Development of Passage Structures for Adult Pacific Lamprey at Bonneville Dam, 2007-2008

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EXECUTIVE SUMMARY

In 2007-2008, we continued efforts to improve adult Pacific lamprey passage at Bonneville Dam with the following study objectives:

1) Design, fabricate, and install a new lamprey passage structure (LPS) at the Washington Shore auxiliary water supply (AWS) channel and monitor lamprey use of this new structure and the existing LPS at the Bradford Island AWS,
2) Monitor lamprey use of the collector at the Washington Shore fishway entrance, and
3) Monitor lamprey use of the top of the Cascades Island fishway.

To achieve these objectives, we used lamprey-activated counters to enumerate lamprey passing through the LPS structures and a terminal trap box to count lamprey that used the entrance collector. We tagged 757 adult lamprey in 2007 and 610 in 2008 with passive integrated transponder (PIT) tags. In 2008, an additional 298 lamprey were tagged with both a half-duplex PIT-tag and a radio transmitter. Antennas to detect PIT tags were integrated into the LPS structures, and an antenna was also operated at the top of the Cascades Island fishway to identify lamprey passage routes and rates of movement.

The new Washington Shore LPS and counter were completely operational by 25 June 2007. The LPS featured a novel "switch-back" design and full-width crests at the top of each of its 45° ramps. The structure allowed lamprey to ascend 9 m along its entire 19.1-m course and volitionally exit into the Washington Shore fishway near its terminus. In each year of operation, 3% of the PIT-tagged lamprey were detected in this LPS, and total counts at its exit were 2,517 in 2007 and 1,985 in 2008. All lamprey detected passed through the LPS successfully with a median passage time of less than 30 min. Larger percentages of PIT-tagged fish used the Bradford Island AWS LPS (4% in 2007 and 8% in 2008). As in previous years, passage efficiency at this structure was over 97%, and median passage times were approximately 45 min.

The Washington Shore entrance collector was operated as an open ramp in 2007-2008, and its performance improved (> 400 lamprey per year, 3% of the PIT-tagged population) relative to 2006. Lamprey use of the entrance collector increased during periods of relatively high river discharge and high tailwater elevation.

In both 2007 and 2008, 8% of the PIT-tagged lamprey were detected at the top of the Cascades Island fishway, indicating that large numbers of fish may become temporarily trapped in this region. There is currently no exit route at this fishway, which is usually closed to salmonids. Consequently, providing a passage route for lamprey in this area might significantly increase overall passage success at Bonneville Dam.

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INTRODUCTION

Structures designed to attract and guide lamprey movements can be used to promote passage wherever these anadromous fish encounter obstacles to migration. In the Pacific Northwest, the need for lamprey conservation has resulted in recent development of such structures to aid spawning migrations of adult Pacific lamprey (*Lampetra tridentata*). Pre-spawning Pacific lamprey that enter the Columbia River must pass four hydropower dams to reach the confluence of the Columbia and Snake Rivers and up to five additional dams to attain spawning areas in headwater streams. Providing safe passage routes for lamprey at these dams is challenging, but was identified by the U.S. Fish and Wildlife Service Lamprey Technical Workgroup as one of the highest priorities for Pacific lamprey recovery in the Columbia and Snake Rivers (CRBLTW 2005). Consequently, developing a robust "toolbox" of lamprey friendly designs is critical to the success of both new fishways and the addition of structures to existing fishways.

After entering the Columbia River, adult Pacific lamprey encounter Bonneville Dam, the first mainstem hydropower dam at river kilometer 235 (Figure 1). Here they have difficulty entering fishways, and those that successfully enter are often obstructed or delayed near the top of fishways (Moser et al. 2002b; Johnson et al. 2009b). In these areas, serpentine weirs present an obstacle to upstream movement, and lamprey routinely aggregate in the adjacent auxiliary water supply (AWS) channels (Moser et al. 2005). Lamprey enter these areas through connecting diffuser gratings or via the picketed lead downstream from the count stations. There is no ready upstream outlet to the dam forebay from the AWS channels, and radiotelemetry results indicated that lamprey reside in the channels for 4 d on average and then typically move back downstream (Moser et al. 2005).

In 2002 we began development of a lamprey-specific fishway to aid lamprey passage from the Bradford Island AWS channel into the Bonneville Dam forebay at Powerhouse 1 (Figure 1). We conducted 2 years of testing on collector design, and in 2004 completed the first lamprey passage structure (LPS) so that lamprey could volitionally move from the AWS into the forebay. We developed a lamprey-activated counter and used half-duplex passive integrated transponder (PIT) technology to monitor lamprey passage events, determine rates of passage through the LPS, and calculate overall LPS efficiency.

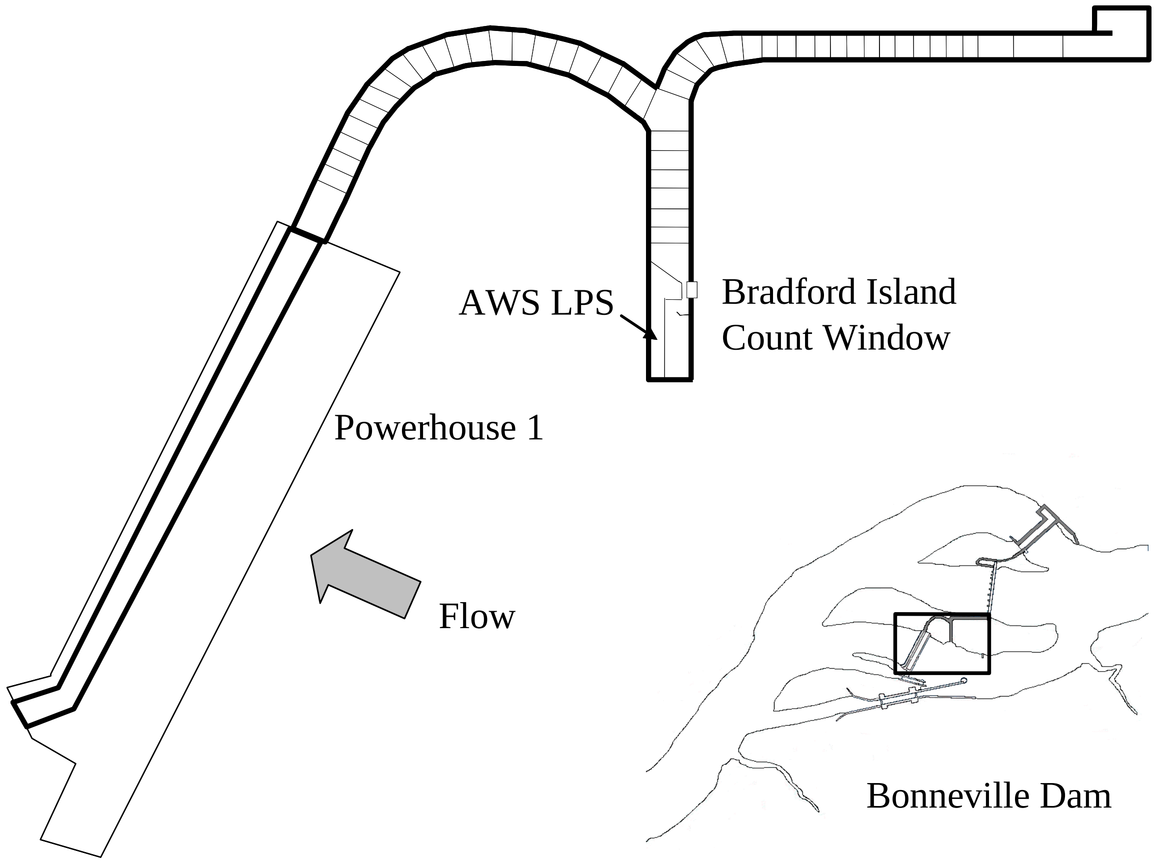

Figure 1. Schematic drawing of the Bradford Island fishway system at Bonneville Dam. The location of the Bradford Island Auxiliary Water Supply LPS (AWS LPS) is indicated by the black arrow.

Results from evaluations of the Bradford Island AWS LPS performance in 2004 and 2005 were promising. On average, 25% of the lamprey estimated to be at the top of the Bradford Island fishway used the LPS, and collection efficiency for marked lamprey released into the AWS channel was up to 42%. In addition, lamprey were typically able to pass through the structure in less than 2 h with 94-96% passage success. However, results from detections of PIT-tagged fish in 2005 indicated that the median time lamprey required to find the LPS was over 1 d, and that collection efficiency could be improved. Lamprey also seemed to have difficulty climbing a relatively long, steep ramp in the LPS.

In 2005 and 2006, we tested operational and structural modifications to the Bradford Island AWS LPS. Reducing flow through the LPS in 2005 did not improve lamprey passage rate or efficiency. However, structural changes to the LPS in 2006 improved both collection efficiency and passage time. These structural changes included addition of a collector ramp, reduction in the length of the steepest ramp, and addition of a broad-crested weir into a large rest box.

Our objectives in 2007-2008 were to:

1) Design, fabricate, and install a new LPS structure at the Washington Shore AWS and monitor lamprey use of this new structure and the existing LPS at the Bradford Island AWS
2) Continue monitoring lamprey use of the LPS collector at the Washington Shore fishway entrance
3) Monitor lamprey use of the top of the Cascades Island fishway

To achieve these objectives, we tagged adult Pacific lamprey with PIT tags, released them downstream from the dam, and recorded passage events at LPS exits and PIT-tag detector sites. We calculated LPS collection efficiency, passage efficiency, and passage rate at each structure using PIT-tagged lamprey detections.

METHODS

Structures Monitored

Auxiliary Water Supply Lamprey Passage Structures

Bradford Island—At the top of the Bradford Island fishway, the AWS LPS is positioned at the upstream end of the AWS channel (Figure 1). The LPS was modified in 2006, but it was not altered in 2007 or 2008 (Figure 2). Therefore, the dimensions and detailed schematic drawings for this structure in 2007-2008 are the same as in Moser et al. (2009).

