Development of Passage Structures for Adult Pacific Lamprey at Bonneville Dam, 2005

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EXECUTIVE SUMMARY

Lamprey passage structures (LPSs) can provide passage routes for migrating adult Pacific lamprey *Lampetra tridentata* in fishway areas where these fish are obstructed or delayed. For example, in 2004, we found that lamprey could successfully pass into the Bonneville Dam forebay via a LPS located in the Bradford Island Auxiliary Water Supply (AWS) channel. Our objectives in 2005 were to modify and evaluate the performance of this LPS and to develop and evaluate a prototype lamprey collector at a Bonneville Dam fishway entrance.

The efficacy of the LPS in the AWS channel was evaluated under two flow conditions using a lamprey-activated counter. We also used passive integrated transponder (PIT) detectors that were integrated into the LPS to examine passage of PIT-tagged lamprey. We surgically implanted adult Pacific lamprey with PIT tags and released them either directly into the Bradford Island AWS channel (n = 841) or to the Columbia River approximately 3 km downstream from Bonneville Dam (n = 78).

We counted 8,889 untagged lamprey as they exited the AWS LPS, and estimated that this represented 29% of the lamprey at the top of the Bradford Island fishway in 2005. Of the PIT-tagged lamprey released into the AWS, 42% were detected in the LPS. Median time required to pass through the LPS was 1.5 h, and of fish detected in the AWS LPS, 94% successfully exited. There was no evidence that lower flow through the LPS resulted in either significantly higher counts of lamprey, more rapid passage rates, or higher passage success.

Detections of PIT-tagged lamprey at McNary and Ice Harbor Dams indicated that some lamprey that used the AWS LPS migrated upstream to and passed over The Dalles Dam. In addition, detections during 2005 of lamprey PIT-tagged in 2004 indicated that some fish were able to overwinter at Bonneville Dam and resume upstream migration during their second year in freshwater.

A prototype entrance collector was placed at the downstream north entrance to the Washington-shore fishway. This was a challenging location, as current velocities emanating from this entrance were high and variable. In addition, it was necessary to install a fully-submerged transition structure to guide lamprey into the collector and provide a seat for the distal end of the collector. After several attempts, the collector was successfully installed in July and was fully operational by mid-August.

The fishway entrance collector was evaluated using a PIT detector and by counting lamprey collected at its terminus. Even though the collector was not fully operational until after the peak of lamprey migration, 4 lamprey were trapped; a promising indication that lamprey were able to find and use this structure in spite of rapid and turbulent flow conditions at the collector entrance.

CONTENTS

EXECUTIVE SUMMARY iii

INTRODUCTION 1

METHODS 5
Structures Tested 5
Auxiliary Water Supply Channel at Bradford Island 5
Washington Shore Entrance Collector 9
Testing Protocol 14

RESULTS 17
Lamprey Counts 17
PIT-Tagged Lamprey 19
Releases to the Auxilliary Water Supply Channel 19
Releases Downstream from Bonneville Dam 23

DISCUSSION 24

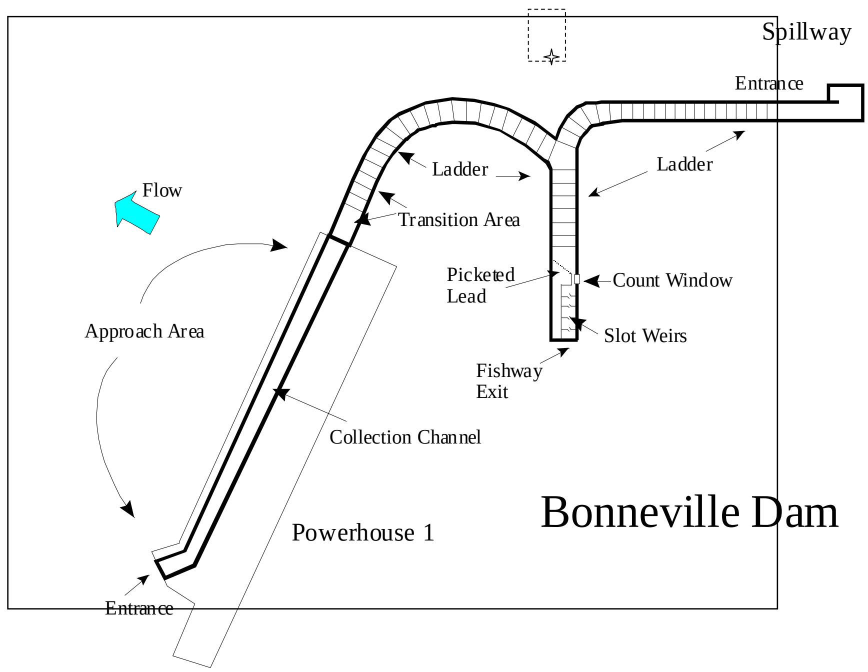
ACKNOWLEDGMENTS 28

REFERENCES 29

INTRODUCTION

Adult Pacific lamprey *Lampetra tridentata* that enter the Columbia River must negotiate four mainstem hydropower dams to reach the confluence of the Columbia and Snake Rivers. Up to five additional dams must then be passed to attain spawning areas in headwater streams. Adult lamprey passage at lower Columbia River dams is poor relative to that of salmonids, and there are particular fishway areas where lamprey are regularly obstructed or delayed (Moser et al. 2002a,b). Therefore, providing safe passage routes through these areas was identified as one of the highest priorities for Pacific lamprey recovery in the Columbia and Snake Rivers (CRLTW 2005).

At Bonneville Dam, impediments to lamprey passage include fishway entrances, collection/transition areas at the bottom of the fishways, and flow-control areas at the top of the fishways (Figure 1). In contrast, lamprey exhibit relatively rapid and successful passage through the pool and weir sections of fishways, where they are exposed to rapid currents. When lamprey encounter obstacles, they often fall back downstream and exit the fishways (Moser et al. 2002a). Consequently, lamprey passage at Bonneville Dam requires 4-5 days, on average. At The Dalles Dam, lamprey exhibit relatively higher passage efficiency and are delayed less (Moser et al. 2002b, 2005b).



lamprey in the forebay upstream from Powerhouse 1.

