Technical Report 2015-11-DRAFT

USE OF PASSAGE STRUCTURES AT BONNEVILLE AND JOHN DAY DAMS BY PACIFIC LAMPREY, 2013 AND 2014

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Executive summary

Efforts to improve the passage of Pacific lamprey (*Entosphenus tridentatus*) at large hydropower dams on the Columbia River have increased in the past decade. Lamprey-specific passage structures, or LPSs, have become useful tools for improving passage at several dams in the Columbia basin. LPSs are designed specifically to accommodate the swimming and climbing behaviors of Pacific lamprey and consist of wetted, inclined ramps that lamprey climb using their oral discs. We describe lamprey use patterns at two LPSs at Bonneville and John Day dams during their first two years of operation (2013-2014).

The passage structure at Bonneville Dam was installed at the north downstream entrance (NDE) of the Washington-shore fishway and was comprised of two distinct designs. The lamprey flume system (LFS) was an entrance modification situated at the base of NDE and was much larger than the more traditional LPS designs. Once above the water's surface, the LFS transitioned into a more conventionally designed LPS on the upper fishway deck. The John Day Dam LPS was installed in the north fishway and was located directly inside the fishway entrance, just upstream from a bollard field. The LPS had a simple, straight-line design, similar to LPSs previously installed at the Cascades Island and Bradford Island auxiliary water supply channels at Bonneville Dam.

The Bonneville Dam LFS-LPS was hindered by a number of operational setbacks that required in-season modifications and evaluations, which likely reduced its utility for collecting/passing lamprey. While the LFS-LPS passed only 29 lamprey in 2013, 545 lamprey were collected in 2014. This accounted for 0.1% and 0.9% of the total numbers of lamprey estimated to have passed the Washington-shore fishway at Bonneville in 2013 and 2014, respectively. Pacific lamprey collected from the LFS-LPS in 2014 were smaller in size than lamprey collected near the Adult Fish Facility (AFF) on the Washington-shore fishway (~ two thirds up the fish ladder).

We conducted several additional assessments to evaluate the limited success of the LFS-LPS. One reason for low passage in 2013 was the de-watering of the structure for several weeks to conduct in-season modifications and to remove a structural bottleneck within the upper LPS. However, changes in tailwater elevation appeared to also result in late-season declines of lamprey collection. Acoustic Doppler current profiler (ADCP) results conducted in the vicinity of the LFS entrances indicated the formation of a possible counter-current at lower tailwater elevations that would have likely reduced lamprey attraction to the structure. Moreover, the lower LFS generated a large plume of 'entrained air', or 'bubble curtain', when operated under higher flow settings (>50% of the flow valve being open, or > 2.3 fps), which led to concerns about both fish deterrence and functionality of the system. Using a high-frequency sonar camera (DIDSON), we were able to obtain only limited information about the extent and location of the 'bubble curtain' under different flow conditions.

In contrast to the low performance of the Bonneville Dam LFS-LPS, the John Day Dam LPS had fairly high success in both years. The John Day LPS passed 111 lamprey in 2013 and improved ~10 fold by collecting 1,228 lamprey in 2014. This accounted for 2.2% and 12.9% of the total number of lamprey estimated to have passed the north fishway at John Day Dam in

2013 and 2014, respectively. The success of the John Day Dam LPS was attributed to its relatively simple design, the strong demersal behaviors exhibited by Pacific lamprey in the bollard field, and the LPS experiencing few operational problems.

Introduction

Pacific lamprey (*Entosphenus tridentatus*) populations have experienced considerable declines during the past decade. In addition to habitat loss and ocean conditions (Moser et al. 2003; Murauskas et al. 2013), large hydropower dams have also been identified as one of the causes for these declines. Specifically, the low passage rates of adult Pacific lamprey at large dams on the Columbia River during their upstream migrations have been extensively documented (<50%, Moser et al. 2002; Johnson et al. 2012; Keefer et al. 2009, 2013). In comparison, >90% of adult salmonids are successful in passing these large dams (Caudill et al. 2007). Hence, improving the passage of native, anadromous Pacific lamprey has become an important priority for the recovery of this species. There is also growing recognition of its cultural and ecological value (Moser and Close 2003; Clemens et al. 2010).

Pacific lamprey have lower passage rates because fishways were specifically designed to facilitate passage of adult salmonids. Traditional fish passage designs (e.g., pool-and-weir, vertical slot) produce high velocity, high turbulence conditions to attract salmonids (Clay 1995). However, Pacific lamprey differ from salmonids in both behavior and swimming mode (Mesa et al. 2003; Keefer et al. 2011; Kirk et al. 2015a, 2015b). The highly selective nature of traditional fishways is not a local phenomenon and the poor passage of non-salmonid species in salmonid-specific fishways has been documented extensively (Moser et al. 2002; Mallen-Cooper and Brand 2007; Noonan et al. 2012). As a result, there has been a growing effort to make passage facilities more conducive to passing an entire suite of species within an ecosystem.

To improve Pacific lamprey passage at dams on the Columbia River, lamprey-specific passage structures (LPSs) have been installed at several facilities in the basin. The design of these structures consists primarily of wetted, inclined ramps that allow lamprey to climb by employing attachment behaviors during their ascent (Kemp et al. 2009; Keefer et al. 2011; Moser et al. 2011). Several LPSs were installed at various locations at Bonneville Dam in the past decade, such as in the Bradford Island fishway, the Cascades Island fishway, and in the auxiliary water supply (AWS) of the upper Washington-shore fishway (Moser et al. 2011; Zobott et al. 2015). These structures have largely been effective and have had fairly high rates of both collection efficiency (12-40%) and passage success (90-100%; Moser et al. 2011; Corbett et al. 2015). As a result, there has been a growing interest in expanding the use of lamprey-specific structures (Thompson et al. 2016).

In 2013, two new LPSs were installed at dams on the lower main stem of the Columbia River. A two-part lamprey passage structure was installed at Bonneville Dam, that had a novel, lamprey-specific entrance design combined with a more traditionally designed LPS. Another traditionally-designed LPS was installed at John Day Dam. The first objective of this study was to describe the adult lamprey use of these structures during their first two years of operation (2013 and 2014). The second objective was to describe the major operational concerns that were made evident during those years and the methods that were used to troubleshoot those problems, with an emphasis on the Bonneville Dam passage structures.

Methods

Bonneville Dam LFS-LPS

The structure installed at the Bonneville Dam Washington-shore fishway consisted of two parts: the Lamprey Flume System (LFS) and the LPS. The LFS was located outside of the north downstream entrance (NDE) of the Washington-shore fishway and served as an entrance modification to shunt lamprey out of the traditional fishways (Figure 1). The LFS was comprised of two large lamprey-specific entrances, one along the bottom of the fishway floor and another higher up in the water column, neither of which could be entered by adult salmonids (Figure 2). Additionally, the construction of the LFS entrance modification had no apparent impacts on salmon passage at NDE (Johnson et al. 2014). Both entrances merged into a single flume passage section that ran parallel to the NDE collection channel. This section was sloped to bring the LFS above the water's surface. Flow to the LFS was controlled by a butterfly valve and was provided by a gravity supply pipe, which was fed from the tailrace. The LFS rose ~50-55 feet above the water's surface to two lamprey rest boxes near the upper fishway deck (rest boxes 1, 2; Figure 3), which transitioned the structure into a traditional lamprey passage structure (LPS).

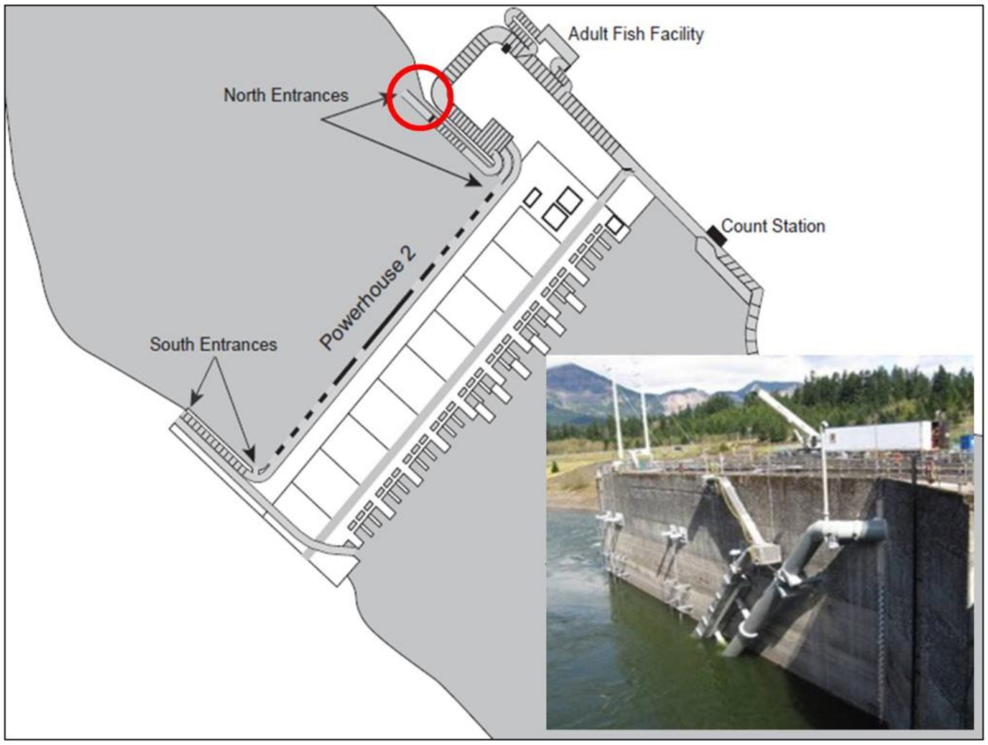

Figure 1. Map of the Washington-shore fishway at Powerhouse 2 of Bonneville Dam. Red circle indicates the approximate location of the LFS-LPS (inset photo) on the north downstream entrance (NDE).