Overall horizontal distance of the LPS was approximately 35.6 m, and elevation gain was 7.9 m. Lamprey ascended one of two collector ramps and passed associated PIT antennas (PIT 1 and 2) before entering Rest Box 1 (Figure 2). They then ascended a short ramp with a broad-crested weir and entered Rest Box 2, a large rest box. From there they passed up a short ramp, through another PIT antenna (PIT 3) and into Rest Box 3. They then traversed a shallow ramp and a long horizontal tube to Rest Box 4

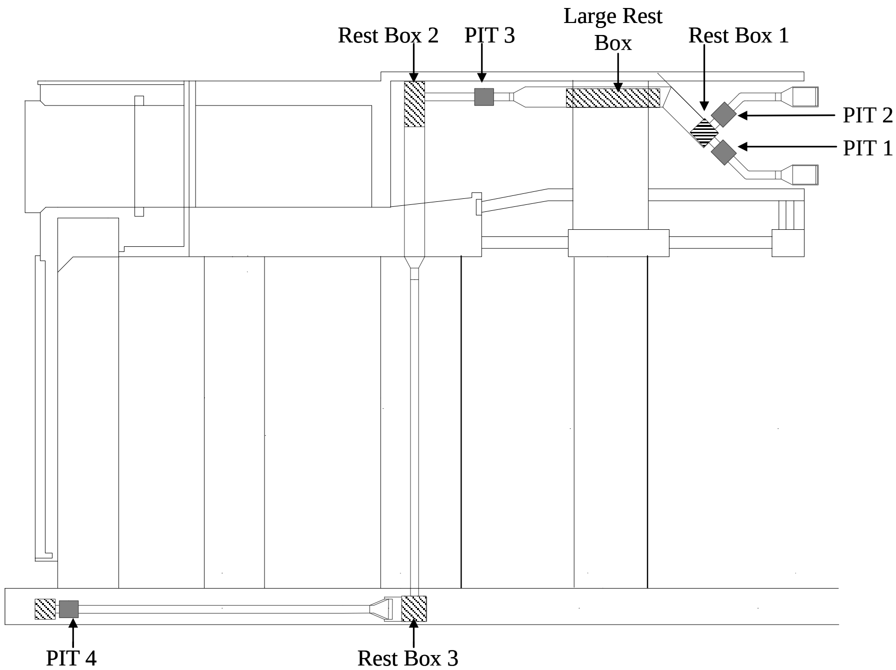

Figure 2. Top view of the Bradford Island LPS with the half-duplex PIT antenna locations (PIT 1-4) indicated.

(Figure 2). The final leg of the LPS included a short ramp, another long horizontal tube and a final PIT antenna (PIT 4). At the terminus to the LPS was an upwelling box fitted with a PVC exit slide.

After exiting the LPS, lamprey dropped into the forebay of Powerhouse 1 at a location approximately 10 m upstream from the exit of the Bradford Island fishway. As in 2006, lamprey that passed down through the exit slide were enumerated when they contacted a large paddle near the exit slide terminus (Moser et al. 2009). A limit switch attached to the paddle was wired to a palmtop computer, which assigned date and time to each passage event.

Columbia River water was supplied at the top of the LPS via a 10.2-cm diameter PVC pipe from two, 3-hp submersible pumps. Flow into the trap box was regulated to maintain a depth of 3 cm on the ramps and approximately 10 cm in the closed tubes. Flow was regulated by an upwelling box at the top of the LPS. This design stimulated lamprey to move onto the exit slide, even though water was passing down the slide.

Lamprey passage was monitored with a series of four, half-duplex PIT antennas integrated into the LPS design (Figure 2). A rectangular PVC sleeve was seamlessly inserted into the chutes leading to Rest Boxes 1, 2, and 4. This was necessary because the aluminum chute itself would attenuate the PIT signal. Each reader comprised a loop antenna of 10 G multistrand wire (wrapped around the PVC sleeve), an outer aluminum housing that acted as a Faraday cage to shield the antenna, a detector, and a palmtop computer that logged the time and date of each detection to a 256 mB memory card. The detectors were synchronized by wiring them together.

Washington Shore AWS LPS—In 2007 we designed, fabricated, and installed a new LPS at the AWS channel near the top of the Washington Shore fishway (Figure 3). While similar in many respects to the Bradford Island AWS LPS, the new Washington Shore AWS LPS incorporated some unique features. As in other structures, this LPS was fabricated of aluminum, with 51-cm wide ramps that terminated in rest boxes that lamprey could only exit in an upstream direction.

In addition to testing the “switchback” design (Figure 5), the Washington-shore AWS LPS also featured a broad crest at the top of each ramp (as in Figure 4D). Unlike the Bradford Island AWS LPS, the same width was used throughout the Washington Shore AWS LPS until lamprey had ascended to the highest point (at the point of entry into the horizontal tube and exit slide, Figure 4E). This design change was made to facilitate lamprey progress at the crest of each ramp.

All of the ramps in the Washington Shore AWS LPS were at 45° and were 51 cm wide, as in the Bradford Island AWS LPS. The entrance into each rest box was fitted with a one-way plastic mesh fyke to prevent lamprey from moving back down the LPS (this was also a feature of the Bradford Island AWS LPS). The counter at the exit slide terminus and water supply system were the same at both LPS structures. The overall length of the Washington Shore AWS LPS was approximately 19 m, with an elevation gain of 9.1 m (Figure 5).

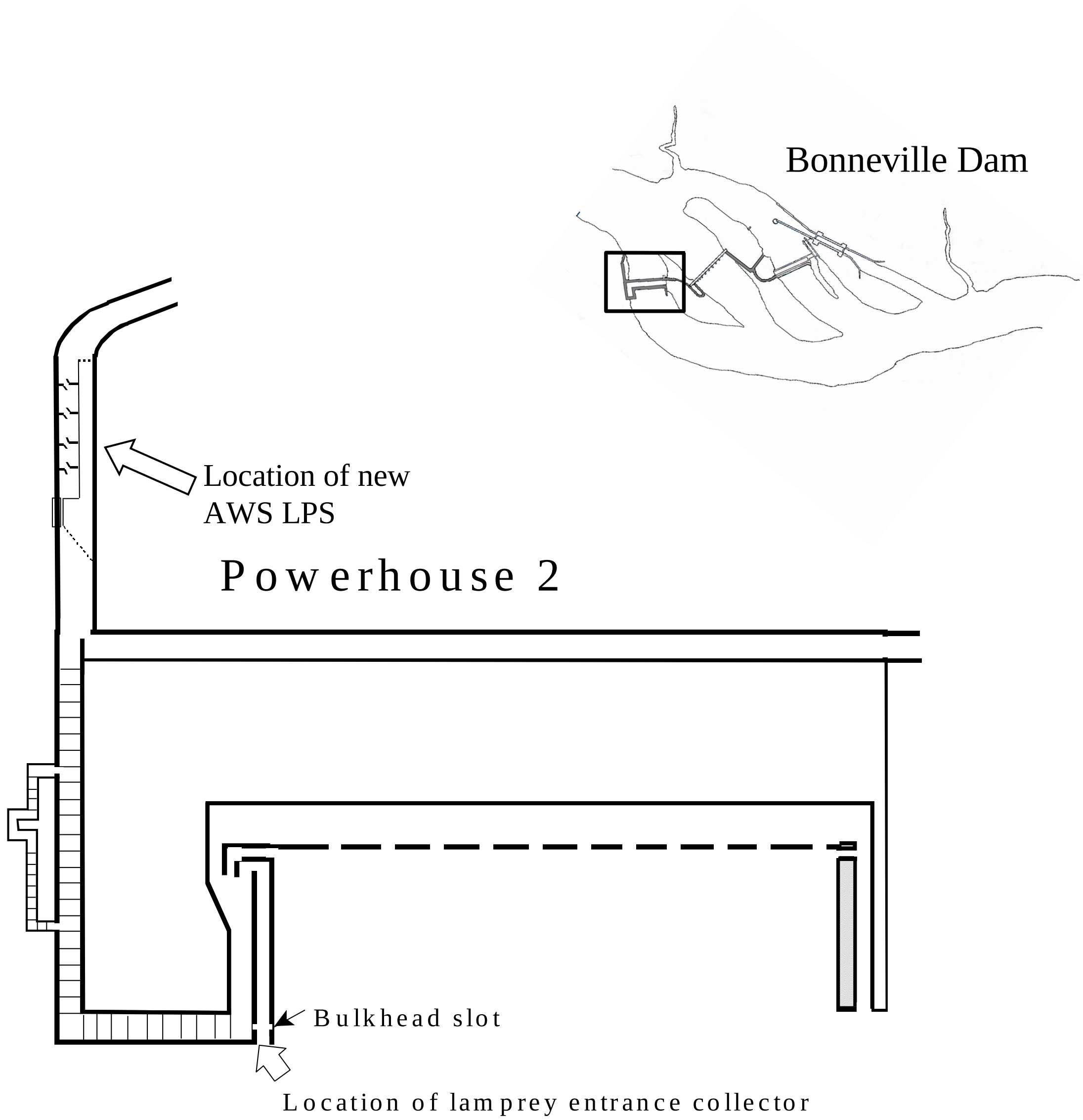

Figure 3. Plan view showing locations of the new AWS LPS and existing entrance collector at the Washington Shore fishway.