Figure 2. De-watered views of serpentine weirs (upper photo) and overflow weirs (lower photo) used in fishways at lower Columbia River dams.

This difference in passage success may be related to flow-control areas at the top of fishways, which differ between Bonneville and The Dalles Dams. Bonneville has serpentine weirs, while The Dalles Dam has overflow weirs (Figure 2). Adult Pacific lamprey are routinely delayed and/or obstructed by serpentine weirs, which are located immediately upstream from the count stations at both the Bradford Island and Washington-shore fishways (Moser et al. 2002c, 2003, 2005a). Thus, to avoid serpentine weirs at Bonneville Dam, some lamprey move into the adjacent auxiliary water supply channel (AWS) through connecting diffuser gratings or via the picketed lead downstream from the count stations (Figure 3). However, there is no ready access to the forebay of Bonneville Dam from the AWS channel. Radiotelemetry studies indicate that lamprey reside in the AWS for 4 d on average, and then typically fall back downstream.

In 2002 and 2003, we designed, installed, and tested lamprey-specific collectors in the Bradford Island AWS channel to attract lamprey into the fishway. Results of this work were encouraging. Up to 18% of the lamprey marked and released to the AWS channel were collected in an "open ramp" type collector. In 2003, over 5,400 lamprey were collected with this structure and released into the forebay of Bonneville Dam at Powerhouse 1.

In 2004, we extended the lamprey passage structure (LPS) so that lamprey could volitionally move from the AWS channel into the forebay of Bonneville Dam. We developed a lamprey-activated counter and used passive integrated transponder (PIT) technology to monitor lamprey passage events and to determine rates of passage through the LPS and overall LPS efficiency (Moser et al. 2006).

An estimated 7,490 non-tagged fish used the AWS LPS and volitionally passed into the Bonneville Dam forebay from the AWS channel in 2004. Detections of PIT-tagged fish revealed that 25% of the lamprey released into the AWS channel entered the LPS, and 96% of fish that entered successfully passed through the device (Moser et al. 2006). Median passage time for the tagged lamprey was approximately 1 h. Also in 2004, laboratory studies indicated that lamprey passage rates through the LPS might be improved by reducing flow through the device (Keefer et al. in press).

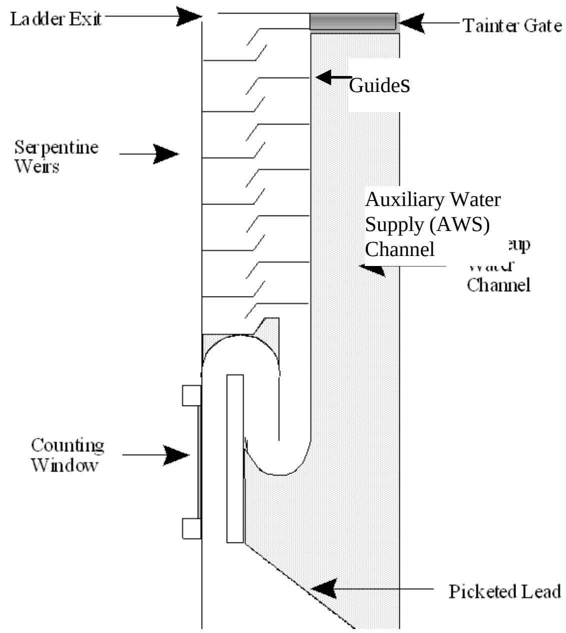


Figure 3. Detail of the top of the Bradford Island fishway.

The first objective of our work in 2005 was to further evaluate lamprey use of the AWS LPS. Using detections of PIT-tagged fish, we were able to determine collection efficiency, passage efficiency, and passage rate during both high and low flow conditions in the structure. Based on 2004 laboratory experiments (Keefer et al. in press), we predicted that lower flow in the LPS would result in more rapid passage rates and higher passage success. Our second objective in 2005 was to design and fabricate a lamprey collector for installation at a Bonneville Dam fishway main entrance. If successful, such a collector could be used in development of lamprey-specific fishways at all lower Columbia River dams.

METHODS

Structures Tested

Auxiliary Water Supply Channel at Bradford Island

The LPS collector in the Bradford Island Auxiliary Water Supply (AWS) Channel was positioned on the west wall at the upstream end of the channel (Figure 3). The collector features an open ramp of 0.5-cm-thick sheet aluminum, which extends from the bottom of the channel to the level of the first rest box (3.3-m elevation, Figure 4). Lamprey may enter the collector ramp at any depth in the water column. The lower 1.3-m section of the ramp was fitted with a heavy rubber flange, which creates a seal against the wall and floor of the channel to help guide lamprey onto the ramp (Moser et al. 2005a). After ascending the 4.4-m-long ramp (at a slope of 1:1), lamprey enter a 1.2-m-long, open, rectangular chute that empties into a rest box (Rest Box 1; Moser et al. 2006). The end of the chute is fitted with a funnel made of 1.2-cm plastic mesh to prevent lamprey from passing back down the ramp after entering the rest box. This "one-way valve" design was incorporated into each LPS rest box.

Figure 4. Photo of the Bradford Island LPS collector. Note the lamprey that is moving up the ramp near the water surface.

Lamprey exit Rest Box 1 via a slightly steeper (slope 1.2:1) ramp of the same construction as the collector ramp. From this ramp, the lamprey pass through a short horizontal chute and into Rest Box 2 (Figure 5). From Rest Box 2 the lamprey climb up a less steep ramp (0.3:1) and pass through a long, closed rectangular tube before dropping into Rest Box 3 (Figure 5). Lamprey then climb a very short, 45° ramp and enter a long, closed tube that terminates at an upwelling box and exit slide (see Moser et al. 2006 for all LPS construction details).

