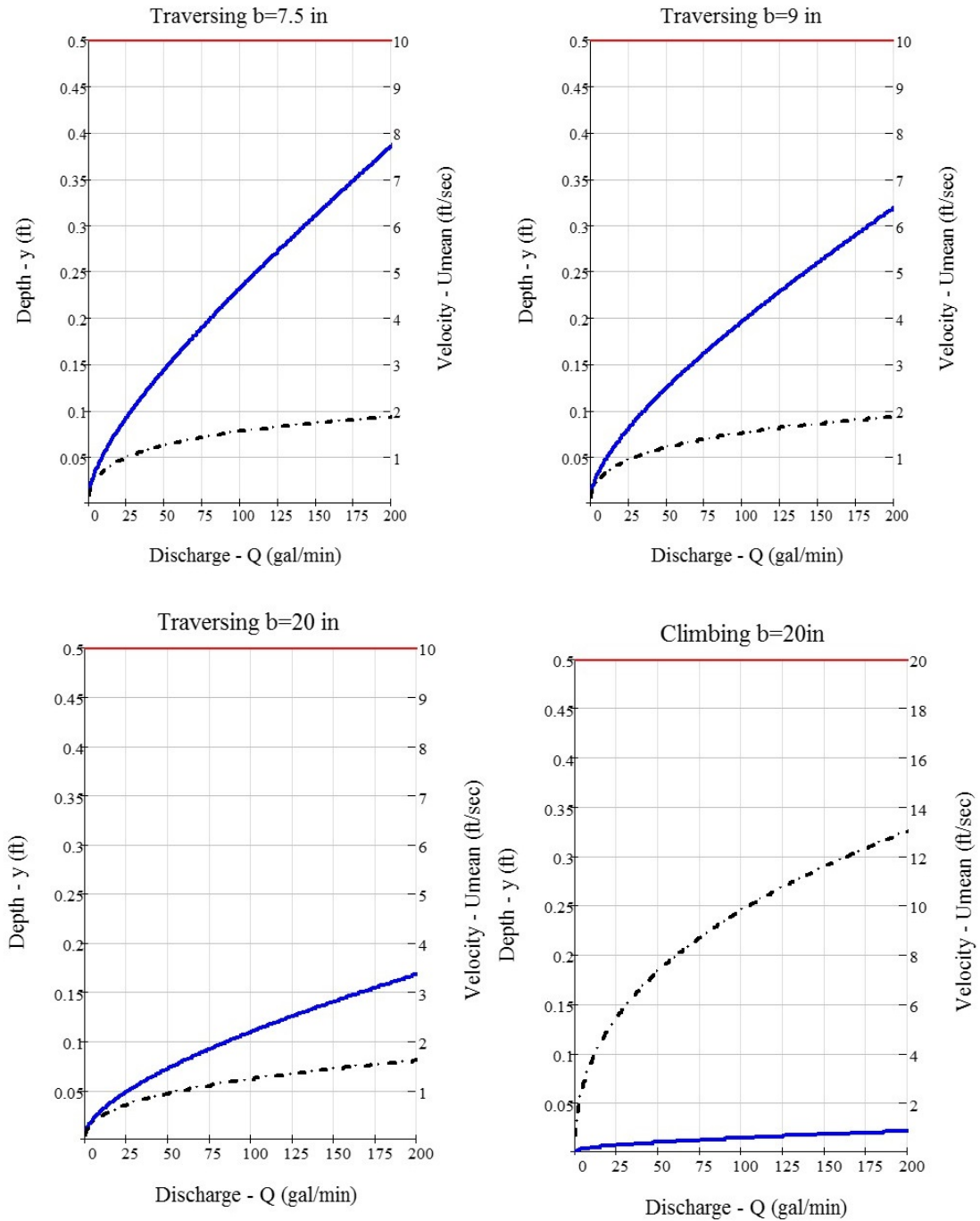


Figure 9. Operating Curves for LPS Ductwork relating flow depth (y), duct width (b), and average velocity. The flow depth is shown with blue solid lines, while mean velocity is shown with black dashed lines.

### *Exit Structures*

LPS exit structures must facilitate lamprey exit without inducing attachment or turnaround. They often incorporate counting mechanisms. Lampreys exit the LPSs via several different exit slide arrangements. For those structures exiting to a dam forebay (such as at BILPS and CILPS), 25° slopes and the ability to dewater the exit slide are critical to both rapid and complete lamprey exits and accurate counts at the slide terminus. In addition, the interior of all exit slides must not allow lamprey attachment, as lamprey will attempt to re-ascend the slide if they are able to attach; perforated plate lining has been effective in these locations.

### *Siting LPS Entrances*

Attraction of lamprey is most successful by siting the entrances in an area where lamprey congregate. Milling behavior indicates that the fish are looking for alternative routes (Moser et al 2011) and are more likely to encounter the structure. Areas with milling often have relatively high fish density and for all these reasons are good potential locations for an LPS. Structural features, fishway flow, and LPS flow all contribute to attraction, although the effect of each is not fully understood at this point. Keefer et al. (2010) observed that jets and waterfalls also attracted lamprey to the structures, while bubble curtains may deter Pacific lamprey. Active use of olfactory cues (e.g., juvenile lamprey pheromones) to attract lamprey to entrances has been proposed, but uncertainty over efficacy and unintended effects such as stalled passage upstream of the input location, leave the concept conceptual. Lamprey attraction is an area of ongoing research.

Site selection for the location of the LPS entrance is perhaps the most critical design consideration because site selection will determine the number of lamprey available for collection by the structure and will also determine whether adequate rheotactic and other cues are present to guide lamprey to the structure. Unfortunately, quantitative estimates of lamprey density in fishways are rarely available. Nonetheless, previous observations provide some guiding principles. The collection efficiency (number collected by LPS / number passing area) between systems is highly variable and causes of the variation are not clearly understood. Discharge from the LPS, flow within the fishway, and location of the LPS entrance relative to other fishway structures all seem to affect LPS collection efficiency.

Lampreys appear to find an LPS most readily when passage efficiency at alternative routes are low, when structural features ‘funnel’ lamprey to entrances, and/or in dead-end channels (e.g., auxiliary water supply areas) where lamprey are milling. Structural guidance also likely plays a role. A prototype LPS ramp similar to that shown in Figure 4 installed prior to development of the LFS/LPS at the Washington Shore Fishway at Bonneville Dam had high attraction flow but low collection efficiency, perhaps because it was located in the tailrace next to the fishway entrance and not within a constrained fishway. Within a constrained area or dead-end channel, siting the entrance of an LPS adjacent to or near bulk flows seems to facilitate attraction of lampreys. Other fishway modifications can also be used to enhance guidance of lampreys toward LPS entrances. Bollard fields at the entrance of Bonneville Cascades Island Fishway Entrance and the John Day Dam North Fishway Entrance are angled toward one fishway wall and the base of LPS entrances in an effort to enhance guidance of lamprey to the LPS entrances (Figure 3).

The designer should orient the initial climb of the LPS with the flow of water in the receiving channel at a location where lamprey densities are high, are likely to be milling, areas with potential structural guidance (walls or constrictions), impediments to linear migration, and with low to moderate flow rates. The usual deployment of the structures is along a wall with the initial climbing ramp extending all the way to the floor and the climbing face of the ramp on the downstream (lee) side of the flow (Figure 4).

### *Siting LPS Exits*

Ensuring that lampreys enter a dam forebay close to its surface and in sufficient depths at all forebay elevations is critical to safe passage into a forebay. However, an exit slide must terminate before reaching the water surface at all forebay elevations, or lamprey will be stimulated to turn around after exiting and attempt to ascend the exit slide from the forebay. The location should minimize potential for orientation and fallback at spillways (e.g., Reischel et al. 2003), fishway exits, or turbine intakes and the potential for the aggregation of predators. A well-designed exit slide rapidly moves fish into the forebay and allows for an automated count system, which reduces labor associated with moving and counting individuals collected by the LPS. The downside of such exit slides is that they are in a static position where predators can learn to target lamprey that use the LPS. Improperly designed slides can result in physical injury or delay of exiting lamprey and can produce unreliable counts. In some cases, it may be necessary to install a volitional release box or other refuge that the lamprey enters after passing through the slide. Such a dark, safe and low-velocity refuge allows lampreys to recover from the LPS exit, re-orient and find their way back into the river channel after the trauma of sliding down the exit (A. Jackson, Confederated Tribes of the Umatilla Indian Reservation, *unpublished data*). Refuge alternatives are critical in areas where a spillway is near the exit location, where predators congregate, or where high water velocity occurs near the exit slide terminus. The temperature of the forebay release location in relation to LPS temperature should be considered because forebay temperatures often differ spatially and are frequently higher than tailrace temperatures (Caudill et al. 2013). An ideal location would minimize the temperature difference between the LPS water temperature and forebay temperature.