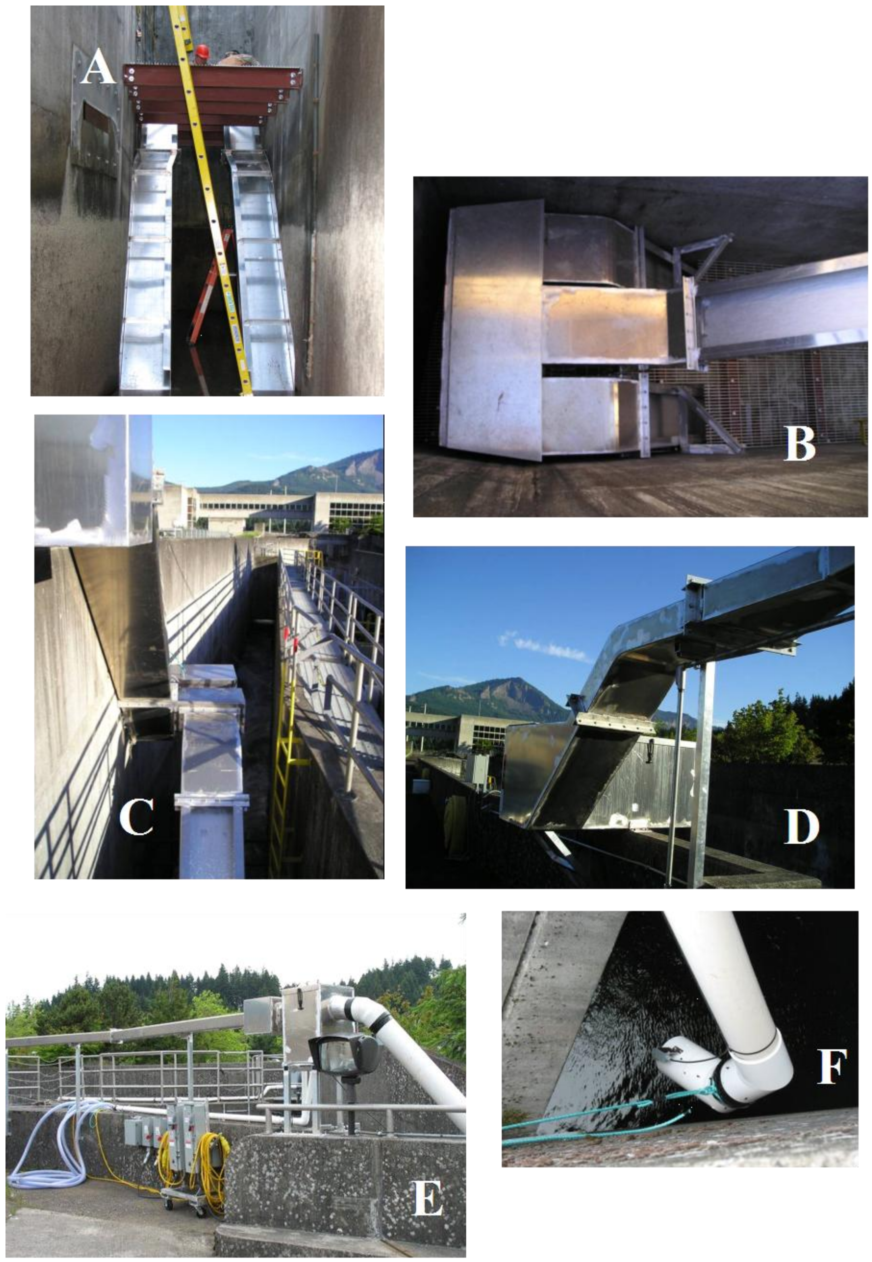

Figure 4. Photos of the Washington Shore AWS LPS showing dual collector ramps (A) leading up to large rest box (B), to a second rest box and PIT detector (C), to a third rest box (D), to the exit PIT detector and upwelling box (E) and exit slide/counter (F).

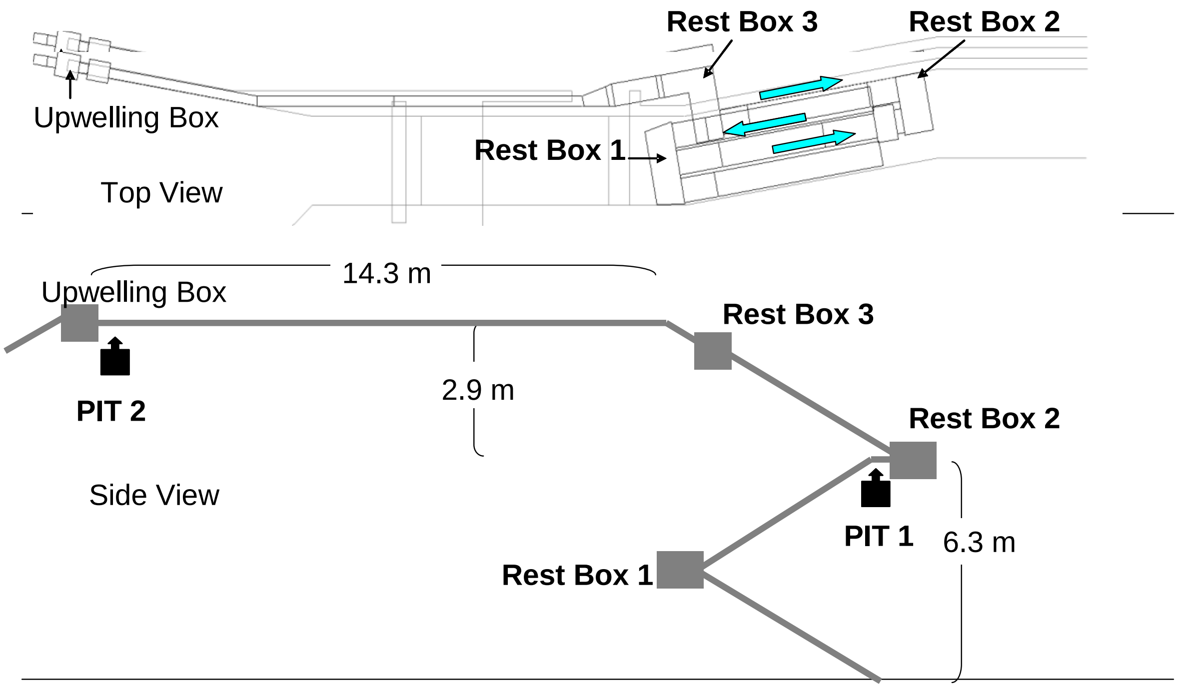

Figure 5 Schematic of the Washington Shore AWS LPS.

Washington Shore Entrance Collector

The Washington Shore entrance collector was located at the downstream north main entrance of the fishway (Figure 3). This location was chosen because radiotelemetry studies have indicated that lamprey entrance efficiency at this location is consistently lower than at all other main entrances (Moser et al. 2005; Johnson et al. 2009b). As in 2006, a crane was used to position and secure the collector at the top of the transition structure (Figure 6, Moser et al. 2009). On 13 May 2007, current velocity at the fishway entrance was reduced so that the collector assembly could be lowered into position and bracketed to the wall (see Moser et al. 2009 for installation details and structure schematics). The structure was fully operational on 31 May 2007. A similar method was used to install the structure in 2008, but it was not watered up in that year until 24 June due to high spring tailwater elevations.

The entrance collector ramp construction was generally the same as in 2006 (Figure 6). It consisted of a 51-cm wide, 12.6-m long aluminum ramp that lamprey entered at the top of the transition structure. In 2006, the ramp was covered with a solid sheet of aluminum to produce a closed ramp. In 2007-2008 we removed this aluminum cover so that lamprey could access the collector ramp from anywhere in the water column. After climbing up the 45° ramp, lamprey entered a 15.2- × 20.3-cm closed chute that passed through a PIT antenna (same construction as in the AWS LPS) and emptied into a 0.6- × 0.6- × 0.9-m trap box (Figure 6). The trap box was accessed daily by a caged ladder and could be hoisted to retrieve lampreys using an electric winch and boom. Lamprey in the trap were enumerated, measured, tagged, and released.

In 2007 we tested the effect of lowering nighttime velocity at the Washington Shore entrance collector site. In 2007, this was accomplished by halving the Washington Shore fishway velocity in the period from approximately 2200 to 0400 on alternating nights. Nights when velocity was reduced (target of 4 ft s^{-1}; 0.5 ft of head) and at normal levels (approximately 8 ft s^{-1}; 1.0 ft of head) were paired, starting on 1 June and continuing through 1 October. Head differential was achieved by operating two small turbine units that normally function to add water to the fishway collection channel.

In 2008, the velocity tests were not systematically conducted at the Washington Shore fishway. However, during the lamprey migration there were many nights when the downstream Washington Shore fishway entrance velocity was reduced to near-zero for several hours during debris removal operations (similar ‘standby’ operations also occurred in 2007). We examined lamprey use of the entrance collector on these nights relative to nights when velocity was at normal levels (i.e., approximately 8 ft s^{-1}; 1.0 ft of head).

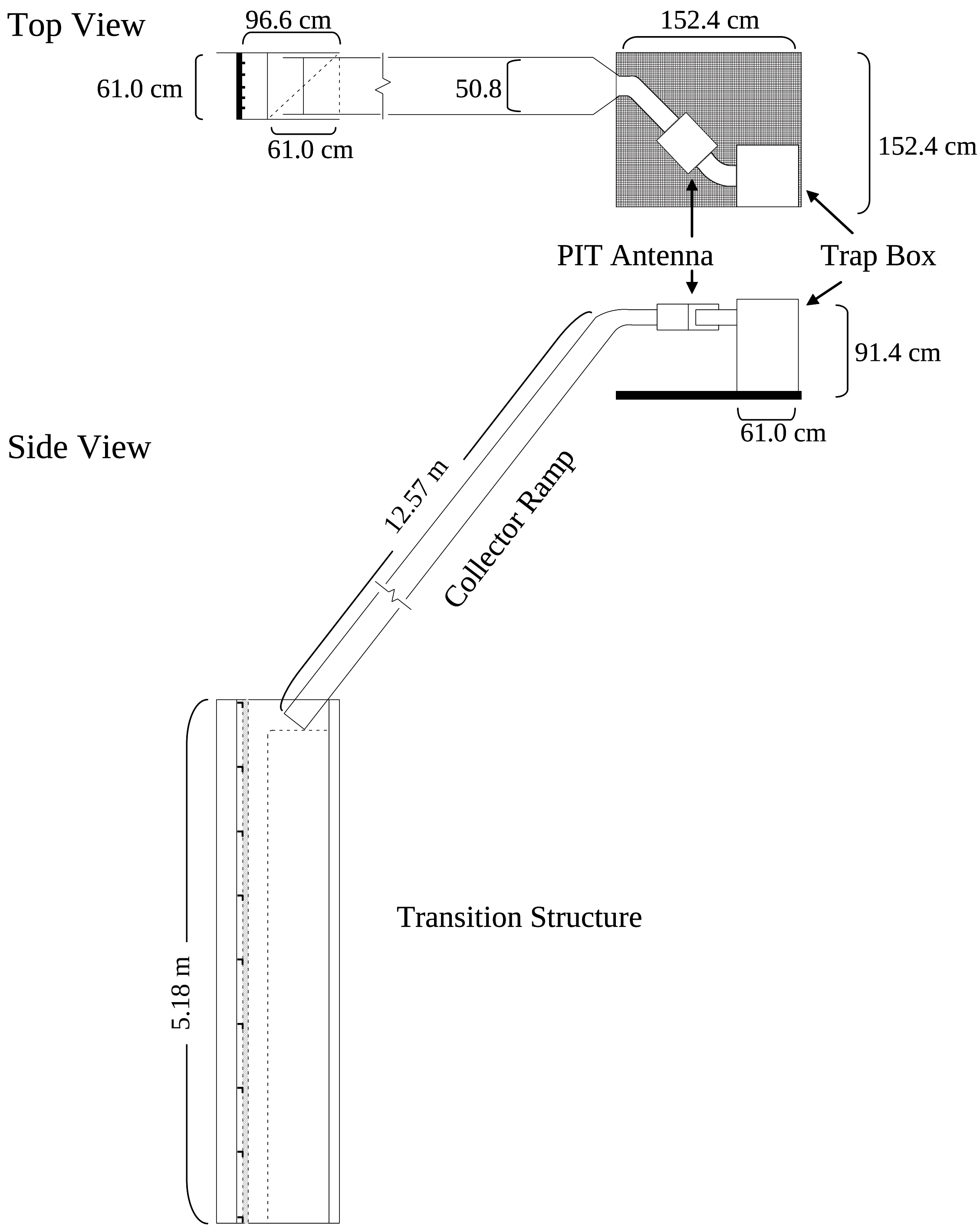

Figure 6. Schematic drawing illustrating dimensions of the entrance collector installed at the Washington Shore downstream north entrance.