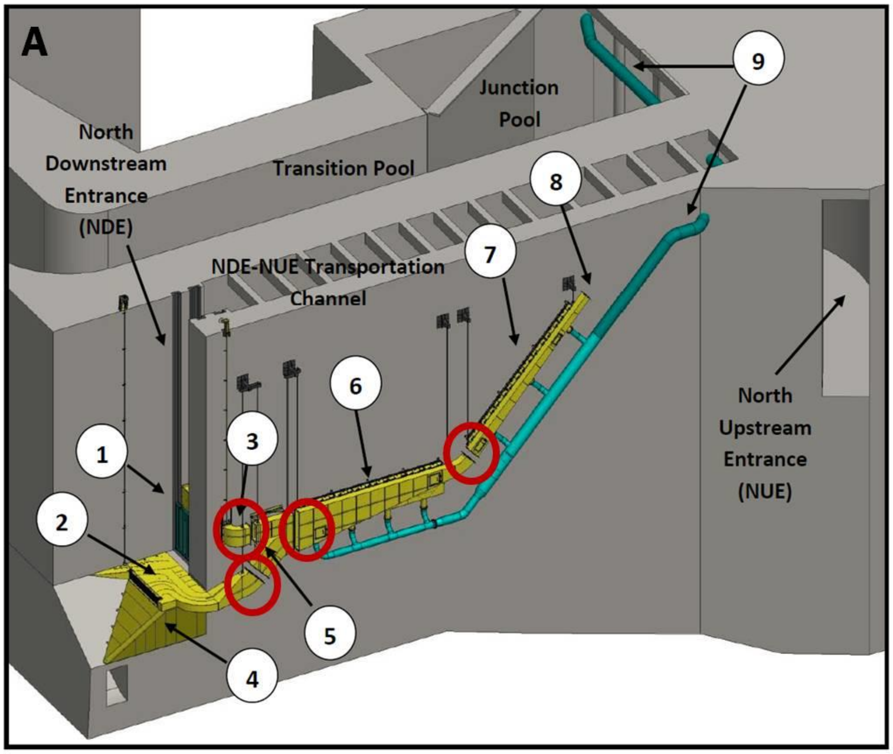

Figure 2. Diagram of the lower LFS structure at NDE with 1) the upper entrance, 2) lower entrance, 3) elbow flume section, 4) collection plate, 5) flow splitter, 6) downstream flume section, 7) upstream flume section, 8) LFS-LPS transition, and 9) gravity water supply. Red circles indicate the location of half-duplex (HD)-PIT receivers.

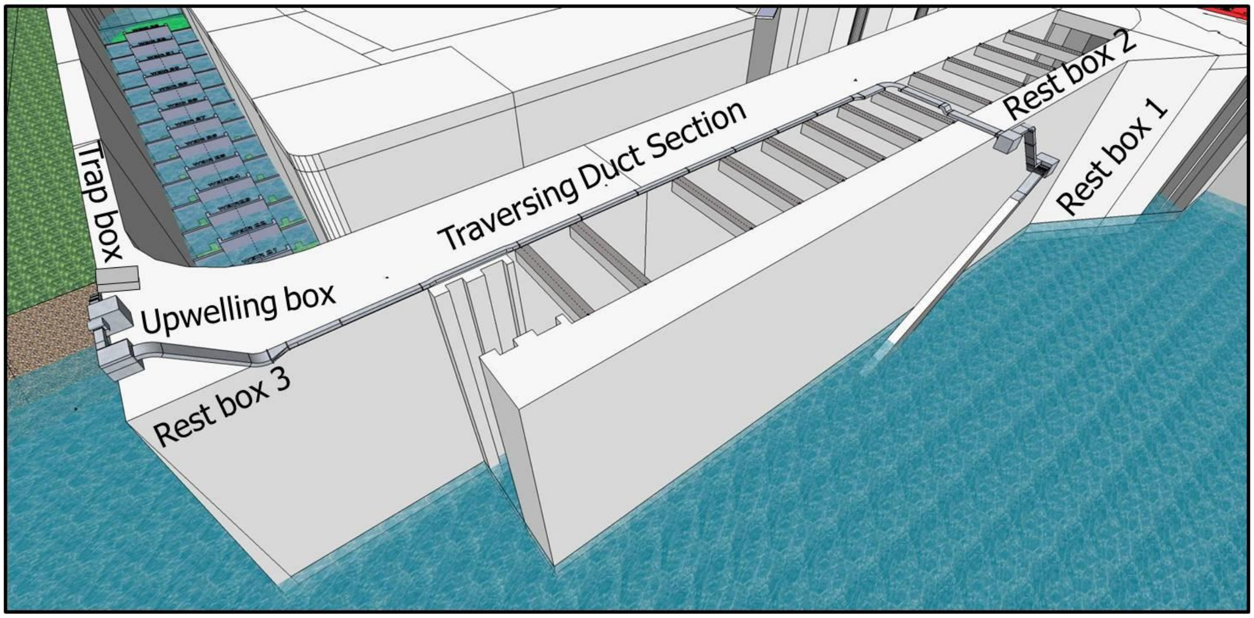

Figure 3. Diagram of the upper LPS structure on the NDE fishway deck.

The LPS on the upper fishway deck consisted of a long, flat duct section for ~150' (~46 m) (Figure 3). Lamprey then ascended a small ramp (~3', ~ 1 m) into rest box 3, which led to an upwelling box (received water that was split between the LPS downstream sections and final trap box), and down an exit chute into the terminal trap box. Several modifications were made to the LPS on the upper fishway deck between 2013 and 2014. First, the original high-platform deck for rest box 3 and the upwelling box was removed and both structures were lowered onto the fishway deck to improve accessibility. The initial idea was to collect lamprey into a mobile trap to avoid handling but the new design made manual inspection of these components much easier. Second, the single pump system used to deliver flow through the LPS on the upper fishway deck was replaced with a double system in order to provide increased flow and serve as a backup should one pump fail. These structural modifications were not likely associated with differences in lamprey collection rates between years. Lamprey were collected from the terminal trap box every day or every other day, scanned for potential half-duplex (HD)-PIT tags, transported via truck in oxygenated river water, and released above Bonneville Dam at the boat ramp in Stevenson, WA (river kilometer [rkm] 243).