For exit slides that deposit lamprey back into a fishway (e.g., Washington-shore AWS LPS), it is important that lamprey have sufficient time to re-orient to the current inside the fishway before being swept downstream and into difficult sections of the fishway (e.g., the serpentine weir sections at Bonneville Dam). In addition, the exit slide should deposit lamprey far enough away from fishway walls and other structures to preclude injury on entry into the fishway. Moreover, water splashing onto the opposite fishway walls from an exit slide can attract lamprey that are already in the fishway and create delay as they attempt to climb the fishway wall. Water dropping from an exit slide should be directed into a fishway at an area with sufficient depth that is relatively predator-free, and does not create attraction to the fishway walls or other structures.

### *Trap-and-Haul vs Volitional Release*

Both trap-and-haul and volitional release into a forebay upstream from the dam can have positive and negative impacts on lamprey that have successfully passed a LPS. Trap-and-haul operations provide the ability to get a very accurate count of lamprey use, allow assessment of

individuals that use the structure (i.e., size, sex, or condition of individual users at various times of year), and allow for directed release at specific safe locations upstream from the dam. However, trap-and-haul is labor-intensive, can result in mortalities if regular maintenance and trap checks are not performed, and involves a greater degree of lamprey handling and concomitant stress than volitional release strategies. Volitional release from a LPS does not require handling of individuals and should therefore be relatively low stress and allow lamprey to enter a forebay during normal activity periods (typically at night).

### *Enumeration of Passage*

As noted above, trap-and-haul operations allow for the most accurate assessment of successful LPS use. In lieu of handling and counting individual lamprey, a number of counting methods have been devised in association with LPS exit slides (Moser et al. 2005, 2011, 2012; Corbett et al. 2013, 2014). Most of these have relied on lamprey contact with a paddle or swing arm as they drop out of the exit slide. The arm is connected to a limit switch, which activates a counter and records individual passage events. Such a system can have outage periods associated with damage from passing lamprey, power failures, software or hardware failures, or human error. Systems that can be downloaded remotely should also allow for manual downloads to prevent system outages during network failures. Adequate firewalls are needed to insure data security. In addition, it is essential that counts from such systems are regularly validated. Attempted use of other methodologies (video, motion activated cameras, electrical impedance counters, etc.) has resulted in either unreliable counts (e.g., double-counting) or have been considered too time-consuming and labor intensive. Improvement of counting technology is needed so that lamprey use of a LPS can be accurately enumerated in real time and at low cost.

### *LPS Hydraulic Parameters and Operational Criteria*

We conducted measurements in a flume to estimate the roughness of a typical LPS fishway so that we could better estimate flow depth at different discharges. We researched the roughness in flume experiments using a seasoned piece of LPS fishway from the Washington Shore Entrance Collector LPS (Moser et al 2006). We recommend implementing the Darcy Friction factor and the Energy Equation to estimate hydraulic conditions within the LPS fishway using the roughness values below. Flows are within the transition roughness regime, and we recommend using the Moody Diagram or an appropriate friction factor correlation to determine the Darcy Friction factor.

The traversing duct condition did not exhibit fully developed flow within the length of flume we tested. Due to the practical need for modeling LPS designs with traversing straightaways that are less than the necessary entrance length of fully developed flow, we recommend using the traversing duct roughness value for nearly fully-developed, subcritical flows, with straightaways less than 12 m (39 ft ) long, and narrow widths with  $\alpha$  between 3 and 4, where  $\alpha=b/y$ . The climbing duct condition was fully developed in all test cases, and therefore we recommend the supercritical, fully developed flow for all climbing ducts. The roughness results are presented in Table 3. Traversing ducts with fully developed flow should also use the supercritical, fully developed roughness. The full experiment method is available in Appendix B.

Table 3. Roughness values ( $\epsilon$ ) and standard deviation ( $\sigma$ ) from laboratory flume experiments

| Duct       | Flow condition                                     | $\epsilon$ (ft) |
|------------|----------------------------------------------------|-----------------|
| Climbing   | Supercritical, fully developed flow roughness      | 1.9 e-5         |
| Traversing | Subcritical, nearly fully developed flow roughness | 1 e-3           |

### *Pacific Lamprey Physical Drag Modeling*

We conducted experiments with a Pacific lamprey model to evaluate the effects of flow velocity and depth on drag force. Using a seasoned piece of LPS fishway from the Washington Shore Entrance Collector LPS (Moser et al 2006), we measured the drag force on a model lamprey for four different depth cases: full submergence flow 0.120 m (4.7 in), equal submergence flow 0.04 m (1.6 in), partial submergence flow 0.015 m (0.6 in), and skin flow of 0.005 m (0.2 in). The full submergence case was used as a baseline for comparison to velocity thresholds in behavioral studies, including: swim velocity  $\approx 0.8 \text{ m}\cdot\text{s}^{-1}$  ( $2.6 \text{ ft}\cdot\text{s}^{-1}$ ) from Mesa et al. (2003), velocity barrier  $\approx 2.5\text{-}3.0 \text{ m}\cdot\text{s}^{-1}$  ( $8.2\text{-}9.8 \text{ ft}\cdot\text{s}^{-1}$ ) from Keefer et al. (2011a), and climbing velocity  $\approx 2.0\text{-}3.7 \text{ m}\cdot\text{s}^{-1}$  ( $6.6\text{-}12.1 \text{ ft}\cdot\text{s}^{-1}$ ) from Reinhardt et al. (2008).

We correlated the swim velocity and velocity barrier values to our drag values to establish a drag threshold for a fully submerged fish. We used  $y/D$  to determine submergence where  $y$  is flow depth and  $D$  is fish diameter, where  $y/D$  was 2.6 for full, 0.9 for equal, 0.3 for partial, and 0.1 for skin flow. We then created a model to estimate what swim behavior the fish would use based on the velocity and drag thresholds established in Table 4. The swim modes that we assumed possible in this model are swim, saltatory swim, or barrier – when a fish will fail to pass. We assumed that climbing is a type of saltatory swim behavior for either the velocity threshold model or drag threshold model. The results shown in Figure 10 indicate that lamprey are at risk of failed passage when velocities are higher than  $\approx 2 \text{ m}\cdot\text{s}^{-1}$  ( $6.6 \text{ ft}\cdot\text{s}^{-1}$ ) and flow depths are between the half diameter and full diameter of the fish, or approximately 0.015-0.04 m (0.6-1.6 in).

We recommend that designers use flow depths  $< 0.1 y/D$ , where  $D$  is the diameter of the fish (1.9-4.8 cm), within the climbing sections to ensure that the fish can ascend. When flow depths are between partial and full submergence ( $0.3 < y/D < 0.9$ ) submergence, the drag model predicts that passage will be most difficult as the resulting drag forces are highest. When  $y/D = 0.1$ , no velocity threshold appears to exist within the skin flow case as the drag on the fish was approximately constant.