In both years, the number of lamprey using the LPS entrance collector varied with lamprey run timing. To account for these changes in lamprey abundance, we reported the number of lamprey collected in the LPS entrance collector trap box as a percentage of the total number of lamprey collected at Bonneville Dam from both Adult Fish Facility (AFF) and entrance collector (LPS) traps. The resulting LPS percentages for each night of LPS operation were arcsine transformed for statistical analyses (Zar 1999). Effects of river discharge (measured at the Bonneville Dam forebay) and fishway entrance velocity manipulations on the arcsine-transformed percentage of lamprey using the LPS entrance collector were examined using analysis of covariance (general linear models procedure, SAS 2000).

Cascades Island Fishway

To assess lamprey use of the upper Cascades Island fishway in 2007-2008, we operated a PIT detector positioned immediately upstream from the picket lead located at the downstream end of the flow-control section of this fishway (Figure 7). This antenna was a 10 G multistrand wire loop positioned inside a 12.8 × 0.9-m rectangular PVC frame. The frame spanned the fishway channel entering the obsolete count station section and was clamped to the existing walkway hand rail to support it in a position approximately 15 cm from the bottom. The read range of this antenna was very limited (5 cm), so only lamprey that were traveling very close to the bottom or sides of the channel could be detected.

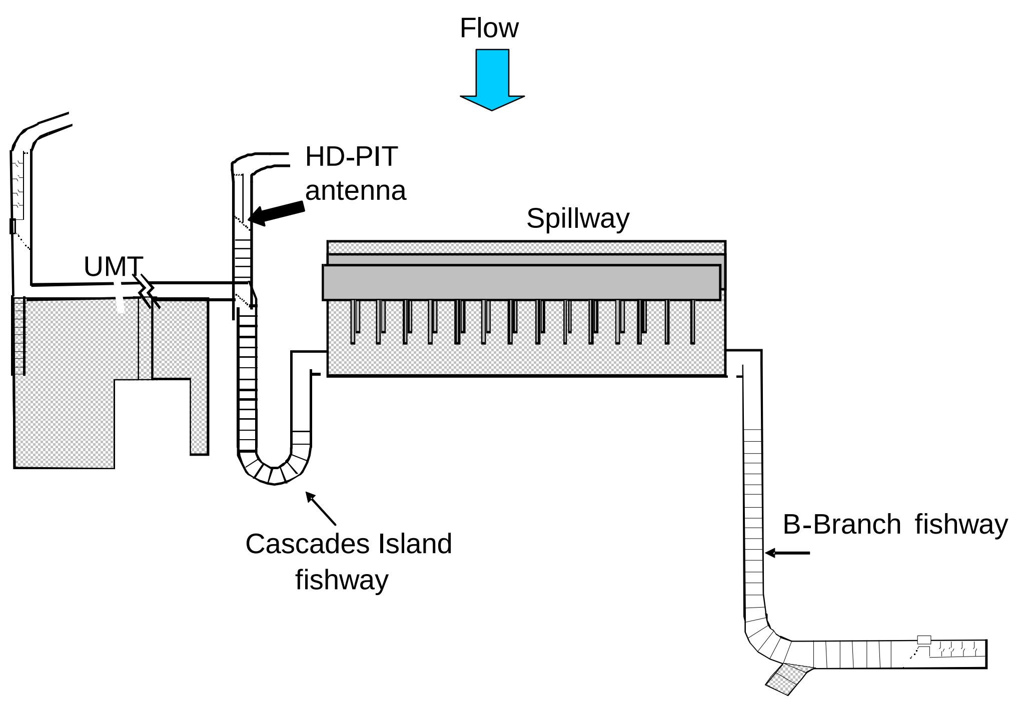

Figure 7. Location of the HD-PIT antenna (block arrow) at the picket lead near the top of the obsolete Cascades Island fishway.

Lamprey Collection and Tagging

We collected lamprey for PIT-tagging with traps set at the Washington Shore fishway. Lamprey were collected from the Washington Shore entrance collector (described above) and from two traps at weirs of the Bonneville Dam AFF fishway. In 2008 we also experimented with a portable trap at the AFF (Figure 8). Traps were deployed each night from approximately 2100 to 0700 PST. Each morning the trapped lamprey were tranferred to a holding tank with running Columbia River water.

After anaesthetizing the lamprey using 60-ppm eugenol, we measured weight (nearest g), total length (nearest 0.5 cm), and girth at the insertion of the anterior dorsal fin (nearest mm) of each fish. We then made a 4 mm incision just off the ventral midline at a location even with the insertion of the anterior dorsal fin. A sterilized half-duplex PIT tag (3 × 32 mm) was inserted into the body cavity. The fish were allowed to recover for at least one hour prior to release approximately 3 km downstream from Bonneville Dam at the Hamilton Island boat ramp.

Figure 8. Portable lamprey trap deployed at Bonneville Dam AFF in 2008.

In 2008, additional lamprey received a smaller (3 × 23 mm) PIT tag and a surgically implanted radio transmitter (see Johnson et al. 2009b for details of radio-tagging technique). For these fish, a larger incision was made, and the PIT tag was inserted first. A catheter was then passed through the body wall approximately 5 cm posterior to the incision, and the radio antenna was threaded through the catheter. The catheter was then pulled through the body wall, and the radio tag was inserted so that it rested anterior to the PIT tag. The incision was closed with simple, interupted sutures, and fish were allowed to recover for at least 1 h prior to release. Release locations for these fish were approximately 3 km downstream from Bonneville Dam at either the Hamilton Island boat ramp or across the river at Tanner Creek (Johnson et al. 2009b).

The number of tagged fish detected in either the Washington-shore entrance collector or at any of the AWS LPS PIT antennas was compared to detections made at PIT antennas operated at the Cascades Island fishway (described above), at other locations at Bonneville Dam, and at other lower Columbia and Snake River dams (see Keefer et al. 2009). In addition to determining passage routes in this way, we were able to compute the time from release to first detection at each structure and the length of time lamprey required to pass between antennas in each LPS.

RESULTS

Lamprey Counts and Trapping

Counts at the Bradford Island AWS LPS were made from 8 May to 22 October in 2007 and from 13 May to 28 October 2008 (Figures 9 and 10). The Washington Shore AWS LPS was installed and watered up by 18 June 2007. However, the counter at the terminus of this AWS was not operational until 25 June. Counts at this structure were made from 25 June to 22 October in 2007 and from 13 May to 28 October in 2008.

In both years there were occassional gaps in the LPS count records due to counter failures (due to power outages). For computation of total numbers of lamprey counted at both the count windows and LPS exit slides, we excluded several days when the LPS counter was not working through the night (Figures 9 and 10). A total of 9,904 lamprey were counted as they exited the LPSs in 2007 and 8,426 lamprey were counted in 2008 (Figures 9 and 10). This represents 71% of the total visual day count in 2007 and 79% of the visual day count in 2008.

In 2007, we operated lamprey traps in the AFF fishway and at the top of the LPS entrance collector at the Washington Shore fishway from 23 May to 6 September. During this time, 1,129 lamprey were captured: 462 (41%) in the LPS collector trap (located outside the Washington Shore fishway entrance), and the remainder (667) in the two AFF traps (located inside the Washington Shore fishway). Mean length of lamprey from the LPS collector trap was significantly greater than that of fish from the AFF traps (65 and 63 cm, respectively; $t = 4.37$, $P < 0.01$) as was mean weight (456 and 418 g, respectively; $t = 5.04$, $P < 0.01$;)

In 2008, the AFF weir and portable traps were operated from 22 May to 5 September, and 889 lamprey were collected; all but 50 of these (94%) were in the weir traps. The LPS collector at the Washington Shore entrance was not operational until 24 June, when Bonneville Dam tailwater levels receded enough to permit safe operation of the trap box. Nevertheless, lamprey collected at the LPS collector trap (n = 490) made up 36% of the total lamprey catch in 2008. As in 2007, mean weight of lamprey from the LPS collector trap was signficiantly greater than that of lamprey from the AFF traps (454 and 441 g, respectively; $t = 2.68$, $P < 0.01$). However, mean length of both groups was 65 cm, and not significantly different ($t = 1.47$, $P > 0.05$).

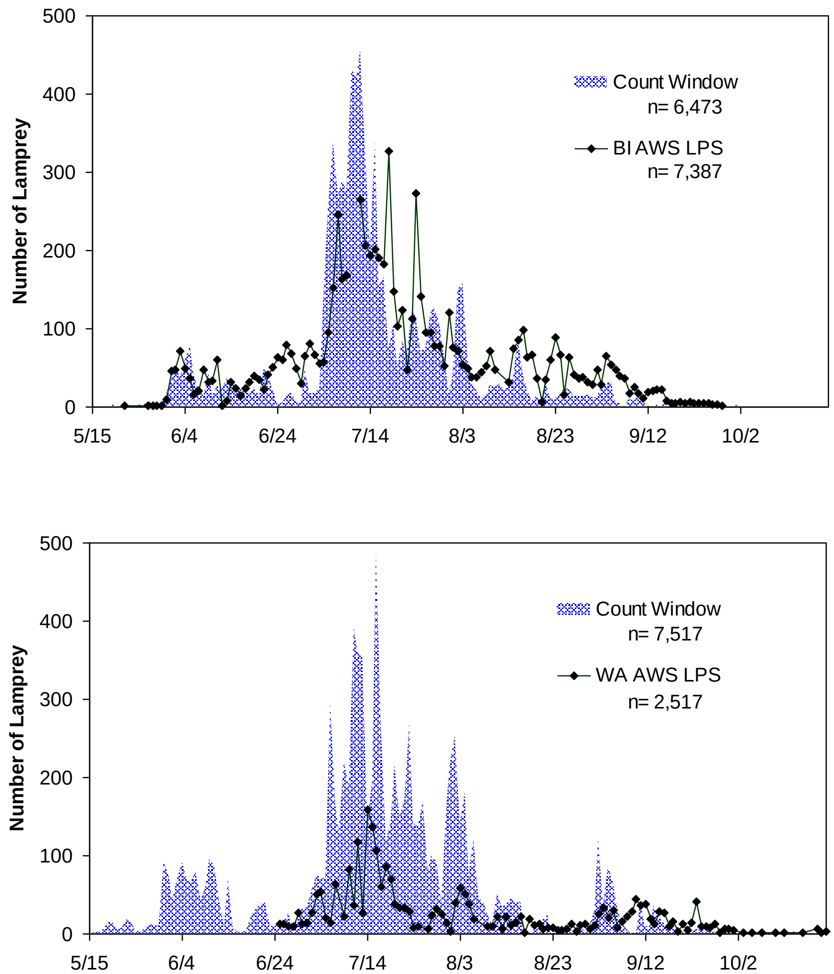

Figure 9. The number of lamprey counted at the count stations (shaded areas) and the number counted at the AWS LPS exit slides (closed diamonds) during the periods of LPS counter operation in 2007 at Bradford Island (BI, top panel) and Washington Shore (WA, bottom panel).