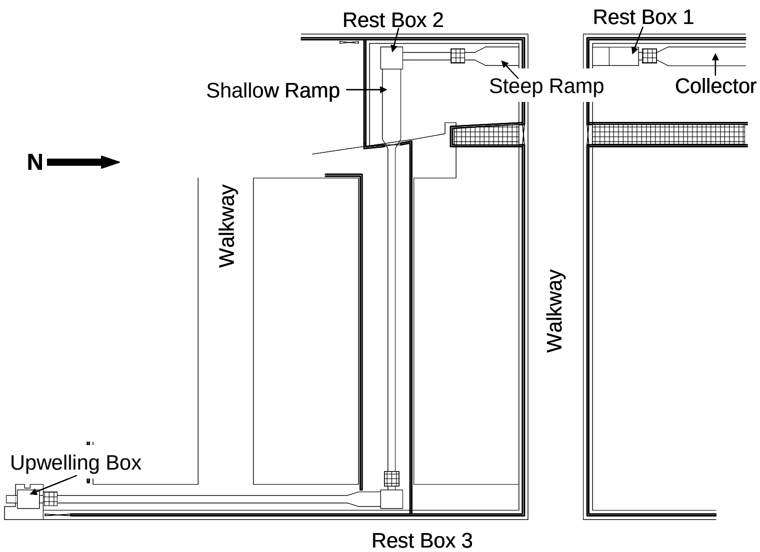


Figure 5. Schematic drawing of the AWS LPS (top view).

The exit slide drops lamprey into the forebay of Powerhouse 1 at a location approximately 10 m upstream from the exit of the Bradford Island fishway (Figure 1).

Lamprey passing down through the exit slide were enumerated when they contacted a large paddle near the exit slide terminus (Figure 6).

A limit switch attached to the paddle was wired to a digital event recorder, which summed the number of lamprey that activated the switch each day. Columbia River water was supplied at the top of the LPS via a 10.2-cm-diameter, flexible corrugated 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 regulation was achieved using an upwelling box at the top of the LPS. In this way, lamprey were stimulated to move onto the exit slide, even though water was passing down the slide.

In 2005 we tested a "low" flow condition in which water depth in the closed tubes was reduced to 5 cm. This was accomplished by releasing water from a drain in the bottom of Rest Box 3 (Figure 5).

Figure 6. Lamprey activated switch at the terminus of the LPS exit slide.

In this way, water level in the upwelling box was maintained to ensure that lamprey would be able to exit the LPS normally. During the low flow condition, flow upstream from Rest Box 3 was the same as that generated during testing in 2004, but half the flow was available in the LPS downstream of Rest Box 3 (including both steep and shallow ramps) (Figure 5).

Lamprey passage was monitored with a series of four PIT detectors integrated into the LPS design (Figure 7). A rectangular sleeve fabricated from sheet PVC was seamlessly inserted into the chutes leading to each rest box and to the exit slide. This was necessary because the aluminum chute itself would attenuate the PIT signal.

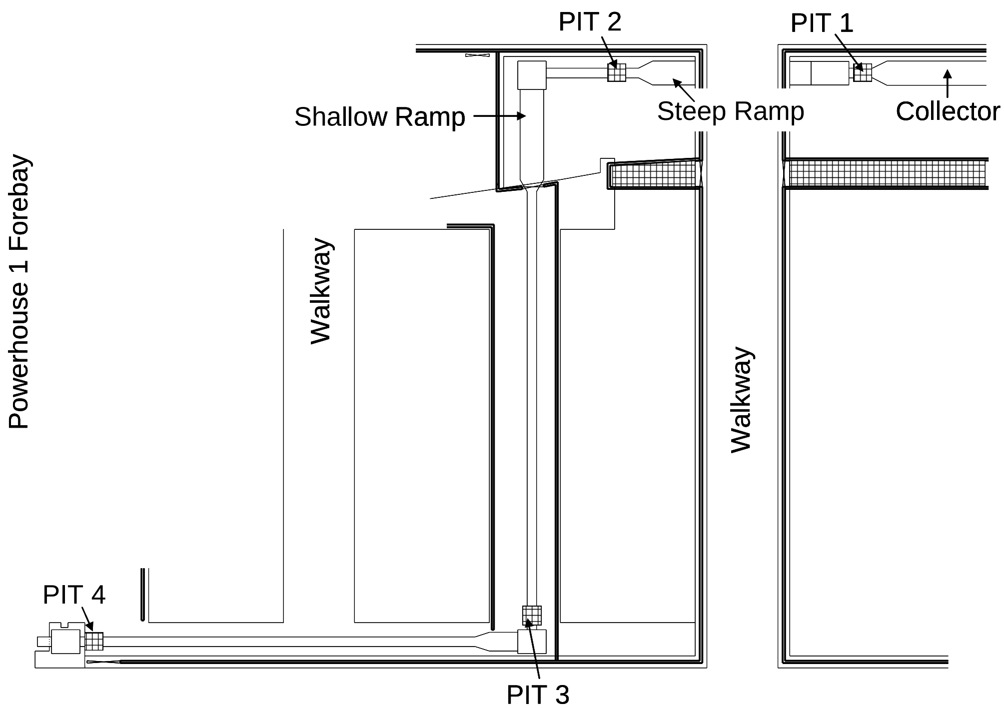


Figure 7. Top view of the Bradford Island LPS with the half-duplex PIT antenna locations (PIT 1-4) indicated.

Each detection antenna was comprised of 10-gauge multistrand wire wrapped around the PVC sleeve. Antennas were shielded with an outer aluminum housing that acted as a Faraday cage. A palmtop computer logged the time and date of each detection to a 256-MB memory card. Detectors were synchronized by wiring them together.