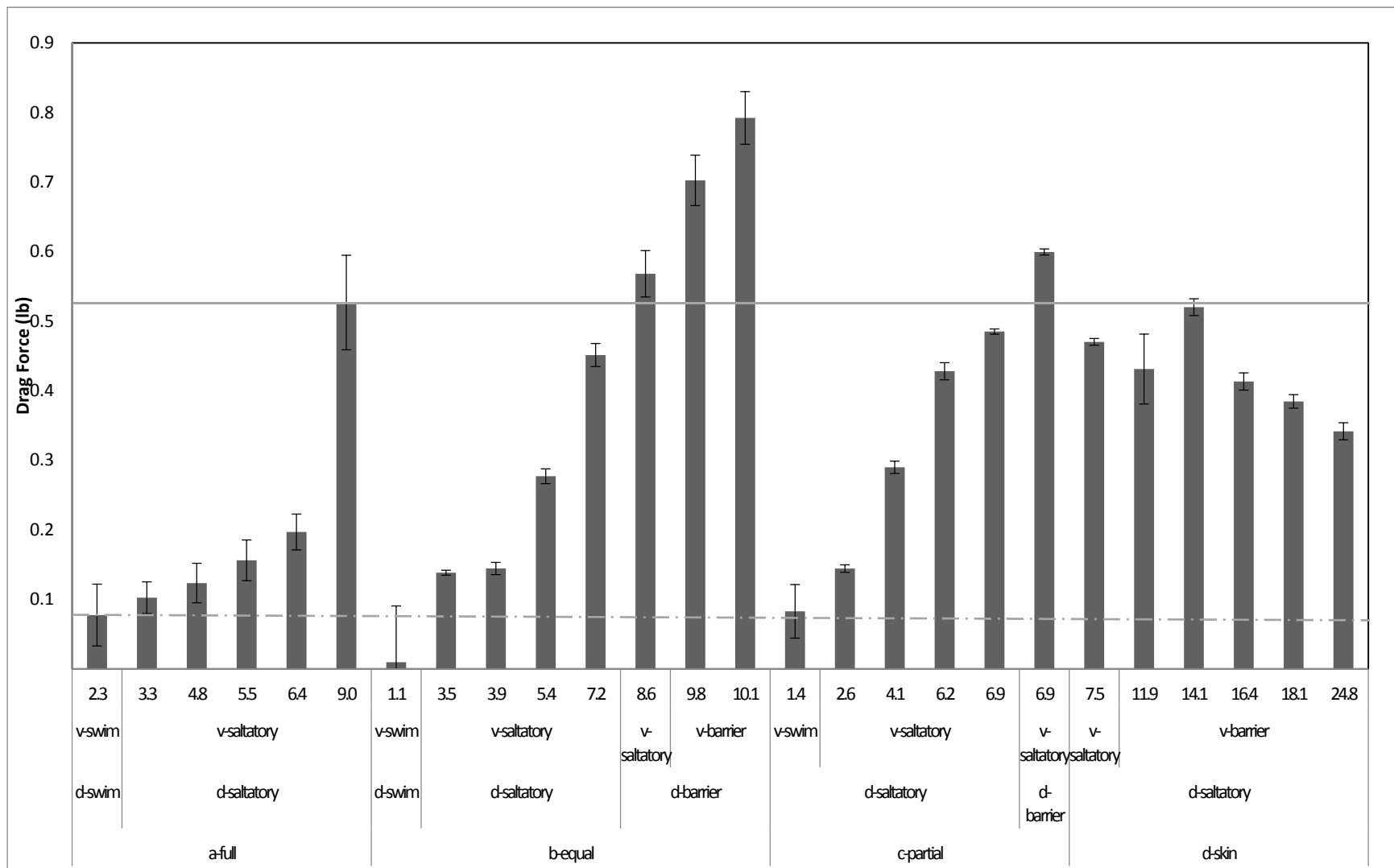


Figure 10. Estimated swim mode for Pacific lampreys relative to submergence based on physical drag results of a model Pacific lamprey. The bottom row of x-axis labels designates the submergence level, where ‘a-full’ represents the fully submerged case of 0.120 m (4.7 in), ‘b-equal’ is equal submergence 0.040 m (1.6 in), ‘c-partial’ is for partial submergence 0.015 m (0.6 in) and ‘d-skin’ if for flow 0.005 m (0.2 in). Next row is the drag model prediction where d is the prefix. Thresholds for the drag model are the grey lines and are based on the fully-submerged experiment results and correlate to the critical swim velocity of 0.34 N (0.08lb, grey dashed line) and the velocity barrier 2.34 N (0.53 lb, grey solid line) values from Table 2. The velocity model of lamprey passage using velocity thresholds of 0.7 m·s<sup>-1</sup> (2.3 ft·s<sup>-1</sup>) and 2.7 m·s<sup>-1</sup> (8.9 ft·s<sup>-1</sup>) for fully submerged flow, with the v prefix, are the third row up. Water velocity is the top row of x-axis labels in ft·s<sup>-1</sup>.

Table 4. Swimming thresholds for Pacific lamprey where critical velocity  $\approx 0.8 \text{ m}\cdot\text{s}^{-1}$  ( $2.6 \text{ ft}\cdot\text{s}^{-1}$ ) from Mesa et al. (2003) and barrier velocity between  $2.5\text{-}3.0 \text{ m}\cdot\text{s}^{-1}$  ( $8.2\text{-}9.8 \text{ ft}\cdot\text{s}^{-1}$ ) from Keefer et al. (2011a) correlated to drag results to determine drag thresholds. The values are used to determine swim mode in Table 3.

| Velocity Threshold                            | Corresponding Drag Force Threshold | Description |
|-----------------------------------------------|------------------------------------|-------------|
| $<2.3 \text{ ft}\cdot\text{s}^{-1}$           | $<0.076 \text{ lbf}$               | Swim        |
| $2.3\text{-}8.9 \text{ ft}\cdot\text{s}^{-1}$ | $0.076\text{-}0.53 \text{ lbf}$    | Saltatory   |
| $>8.9 \text{ ft}\cdot\text{s}^{-1}$           | $>0.53 \text{ lbf}$                | Barrier     |

### *Other Considerations*

While early collection ramps included closed and baffled designs, we now recommend that any submerged portion of the collection ramp climbing duct should be open to allow the fish to access the climbing duct at all levels within the water column. Above the water level, the climbing duct should be covered to prevent sunlight exposure, which results in algal growth that needs to be removed seasonally. All traversing ducts should be covered. Most components should have hinged lids to allow for inspection and observation during the passage season.

LPSs are very small fishways that can effectively bypass barriers for Pacific lamprey, but their small size makes them sensitive to pollutants and repulsive cues. The size of the structures can amplify the effects of vibrations, chemical signatures, and distressed fishes. All lampreys are very sensitive to chemical cues including human contact with submerged surfaces, chemicals, oils, etc. (Johnson et al. 2009; Wagner et al. 2011). Careful maintenance without the use of chemicals and sufficient time to flush the system are important to ensure lamprey use of a LPS. Any injured or dead fish must be removed quickly, as the olfactory cues may deter use of the structure. The metal structure of the LPS will conduct vibration throughout the system, so vibrational sources should be limited or isolated.

Due to the siting and configuration of the existing LPSs at Bonneville and John Day dams, water temperature has not been a critical parameter. Future installations may result in thermal stress within a LPS due to direct heating via solar exposure, and consideration should be taken to minimize temperature increases through the structure as temperature differences along fish passage structures can impede passage in other species (Caudill et al. 2013). The effects of temperate gradients on Pacific lamprey passage have not been examined. We conservatively recommend temperature differences between the tailrace and LPS entrance and between the LPS entrance and exit should be  $< 0.5^{\circ}\text{C}$ .

## **Discussion**

LPS systems built to date successfully pass large numbers of adult lamprey, but some uncertainty remains about the optimal climbing conditions. For instance, some results point to increased climbing efficiency with lowered discharge (Keefer et al. 2010), and other research indicates that discharge has no effect (Moser et al. 2011). Kemp et al. (2009) observed that the climbing behavior for a given population is highly variable between individuals, while other

research indicates discharge and slope angle are interrelated parameters of climbing behavior (Reinhardt et al. 2008). Recent research indicates that reducing discharge will reduce the drag force on climbing Pacific lamprey (Zobott et al. 2013; Appendix B) and could improve passage efficiency within a LPS. Reducing the discharge may improve climbing, but may adversely affect the attraction and guidance of Pacific lamprey to the entrances of LPS systems in some locations (Moser et al. 2008; Keefer et al. 2011; Johnson et al. 2012). A potential hybrid approach would be to supplement flow at or near the LPS entrance to provide guidance and attraction flow while holding discharge within the LPS to low values, particularly in structures with long vertical runs. Any hybrid design would have to be carefully designed and evaluated to prevent jumping and injury or delay to co-migrating adult salmon.

Pacific lamprey seem to have difficulty ascending supercritical flow with moderate slopes based on experimental results where greater efficiency for the climbing behavior was observed when the slope was 1.0 compared to 0.325 at the high discharge of  $7.8 \text{ L}\cdot\text{s}^{-1}$  (124 gpm) (Reinhardt et al. 2008). Current research on Pacific lamprey drag forces indicates that flow depth is a critical climbing duct parameter and could explain the behavioral differences observed above because  $y/D$  increases as slope decreases at a given discharge. We recommend that traversing ducts be set at a slope  $\approx 0.003$  and the climbing ducts to slope of 1.0. Slope deviations should be carefully designed to ensure flow depths have a  $y/D$  of 0.1 or less. Designers can change several parameters within the climbing duct to maintain the recommended  $y/D$ : reduce the discharge within the climbing sections, increase the width, or increase the slope. Only the latter has been evaluated with behavioral studies.