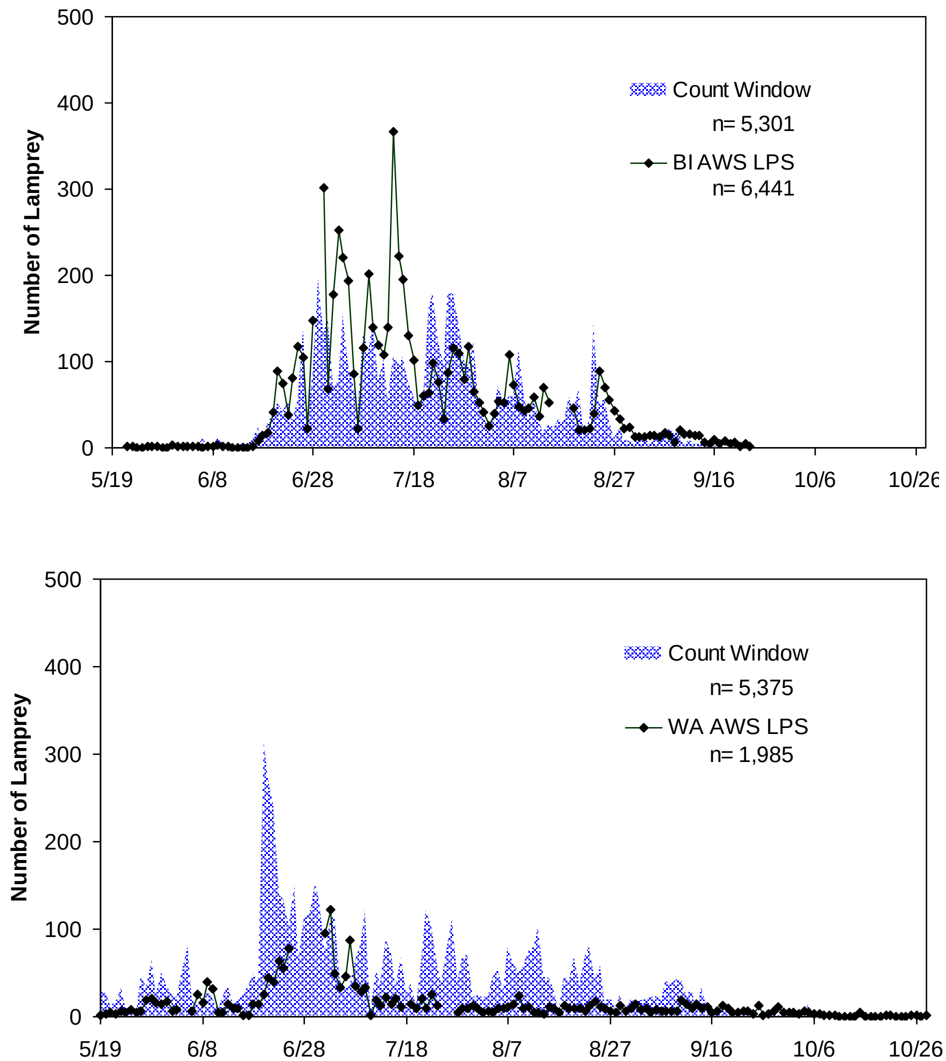

Figure 10. The number of lamprey counted at the count stations (shaded areas) and the number counted at the AWS LPS exit slides (closed diamonds) during the periods of LPS counter operation in 2008 at Bradford Island (BI, top panel) and Washington Shore (WA, bottom panel).

We computed the percentage of lamprey caught in the LPS collector trap relative to those captured in traps set inside the fishway. In 2007, river discharge had a signficant effect on lamprey use of the LPS collector, with more lamprey collected in the LPS trap on nights when discharge was relatively high ($F = 8.46$, $P < 0.05$; Figure 11). The same effect of river discharge on lamprey use of the LPS collector was even more signficiant in 2008 ($F = 27.73$, $P < 0.01$, Figure 12). Interstingly, lowering the flow emanating from the fishway entrance during the night had no effect on lamprey use of the LPS collector in 2007 ($F = 3.16$, $P > 0.05$, Figure 13) or 2008 ($F = 0.10$, $P > 0.05$).

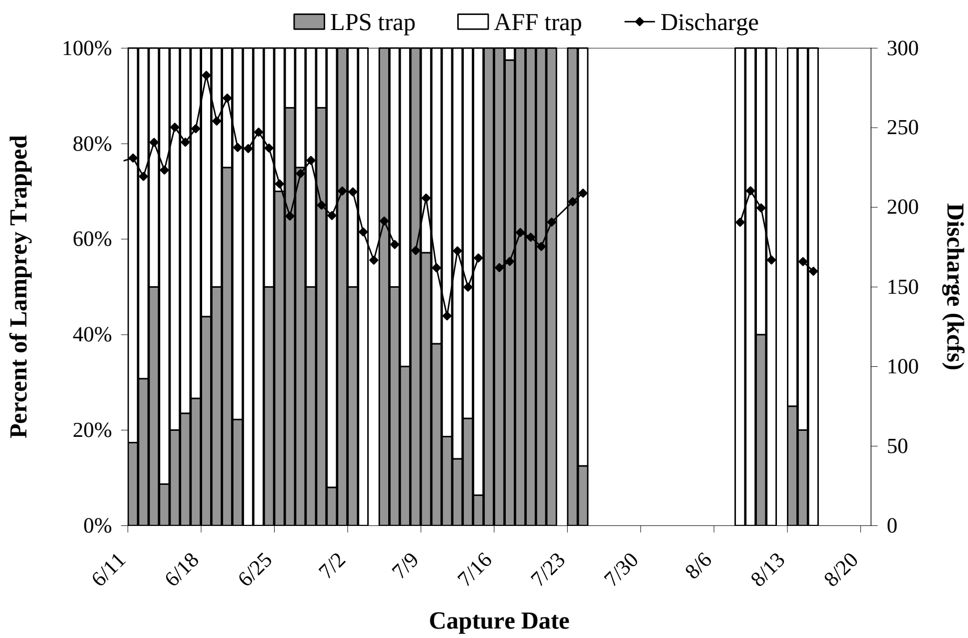

Figure 11. The percentage of lamprey trapped in the Washington Shore fishway as a function of trap location (open bars = Adult Fish Facility, shaded bars = entrance LPS) and river discharge (diamonds) in 2007.

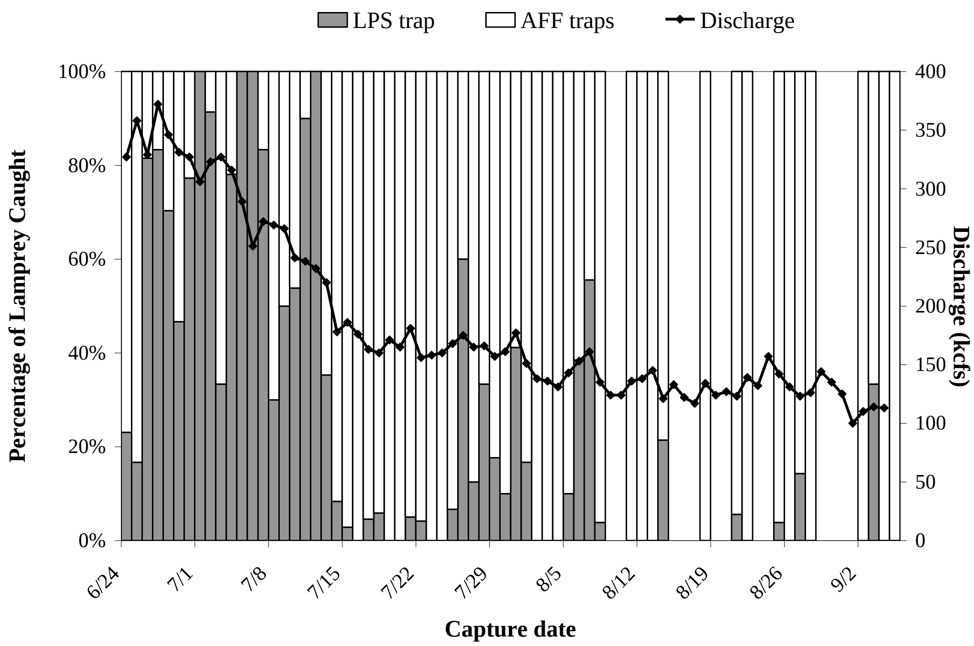

Figure 12. The percentage of lamprey trapped in the Washington Shore fishway as a function of trap location (open bars = Adult Fish Facility, shaded bars = entrance LPS) and river discharge (diamonds) in 2008.

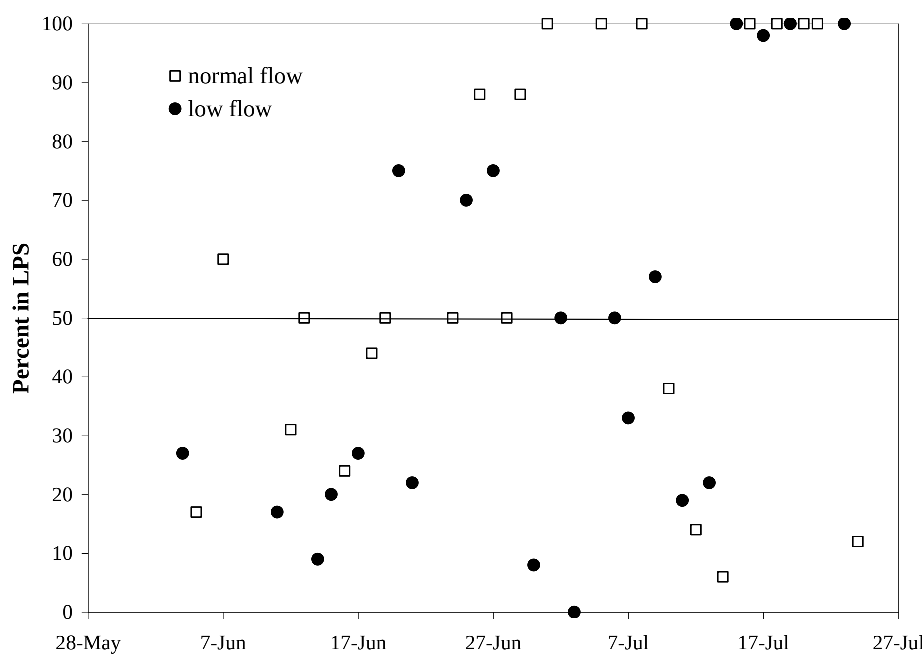

Figure 13. The percentage of lamprey caught in the LPS collector trap on nights with normal fishway entrance flow (open squares) and reduced flow (solid circles) in 2007.