An additional PIT detector was positioned in the AWS channel immediately upstream from the picketed lead (Figure 8), which directs fish to the Bradford Island count window (Figure 3). This detection antenna was comprised of a 10-gauge multistrand wire loop positioned inside a 12.8- by 0.9-m rectangular PVC frame. The frame spanned the entire width of the AWS channel and was supported in position approximately 15 cm from the bottom by clamping it to the hand rail of the existing walkway (Figure 8). 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 8. View looking downstream from the Bradford Island AWS. The location of the AWS channel PIT antenna (just upstream from the picketed lead) is denoted in white.

Washington Shore Entrance Collector

The prototype entrance collector was installed at the downstream north main entrance to the Washington-shore fishway (Figure 9). This location was chosen because radiotelemetry studies have indicated that lamprey entrance efficiency at this location is consistently lower than at all other main fishway entrances (Moser et al. 2005a). This was a challenging site for installation because the floor of the fishway does not extend beyond the mouth of the entrance (Figure 10). It was therefore necessary for divers to attach a transition structure below the elevation of the fishway floor, both to guide lamprey onto the collector ramp and to provide a seat for securing the bottom of the ramp (Figure 10).

The transition structure was a 5.2-m-long, vertical aluminum chute that terminated in a rounded crest, to aid lamprey movement into the collector (Figure 11). The structure was 0.6 m wide and fitted with a 5-cm bar grate (10 cm on center) to prevent sea lions from accessing lamprey that were climbing up this structure (Figure 11).

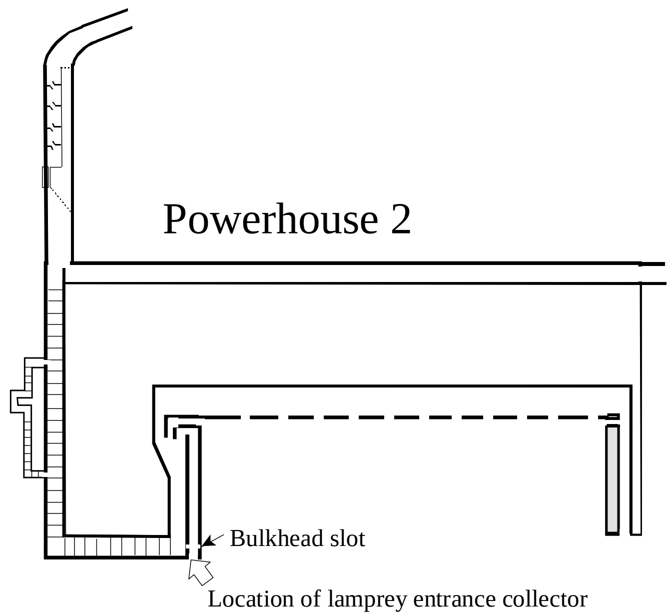


Figure 9. The prototype entrance collector was located at the downstream north main entrance to the Washington-shore fishway.

Installation at this site was also difficult because current velocities emanating from the fishway entrance were extremely high and variable. Initially, the collector ramp was winched down onto the top of the transition structure using a 0.6-cm wire cable with a breaking strength of 2,582 kg. This allowed for accurate seating of the collector onto the top of the transition structure. However, during the first night after deployment of the collector ramp (22 June), the cable holding it parted.

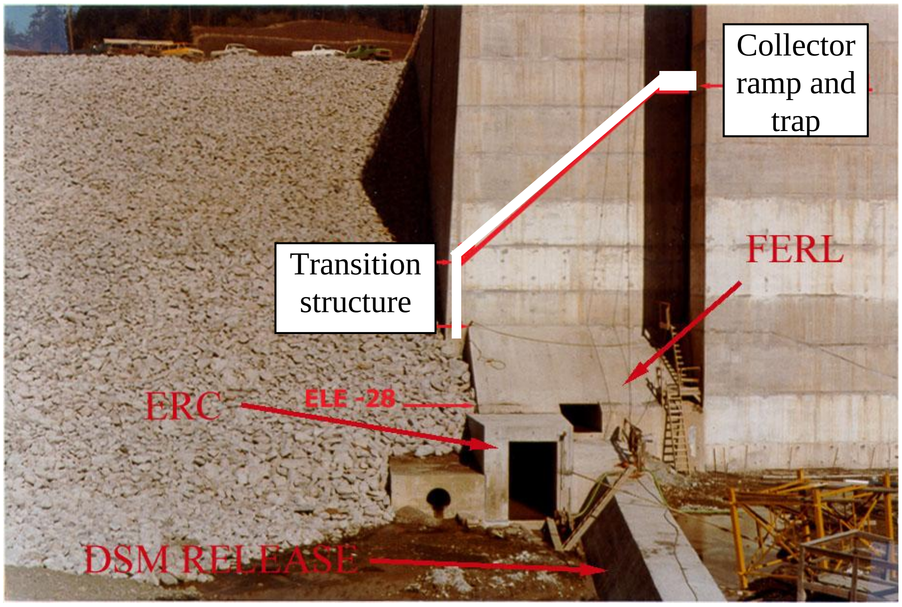


Figure 10. Dewatered view of the Washington-shore downstream north entrance with the position of the entrance collector and the transition structure denoted. (FERL Fisheries Engineering Research Lab)

Figure 11. Transition structure (top view) to guide lamprey into the collector and provide a seat for the collector base. The structure was fabricated at the Northwest Fisheries Science Center Pasco Research Station. Bars were attached to prevent sea lions from accessing lamprey as they climb up this submerged structure.

To secure the collector ramp without having to conduct further dive operations, a metal hold-down was devised and fabricated using a 10- by 15- by 1-cm steel beam. The hold-down was anchored to the wall and extended from above the concrete deck to the base of the collector ramp (Figure 12). It was held in place by a series of three removable brackets bolted to the wall. To install the hold-down, a crane was used to position and connect it to the collector ramp base above the water surface.