Each LPS system is a combination of the individual components and functions slightly differently. We outlined design criteria based on functional LPS designs. Current research on new LPS design elements include wetted wall and lower gradient climbs, but we caution against implementation of new concepts without sufficient testing of fish response to ensure passage. The designer should be aware that structural changes will affect Pacific lamprey passage behavior and that there is still uncertainty on best practices for LPS designs.

## **Site-Specific “Lessons Learned” and Recommendations**

### *Bradford Island LPS*

The Bradford Island LPS (BILPS) has been operational the longest of the LPS systems and passes thousands of adult lamprey each year, though there are still improvements that could be made. The exit slide deposits lamprey into the forebay at a location that is too close to the traditional fishway exit. Hence, a portion of lamprey exiting the LPS in each year falls from the exit slide and immediately re-enters the traditional fishway. Some of these lampreys never re-ascend the fishway (Moser et al. 2012; Corbett et al. 2013). Lengthening the exit slide would allow lamprey to enter the forebay from a lower height and at a position further from the traditional fishway exit. In 2014, a hinged joint was added to the top of the exit slide to allow access to the slide terminus and to facilitate maintenance of the count mechanisms.

### *Washington AWS LPS*

The Washington Shore AWS LPS (WSLPS) was built after many of the improvements were already made to the BILPS, so its design incorporated lessons learned from the prototype design. However, modifications were needed and, in some cases, are still needed to improve maintenance and functionality. For example, not all of the rest boxes of the WSLPS are easily accessed from the deck or from platforms built to support the LPS. Maintenance and inspection of these rest boxes would be facilitated by improving access to them.

The exit slide for the WSLPS empties into the upper end of the Washington-shore fishway upstream from the serpentine weir section. Due to space limitation, the original exit slide included a 90° turn near its terminus so that the slide would feature a shallow angle and still fit within the dimensions of the fishway at the exit location. However, the bend at the terminus caused lamprey to slow and hold before exiting the structure. Addition of a plastic mesh insert to speed their exits did not fix the attachment problem, and the mesh eventually failed, blocking lamprey passage. Thereafter, the slide was shortened and made steeper so that lamprey would fall rapidly through the slide and the interior of the slide was lined with rolled perforated plate to preclude screen failure. Increasing the exit slide slope was not ideal because the steeper slide angle (51°) resulted in very rapid lamprey speeds and produced count errors. In addition, the lampreys dropped into the fishway from a greater height and were disoriented and had a greater tendency to move downstream in the fishway after exiting the LPS. Changing the orientation of the exit slide to allow a longer length resulted in water splashing on the opposite wall and lamprey attempting to climb that wall as a result. The slide was re-positioned at 51° and in 2014 an impedance counter was tested to see if count accuracy could be improved. The impedance counter did not work in the WSLPS because most lamprey were above the water level as they passed over detection equipment and did not create a measurable change in conductivity. Ideally, the exit slide angle should be reduced to 25° and the slide should be re-positioned to enter the fishway further upstream where there is more room to allow lamprey to exit the slide without dropping from an excessive height.

### *Cascades Island LPS*

The Cascade Island LPS (CILPS) structure was unique in that the entrance collection ramp and initial rest boxes were completely inaccessible after installation. As a result, automatic purge valves were installed to allow purging of each rest box remotely when the structure was not in use. Thus far, these valves have been maintenance-free and have functioned as intended. Such devices may be needed at future construction where portions of a structure are inaccessible.

Initially, lampreys were observed to have difficulty ascending the entrance collection ramp, which was the steepest and longest climbing ramp built to date. The situation was remedied by reducing flow on the ramp by de-watering at rest boxes further upstream in the structure. Eventually, lower flow was maintained when a volitional exit was installed and watered up. However, lampreys still have difficulty ascending the steep ramp, as evidenced by video observations. One problem that could be addressed is that the ramp includes a “jog” in the middle to accommodate positioning of support brackets. By forcing lamprey to change their lateral position on the ramp as they climbed, the ramp was rendered less efficient. Future structures should feature straight climbing ramps, particularly those with steep angled climbs.

Alternatively, shorter runs with lower slopes could have been achieved, but would require alternative access to rest boxes that would be suspended on the fishway wall for inspection and maintenance by use of caged ladders or similar. In addition, small discontinuities in the surface of the steep entrance ramp may have caused impediments to lamprey climbing. Small (< 2mm) silicone burrs were enough to cause lamprey to lose suction and drop off the steep ramp.

Initially, rest boxes in the CILPS structure were not large enough to allow for narrow mesh entrance fykes, like those installed at the AWS LPSs. As a result, lamprey regularly fell back downstream after ascending the structure (Moser et al. 2012; Corbett et al. 2013). The wider fykes were replaced with narrower, shorter fykes constructed of perforated plate in 2011. These fyke designs were shorter and lamprey could still fall back through them. In 2012, one rest box was fitted with a series of lightweight flap gates (“fingers”) that lamprey could push open to enter the rest box. Lampreys appear to use the modified type of fyke and fewer fallbacks were observed, but further testing is needed (Corbett et al. 2014).

The initial CILPS did not provide platforms for accessing all rest boxes and the upper traversing duct was not high enough to allow safe passage for people accessing the stairway beneath it. Ultimately, the traversing section was raised to allow adequate head clearance. However, as a result lampreys were required to be eventually dropped to a lower elevation so that subsequent traversing ducts would provide adequate downstream flows. The CILPS was fitted with a “pond” or large mid-LPS rest box that lamprey dropped into before continuing passage to the exit slide. The pond has functioned as intended and allows a mid-LPS count location and the opportunity to trap or sample lamprey from the forebay deck level. Future designs could take advantage of the novel “pond” design element to achieve necessary changes in elevation through the LPS course (Figure 11). Similarly, elements of the pond design could be applied to LPS exits.

Another novel element in the CILPS was the installation of a long ( $\approx 70$  m, 230 ft) 25 cm diameter (10 in) PVC exit slide (Corbett et al. 2014). All previous traversing sections were rectangular in cross-section. The nearly horizontal ( $s = 0.00174$ ) exit pipe apparently functioned to allow lamprey egress with minimal delay and maximal efficiency. Incorporation of such inexpensive PVC elements may be possible in future designs, particularly for long horizontal stretches. In 2014, the PVC pipe was fitted with four inspection hatches (previously it was impossible to check the pipe for dead lamprey or other maintenance issues). To date, these hatches have provided adequate maintenance access.

The weakest element of CILPS is at the upwelling box and exit slide. The upwelling box features a  $70^\circ$  turn at the transition to the exit slide. As a result, the lampreys lose momentum and become less likely to enter the exit slide. In addition, the slide was initially at too shallow of an angle ( $11^\circ$ ) to facilitate rapid lamprey egress and it was not completely free of attachment surfaces. For these reasons, lampreys were stimulated to try swimming upstream within the exit slide and to attach and delay passage when inside the slide. In 2014 the slide was angled downward to the maximal point achievable in its current location ( $17^\circ$ ) and completely lined with rolled perforated plate. These improvements helped to increase lamprey egress and count accuracy. Ideally, the exit slide should transition in a straight line from the upwelling box, so that delay and turnaround at the upwelling box is eliminated.



Figure 11. The pond feature of the CILPS. The arrows indicate the direction of fish movement through the box. The lamprey first encounter an upwelling box (upper left) that receives water pumped up from the pond (large aluminum tank in center of photo). Lamprey drop from the upwelling box into the pond and then volitionally enter the PVC exit pipe that leads them to the structure terminus and exit slide. The pond can be closed off from the PVC exit slide if the structure is to be operated as a trap.

The water supply for CILPS, and other LPS sites, was drawn from the forebay and was fitted with screens to prevent salmonid entrainment. Problems arose when screens became blocked with debris and pumps subsequently burned out. An alarm system was installed to alert Project personnel when pumps were not operational. All future LPS systems should incorporate failsafe systems to protect lamprey if there is a power outage or if pumps fail. Similarly, designs should include consideration of the potential for monitoring temperature differences between the LPS and the tailrace.