Tagged Lamprey

Lamprey we tagged were primarily collected from the AFF traps (71% in 2007 and 60% in 2008); the remaining fish in each year were collected from the LPS collector trap. We tagged 757 lamprey with half-duplex PIT tags from 24 May to 20 August 2007. To avoid potential lamprey mortality due to handling stess, we did not trap fish between 24 July and 7 August 2007 when water temperature exceeded 21°C (Ocker et al. 2001). In 2008, we tagged 610 lamprey from 18 June to 5 September. In addition, 298 lamprey were tagged with both a radio transmitter and 23-mm PIT tag (Johnson et al. 2009a). In both years the mean size of PIT-tagged fish was 65 cm and mean girth at the insertion of the first dorsal fin was 11 cm.

The fish bearing a PIT-tag only were released 3 km downstream from Bonneville Dam along the Washington shoreline. Of fish that were double-tagged in 2008 (PIT and radio transmitter), 149 were released 3 km downstream from Bonneville Dam along the Oregon shore, and the remainder were released along the Washington shore.

Axiliary Water Supply Lamprey Passage Structures

Bradford Island—Of the 757 PIT-tagged fish released downstream from Bonneville Dam in 2007, 31 (4%) were detected at the Bradford Island AWS LPS. In addition, 3 PIT-tagged fish that we released downstream from Bonneville Dam in 2006 were detected in the AWS LPS in 2007. The three overwintering fish passed through the Bradford Island LPS on 20 June, 13 July, and 18 July 2007. In 2008, 51 of the 610 PIT-tagged fish were detected in the LPS (8%) and 14 of the 298 double-tagged fish were detected (5%). In addition, 3 fish that were tagged in 2007 were detected in the LPS in 2008: two on July 1 and one on July 17. All three of these overwintered fish passed through the LPS successfully.

The time that lamprey took to find the Bradford Island LPS after release downstream from Bonneville Dam was extremely variable. In 2007, the median number of days from release to first detection in the LPS was 6.4 (Table 1), but the range was 1-73 d. Similarly, in 2008 the lamprey took a median of 5.5 d to find the LPS (range 1-47 d). More lamprey were detected at the top of the west collector ramp than the east ramp in each year: 71% in 2007 and 61% in 2008. The lamprey took fewer days to find the west ramp in 2007 (median 4.7 in 2007) but longer to find it than the east ramp in 2008 (median 7.5 d). In 2007, one fish initially entered the west ramp, then fell back downstream and re-ascended the east ramp, passing successfully.

In 2007, 31 of the 34 fish successfully passed through the LPS and in 2008 all of the lamprey passed through and were detected at the LPS exit. Of the three fish that were not detected at the LPS exit in 2007, two were only detected for a few seconds at the top of the west collector ramp (PIT 2, Figure 2). Both of these fish were detected at the Bradford Island fishway exit (Figure 1) less than 1 h later. It is likely that these fish passed through the LPS and were missed by the detector at the LPS exit. The third fish was detected at PIT 3 (Figure 2), but was not detected thereafter.

In the two study years, lamprey exhibited similar passage times through the LPS. Median time from first detection at the top of each collector ramp to first detection at PIT 2 (Figure 2) was 14.2 min (sd 4.3 min, range 7-23 min) in 2007 and 11.9 min (sd 90.1 min, range 6 min–12.6 h) in 2008. In both years median time lamprey took to travel from the top of the collector ramp to the LPS exit (PIT 4, Figure 2) was < 50 min (Table 1). In 2008, fish with only a PIT tag passed the LPS in a median of 43 min and those with a PIT tag and radio transmitter took a median of 59 min. However, this difference was not statistically significant (t = 1.06, P > 0.05).

Table 1. Comparison of lamprey passage times (d), rates (m/h), and efficiencies for the Bradford Island AWS LPS and the Washington Shore AWS LPS. Standard deviation is given in parenthesis.

	2007		2008	
	Bradford Island	WA Shore	Bradford Island	WA Shore
Median days to first LPS detection	6.4 (15.8)	14.4 (21.5)	5.5 (12.0)	9.5 (17.3)
Median minutes in LPS	42.8 (13.3)	28.1 (209.9)	45.3 (91.4)	25.2 (34.0)
Median rate ($m\ h^{-1}$)	54.1	52.5	47.5	65.2
Passage efficiency (%)	91.2	100	100	100

PIT-tagged fish were detected using the Bradford Island fishway exit, in addition to or instead of the LPS (Figure 1). In 2007, 92 (12%) of the PIT-tagged fish were detected at the fishway exit and were not detected using the LPS. Of the fish that used the LPS in 2007, 10 (30%) were subsequently detected at the fishway exit. The time from last detction at the LPS exit to first detection at the fishway exit ranged from 1 min to 2.6 d (median 13 min). In 2008, 87 (14%) of the PIT-tagged fish were detected at the fishway exit and were not detected using the LPS. Of the 51 lamprey that used the LPS, 5 (10%) were subsequently detected at the Bradford Island fishway exit from 4 to 48 min later (median 11 min).

In each year, some lamprey that exited the LPS or Bradford Island fishway exit were later detected at upstream PIT-tag monitoring sites. In 2007, 15 (48%) of the fish that used the LPS were detected at upstream sites, and in 2008, 27 (54%) were detected at upstream sites. In contrast, of the fish detected exiting the Bradford Island fishway without using the LPS, 77% were detected at upstream sites in 2007 and 63% in 2008.

Washington Shore—Of the 757 PIT-tagged fish released downstream from Bonneville Dam in 2007, 24 (3%) were detected at the Washington Shore AWS LPS and all of them passed to the exit. In addition, 2 PIT-tagged fish that we released downstream from Bonneville Dam in 2006 were detected in this LPS in 2007. These overwintering fish successfully passed through the LPS on 9 and 23 July 2007.

In 2008, 16 (3%) of the 610 PIT-tagged fish were detected in the LPS and all of them passed through the LPS to the exit. None of the fish with both PIT and radio tags were detected. In addition, 2 fish that were tagged in 2007 were detected in 2008: one on July 1 and one on July 17. Both of these overwintered fish passed through the LPS successfully.

The time that lamprey took to reach the Washington Shore LPS after release downstream from the dam was extremely variable. In 2007, the fish took a median of 14 d to find the LPS after release (Table 1). However, the range was 2-96 d. Similarly, in 2008 median time from release to the first LPS detection was 9.5 d (range 2–56 d). In both years, passage time from release to first LPS detection was longer at the Washington Shore AWS LPS than at the Bradford Island AWS LPS (Table 1).

In the two study years, lamprey exhibited similar passage times through the Washington Shore LPS. In 2007, median time from first detection at the first LPS PIT antenna (PIT 1, Figure 6) to the last detection near the LPS exit (PIT 2, Figure 6) was 28 min (range 16.1 min–16.5 h). Only one fish took longer than 1 h to pass the LPS, and this individual arrived at PIT 1 at 0719 and presumably stayed in Rest Box 2 or 3 (Figure 6) through the daylight hours, resuming migration at 2347 that night. Passage of one fish was missed at PIT 1 but detected at PIT 2. Similarly, one fish was missed at PIT 2 but was detected at the fishway exit 1 h after passing PIT 1.

In 2008, PIT-tagged lamprey took 25.2 min (range 19.0 min–2.6 h) to pass the LPS between PIT 1 and PIT 2 (Figure 6). One of the fish was detected at PIT 2 and then at PIT 1 4.7 h later. It ascended to PIT 2 a second time and apparently exited the LPS successfully. This fish was not detected elsewhere in the Washington Shore fishway, so it is impossible to know whether it exited the LPS on the first attempt, or whether it fell back within the structure. This fish was originally tagged in 2007. Two fish were detected at PIT 1 but were missed at PIT 2 and detected at the fishway exit < 1.5 h later.

PIT-tagged fish that had not used the LPS were also detected at the Washington Shore fishway exit (Figure 1). In 2007, 198 (26%) of the PIT-tagged fish were detected at the fishway exit and were not detected in the LPS. The Washington Shore LPS exits into the Washington Shore fishway downstream from the fishway exit. Of the 24 fish that used the LPS in 2007, 21 (88%) were detected as they migrated upstream and exited at the fishway exit. Time from last detction at the LPS exit to first detection at the fishway exit ranged from 4 min to 11 h (median 29.4 min). Of the 3 fish that were not detected at the fishway exit after using the LPS, 2 were subsequently detected upstream at other dams. Therefore, it is likely that they were missed by the Washington Shore fishway exit antenna.

In 2008, 120 (20%) of the PIT-tagged fish were detected at the Washington Shore fishway exit and were not detected using the LPS. Fourteen (93%) of the 15 lamprey that used the LPS were subsequently detected at the fishway exit. The time they took to travel from the LPS exit to the fishway exit ranged from 6 min to 2 h (median 31.5 min).

Lamprey detected as they exited the LPS and the Washington Shore fishway exit were often detected at upstream sites monitored for PIT tags. In each year, half of the fish that used the LPS were detected at upstream sites: 12 of 24 in 2007 and 8 of 16 in 2008. Similarly, of fish detected exiting the fishway without using the LPS, 65% in 2007 and 52% in 2008 were detected at upstream sites.

Washington Shore Entrance Collector

Of fish tagged in 2007, 12 with PIT tags (2%) and 2 with radio transmitters (5%) used the Washington Shore entrance collector. In addition, one fish PIT-tagged in 2006 was also detected. All fish with PIT-tags passed the antenna during the night (between 2300 and 0600). Eight fish entered the collector during nights when velocity at the Washington Shore entrance was reduced, and four of these entered on a single night (15 July). The others entered during normal entrance operations. Median time from release downstream from Bonneville Dam to first detection in the collector was 1.7 d (range 13 h–27 d, sd = 10.1 d). All fish recaptured at the trap box were released downstream from Bonneville Dam. One of these releases was detected at the Washington Shore LPS 21 d after the second release date.