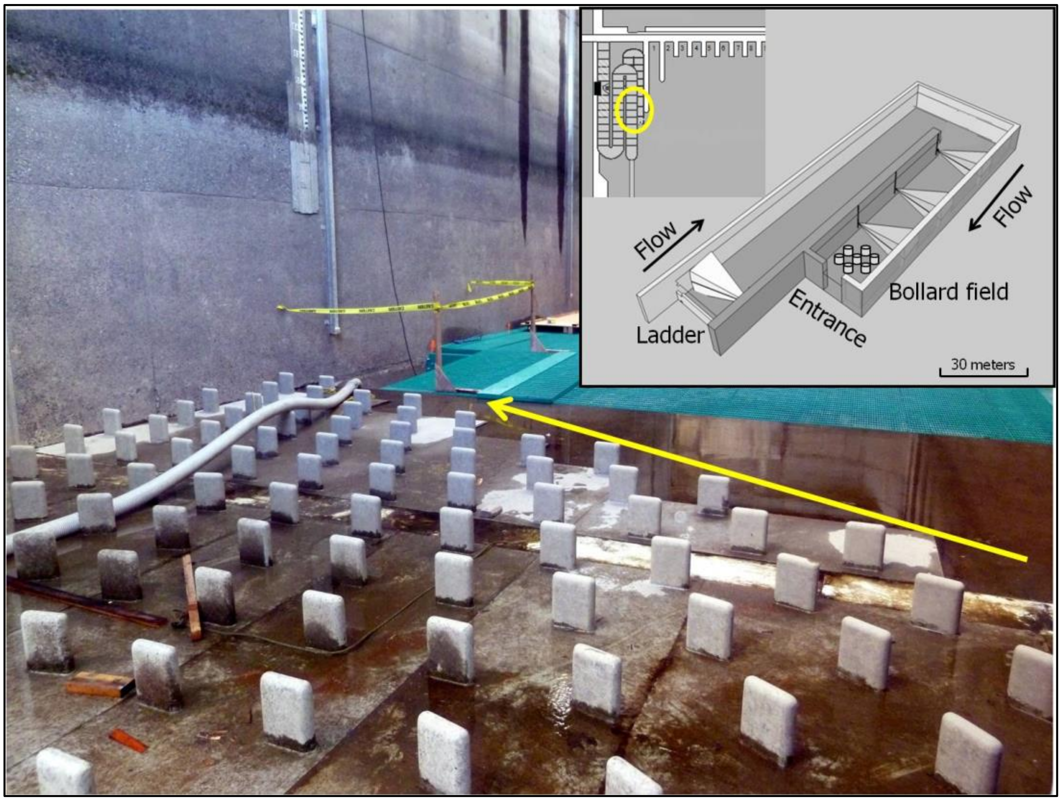

Figure 4. Photograph of the bollard field and location of the LPS (see Figure 5A) in the lower north fishway at John Day Dam. Yellow arrow shows the angled nature of the bollard field. Inset diagram is of the lower fishway sections inside the north fishway adapted from Kirk et al. (2014, 2015a). Yellow circle in inset picture shows the approximate location of the LPS in the north fishway (note that the collection channel did not have weirs in the lower section – weirs in the image are from the overlapping section of the fishway).

John Day Dam LPS

The John Day LPS had a simpler design than the LFS-LPS and was similar to the LPSs in the auxiliary water supply channels at Bonneville Dam (see Moser et al. 2011). The LPS was located ~50’ (~15 m) inside the John Day north fishway at the end of the bollard field (inset Figure 4). The bollard field was installed to reduce velocities along the fishway floor and was angled intentionally to guide lamprey to the LPS (Kirk et al. 2014; Figure 4). Flow for the LPS was provided by a submersible pump in the fishway AWS. The John Day LPS consisted of no turns and had only two sections of climbing ramp separated by one rest box (Figure 5A). This provided a direct route to the upper fishway deck and terminal trap box (Figure 5B). It gained 35’ (10.7 m) in total elevation from the fishway floor and was ~46’ (~14 m) long. The initial climbing ramp was an uncovered ramp design for most of the distance leading up to the only rest box. The second climbing ramp led fish into the upwelling box on the fishway deck, with an exit chute leading to a terminal trap box. Lamprey were collected from the trap box daily, scanned for potential HD-PIT tags, and released above the dam’s navigation lock on the north shore (rkm 346). Further details on the specific design features of both the Bonneville and John Day Dam passage structures can be found in a comprehensive report by Zobott et al. (2015).

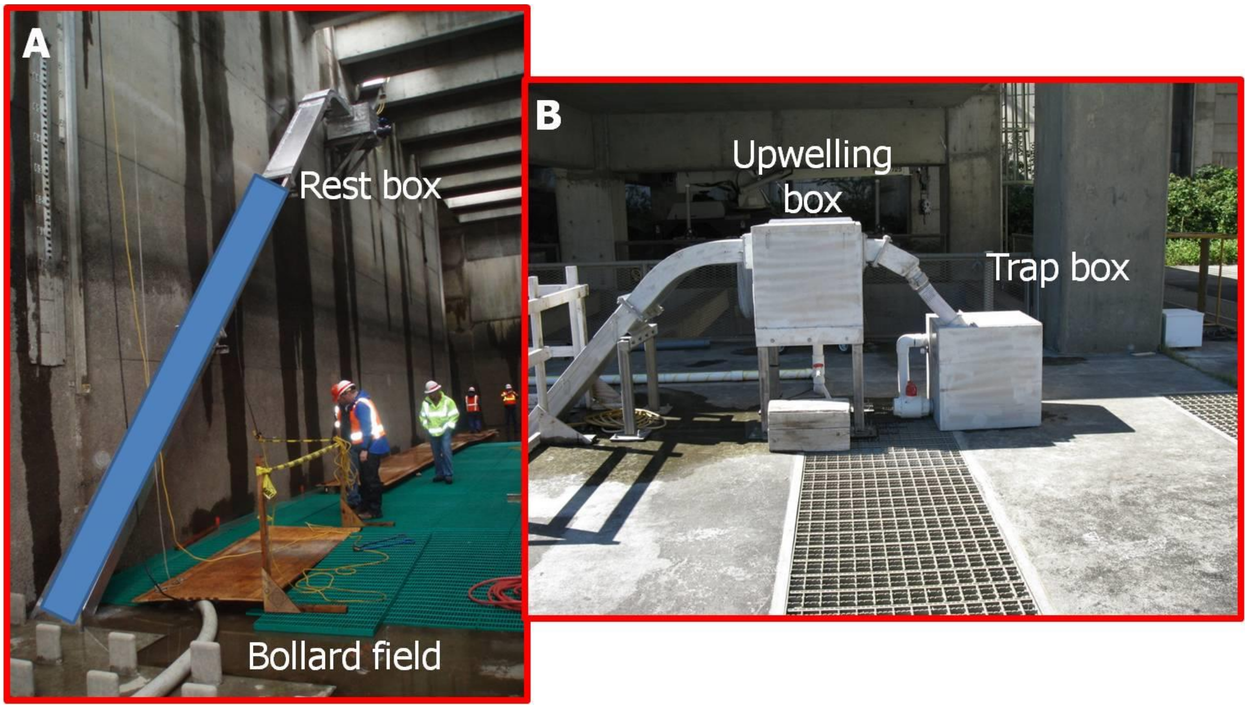

Figure 5. Photographs of the John Day LPS A) entrance ramp at the bollard field leading to a restbox and B) upwelling box and terminal trap box on the upper fishway deck.

Evaluation of lamprey use and behavior

We used the number of fish collected and detection frequencies of lamprey HD PIT-tagged at Bonneville Dam (released downstream at the Hamilton boat launch [rkm 232]) to evaluate the effectiveness of the LFS/LPSs. The collection efficiency for the Bonneville LFS-LPS was calculated as the number of lamprey collected from the LFS-LPS divided by the total (daytime + nighttime) number of lamprey counted at the Washington-shore fishway count window. The collection efficiency for the John Day LPS was calculated as the number of lamprey collected from the LPS divided by the total (daytime + nighttime) number of lamprey counted at the north fishway. In 2014, we also collected and anesthetized lamprey from the LFS-LPS trap box on 14 dates throughout the migration season (10 June to 8 August) to collect body measurements on the population of fish using the structure. Fish were measured for body length, weight, and girth similar to previous tagging studies (Keefer et al. 2014, 2015; Kirk et al. 2015b).

Lamprey passage was monitored through the lower LFS at Bonneville Dam using a series of HD-PIT antennas placed at four locations in the lower LFS (Figure 2). The populations of Pacific lamprey monitored were HD-PIT tagged and double tagged HD-PIT/radiotelemetry samples from 2013 and 2014 at Bonneville Dam. We also documented LPS use at John Day Dam for a sample of 100 HD-PIT tagged lamprey at John Day from 14-24 July 2014. Full details on collection, tagging, sample sizes, and extensive passage details for the lamprey tagged at Bonneville and John Day can be found in Keefer et al. (2014, 2015).

We evaluated the effect of different flows through the LFS on lamprey collection efficiency in 2014 using a randomized block design. A high flow treatment (3 fps, 0.9 m/s) and a low flow treatment (1.25 fps, 0.4 m/s) were alternated diurnally (day vs. night) in a 2 ×2 treatment design. The 4 flow scenarios were: 1) both daytime and nighttime flows being held constant at 3 fps (HDHN), 2) daytime flows at 3 fps and nighttime flows at 1.25 fps (HDLN), 3) daytime flows at 1.25 fps and nighttime flows at 3.0 fps (LDHN), and 4) constant flows at 1.25 fps during both periods (LDLN). All four treatments were equally and randomly distributed across four different time periods, which were from 27 July to 1 August, 2-6 August, 7-11 August, and 12-18 August. In 2013, LFS flows were held constant at ~1 fps.