### *Washington Shore Lamprey Flume LPS*

The Washington Shore Fishway Lamprey Flume (WSF) is a combination structure. The collection of the fish for the WSF is done with the Washington Shore Ladder Entrance Modification (WSEM) with a closed ramp design. The water supply for the WSF portion is from the forebay and is gravity controlled. The collection of the WSF-WSEM is done with two separate underwater entrances which combine and transition into a closed duct. The upper section is a typical LPS that begins at the end of the WSEM near the waterline and has a pumped water supply from the spillway. The WSF-LPS section begins above the water level on the south wall of the Washington Shore Fishway.

The routing of the WSF-LPS section was constrained by operational considerations at the dam and resulted in longer traversing duct runs than otherwise necessary. Similar considerations required routing of climbing ducts and turning rest box along the south wall, which are difficult to access and inspect. Future designs should carefully consider the need for in-season access for inspection and maintenance by including ladders and platforms for access without crane support. The traversing section meanders over the dam with multiple cross section changes and a couple of very small elevation changes in order to accommodate the structural supports. The design used either a climbing slope ( $S = 1.0$ ) or a traversing slope ( $S \approx 0.003$ ). The elevation changes are short ramps with smooth radius transitions in a wide cross section ( $b = 1.6$  ft). These features are new to WSF-LPS implementation and have velocities that are supercritical. The last short ramp attaches to a rest box and the initial design had a short low-slope straightaway at the top before the fyke. The crested transition may be difficult for the fish to move past into the rest box because they cannot attach to the perforated surface of the fyke as they crest the ramp through supercritical and accelerating flow. Future rest box entrances should have a minimum of a body length low-slope distance (approximately 0.6 m) at the tops of ramps prior to the perforated surface on the fyke to ensure the fish can get into the box. Another option would be to eliminate the perforated surface to allow the fish to drop into the pool at the top of the crest, although some fallback would be likely.

The original design was to collect fish in a tank on a truck to facilitate no-handle transport and required an elevated exit section at the end of the fishway. Due in part to space constraints, there was no platform or ladder access to the rest box or upwelling box, which made inspections nearly impossible while conforming to safety requirements. Subsequently, the water supply box and exit section was lowered to improve access. Fish must now be moved from the trap box into the transport tank by hand, but the exit section is easily inspected and maintained. Further modifications for direct collection into a transport tank may be necessary if large numbers of lamprey begin using the structure, either through re-elevation of the water supply box and exit or the use of a gantry crane to lift the trap box onto a truck or trailer.

The fyke design in WSF-LPS is different from other LPS systems. They are formed out of perforated aluminum and bolted through the rest box and attaching duct. First, we recommend segregating the fyke from the duct and rest box interface for ease of assembly. Second, the fyke had a tapered design with a lid which is not necessary because the fish do not jump and only the floor of the fyke is submerged.

We originally used one pump to deliver the full discharge and had a second pump on standby if the first pump failed. The pump was deployed in a temporary configuration with a cable and a weight, which led to the power wire being abraded and shorting out the pump. We replaced the original single pump system with two pumps after the first season of operation (2013) as described in the pumping section, with flexible PVC pipe, and trollies to guide the pumps and piping down into the tailrace. We controlled the flow of water with a manifold and a butterfly valve so that the operators could more accurately control the discharge.

### *John Day LPS*

The LPS installed at the John Day Dam North Fishway Entrance was analogous to the CILPS because both were installed just upstream of fishway entrances with bollard fields. The John Day LPS (JDLPS) collection ramp slope ( $S = 1.0$ ) and other design parameters were very similar

to those at the Bonneville AWS LPSs, with the exception that lamprey are collected at the tailrace deck and hauled to the forebay. The JDLPS started collecting fish immediately and collection rate has increased during the two years of operation, with 1,228 adult lamprey collected in 2014 (compared to a total daytime count at both fishways at the dam of 8,135). No major modifications to the system have been performed and the success to date likely results in a combination of collection ramp siting, high movement rates of lamprey in the lower John Day North Fishway channel near the entrance and LPS ramp (Kirk et al. 2015a), and use of simple, straight-lined LPS with standard 1.0 slope climbing ramps, relatively little elevation gain, distance traversed, or direction changes. We note that lampreys were released to the John Day forebay at the end of the navigation lock pier nose and preliminary observations suggest an unusually high rate of fallback among a sample of HD-PIT tagged adults. Consequently, future releases will occur further upstream along the Washington shore.

### *Experimental Waterfall Collector*

The waterfall collector has not been evaluated in a fishway, but laboratory-based experimental results have been promising. We observed that when lamprey are moving upstream within a fishway (as in a serpentine weir section), an impediment (i.e., 2-in diameter conduit) sited on the wall may incite lamprey to investigate vertical routes. We simulated a similar ‘speed bump’ on the upstream side of the experimental waterfall structure, but then were not able to test it in an area where lamprey were moving directionally. A waterfall collector could be added as originally intended to provide a route out of serpentine weir sections (or out of other fishway segments), incorporated into lamprey passage structures at collection points, or to navigate space constraints or imposed impediments to linear movement.

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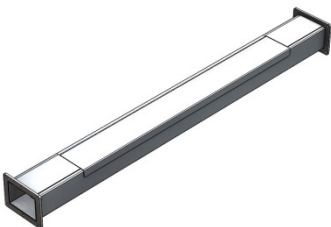
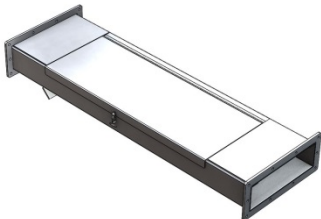
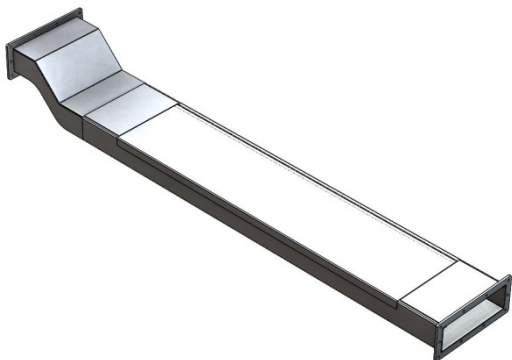
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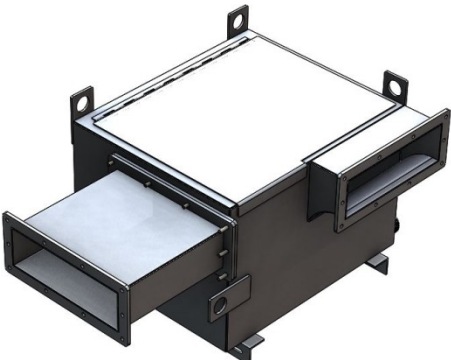
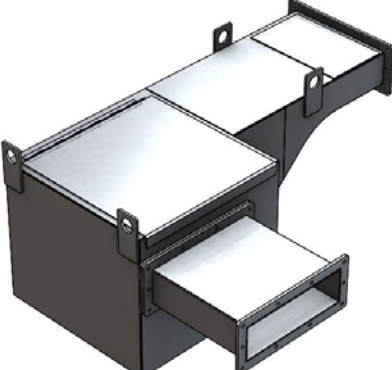
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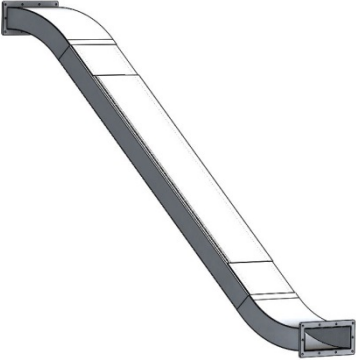
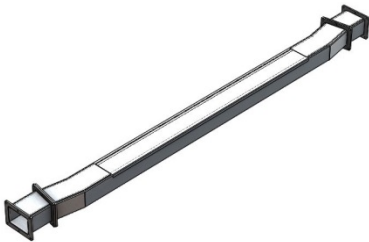
## Appendix A