An underwater camera was mounted on the collector ramp to view the seal between the transition structure and the base of the connector (Figure 13). The current velocity emanating from the fishway entrance was then reduced so that the assembly could be lowered into place and seated properly onto the transition structure (Figure 13). The hold-down was then bracketed to the wall and jacked down from the top to create a seal with the transition structure. This installation was completed on the evening of 21 July.

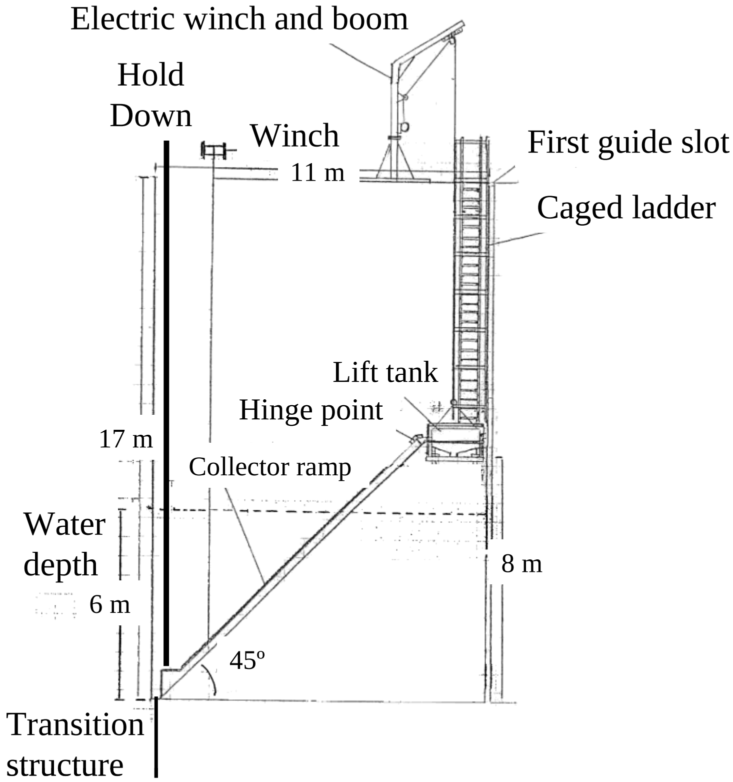


Figure 12. Side view (north wall) of the prototype entrance collector at the downstream Washington-shore fishway entrance.

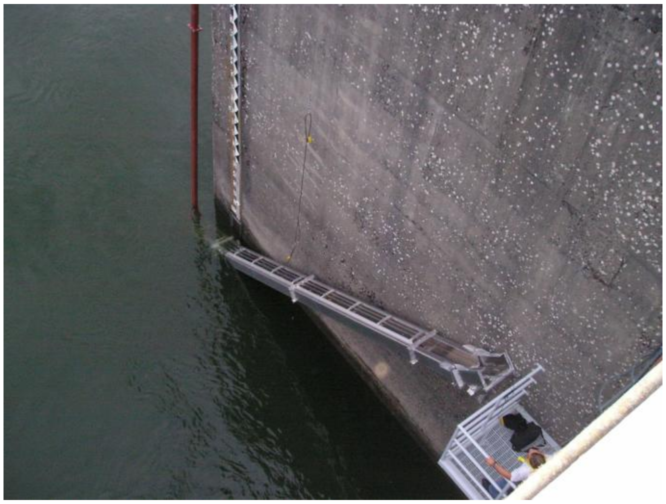


Figure 13. Top: Collector assembly being lowered into place. Note the steel beam attached to the distal end of the collector, which was used to hold the whole assembly in place. Bottom: Collector ramp prior to submersion showing the camera used to position it on the transition structure.

The collector ramp was constructed of 0.5-cm aluminum plate and was 51 cm wide by 12.6 m long (Figure 14). It extended upward through the water column at an angle of 45°. To prevent sea lions from accessing lamprey that were climbing the ramp, a 5-cm bar grate (10 cm on center) was installed over the ramp (Figure 13). The collector ramp terminated in a 15.2- by 20.3-cm closed tube, which passed through a PIT antenna (same construction as in the AWS LPS). The PIT antenna was connected to a detector on the deck. Lamprey passed from the tube through a plastic mesh funnel and dropped into a 0.6- by 0.6- by 0.9-m trap box (Figure 14). The trap box was accessed by a caged ladder and could be hoisted to retrieve lampreys using an electric winch and boom (Figure 15).

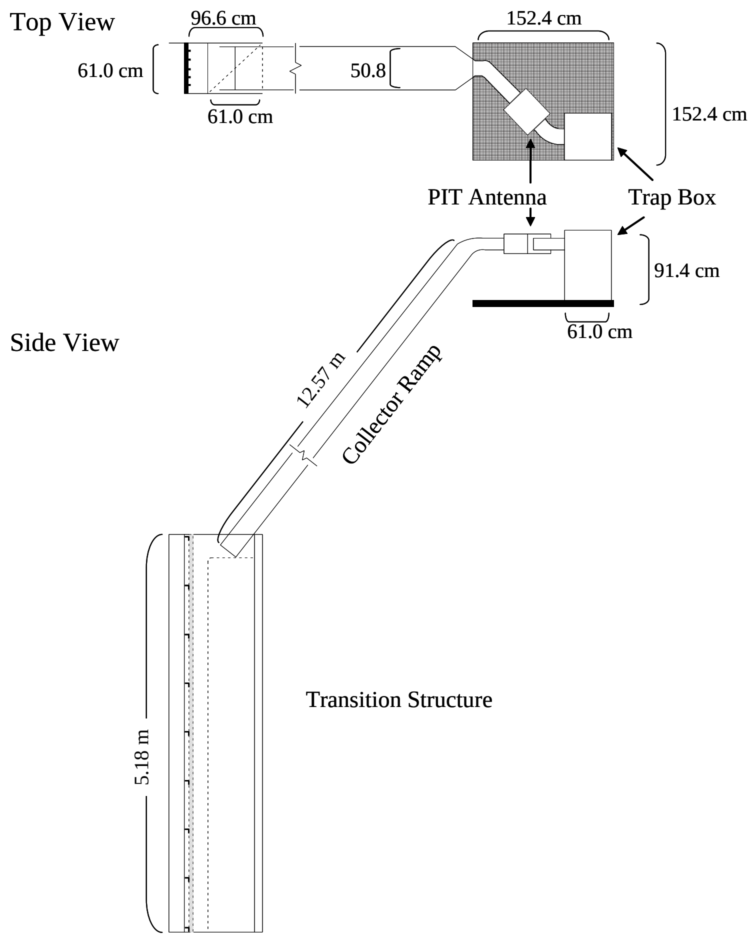


Figure 14. Schematic drawing illustrating dimensions of the entrance collector installed at the Washington-shore downstream north entrance.