Of fish tagged in 2008, 17 with only a PIT (3%), 3 with PIT and radio tags (1%) and 1 with only a radio tag (0.3%) used the Washington Shore entrance collector. In additon, one fish PIT-tagged in 2007 was detected using the entrance collector. One of the PIT-tagged fish apparently fell back downstream after initial detection at the antenna, as it was not found in the trap box. All fish with PIT-tags were detected at the antenna during the night (between 2200 and 0500). Moreover, all but one of these fish entered the Washington entrance collector during normal entrance velocities (i.e., only one fish made an entry during standby operations for debris removal). The median time from release downstream from Bonneville Dam to first detection in the collector was 1.5 d (range 8 h–39 d, sd = 8.8 d). All fish recaptured at the trap box were released downstream from Bonneville Dam. Two of these were detected at the Washington Shore LPS 5 and 6 d after the second release date.

Cascades Island

Of fish PIT-tagged in 2007, 8% (n = 64) were detected at the Cascades Island flow control area. We detected one additional fish in 2007 that was tagged in 2006. In 2008, we detected 59 fish at the Cascades Island antenna: 51 tagged with only a PIT tag and 8 tagged with both a PIT and a radio transmitter. Thus, 8% (51/610) of the PIT-only fish and 3% (8/298) of the double-tagged fish were detected at this site. No fish tagged in 2007 were detected at the Cascades Island antenna in 2008.

Fish detected at the Cascades Island PIT antenna in 2007 took about the same median length of time to get to that point after release (10.9 d, standard deviation = 15.3 d, range 1- 95 d) as lamprey first detected at the Washington Shore LPS. The time lamprey spent in the vicinity of this antenna ranged from a few seconds to 38 d (median 1 d). Results were similar in 2008. The median time to first detection at the top of the Cascades Island fishway after release was 8.6 d (sd = 12 d , range 2–49 d), and fish spent up to 19 d in the vicinity of this detector (median 1.9 d).

Of the 64 lamprey detected at the Cascades Island flow control area in 2007, 23 (36%) were subsequently detected at upriver dams. Five fish were detected at the Washington Shore AWS LPS after leaving the Cascades Island detector. In addition, two fish were captured at the Washington Shore entrance collector and released downstream before they were detected at the Cascades Island detector. One fish exited the Bradford Island AWS LPS before detection a week later at the Cascades Island fishway detector. Of the 59 lamprey detected at the Cascades Island flow control area in 2008, 19 (32%) were subsequently detected at upriver dams. Two fish were detected at the Washington Shore AWS LPS after leaving the Cascades Island detector.

DISCUSSION

The LPS exit counts and half-duplex PIT detection allowed interannual comparisons and testing of LPS structures and operations. These methods provided both highly accurate absolute counts (based on exit counter validation) and computation of passage time and efficiency for various design elements (based on PIT results). Moreover, collateral benefits accrued from coordination with basin-wide PIT detection (e.g., Keefer et al. 2009) and tag recovery from upstream fisheries (J. Graham, Confederated Tribes of Warm Springs Reservation of Oregon, unpublished data). For example, these programs provided data to indicate that many lamprey proceeded upstream and even ultimately arrived in spawning tributaries after using the LPSs.

Adult lamprey readily used both passage structures located in the AWS channels at Bonneville Dam. This success was undoubtedly a function of structure design and operation, as well as site selection. Radiotelemetry indicated that lamprey are attracted to and accumulate in the AWS channels (Moser et al. 2002b; Johnson et al. 2009b). Moreover, laboratory testing indicated that adult lamprey are able to find and use an LPS collector most readily when there is no upstream alternative (Keefer et al. in review). Therefore, the AWS channels are an ideal area to collect lamprey without effects on other fish species.

Lamprey use of the Bradford Island AWS LPS increased in relation to the estimated abundance at the top of the fishway in every year of LPS operation (Table 2). However, the absolute numbers of lamprey counted at the LPS exit in 2007-2008 were lower than those in 2004-2006 due to the two- to threefold reduction in total lamprey abundance in later years. In consequence, total LPS counts substantially exceeded the day counts at the Bradford Island count window in 2007 and 2008 (Figures 9 and 10).

We used the daytime visual counts to estimate the number of lamprey at the top of the Bradford Island fishway. These counts were expanded by 200% to account for the fact that most lamprey are active at night (Moser and Close 2002). The resulting abundance estimates were 19,420 lamprey in 2007 and 15,903 lamprey in 2008. Thus, collection efficiency for the Bradford Island AWS LPS was higher in 2007 (38%) and 2008 (40%) than in any previous year (Table 2).

Table 2. Lamprey abundance estimates from visual daytime counts, the LPS counts, and collection efficiency (% of abundance estimate that used the LPS) at each structure in 2004–2008.

	Bradford Island		Washington Shore	
	Abundance	LPS count	Abundance	LPS count
2004	35,913	7,490 (21%)		
2005	30,771	9,242 (30%)		
2006	44,586	14,975 (34%)		
2007	19,420	7,387 (38%)	22,551	2,517 (11%)
2008	15,903	6,441 (40%)	16,125	1,985 (12%)

Why does collection efficiency apparently continue to improve? One possibility is that the increases in collection efficiency were an artifact of enumeration at the count station. Our abundance estimates at the top of the Bradford Island fishway were obtained by multiplying the Bradford Island count (at the count window) by a factor of three, to account for the fact that the window counts are only made during the day, when only about one third of the lamprey are active (Moser and Close 2002). A change in the proportion of lamprey passing the count window during the day would affect our abundance estimate and the resulting estimate of collection efficiency.

In 2007 and 2008, video counts were made of lamprey passing Bonneville Dam count stations at night (Clabough et al. 2009). These observations indicated that the proportion of lamprey passing the count window at night varies seasonally, among years, and also differs between count windows. In May–August 2007, Clabough et al. (2009) determined that 46% of the lamprey at the Bradford Island count window passed during the day. The resulting estimate of total lamprey abundance at the top of this ladder was 26,855. The 7,387 lamprey that used the LPS represented 27% of this estimate. In contrast, night counts made in May–September 2008 at Bradford Island (6,452) were actually less than the day count (6,789). Thus, lamprey counted at the LPS exit in 2008 represented 49% of the total visual count in 2008. Clearly, using visual counts to estimate lamprey abundance is problematic (Clabough et al. 2009).

A second possible reason for the increase in collection efficiency is that the number of lamprey with access to the LPS could have changed over time. Lamprey must enter the AWS channel to use the LPS and the factors that determine AWS entry are poorly understood. Radiotelemetry data indicated that 29 and 32% of the radio-tagged lamprey at the top of the Bradford Island fishway entered the AWS channel in 2007 and 2008 (Johnson et al. 2009a, 2009b). If this percentage is higher than in previous years, it may account for the observed increase in LPS collection efficiency. To obtain more accurate estimates of LPS collection efficiency, a better understanding of lamprey behavior at the top of the fishway is needed.

Finally, it is possible that collection efficiency in 2007 and 2008 was higher than in 2006 because new construction in 2006 made the metal surfaces relatively unattractive to lamprey in that year. In 2006, dual collector ramps were installed, changes were made to rest boxes, and the steep ramp was modified (Moser et al. 2009). We have observed that lamprey do not use new metal structures as readily in the first year following installation (Moser et al. 2009). Eventual "seasoning" of the metal surfaces and algal growth seems to make the installations more acceptable to lamprey, which have an extremely sensitive olfactory system (Robinson et al. 2009).

The new LPS installed at the Washington Shore AWS had lower estimated collection efficiency than the Bradford Island AWS LPS (Table 2) in 2007. This could have been attributed to the fact that the new installation had not had time to season. However, collection efficiency in 2008 was only slightly better (12%). Radiotelemetry data from 2007-2008 indicated that only 6% of lamprey at the top of the Washington Shore fishway entered the AWS channel (Johnson et al. 2009b). This could be the reason for the large difference in collection efficiency we noted between the LPS collectors at Bradford Island and the Washington Shore (Table 2).

Configurations of the AWS channel entrance and picketed leads at the two fishways are different and may contribute to lower lamprey use of the Washington Shore AWS channel than the one at Bradford Island (Figure 14). The Bradford Island picketed lead is positioned at a more acute angle to the fishway, and the picket spacing is wider (generally 2.5 cm) than at the Washington Shore (mostly < 2.0 cm). The Washington Shore fishway also features a concrete step immediately downstream from the AWS entrance (Figure 15). All of these differences could contribute to relatively low use by lamprey of the Washington Shore AWS and the LPS at its upstream end.

As in 2006, more fish used the west ramp than the east ramp of the Bradford Island AWS LPS in both 2007 and 2008. Preference for the west ramp may be due to the channel configuration downstream from the LPS (Figure 16). If lamprey contact and pass through the picketed lead on the west wall of the channel, they can move along the wall all the way up to the LPS collector. On the east side, the fish would have to negotiate a more circuitous route to find the collector on the east wall. In addition, an obsolete underwater wooden weir in the AWS channel just upstream from the picketed lead may direct fish towards the west side of the channel (Figure 16).

Figure 14. Picketed lead configuration at the dewatered Bradford Island fishway looking downstream (top) and the dewatered Washington Shore fishway looking downstream (bottom).

Figure 15. Picketed lead configuration at the dewatered Washington Shore fishway looking upstream from the upstream migrant tunnel (UMT).

Half-duplex PIT detection allowed interannual comparisons of LPS performance by allowing computation of both passage rates and passage efficiency. In addition, use of PIT-tagged lamprey permitted examination of various passage routes and the relative contribution of each LPS to overall lamprey passage success at Bonneville Dam.

In 2007-2008, median time from release to first detection of PIT-tagged lamprey in the Bradford Island AWS LPS was less than a week, but lamprey took almost twice as long to find the Washington Shore AWS LPS. This probably reflects the greater difficulty lamprey have in passing through the Washington Shore fishway relative to the Bradford Island fishway complex (Moser et al. 2005; Johnson et al. 2009b). Many structural and operational features of the Washington Shore fishway conspire to delay lamprey passage (Keefer et al. 2010).

Figure 16. Dewatered Bradford Island AWS channel (looking downstream) with wooden weir and orifice.