Bonneville Dam LFS-LPS troubleshooting assessment

The LFS-LPS experienced a number of setbacks, which required both in-season and post-season assessments (Table 1). The first major concern was the presence of ‘entrained air’. Within days of beginning operation in 2013, a ‘surface boil’ developed near the lower LFS under high flow conditions. Furthermore, there was a large plume, or ‘bubble curtain’, that appeared to emanate from the LFS entrance during high flow conditions (Figure 6). This led to concerns that the plume was deterring or impeding fish passage. The entrained air patterns were initially suspected to be a result of the structural damages sustained to the exterior support rods during pre-season evaluations, but an inspection with a remotely operated vessel (ROV) in mid-July 2013 revealed only minor damage to the lower LFS.

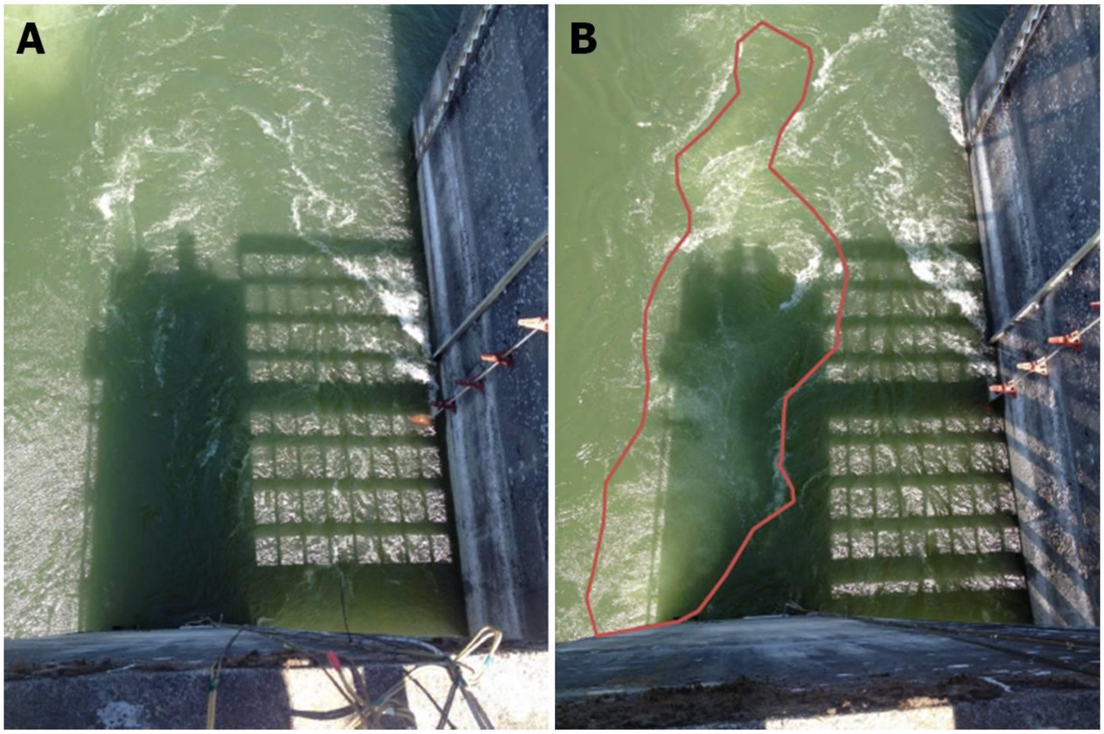

Figure 6. Photographs showing the formation of the bubble plume, or ‘bubble curtain’, emanating from the LFS entrances as a result of entrained air. A) With the valve open at 24% (~1 fps, ~0.3 m/s) no bubble plume is visible, and B) the bubble plume (outlined red) became persistent with the flow valve open at greater than 50% (~2.3 fps, ~0.7 m/s).

We used a dual-frequency identification sonar (DIDSON) camera to evaluate the presence of the bubble curtain in an attempt to understand the source of the entrained air. We deployed it at NDE on an I-beam previously used for evaluations of lamprey behavior around the LFS entrance slot (Kirk et al. 2014). We attempted to evaluate the presence and extent of the bubble curtain under two different scenarios: 1) with both the lower and upper LFS entrances open, and 2) with the upper LFS entrance closed. When both entrances were open, we deployed the DIDSON with a very small angle (-6°), almost perpendicular to the flow (Figure 7A), to evaluate the downstream extent of the bubble curtain. We also deployed it from the upper entrance and directed it upstream towards the upper entrance (Figure 7B). Two similar deployments occurred when the upper entrance was closed, except the camera was tilted at a downward angle (-43°) to evaluate the bubble curtain near the lower entrance (Figure 7C, 7D). We evaluated the presence of the bubble curtain for a total of four different deployments under five different flow settings (0, 20, 40, 55, and 70% open), which translated to entrance velocities of approximately 0 fps, 0.8 fps, 1.8 fps, 2.5 fps, and 3.0 fps (0-0.9 m/s) (*Steve Schlenker, USACE, personal communication).* Details on the operation and deployments of the DIDSON camera can be found in Kirk et al. (2014, 2015a).

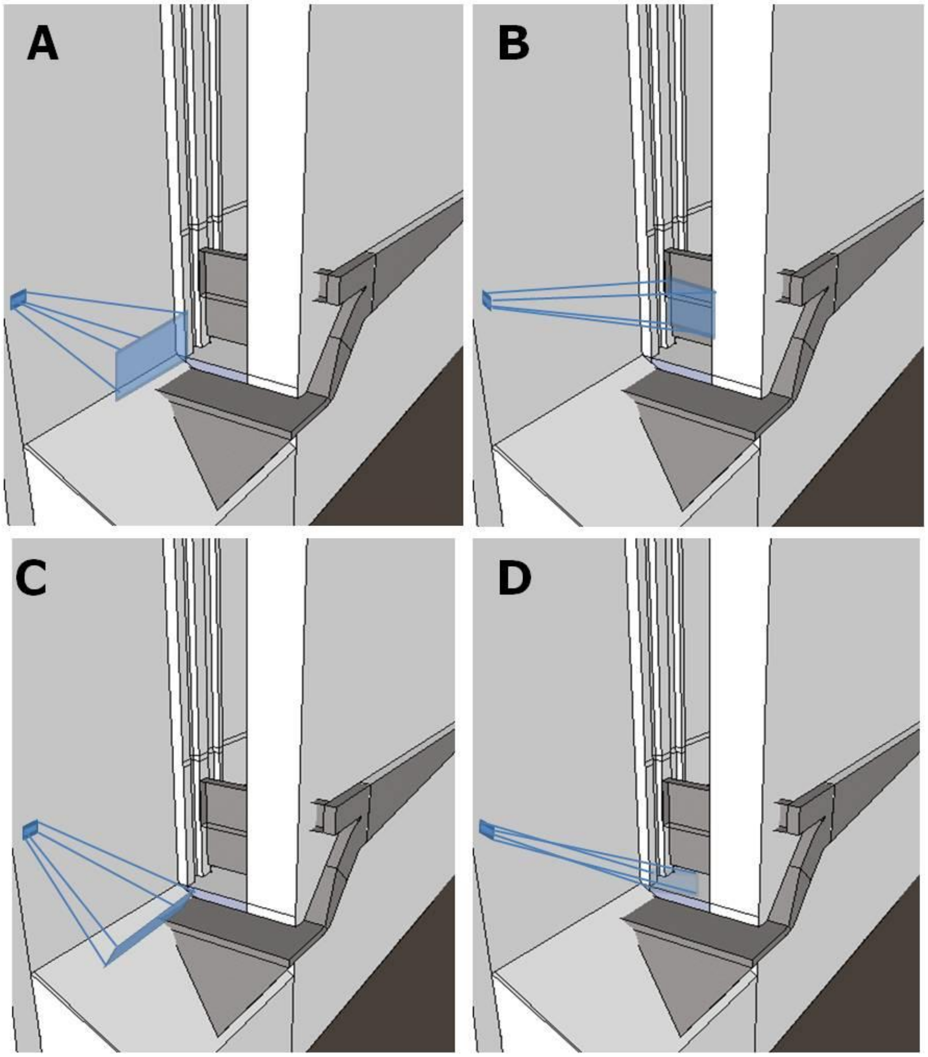

Figure 7. Four different deployments using the DIDSON camera to identify the potential source and extent of the bubble curtain. Two deployments consisted of both the lower and upper entrances being open with one view: A) almost perpendicular to the flow and another B) aimed upstream at the upper LFS entrance. The other two deployments consisted of the upper entrance being closed with one view: C) perpendicular to the flow tilted downwards to the lower entrance and another D) tilted downwards aiming upstream.