Figure 15. Top view of the trap box at the terminus of the entrance collector.

Testing Protocol

We collected lamprey for PIT-tagging with a trap at the Bonneville Dam Adult Fish Collection and Monitoring Facility. The trap was deployed each night from approximately 2100 to 0700 PDT. Each morning, trapped lamprey were transferred to a holding tank with flow-through Columbia River water.

After anaesthetizing the lamprey using 60-ppm clove oil, we measured the 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 mm × 32 mm) was inserted into the body cavity.

Most PIT-tagged lamprey were released directly into the AWS channel to obtain estimates of LPS efficiency. To help lamprey acclimate upon release, they were lowered into the AWS channel in an open aluminum release box (Figure 16). Lamprey could volitionally leave the release box at any time after it was submerged. The LPS efficiency was computed by dividing the number of AWS releases that were detected in the LPS by the total number of AWS releases. However, the study area was not closed. That is, lamprey could leave the AWS before they had investigated the LPS, resulting in a potential underestimate of LPS efficiency.

Figure 16. PIT-tagged lamprey being lowered into the Bradford Island AWS.

Starting on 21 June, flow in the LPS was alternated daily during the week between high and low flow treatments. For weekends, the flow condition on Friday was continued on Saturday and Sunday. The number of lamprey that used the LPS during each day was recorded by a digital event recorder on the exit slide. We used a *t*-test to compare the number of lamprey counted during high and low flow treatments. We also used a one-tailed *t*-test of the hypothesis that PIT-tagged lamprey entering during the low flow condition required less time to traverse the LPS (the time from detection at the top of the collector to detection at the exit slide) than those entering during the high flow condition.

To assess lamprey use of the Washington-shore entrance collector, the trap at the collector terminus was checked daily and lamprey in the trap were enumerated, measured, and released. At approximately weekly intervals, we also viewed the entrance to the collector with the underwater camera mounted at its distal end (Figure 13).

To further determine lamprey use of the AWS LPS and entrance collector, we released some PIT-tagged lamprey approximately 3 km downstream from Bonneville Dam at the Hamilton Island boat ramp. We then calculated the percentage of these lamprey that entered either the entrance collector or the AWS LPS and the time from release to first detection at either structure.

RESULTS

Lamprey Counts

Counts at the AWS LPS were made from 6 June to 12 September. During this time, 9,242 lamprey were counted (Figure 17). This number included 338 PIT-tagged lamprey that were detected at the LPS exit slide (PIT 4, Figure 7). Of these 338 lamprey, 3 had been tagged and released in 2004. The remaining 335 were tagged in 2005 and released either to the Bradford Island AWS channel (n = 333) or downstream from Bonneville Dam (n = 2).

During the flow experiments (21 June-12 September), we compared LPS counts of lamprey during each treatment (Figure 18). There were 3,791 lamprey counted during the days with consecutive, alternating treatments: 1,958 (52%) during the high flow treatment and 1,833 (48%) during the low flow treatment. A paried *t*-test revealed no significant difference (P = 0.5) in the number of lamprey counted during each treatment.

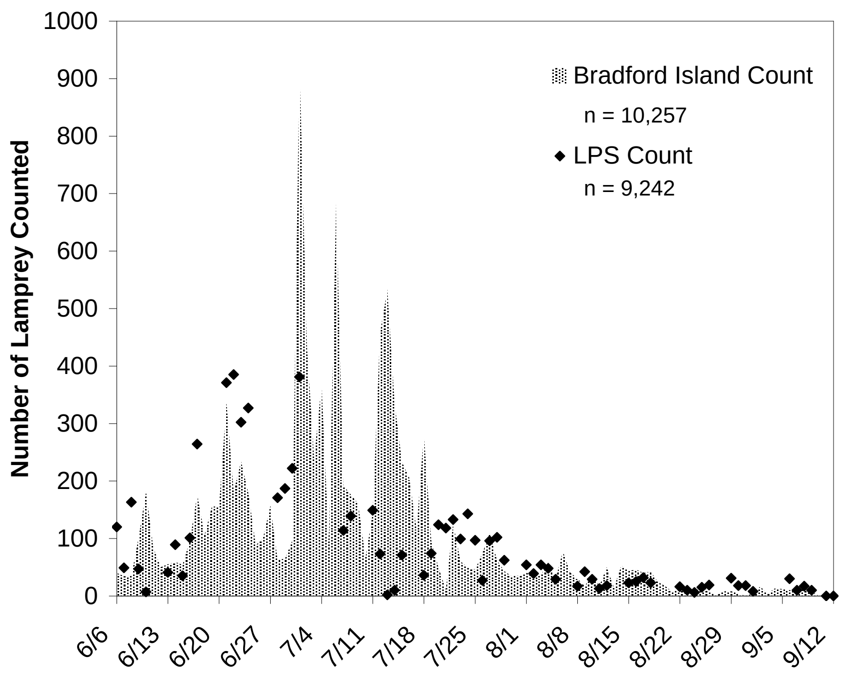


Figure 17. The number of lamprey counted at the Bradford Island count station (shaded area) and the number counted at the upstream end of the Bradford Island LPS (closed diamonds).