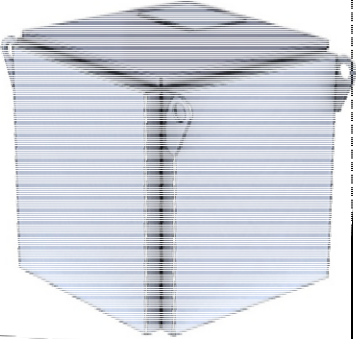
*Catalog of components in Parts Library- from WSFLPS designs 2013, 2014*

| Thumbnail                                                                           | Description                           | Parasolid Link (.x_t)                                                                                                                                                             |
|-------------------------------------------------------------------------------------|---------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|    | Narrow traversing duct                | <a href="https://www.dropbox.com/s/bmt9ntb12lbn8k9/Channel_6x9_10ft_2014.x_t?dl=0">https://www.dropbox.com/s/bmt9ntb12lbn8k9/Channel_6x9_10ft_2014.x_t?dl=0</a>                   |
|    | Wide traversing duct or Climbing duct | <a href="https://www.dropbox.com/s/16cvelcprx1i9lp/Channel_6x20_6ft_2014.x_t?dl=0">https://www.dropbox.com/s/16cvelcprx1i9lp/Channel_6x20_6ft_2014.x_t?dl=0</a>                   |
|   | Wide traversing duct with step        | <a href="https://www.dropbox.com/s/9m48gaksxv6brxr2/Channel_6x20_9ftStep_2014.x_t?dl=0">https://www.dropbox.com/s/9m48gaksxv6brxr2/Channel_6x20_9ftStep_2014.x_t?dl=0</a>         |
|  | Short climb with transitions          | <a href="https://www.dropbox.com/s/pb7gsqo6daopj50/shortened%20final%20climb_2014.x_t?dl=0">https://www.dropbox.com/s/pb7gsqo6daopj50/shortened%20final%20climb_2014.x_t?dl=0</a> |
|  | 90° turn constant radius              | <a href="https://www.dropbox.com/s/gectn3p3c6phd3p/Tran_90deg_Elbow_2014.x_t?dl=0">https://www.dropbox.com/s/gectn3p3c6phd3p/Tran_90deg_Elbow_2014.x_t?dl=0</a>                   |
|  | Expansion/Contraction for traversing  | <a href="https://www.dropbox.com/s/17h6893ixodgtr0/Expansion_01_2014.x_t?dl=0">https://www.dropbox.com/s/17h6893ixodgtr0/Expansion_01_2014.x_t?dl=0</a>                           |

| Thumbnail                                                                           | Description                     |                                                                                                                                                                               |
|-------------------------------------------------------------------------------------|---------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|    | Low profile right turn rest box | <a href="https://www.dropbox.com/s/g50lek85ngqc8g7/Rest_Box_002_2014_W_Entrance.x_t?dl=0">https://www.dropbox.com/s/g50lek85ngqc8g7/Rest_Box_002_2014_W_Entrance.x_t?dl=0</a> |
|    | Standard right turn rest box    | <a href="https://www.dropbox.com/s/0pu2ekwwqhwmwe9/Rest_Box_003_2014.x_t?dl=0">https://www.dropbox.com/s/0pu2ekwwqhwmwe9/Rest_Box_003_2014.x_t?dl=0</a>                       |
|  | Uturn Rest box                  | <a href="https://www.dropbox.com/s/q2vz79hxddbini0/Rest_Box_001_2014_W_Entrance.x_t?dl=0">https://www.dropbox.com/s/q2vz79hxddbini0/Rest_Box_001_2014_W_Entrance.x_t?dl=0</a> |
|  | Upwelling box                   | <a href="https://www.dropbox.com/s/woip7abti1bmk04/Upwelling_Box_2014.x_t?dl=0">https://www.dropbox.com/s/woip7abti1bmk04/Upwelling_Box_2014.x_t?dl=0</a>                     |

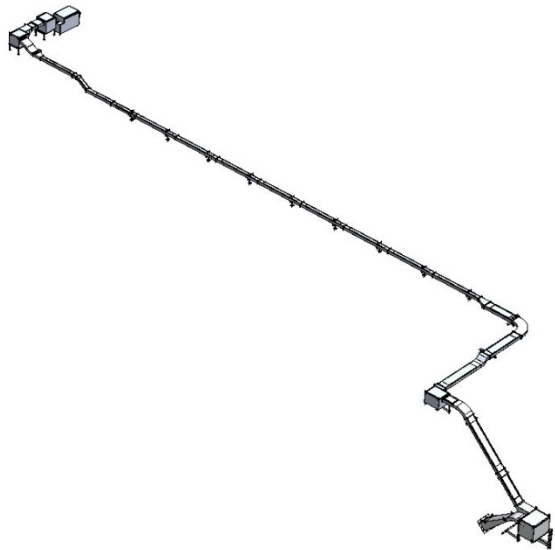
| Thumbnail                                                                           | Description                                                                             |                                                                                                                                                                                                         |
|-------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|    | Bracket to attach traversing duct to structural stand                                   | <a href="https://www.dropbox.com/s/ad7hp-eevnroeabk/Traversing_Bracket_Channel_6x9_2014.x_t?dl=0">https://www.dropbox.com/s/ad7hp-eevnroeabk/Traversing_Bracket_Channel_6x9_2014.x_t?dl=0</a>           |
|    | Structural stand for traversing duct                                                    | <a href="https://www.dropbox.com/s/flnt9xfawfkygi6/Str_stand-03-2_2014.x_t?dl=0">https://www.dropbox.com/s/flnt9xfawfkygi6/Str_stand-03-2_2014.x_t?dl=0</a>                                             |
|    | Structural stand for rest box or upwelling box, short enough to access without platform | <a href="https://www.dropbox.com/s/lelq6dzywa7b7cz/Lamprey%20Exit%20Box%20Platform-mod2_2014.x_t?dl=0">https://www.dropbox.com/s/lelq6dzywa7b7cz/Lamprey%20Exit%20Box%20Platform-mod2_2014.x_t?dl=0</a> |
|   | Structural stand for rest boxes or upwelling boxes, tall enough to pass under           | <a href="https://www.dropbox.com/s/1k8m38xaquwgva7/Lamprey%20Exit%20Box%20Platform_2013.x_t?dl=0">https://www.dropbox.com/s/1k8m38xaquwgva7/Lamprey%20Exit%20Box%20Platform_2013.x_t?dl=0</a>           |
|  | Structural brackets for large rest box                                                  | <a href="https://www.dropbox.com/s/831tn3nd02ieazk/Str_brac_03-1_2014.x_t?dl=0">https://www.dropbox.com/s/831tn3nd02ieazk/Str_brac_03-1_2014.x_t?dl=0</a>                                               |
|  | Structural bracket for climbing duct                                                    | <a href="https://www.dropbox.com/s/khnxxg0j4ot156t/Str_brac_05_2014.x_t?dl=0">https://www.dropbox.com/s/khnxxg0j4ot156t/Str_brac_05_2014.x_t?dl=0</a>                                                   |

| Thumbnail                                                                           | Description                                                            |                                                                                                                                                                                   |
|-------------------------------------------------------------------------------------|------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|    | Climbing duct with transitions at top and bottom                       | <a href="https://www.dropbox.com/s/7q4fvd0torq0b4p/Climbing_6x20_Transitioned.x_t?dl=0">https://www.dropbox.com/s/7q4fvd0torq0b4p/Climbing_6x20_Transitioned.x_t?dl=0</a>         |
|    | Traversing jog around                                                  | <a href="https://www.dropbox.com/s/c1zmg4s4g345b6k/Channel_6x9_Jog_2013.x_t?dl=0">https://www.dropbox.com/s/c1zmg4s4g345b6k/Channel_6x9_Jog_2013.x_t?dl=0</a>                     |
|   | Jogging traversing duct                                                | <a href="https://www.dropbox.com/s/4izhkg92zj1kxty/Channel_6x9_Jog-10FT-mod2_2014.x_t?dl=0">https://www.dropbox.com/s/4izhkg92zj1kxty/Channel_6x9_Jog-10FT-mod2_2014.x_t?dl=0</a> |
|  | Climbing duct crest, transitions from climbing duct to traversing duct | <a href="https://www.dropbox.com/s/3q7s8oud9i2xhx8/Climbing_Transition2_2014.x_t?dl=0">https://www.dropbox.com/s/3q7s8oud9i2xhx8/Climbing_Transition2_2014.x_t?dl=0</a>           |
|  | Transition straightaway                                                | <a href="https://www.dropbox.com/s/h2w7xvgv1cnbhmh/Channel_6x20_20in_2014.x_t?dl=0">https://www.dropbox.com/s/h2w7xvgv1cnbhmh/Channel_6x20_20in_2014.x_t?dl=0</a>                 |