The second major concern was the substantial decline in lampreys collected throughout the migration season (see Results). Moreover, 3 of the 16 lamprey collected on 14 June 2013 were found dead in the lower LFS (Table 1). Initial concerns that in-season modifications impeded passage into the LPS were heightened as lamprey still failed to use the system by the end of 2013 (Table 2). We observed similarly low numbers in late 2014 and concerns developed about potential interactions between LFS attraction flows and tailwater elevation. We deployed an acoustic doppler current profiler (ADCP) to evaluate hydraulic patterns throughout the water column near the LFS entrance slot.

Table 1. Timeline of important Operation, modification, and troubleshooting events related to the Bonneville Dam LFS-LPS in 2013 and 2014.

Year	Date	Event details
2013	3/7	During early season tests, the support rods for the lower LFS broke and created substantial vibration in the passage structure
	6/4	LFS-LPS started for season; 1 lamprey was collected during the first overnight period
	6/11	Surface boils developed near the lower LFS under high flow conditions, leading to concerns about a bubble curtain impeding lamprey entrance into the LFS
	6/14	13 lamprey were collected from rest box 2 over a two day period; 3 of which were dead, indicating the presence of a possible bottleneck in the upper LPS
	6/15	Video analysis of lamprey inside rest box 3 identified that lamprey had difficulty passing the exit fyke, which had a plastic mesh cover
	6/25	LFS-LPS dewatered for in-season modifications to fabricate new exit fykes for the upwelling box and rest box 3, as well as a new exit chute for the terminal trap box.
	7/11	ROV inspection was conducted on the lower LFS entrances to identify any potential damages or causes of the surface boil. No major structural issues were found
	7/12	LFS-LPS restarted for season
	8/10	Picket leads were flushed to remove any possible debris or dead fish that may have been deterring movement into the LFS
	8/20	LFS-LPS turned off for season
2014	5/19	LFS-LPS started for season; 18 lamprey were collected during the first overnight period
	6/2	Conducted evaluations to determine how much velocity created the formation of the bubble curtain near the lower LFS.
	9/10	LFS-LPS turned off for season
	11/19	Evaluation of LFS bubble curtain and surface boil with DIDSON camera; ADCP measurements to characterize flow patterns at LFS entrances

Results

Bonneville Dam LFS-LPS

In 2013, the LFS-LPS structure had very few lamprey pass. Only 29 lamprey were collected the entire season (5 June to 20 August). We estimated collection efficiency to be 0.1% based on the total Washington-shore counts (Figure 8A), with most lamprey (79%) passing in late June (Figure 8B). The low collections in 2013 were partially attributed to the presence of a bottleneck within the upper LPS passage structure which prevented lamprey from reaching the terminal trap box (Table 1). Instead, lamprey appeared to be ‘milling’ within the system for several days based on evidence that lamprey were rejecting the plastic mesh that covered the entrance fyke. We conducted in-season modifications (25 June-11 July) to remove the plastic mesh and we fabricated a new entrance fyke to improve passage. After the system was re-started, however, only six fish passed during the remainder of the season (Figure 8B).

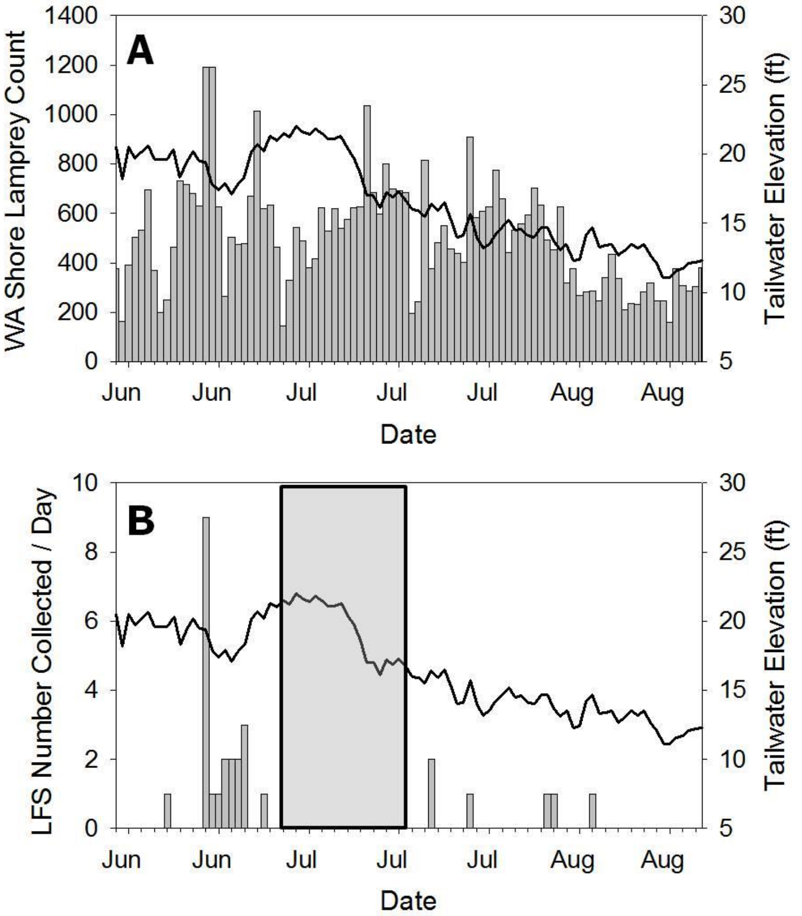

Figure 8. Counts of Pacific lamprey in 2013: A) passing the Washington shore fishway (bars), and B) collected from the LFS-LPS in relation to date and tailwater elevation (line). Area highlighted grey in B) indicates LFS dewatering period for in-season modifications.

Collection numbers increased in early 2014, with 545 lamprey collected from the LFS-LPS from 20 May to 10 September. Collection efficiency increased to 0.89% of the total Washington-shore counts. However, collection numbers decreased markedly as the season progressed, much like they did in 2013. 78% of the total collection was collected prior to 11 June, with a large decline in collection numbers thereafter (Figure 9B). There was a significant, negative correlation between the number of lamprey caught in the LFS-LPS and date for both 2013 (n = 65, r = -0.37, P = 0.002; Figure 8B) and 2014 (n = 133, r = -0.57, P < 0.001; Figure 9B). There were 4 recaptures of HD PIT-tagged lamprey in the Bonneville LFS-LPS trap box in 2014; 3 were fish tagged in 2013 (i.e., second year migrants that overwintered). Interestingly, lamprey collected from the LFS-LPS in 2014 for body size measurements (n = 51) had significantly smaller body sizes than the lamprey collected at the AFF for radiotelemetry and HD PIT-tag studies in 2014 (analysis of variance [ANOVA]; F =16.85, P < 0.001; Figure 10).

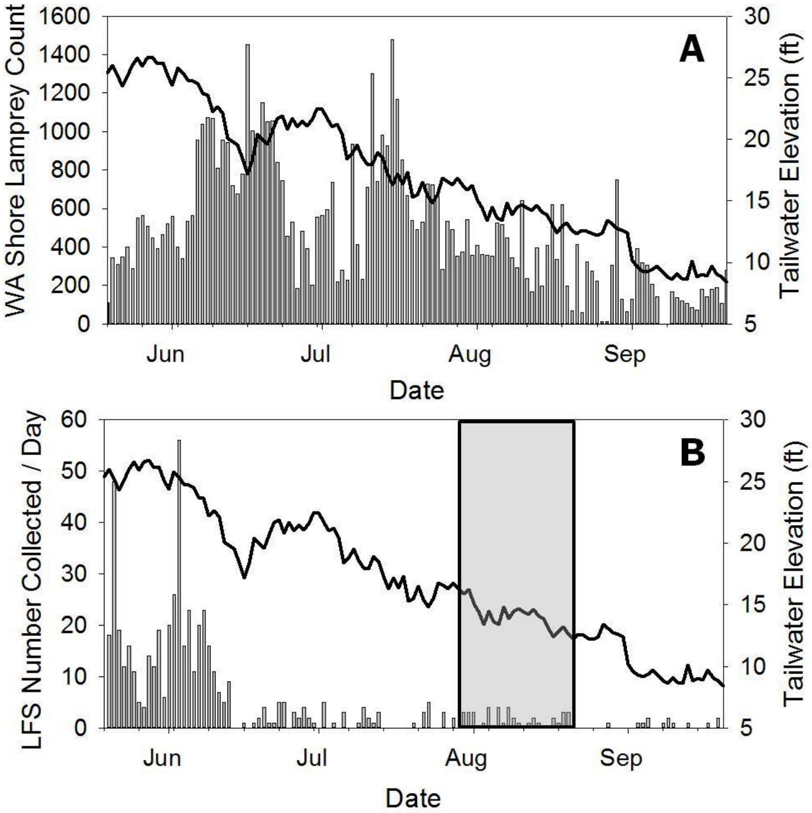

Figure 9. Counts of adult Pacific lamprey in 2014: A) passing the Washington shore fishway (bars), and B) collected from the LFS-LPS in relation to date and tailwater elevation (line). Area highlighted grey in B) indicates period of LFS flow trials.