The time PIT-tagged lamprey required to reach an LPS was similar to passage time from release to detection at the top of the fishway exits. In 2006, lamprey took 11.5 d to reach the LPS (Table 3) and 9.6 d to pass the fishway exits (Daigle et al. 2007). In 2007, median passage time from release to the fishway exits was shorter (6.5 d, Keefer et al. 2008). However, the passage time from release to LPS entry was also shorter in that year (Table 3). These results suggest that lamprey entering the AWS channels take a similar amount of time to traverse the lower fishway as those that do not, and that lamprey do not reside in the AWS for extended periods. However, future results from fish tagged with both radio and PIT tags will help to elucidate these patterns.

After lamprey entered the LPSs, their passage through the structures was rapid and efficient. As in 2006, the median time that PIT-tagged fish took to pass through the entire structure did not exceed 45 min in either 2007 or 2008. Moreover, in all three years, 97–100% of lamprey that entered the LPS appeared to pass through the structure (in 2007, although 31 of 34 fish were detected at the exit slide, it is likely that 33 of 34 fish actually passed through based on fishway exit detections, Table 3).

Table 3. Results of Bradford Island AWS LPS detections of PIT-tagged lamprey in 2006-2008. Passage efficiency is the percentage of fish detected in the LPS that made it to the LPS exit. Median days from release to first detection in the LPS (sd) and median passage times (sd) through the steep and nearly horizontal sections of the LPS are given in hours.

			Median time to pass (h)	
	Passage efficiency (%)	Median time to first detection (d)	Steep	Horizontal
2006	141/142 (99)	11.5 (13.7)	0.2 (2.9)	0.5 (0.1)
2007	31/34 (91)	6.4 (15.8)	0.2 (0.1)	0.5 (0.1)
2008	50/50 (100)	5.5 (12.0)	0.2 (0.1)	0.5 (0.1)

These results suggest that improvements in configuration of the Bradford Island AWS LPS made in 2006 (detailed in Moser et al. 2009) continue to produce consistently high passage efficiency. By reducing the length of steep ascents, the time lamprey required to pass from the collector ramp to PIT 3 was reduced by a factor of four (Moser et al. 2009). High-speed video recordings of lamprey as they ascended the steep and shallow ramps at the Bradford Island LPS under high and low flow indicated that short, steep (45°) ramps with low flow optimize lamprey climbing (Reinhardt et al. 2008). However, studies of lamprey climbing indicated that lamprey tire quickly and require longer rest and recovery periods after climbing repeatedly (Kemp et al. 2009). Thus, when steep (>45°) ramps are used, we recommend that the length of these ramps be minimized.

Experimental work in the laboratory and our field observations guided development of the Washington Shore LPS. Laboratory experiments indicated that lamprey attachment is most effective on hard, smooth surfaces (like the polished aluminum used in the LPSs, Adams and Reinhardt 2008) and that ramp angle has little effect on lamprey passage success (Keefer et al. in review). Indeed, Pacific lamprey successfully made multiple ascensions of perfectly vertical 2-m high aluminum walls in the laboratory (Kemp et al. 2009).

PIT-tagged lamprey that entered the Washington Shore LPS exhibited rapid passage (25–28 min) and 100% passage efficiency from PIT 1 to the exit slide (Table 1). However, the PIT 1 detector on this LPS was upstream from the first rest box (Figure 5). Therefore, some lamprey that ascended the collector ramp may have fallen back at the rest box or on the steep ramp without being detected. Because PIT 1 in the Washington Shore structure was further upstream than PIT 1 at Bradford Island, the distance lamprey traveled between PIT 1 and the exit slide was shorter than at the Washington Shore LPS. Consequently, even though lamprey passed between detectors faster at the Washington Shore LPS, their passage rate (m h^{-1}) was similar to or slower than those at the Bradford Island LPS (Table 1).

At both Bradford Island and the Washington Shore fishways, some lamprey were detected at PIT antennas at the fishway exits subsequent to exiting the LPSs. At Bradford Island, this indicated that fish fell back downstream after exiting the LPS (30% in 2007 and 10% 2008). In contrast, at Washington Shore, the fishway exit is upstream from the LPS exit, indicating that fish moved upstream and exited the fishway after using the LPS (96 % in 2007 and 93% in 2008).

Fish that fell back downstream and into the fishway after exiting the Bradford Island LPS did so after a median time of 11-13 minutes. It is likely that they were disoriented after falling out of the exit slide and had difficulty orienting to the river environment immediately upon entry into the dam forebay (Moser et al. 2009). Moreover, the Bradford Island fishway exit is only 10 m from the LPS exit (Figure 1), increasing the likelihood that a searching lamprey would find its way back into the ladder exit. We recommend the installation of a volitional release box at this LPS exit (A. Jackson, Confederated Tribes of the Umatilla Indian Reservation, unpublished data). A design of this type retains lamprey after LPS exit and requires that they find their way out of the release box. This may reduce the disoriented searching that results in downstream movement.

Data from PIT-tagged fish indicated that the number of lamprey using lamprey passage structures as a passage route was significant. As in 2006, large numbers of PIT-tagged lamprey were released below Bonneville Dam in 2007 and 2008. Examination of their passage routes indicated that in 2006-2008, 4-8% of PIT-tagged lamprey used the Bradford Island LPS and 3% of PIT-tagged lamprey used the Washington Shore LPS. Thus, the potential improvement in lamprey passage efficiency that could be attributed to operation of both structures ranged from 7-12%.

Similar numbers of lamprey used the Bradford Island fishway exit and the adjacent AWS LPS; but this was not the case at the Washington Shore fishway, where many more lamprey used the traditional exit than the AWS LPS route. More lamprey are attracted to and enter the Washington Shore fishway complex, due to attraction flows generated by operation of Powerhouse 2 (Moser et al. 2005; Johnson et al. 2009b) Consequently, improving collection efficiency at the Washington Shore AWS LPS could result in substantial increases in lamprey passage efficiency. To this end, research should be focused on identifying obstacles to lamprey use of the Washington Shore AWS LPS.

As in 2006, approximately half of the lamprey that passed over Bonneville Dam via an LPS were subsequently detected at upstream dams. This result indicates that use of the LPSs did not prevent fish from proceeding upstream in a normal fashion. However, fish that passed a fishway exit without using the LPS were detected at a higher rate at upstream dams. The reason for this discrepancy is unknown, but could result from fallbacks that occur at the LPS exit. It is also possible that using the LPS is more energetically costly than other routes, resulting in lower overall escapement. Due to low sample sizes used to make these comparisons, it is difficult to determine whether the pattern is real, let alone the causal mechanisms. However, the implications of passage effects for lamprey management are important, and this topic should be addressed to ensure that no negative effects stem from LPS use.

In each year the LPSs provided a passage route for a handful of fish that were PIT-tagged in the previous year. These results mirror those of other studies that indicate that a small percentage of the adult lamprey collected in Bonneville Dam fishways do not pass upstream in the year they are tagged (Keefer et al. 2009). Apparently, these fish overwinter downstream from Bonneville Dam and are capable of successful passage the following summer. Whether they are able to successfully reproduce after missing the peak of spring spawning in tributary streams is unknown.

The second objective of this study was to assess the efficacy of a lamprey collector positioned outside the downstream north entrance to the Washington Shore fishway. Fishways at Bonneville Dam have historically created a bottleneck to adult lamprey passage (Moser et al. 2002a,b, 2005; Johnson et al. 2009b). An efficient collector positioned outside a main entrance could help lamprey to bypass this troublesome area and improve overall dam passage.

The entrance collector we tested was installed in 2005. In 2006 it was operated as a closed-tube collector for the entire lamprey migration season, but only 135 lamprey used the collector (1% of the PIT-tagged population, Moser et al 2009). In 2007 and 2008, the collector was operated as an open ramp, and lamprey use increased (> 400 fish each year and up to 3% of the PIT-tagged population).

An open-ramp collector allows lamprey to enter throughout the water column (Moser et al. in review). The fact that this configuration worked better than a closed tube indicates that lamprey approaching the fishway entrance were moving along the concrete walls or swimming in the water column, in addition to moving along the bottom. Obtaining visual evidence for lamprey orientation as they approach fishway entrances is critical to development of effective LPS collectors. We recommend that future studies employ the use of video or acoustic imagery to document fine-scale lamprey behavior near fishway entrances.

During use of the closed tube in 2006, we noted that the entrance collector was more effective during periods of low river discharge. In contrast, lamprey use of the open ramp collector increased significantly with increased river discharge. This may simply have been a function of tailwater elevation. At higher tailwater, lamprey had more areas to access the submerged open ramp. Moreover, after finding the ramp, lamprey would have to climb a shorter distance out of the water than when tailwater levels were low.

Surprisingly, reducing the Washington Shore fishway water velocity at night had no effect on relative lamprey use of the collector ramp. Experimental reductions of nighttime fishway discharge have generally resulted in higher entrance efficiency, presumably due to lower velocity barriers at entrance bulkheads (Johnson et al. 2009b. Apparently this is a very near-field phenomena (Keefer et al. in review), as there was no obvious effect on lamprey use of the collector ramp, which is positioned approximately 10 m downstream from the entrance bulkheads.

The entrance collector has great potential for improving lamprey passage. Results from laboratory assessment of migrating lamprey indicated that a broad range of variables stimulate lamprey movements (Keefer et al. 2010, in review). Further elucidation of these factors and their combined effects on lamprey movements is needed to improve LPS collector design, particularly in cases where lamprey are not aggregated near an LPS collector and must be attracted to enter from afar.

A final objective of this work was to determine lamprey use of the obsolete fishway exit at the top of the Cascades Island fishway. Visual observations during fishway maintenance indicated that lamprey regularly enter this area and may become trapped (T. Mackey, USACE, personal communication). Moreover, in 2006 detections of PIT-tagged fish at the picketed lead downstream from the Cascades Island count window indicated that 6% of the lamprey released downstream from Bonneville Dam find their way into the top of this fishway.

In both 2007 and 2008, 8% of the PIT-tagged lamprey released downstream from Bonneville Dam entered the top of the Cascades Island fishway. In each year, some fish were detected as they resided in this area for weeks at a time, suggesting that they were unable to find an upstream passage route. In addition, lower percentages (32–36%) of fish detected at this site were later detected at upstream dams compared to fish detected at either AWS LPS or at fishway exits. These observations further support the idea that lamprey behind the picketed leads at the obsolete Cascades Island count station area have difficulty passing upstream.

As improvements are made to entrance success at the Cascades Island fishway entrance, the percentage of lamprey using the top of this ladder could increase. Therefore, monitoring of lamprey presence in this area should be continued. Eventually, it may be necessary to reduce lamprey access to the top of this ladder (e.g., by reducing picketed lead spacing). Alternatively, an LPS route could be provided to facilitate lamprey movement into the forebay from this area.

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