| Thumbnail                                                                          | Description                                                     |                                                                                                                                                                                      |
|------------------------------------------------------------------------------------|-----------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|   | <p>Large trap box</p>                                           | <p><a href="https://www.dropbox.com/s/q3qpp1scdipvl11/60x30x30_storage%20tank_2014.x_t?dl=0">https://www.dropbox.com/s/q3qpp1scdipvl11/60x30x30_storage%20tank_2014.x_t?dl=0</a></p> |
|   | <p>Large trap box, from 2013 installation-modified to above</p> | <p><a href="https://www.dropbox.com/s/yvr6dj0qrzj27r8/60x30x30_storage%20tank_2013.x_t?dl=0">https://www.dropbox.com/s/yvr6dj0qrzj27r8/60x30x30_storage%20tank_2013.x_t?dl=0</a></p> |
|  | <p>Small trap box</p>                                           | <p><a href="https://www.dropbox.com/s/ks0xp3ekba7hwoa/30x30x30_storage%20tank_2013.x_t?dl=0">https://www.dropbox.com/s/ks0xp3ekba7hwoa/30x30x30_storage%20tank_2013.x_t?dl=0</a></p> |

| Thumbnail                                                                          | Description |                                                                          |  |
|------------------------------------------------------------------------------------|-------------|--------------------------------------------------------------------------|--|
|   |             | BILPS Fyke, plastic mesh rolled into a cone                              |  |
|   |             | CILPS, WSALPS, Perforated aluminum funnel                                |  |
|   |             | CILPS, WSALPS, Perforated aluminum and metal fingers to prevent fallback |  |
|  |             | WSFLPS, JDLPS, perforated aluminum, fully enclosed                       |  |

Additional parts available in the dropbox folders:

|                                                                                     |                          |                                                                                                                                                                             |
|-------------------------------------------------------------------------------------|--------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  | Parasolids               | <a href="https://www.dropbox.com/sh/s0mlnmujkiioqh1/AABg5LZLBGf7TQE3y0_KWfDwa?dl=0">https://www.dropbox.com/sh/s0mlnmujkiioqh1/AABg5LZLBGf7TQE3y0_KWfDwa?dl=0</a>           |
|                                                                                     | Solidmodels-Solidworks   | <a href="https://www.dropbox.com/sh/s0mlnmujkiioqh1/AABg5LZLBGf7TQE3y0_KWfDwa?dl=0">https://www.dropbox.com/sh/s0mlnmujkiioqh1/AABg5LZLBGf7TQE3y0_KWfDwa?dl=0</a>           |
|                                                                                     | Full Assembly, Parasolid | <a href="https://www.dropbox.com/s/w1flf8vtmrb2gix/BonnWaShoresLadder_LPS_2014.x_t?dl=0">https://www.dropbox.com/s/w1flf8vtmrb2gix/BonnWaShoresLadder_LPS_2014.x_t?dl=0</a> |

DropBox login/email: [LPSdigitalLibrary@yahoo.com](mailto:LPSdigitalLibrary@yahoo.com)

password: idaho.vandal.1

## Appendix B

### *Effective Roughness Determination*

The Lamprey Passage Structure fishways (LPS) are typically made out of aluminum, rectangular ductwork. During our design process, we wanted to predict the velocities and flow depths of different LPS cross sections to ensure the designs were suitable for fish passage. We initially used a roughness value for aluminum of (0.002 mm). The predicted velocities from this model were higher than the research findings for suitable velocities for Pacific Lamprey passage (Moser et al. 2011; Reinhardt et al. 2008; Keefer et al. 2011). Due to the discrepancies between reported velocities and the hydraulic modeling we did during our design process, we investigated LPS roughness experimentally. The results and methods of our roughness determination are below.

We first evaluated previous LPS research to estimate the roughness value. With the given discharge ( $Q$ ) and the area ( $A$ ), where flow depth is ( $y$ ) and width ( $b$ ):  $A = b \cdot y$ , we solved for the mean velocity ( $U_{mean}$ ) using conservation of mass:  $Q = U_{mean} \cdot A$ , for the reported hydraulic conditions from fish behavioral research done for LPS development by Moser et al. (2011) of ( $S = 0.0035$ ,  $Q = 7.8 \text{ L} \cdot \text{s}^{-1}$ ,  $b = 0.19 \text{ m}$ ,  $y = 0.1 \text{ m}$ ). We estimated the friction factor using the energy equation where ( $f$ ) is the Darcy friction factor, ( $g$ ) is gravity, slope is ( $S$ ), mean velocity is ( $U_{mean}$ ) and the hydraulic diameter is  $D_h = \frac{4 \cdot A}{2 \cdot y + b}$ :

$$f = \frac{S \cdot D_h \cdot 2g}{U_{mean}^2} \quad (1)$$

We then applied the Moody diagram and determined that the flow was on the edge of the transitional roughness regime using the determined Darcy friction factor and the Reynolds number. Therefore, we implemented the Haaland correlation (Kakac et al. 1987) to explicitly solve for the Darcy friction factor as a function of effective roughness,  $\epsilon$ , where  $\nu$  is the kinematic viscosity at 10°C.

$$f = 4 \cdot \left( 3.4735 - 1.5635 \cdot \ln \left[ \left( \frac{2 \cdot \epsilon}{D_h} \right)^{1.11} + \frac{63.635 \cdot \nu}{D_h \cdot U_{mean}} \right] \right)^{-2} \quad (2)$$

The resulting roughness value for the reported hydraulic conditions of Moser et al. (2011) was 11 mm for a traversing duct section. We applied the Moser traversing duct roughness for the climbing duct condition, but the resulting mean velocities did not match those reported for the climbing duct in Reinhardt et al. (2008). We then solved for the effective roughness using the reported values from Reinhardt et al. (2008) for the climbing ducts, ( $U_{mean} = 3.07 \text{ m/s}$ ,  $Q = 7.8 \text{ L} \cdot \text{s}^{-1}$ ), and slope ( $S = 1.0$ ). The traversing roughness and climbing roughness results based on reported data in published resulted in two roughness values differing by more than two orders of magnitude (Table 1). Descriptions of the measurement locations were not included in the literature. We note that the reported measurements from previous LPS research were not intended for hydraulic modeling, and the entrance length, depth, and slope were difficult to measure to the necessary accuracy to derive the effective roughness value.

Table 1. Reported depth, velocity and discharge for LPS systems and the derived effective roughness using the Haaland correlation.

| Reported values and resulting effective roughness using Haaland Correlation |      |        |              |         |        |      |          |       |                 |                            |
|-----------------------------------------------------------------------------|------|--------|--------------|---------|--------|------|----------|-------|-----------------|----------------------------|
| Q<br>(L/s)                                                                  | b(m) | y (m)  | $\alpha=b/y$ | S (m/m) | V(m/s) | Fr # | Re #     | f     | $\epsilon$ (mm) | Source                     |
| 7.8                                                                         | 0.19 | 0.10   | 2            | 0.0035  | 0.41   | 0.4  | 1.53E+04 | 0.079 | 11              | Moser et al. (2011)        |
| 7.80                                                                        | 0.50 | 0.0044 | 114          | 1       | 3.07   | 14.8 | 1.40E+04 | 0.041 | 0.18            | Reinhardt et al.<br>(2008) |

Absolute roughness is constant and absolute for a material, like aluminum. The roughness for aluminum should be similar to brass and the roughness for brass is 0.002 mm (White 2003). The brass value, when used for hydraulic modeling of LPS systems, resulted in velocities that were too high based on the velocities measured by Moser et al. (2011) and Reinhardt et al. (2008) for lamprey to successfully pass the system. Roughness values are used to determine the appropriate slope and discharge to provide a passable velocity when designing a new LPS system. Roughness for aluminum is slightly different from brass, but not by 3 or 4 orders of magnitude as indicated by initial estimates in Table 1.

Effective roughness is much different, and expresses the artificial or calibrated roughness value for a hydraulic system where the flow may or may not be fully developed within a reach. Manning's n is an effective roughness that is determined empirically from streams or channels by measuring the depth, velocity, slope, and width for a given reach. Absolute roughness is a real parameter of a material or assembly and effective roughness is a hydraulic calibration used to accurately describe the flow parameters. Both are used in hydraulic calculations, although effective roughness is the typical value used in open channel flow calculations. Accurate depth measurement is critical in determining the effective roughness.