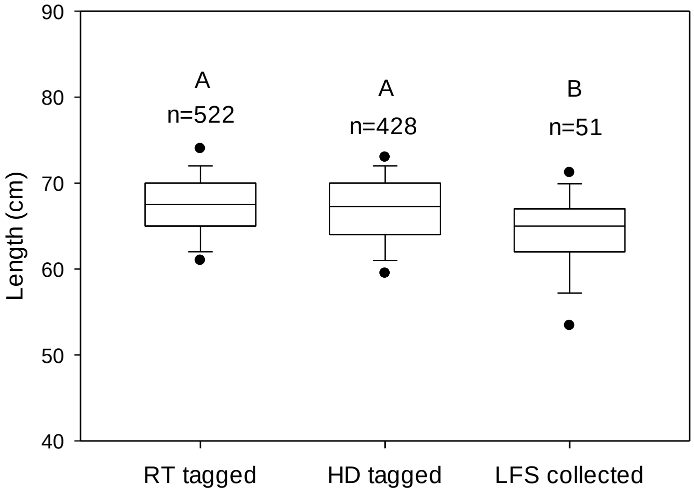

Figure 10. Comparison of total body lengths of Pacific lamprey collected in 2014 radiotelemetry (RT) studies, 2014 HD PIT-tag studies, and directly from the LFS-LPS trap box in 2014. Details on radiotelemetry (RT) and HD PIT studies can be found in Keefer et al. (2014, 2015). Different letters indicate samples with significantly different body lengths based on Tukey's honest significant difference (HSD) test (*P* < 0.05).

We had limited PIT-tag information with which to evaluate the passage of lamprey though the LFS-LPS structure. Only ten tagged lamprey were detected on the HD-PIT antennas inside the lower LFS in 2013 (3 lamprey) and 2014 (7 lamprey). Six lamprey were detected at the uppermost antenna inside the LFS and only one lamprey tagged in 2014 successfully ascended the entire LFS-LPS system and was collected inside the trap box. The remaining five lamprey were eventually detected exiting the LFS. The passage time through the lower LFS structure for the single lamprey collected from the trap box was 10.5 minutes. The amount of time spent in the LFS-LPS for the remaining 9 lamprey was highly variable, ranging from 15 s to 20 h.

Table 2. Results from the randomized block flow test at the Bonneville Dam LFS-LPS showing the mean tailwater elevation, mean counts of lamprey passing the Washington-shore ladder, mean number of lamprey collected from the LFS each day, and the standard deviation (SD) of collection numbers for the four experimental treatments.

Treatment	Number of days	Mean Tailwater elevation (m)	Mean WA-shore ladder count	Mean Lamprey/day	SD
High Day-High Night	6	14.3	452	1.2	1.5
High Day-Low Night	5	14.5	398	1.0	1.2
Low Day-High Night	5	14.7	357	2.2	0.4
Low Day-Low Night	7	14.5	408	1.7	1.9

Results from the late-season randomized flow tests did not yield substantially insightful results because only 35 lamprey were collected from the LFS during the 23-day trial (Figure 9B). The treatment with the highest collection numbers was low flow days-high flow nights (2.2 lamprey per day) and the lowest was the high flow day-low flow night (1.0 lamprey per day; Table 2). Interestingly, the low day-high night treatment also had the lowest standard deviation and the fewest mean number of lamprey passing the WA-shore during those treatments (i.e., highest collection efficiency), indicating perhaps more consistency in lamprey collection. The number of lamprey collected under high flow treatments at night (*n* = 11, *mean* = 1.6) was similar to numbers collected during the day (*n* = 12, *mean* = 1.4). However, lamprey collection numbers were nearly twice as those for low daytime flows (*n* = 12, *mean* = 1.9) compared to high daytime flows (*n* = 11, *mean* = 1.1).

Observations of the’ bubble curtain’ from the DIDSON camera yielded similar results to on-site observations. Videos from most deployments showed more turbulent plumes of entrained air when the flow valves were at 70% (3.0 fps, 0.9 m/s) and 55% (2.5 fps, 0.8 m/s) open compared to 20% (0.8 fps, 0.2 m/s) and 40% open (1.8 fps, 0.5 m/s; Figure 11). However, we were unable to observe any noticeable difference in the flow conditions when both entrances were open compared to when only the upper entrance was closed.

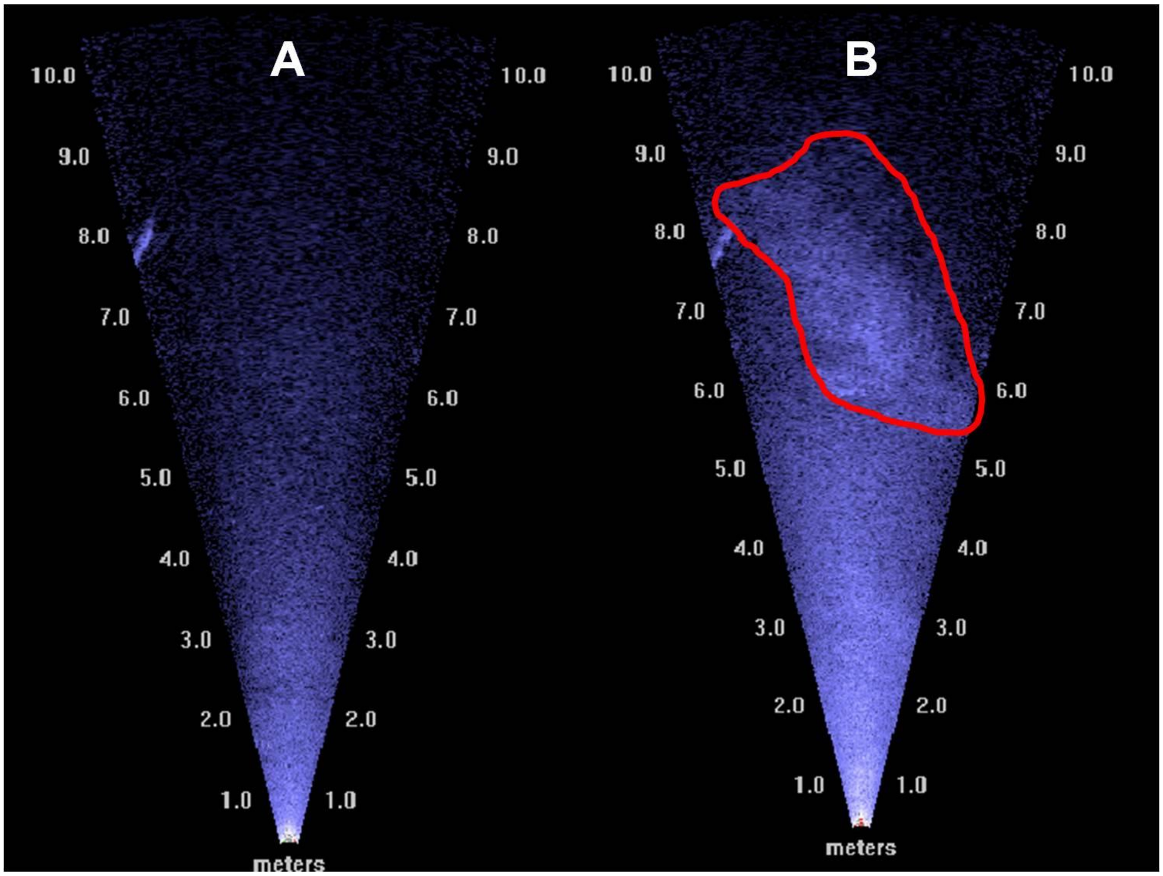

Figure 11. DIDSON images looking upstream at the upper LFS entrance with both entrances open (Figure 7B) for flow settings of: A) 20% (0.8 fps) and B) 70% (3.0 fps). The entrained air plume (outlined in red) was consistently visible under higher flow settings and absent under lower settings.

ADCP results

ADCP observations were largely consistent with CFD modeling (Figure 12), revealing relatively low velocities below the entrance weir. The coarse resolution of the ADCP observations prevent rigorous conclusions, but observed velocity indicated very low attraction velocity or reversing flows near the benthos and LFS entrances during the November observations during low tailrace conditions.