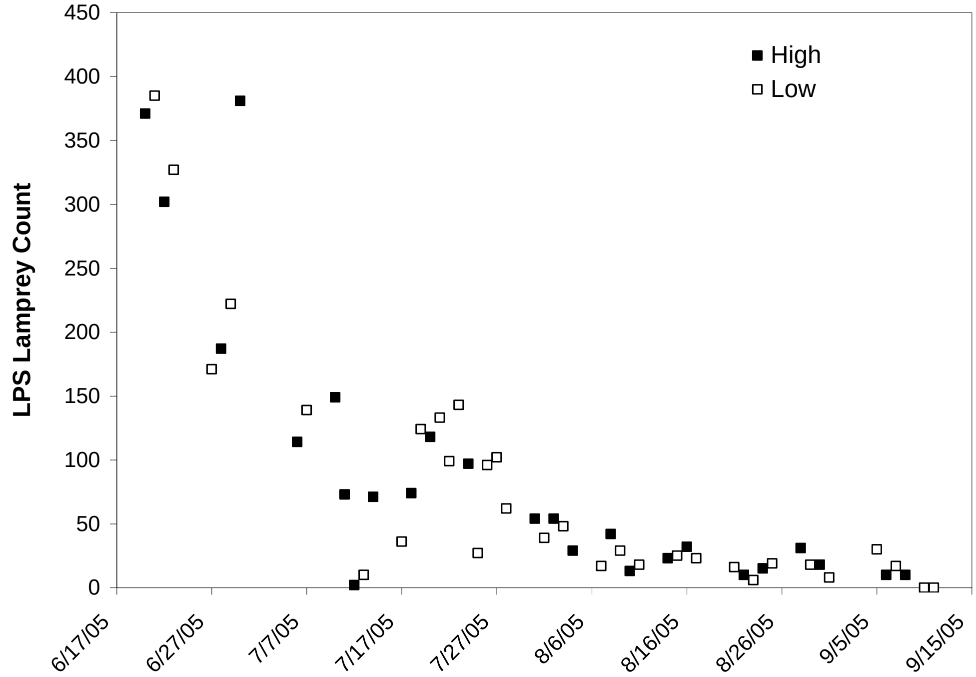


Figure 18. Number of lamprey counted exiting the LPS during low-flow (open squares) and high-flow (closed squares) treatments.

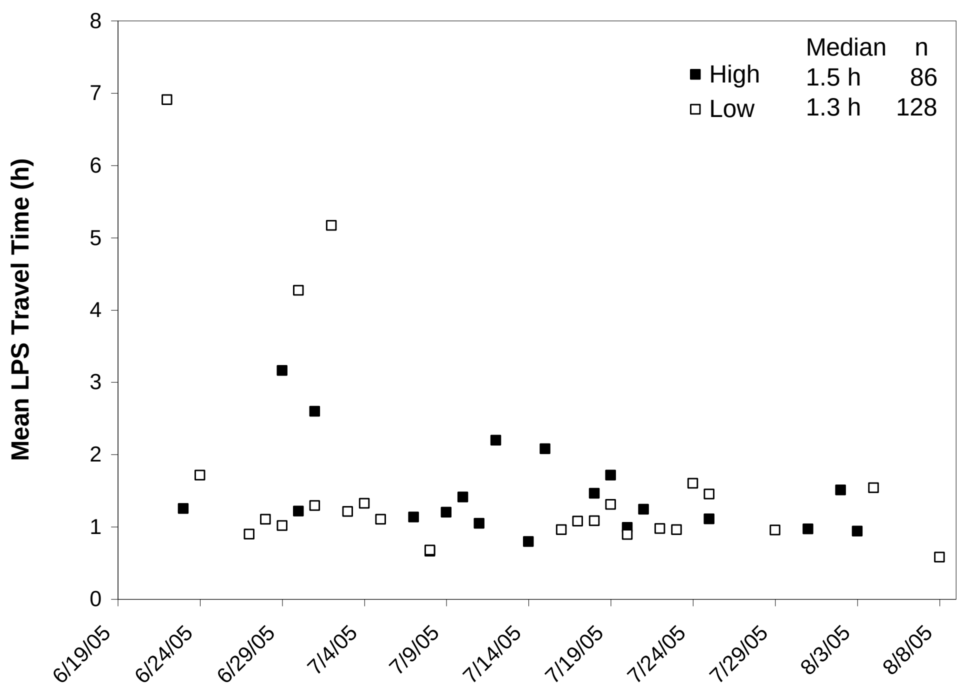


Figure 19. Mean time lamprey required to pass through the LPS during low-flow (open squares) and high-flow (closed squares) treatments.

Lamprey were sampled at the Washington-shore entrance collector trap from 22 July to 12 September. Four lamprey were trapped: one on 27 August, one on 2 September, and two on 8 September. These fish ranged from 58 to 71 cm in length and from 272 to 518 g in weight. No lamprey were viewed with the underwater camera located at the distal end of the entrance collector, and no lamprey were noted during nightly surface inspections of the ramp.

PIT-Tagged Lamprey

We tagged and released 919 lamprey from 6 June to 8 September. Water temperature during this period ranged from 15.3 to 22.1°C. To avoid potential mortality due to handling stess, we did not trap fish in late July and early August, when water temperature exceeded 21°C (Ocker et al. 2001). Most (841) PIT-tagged fish were released directly into the AWS channel (6 June to 22 July), and the remainder (78) were released downstream from Bonneville Dam (7 July to 8 September).

Releases to the Auxilliary Water Supply Channel

Of the 841 PIT-tagged fish released into the AWS channel, 353 were detected in the LPS (42%) and 222 (26%) were detected as they passed the antenna at the downstream end of the channel (Figure 8). Seven of the 222 lamprey detected in the AWS channel had entered the LPS prior to detection in the AWS channel. One of these 7 passed successfully through the LPS, but was detected again in the AWS channel 12 d later and did not reascend the LPS. The remaining 6 were initially detected in the LPS, but then fell back downstream and were subsequently detected in the AWS channel. One of these fish was later detected as it passed up the LPS a second time and exited into the forebay. For the remaining 215 fish, median time from release to first detection in the AWS channel was 1.51 d (range = 18 min – 44.8 d, standard deviation = 5.4 d).