Aluminum oxidizes overtime, and can corrode due to galvanic interactions between surfaces of dissimilar metals or materials. As a result, the seasoned aluminum absolute roughness value for LPS will likely be higher than the typically values used for aluminum or similar metals in hydraulic modeling. Also, the assembly of the ductwork into an LPS includes misalignment between traversing duct of approximately 3 mm and 1.6 mm for climbing ducts and the misalignment will increase the effective roughness of an LPS assembly. Determining the seasoned aluminum effective roughness value for an LPS assembly would enable accurate design as well as a tool for determining discharge and velocity for a measured depth within LPS ductwork. Consequently, we performed flume experiments to empirically determine the appropriate effective roughness for seasoned LPS systems and carefully measured the depth, slope, and discharge for subcritical and supercritical flow conditions. Supercritical conditions would be typical of climbing ducts and subcritical conditions would be typical of traversing ducts. The resulting roughness values would be applied to determine the velocity and discharge for a given depth of flow within an LPS section based on the flow conditions.

## Methods

We did a series of flume experiments using a seasoned section of LPS fishway from the Washington Shore Fishway experimental LPS (Moser et al. 2010) to evaluate the roughness

discrepancy observed above between the calculated roughness for the traversing ducts and climbing ducts in Table 1. We used 3 sections of LPS duct that were siliconed and bolted together in the typical manner for an LPS for the test section. The respective lengths of LPS duct comprising the test section starting at the head box to end of the test section are: 4 m, 4 m, and 3 m. The width of the ducts was 0.235 m. We measured flow depth over the last 5 m of the test section with an ultrasonic depth gage on a robotic cart to a tolerance of ( $\pm 0.0005$  m). Fully developed flow was determined based on the depth of the flow attaining a constant value where variance was less than 0.001 m. We also estimated the entrance length,  $L_e$ , for turbulent flow using  $L_e/D_h = 4.4 \cdot Re^{1/6}$  (White 2003) (Table 3). The slope of the flume was determined using a slope meter with 0.01% accuracy. Discharge was measured to  $\pm 0.5\%$ . We calculated the roughness for a range of supercritical discharges with ( $S = 0.02$ ,  $6.1 \text{ L} \cdot \text{s}^{-1} < Q < 32 \text{ L} \cdot \text{s}^{-1}$ ) and subcritical discharges ( $S = 0.003$ ,  $7.9 \text{ L} \cdot \text{s}^{-1} < Q < 9.5 \text{ L} \cdot \text{s}^{-1}$ ) with the full results available in Table 3.

## Results

The effective roughness did not vary with aspect ratio, but did vary with flow condition (Table 2), and  $L_e/L$  (Table 3). The apparent difference between the supercritical and subcritical effective roughness results indicates that the flow does not fully develop in the traversing duct (subcritical flow condition) within the 11 m test section used for the experiments. The fully developed roughness value of the assembled ducts is represented by the supercritical results where  $\varepsilon$  is 0.05 mm. The artificial, effective roughness result of the subcritical tests was found to be 11 mm, and reflects that the flow was still developing when measured. The subcritical result can still be used as an effective roughness, or artificial roughness for modeling depth, velocity, and discharge, within the traversing ducts. It is important to only apply the result to a straightaway of 11 m for the narrow traversing duct where the width is approximately 0.235 m.

The subcritical condition was nearly fully developed as the water surface varied less than (1 mm) in depth over the test section of the flume, but still gradually varying. Other indications that the flow was still developing are that the entrance length ratio of  $L_e/L$  was greater than 40% for all subcritical runs. The subcritical condition also had low aspect ratios, where  $\alpha$  is the aspect ratio and  $\alpha = b/y$ , indicating that the flow was poorly mixing. In contrast, the supercritical condition was fully developed for all conditions, as indicated by the entrance length ratio where  $L_e/L$  was less than 40% for all runs. White (2003) indicates that entrance effects are significant when the entrance length ratio is large.

Typically, LPS designs are retrofits of existing structures that must zig-zag around essential components, thereby making the fully developed condition rare in traversing ducts. The nearly fully developed flow effective roughness value allows designers to accurately describe the water surface without the fully developed condition. Use of multiple roughness values is common in open channel, one-dimensional models such as HEC-RAS or Manning's equation where roughness is one of the calibration factors used to converge the modeled water surface with the observed water surface. The duct wall material roughness value from our experiments for fully developed flow and climbing duct is 0.05 mm, and the effective roughness value for the nearly fully developed or traversing duct is 2.9 mm (Table 2).

Table 2. Roughness values for LPS fishway hydraulic modeling from flume experiments.

| Duct       | Flow condition                                     | Avg $\epsilon$<br>(mm) | Stdev<br>$\sigma$<br>(mm) |
|------------|----------------------------------------------------|------------------------|---------------------------|
| Climbing   | Supercritical, fully developed flow roughness      | 0.05                   | 0.01                      |
| Traversing | Subcritical, nearly fully developed flow roughness | 2.9                    | 1.0                       |

### Recommendations

One-dimensional hydraulic models typically use the fully developed roughness value for hydraulic calculations. We recommend that the LPS designer use the duct wall material roughness for the supercritical flow in climbing ducts when  $L_e/L < 40\%$ , and the traversing roughness shown in Table 2 for the subcritical flows having  $L_e/L > 40\%$  (Table 3). The designer should also use the duct wall material roughness when the ratio of entrance length to overall length is very small  $L_e/L < 10\%$  (e.g. traversing duct is very long),  $L_e/L < 10\%$ .

Our recommendation would be to implement the Haaland correlation (Eqn 2) (Kakac et al. 1987) and the roughness values of seasoned LPS in Table 2 to find the friction factor for hydraulic calculations for LPS designs.

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Table 3. Roughness values for LPS fishway hydraulic modeling from flume experiments, complete results. L is the length of the experimental duct reach, and was 11 m.

| Supercritical flow condition |       |       |              |         |        |      |          |           |         |           |             |       |                 |
|------------------------------|-------|-------|--------------|---------|--------|------|----------|-----------|---------|-----------|-------------|-------|-----------------|
| Q (L/s)                      | b(m)  | y (m) | $\alpha=b/y$ | S (m/m) | V(m/s) | Fr # | Re #     | $D_h$ (m) | $L/D_h$ | $L_e/D_h$ | $L_e/L$ (%) | f     | $\epsilon$ (mm) |
| 6.2                          | 0.235 | 0.022 | 11           | 0.02    | 1.2    | 5.7  | 1.70E+05 | 0.074     | 148     | 33        | 22          | 0.02  | 0.06            |
| 7.9                          | 0.24  | 0.025 | 9            | 0.02    | 1.3    | 5.4  | 2.11E+05 | 0.083     | 133     | 34        | 26          | 0.019 | 0.05            |
| 9.4                          | 0.24  | 0.028 | 8            | 0.02    | 1.4    | 5.2  | 2.46E+05 | 0.091     | 121     | 35        | 29          | 0.018 | 0.05            |
| 15.6                         | 0.24  | 0.039 | 6            | 0.02    | 1.7    | 4.4  | 3.79E+05 | 0.118     | 93      | 37        | 40          | 0.017 | 0.04            |
| Subcritical flow condition   |       |       |              |         |        |      |          |           |         |           |             |       |                 |
| 6.3                          | 0.235 | 0.062 | 4            | 0.003   | 0.43   | 0.7  | 1.34E+05 | 0.162     | 68      | 31        | 46          | 0.049 | 3.7             |
| 6.3                          | 0.235 | 0.058 | 4            | 0.003   | 0.46   | 0.8  | 1.37E+05 | 0.155     | 71      | 32        | 45          | 0.043 | 3.2             |
| 6.3                          | 0.235 | 0.058 | 4            | 0.003   | 0.46   | 0.8  | 1.37E+05 | 0.155     | 71      | 32        | 45          | 0.046 | 4.5             |
| 7.9                          | 0.235 | 0.072 | 3            | 0.003   | 0.47   | 0.7  | 1.59E+05 | 0.179     | 62      | 32        | 53          | 0.047 | 1.4             |
| 7.9                          | 0.235 | 0.07  | 3            | 0.003   | 0.48   | 0.7  | 1.60E+05 | 0.175     | 63      | 32        | 52          | 0.043 | 2.3             |
| 9.5                          | 0.235 | 0.073 | 3            | 0.003   | 0.56   | 0.8  | 1.90E+05 | 0.180     | 61      | 33        | 55          | 0.035 | 2.7             |
| 10.4                         | 0.235 | 0.092 | 3            | 0.003   | 0.48   | 0.5  | 1.90E+05 | 0.206     | 53      | 33        | 63          | 0.051 | 2.6             |