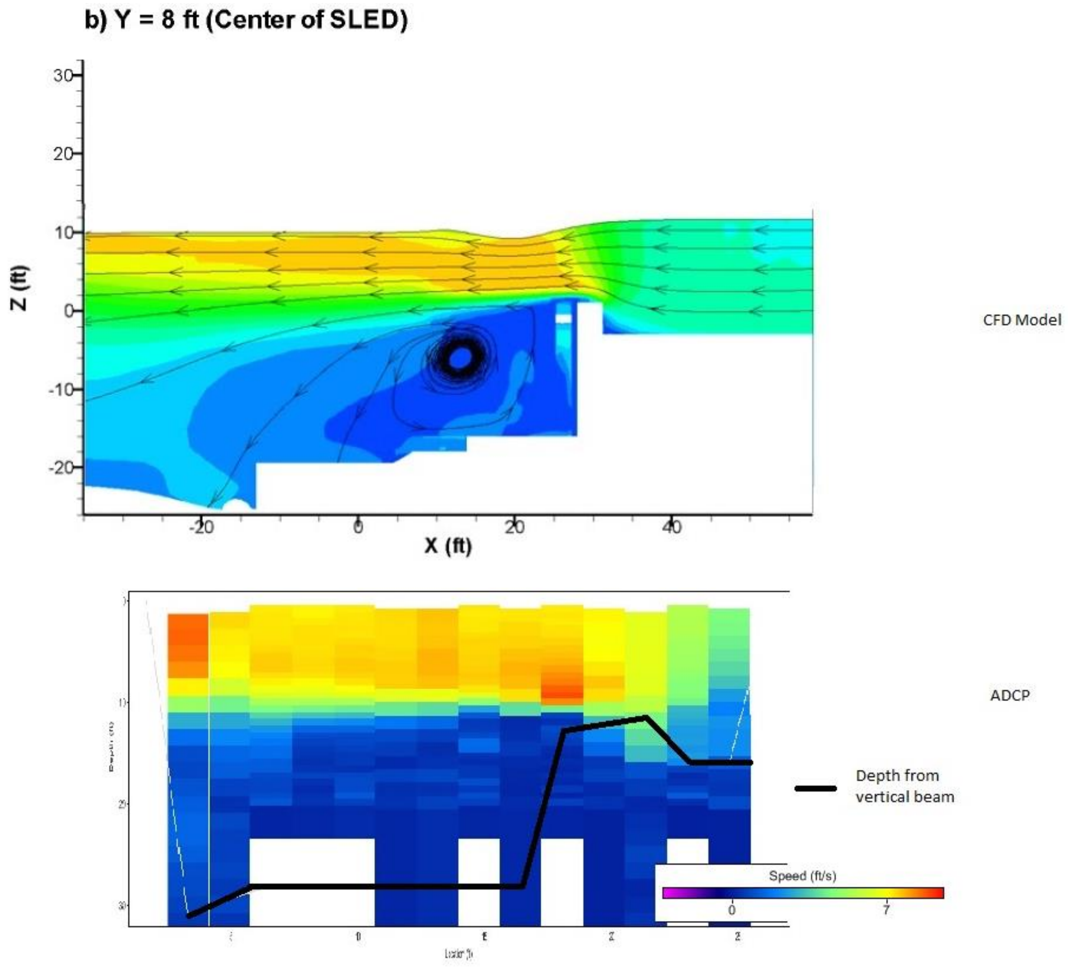

Figure 12: Longitudinal velocity (i.e., upstream-downstream) from AECOM (2012) CFD modeling (upper) and the November 2014 UI ADCP observations (lower).

John Day Dam LPS

The John Day LPS was more efficient at collecting lamprey than the Bonneville Dam LFS-LPS. John Day LPS collection numbers were largely proportional to the north fishway lamprey counts throughout the migration season in both years. In 2013, the John Day LPS collected 111 lamprey between 19 July and 11 September, which was 2.2% of all lamprey counted passing the north fishway (Figure 13a). Collection efficiency increased ~six times in 2014, with the LPS collecting 1,228 lamprey between 25 June and 30 September. This was estimated to 12.9% of the total number that passed via the north fishway (Figure 13b). Four of the 111 lamprey collected in 2013 (3.6%) and 17 of the 1,228 captured in 2014 (1.4%) were HD-PIT recaptures from tagging studies.

A subset of 100 lamprey from the sample of 1,228 (8.1%) collected in the LPS in 2014 was HD PIT-tagged and released upstream from the navigation lock for a complementary study (Keefer et al. 2015). The mean body length of lamprey tagged from the John Day LPS was 66.6

cm (SD = 3.9), which was similar to the samples tagged in the Bonneville Dam AFF (mean = 67.3 and 66.5 cm; Figure 10). Forty-one (41.0%) of the lamprey released at the navigation lock subsequently fell back over John Day, and 30 of the 41 (73.2%) lamprey were detected passing John Day again; 3 (10.0%) of the 30 lamprey were recaptured in the LPS.

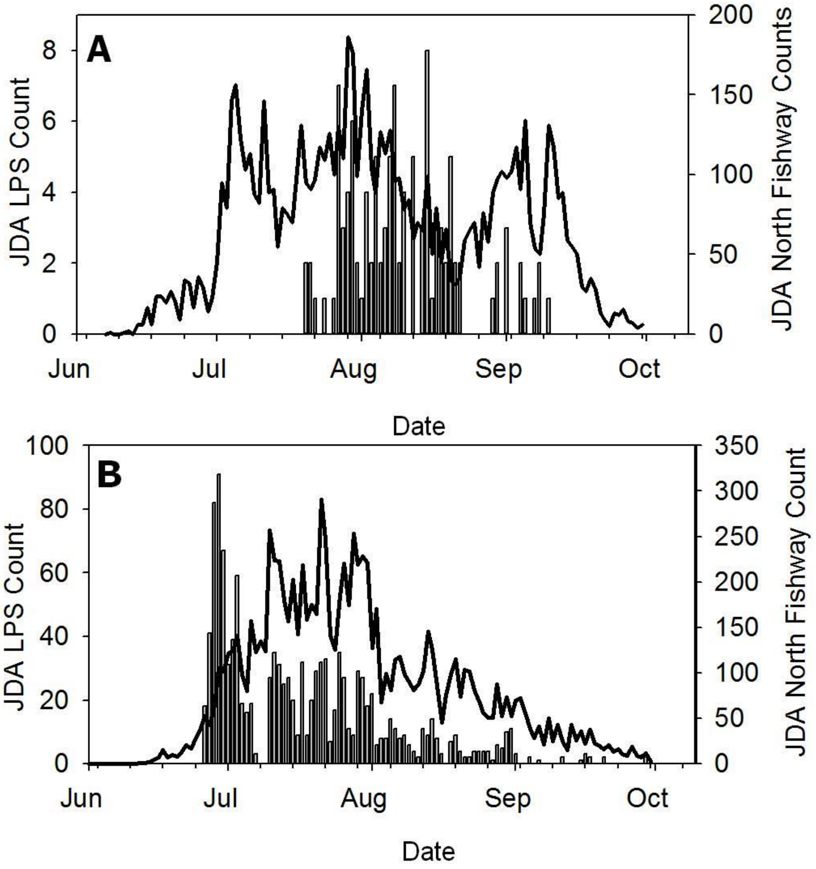

Figure 13. Counts of Pacific lamprey passing the John Day LPS (bars) in: A) 2013 and B) 2014 in relation to date and the number of lamprey passing the John Day north fishway (line).

Discussion

The collection efficiency of both the Bonneville LFS-LPS and John Day LPS were significantly lower than estimates reported for other LPS structures at Bonneville Dam, but the new structures also were also situated in unconstrained locations relative to the LPSs in auxiliary water supply (AWS) channels. Moser et al. (2011) reported 21% collection efficiency for an LPS in the Bradford Island AWS during its first year of operation and estimated collection efficiency rose to 40% by its fifth year of operation. Collection efficiency at an LPS in the Washington-shore AWS had collection efficiency estimates of 11% and 12% during its first two years of operation. The John Day LPS had a comparable estimate (12.9%) during its second year of operation. The highest collection efficiency of the Bonneville LFS-LPS was 0.9%, which also occurred during the second year of operation. The efficiency of these structures is almost certainly site-dependent. For example, structures located in the AWSs likely collect more lamprey because these LPSs offer the only possible upstream route in dead-end areas. In contrast, structures near fishway entrances are but one of multiple migratory paths available to lamprey.

There were multiple reasons for the poor performance of the Bonneville Dam LFS-LPS. One of the most persistent concerns was the entrained air and especially how the bubble curtain emanating from the LFS entrances may have impeded fish. Attempts to minimize the bubble curtain were addressed by keeping LFS flows below 50% open, the level at which the bubble curtain began forming (Figure 11). Unfortunately, the DIDSON observations did not provide insights into the source of the bubble curtain (i.e., upper versus lower entrance). Regardless of the entrained air, the LFS-LPS captured lamprey fairly consistently for the first several weeks of 2013 and 2014. Unfortunately, the presence of a bottleneck in the LPS on the upper fishway deck in 2013 prevented lamprey from reaching the terminal trap box, which required dewatering for 2.5 weeks (Table 1). Upon re-starting the structure, very few lamprey were collected for the remainder of the season (Figure 8B). Concerns about whether seasonal changes influenced collections were not clear until 2014, when late season declines were repeated (Figure 9B).

We think the late season declines in collection efficiency for the LFS-LPS structure were likely associated with changes in tailwater elevation. The underlying mechanism may be poor attraction flow from the LFS and inadequate surrounding guidance flow, which may actually reverse and create a counter-current at the entrance as tailrace elevation drop (Figure 14). Attraction to the lower LFS entrance would likely be limited already given the primary high-velocity attraction jet that fish would orient towards is located near the water's surface at NDE (AECOM 2010; Kirk et al. 2015a). Results from a previous DIDSON study showed that the lower LFS entrance had one of the lowest lamprey entrance rates reported at NDE, compared to observations higher in the water column (Kirk et al. 2014). However, results from the flow tests did not necessarily suggest that high flow conditions improved collection ability, despite these tests being performed at lower tailwater elevations (Table 2). Nonetheless, we think that increasing attraction flows at the lower LFS is necessary for maintaining performance throughout the migration season given the results from the ADCP deployments.

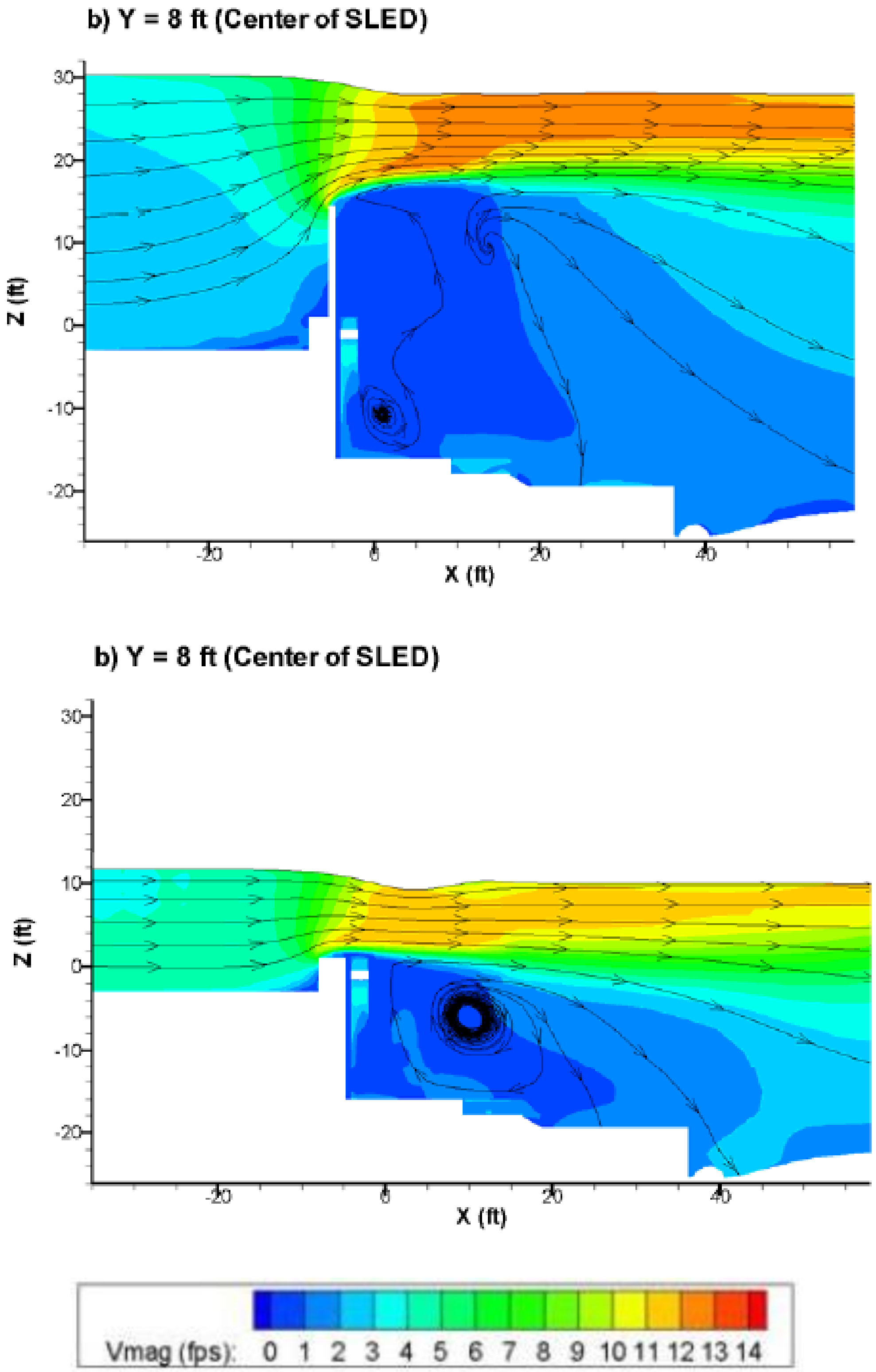

Figure 14. From AECOM (2012) Figure H-7, Tailwater 37’ (upper) and 10’ (lower) illustrating the increasing strength of counter current flow at the LFS-LPS entrances with decreasing flow.

In contrast, the John Day LPS had much higher success passing lamprey. This was likely attributable to the strong demersal tendencies observed for lamprey in the lower north fishway (Kirk et al. 2015a). During an observational study with the DIDSON camera, most lamprey were observed within a 2 m range of the LPS and it is possible that the intentionally angled design of the bollard field along the John Day fishway floor improved lamprey guidance to the structure. Furthermore, the presence of the bollard field and the depth of the fishway entrance (~3 m) may have allowed lamprey to simultaneously employ both rheotactic and demersal behaviors, unlike the deeper entrance environment at Bonneville (USACE 2010; Kirk et al. 2014). The success of the John Day LPS may also have been attributed to the straight-lined climbing ramp and a relatively small gain in elevation (Zobott et al. 2015). Regardless of why the John Day LPS performed better than the Bonneville LFS-LPS, future operation of the LPS should improve lamprey passage at John Day Dam given that the lower fishway is hypothesized to be an important bottleneck for passage in the north fishway (Kirk et al. 2014, 2015a).

The collection efficiency of the new structures at both John Day and Bonneville dams improved from 2013 to 2014 by ~10%. Increased use of lamprey-specific structures across years has been documented previously and one hypothesis is that the newly furbished surfaces of LPSs emit chemical signals that deter lamprey from using the structure initially (Clabough et al. 2011; Moser et al. 2011; Thompson et al. 2016). Given the important role of olfactory cues during the migrations of anadromous lamprey (Bjerselius et al. 2000; Yun et al. 2011), we think that increased use should be observed through time as the LPSs become ‘seasoned’ (e.g., coated with biofilms, lamprey slime, etc.). This hypothesis was also proposed for explaining why Chinook salmon displayed much lower entrance efficiencies through the Cascades Island fishway in the year that an LPS was installed compared to the following year (Jepson et al. 2011).

Although the size-selective pattern of lamprey passage at large Columbia River dams has been extensively documented, the specific explanation for this pattern remains unclear. Several hypotheses suggest that larger lamprey having higher energetic condition and therefore larger fish migrate longer distances (Keefer et al. 2009a; Hess et al. 2014). The smaller body lengths of lamprey collected from the Bonneville LFS-LPS provided circumstantial evidence that traditional fishways may act as selective filters against smaller lamprey (Figure 10). Moreover, high velocity and turbulence within many fishways designed for Pacific salmonids often exceed the swimming capabilities of Pacific lamprey (Clay 1995; Johnson et al. 2012).

The relationship between body size and swimming performance is well documented for many species (Beamish 1974; Haro et al. 2004). However, a previous study did not find that larger lamprey had a higher probability of passing strenuous passage conditions in an experimental flume. Instead, results revealed indirect evidence for the role of energetic condition in explaining passage with lamprey of shorter dorsal distances (measurement between the two dorsal fins indicating potential maturation state and energetic condition; Clemens et al. 2009) having lower probabilities of passage (Kirk et al. 2015b). On balance, we think that size-selective passage occurs as a result of the cumulative effects on endurance at both local (i.e., within dam fishways) and at larger scales (i.e., dam-to-dam). Providing passage structures optimized specifically for the swimming and climbing behaviors and capabilities of Pacific lamprey should help reduce selective passage observed for this species at large hydropower dams in the Columbia River.

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