Roughly half (n = 96) of the PIT-tagged lamprey detected at the downstream end of the AWS channel after release were first detected on the day of release. For fish detected multiple times at this antenna (n = 131), the miniumum time between detections was 2 seconds and the maximum time was 42.7 d (median = 3.2 h, SD = 6.2 h). In most cases it was impossible to determine whether a fish detected multiple times had left the AWS channel between detections. However, one fish was detected at the Bradford Island fishway exit 3 d after detection in the AWS channel and was then detected again in the AWS channel 1 d later. While it is likely that many fish detected only in the AWS channel (n = 136) left the AWS channel and were not available to the LPS thereafter, there is insufficient data to confirm this assumption.

For PIT-tagged fish released directly into the AWS channel, median time required to pass into the LPS was about the same as that required to reach the downstream end of the channel. Time from release to first detection at PIT 1 (Figure 7) ranged from 1.3 h to 45.4 d (median = 1.7 d, standard deviation = 4.9 d, n = 303). All but 50 fish were first detected at PIT 1. Of these 50 fish, 37 were missed at both PIT 1 and PIT 2 and were first detected at PIT 3. No fish were detected at PIT 4 that had not been previously detected at a downstream LPS antenna.

All but 20 of the PIT-tagged lamprey detected in the LPS were detected at PIT 4 (Figure 7), indicating that at least 94% of lamprey that entered the LPS successfully passed into the forebay. Of the 20 fish not detected at PIT 4, 1 was detected at PIT 3; the remaining 19 apparently did not ascend above PIT 1. Of these 19 unsuccessful fish, 15 were first detected at PIT 1 prior to the start of the flow experiments. During this time (11 June to 17 June), flow through the LPS was high (the normal condition). Interestingly, 6 (30%) of the 19 unsuccessful lamprey attempted passage on the same night (14 June). After we began the flow experiments on 20 June, only 5 fish were unsuccessful: 2 during the high flow treatment and 3 during the low flow treatment.

Seven of the 20 fish that fell back downstream and out of the LPS were later detected at other Bonneville Dam locations (see Daigle et al. in press), and 6 were detected in the AWS channel. All 20 of these detections occurred between 2 h and 23 d after fish exited the LPS. One of these fish was subsequently detected in the Washington-shore fishway 79 d later, but was not detected exiting that fishway. One of the seven fish was not detected at the AWS antenna, but 8 d after leaving the LPS was detected at the Bradford Island fishway exit and was detected again at McNary Dam 15 d later (Daigle et al. in press).

Nineteen (6%) of the lamprey that successfully exited the LPS (i.e., were detected at PIT 4) were subsequently detected at the Bradford Island fishway exit. Almost all of these detections occurred between 3 and 21 min after passage at PIT 4. However, one fish was detected at the fishway exit 2 d after exiting the LPS. Two of the fish detected at the exit after LPS passage were later detected at upstream dams (McNary or Ice Harbor) where half-duplex PIT antennas were operated (Daigle et al. in press). None of these fish were detected downstream from the exit. A total of 28 lamprey that passed through the LPS were subsequently detected at McNary or Ice Harbor dams.

We computed the time fish required to travel upstream between LPS PIT antennas. For this analysis, only fish that did not fall back downstream in the LPS were included. Median passage time from first detection at PIT 1 to first detection at PIT 2 (steep ramp section) was 58.4 min (Table 1). To obtain this estimate we omitted 17 lamprey that ascended to PIT 1, but then fell back downstream and ascended the LPS a second time (usually 2-4 d later). We noted that 12 (71%) of the lamprey that exhibited this behavior made their first attempt during 13-15 June. In addition, the maximum times recorded for passage from PIT 1 to PIT 2 (two fish that took more than 1 d) also occurred during this period. When we excluded these two fish from the analysis, the maximum passage time through this section was 4.7 h.

Table 1. Travel times (h) between PIT detectors for PIT-tagged lamprey that entered the LPS.

	Passage time (h)			
	PIT 1 to 2	PIT 2 to 3	PIT 3 to 4	PIT 1 to 4
N	182	165	287	261
Median	0.97	0.44	0.19	1.51
Min	0.19	0.16	0.05	0.53
Max	48.93	19.30	33.47	74.75

In comparison to the time they spent on the steep ramp section, lamprey generally required less time to pass between both PIT 2 and 3, a shallow ramp section (median = 0.44 h), and PIT 3 and 4, a flat section except for one short ramp (median = 0.19 h; Table 1). For the calculation of travel time from PIT 3 to PIT 4, 9 lamprey were omitted from the analysis due to a PIT detector failure on the nights of 18 and 19 June.

Lamprey required a median time of 1.51 h to travel the entire distance from PIT 1 to PIT 4 (Table 1). For this analysis, two additional fish were omitted because they fell back downstream within the LPS after passing PIT 2. The maximum time that lamprey required to ascend the LPS (from PIT 1 to PIT 4) was 74.75 h (3.1 d). There were 15 fish that stayed in the LPS for more than 5 h. All of these fish exited the LPS between 16 and 24 June. In all but one case, these lamprey were in the LPS for less than 24 h.

To test the effects of flow on LPS travel time, we compared the time lamprey required to pass from PIT 1 to PIT 4 during each flow treatment. Only lamprey that entered the LPS during the flow study (20 June-12 September) were included in the analysis (n = 214). Median travel time was 1.47 h (SD = 22.3 h) during the high flow treatment and 1.34 h (SD = 15.6 h) during the low flow treatment. A *t*-test indicated no significant difference between the two treatments in travel time through the LPS ($P > 0.05$; Figure 19).

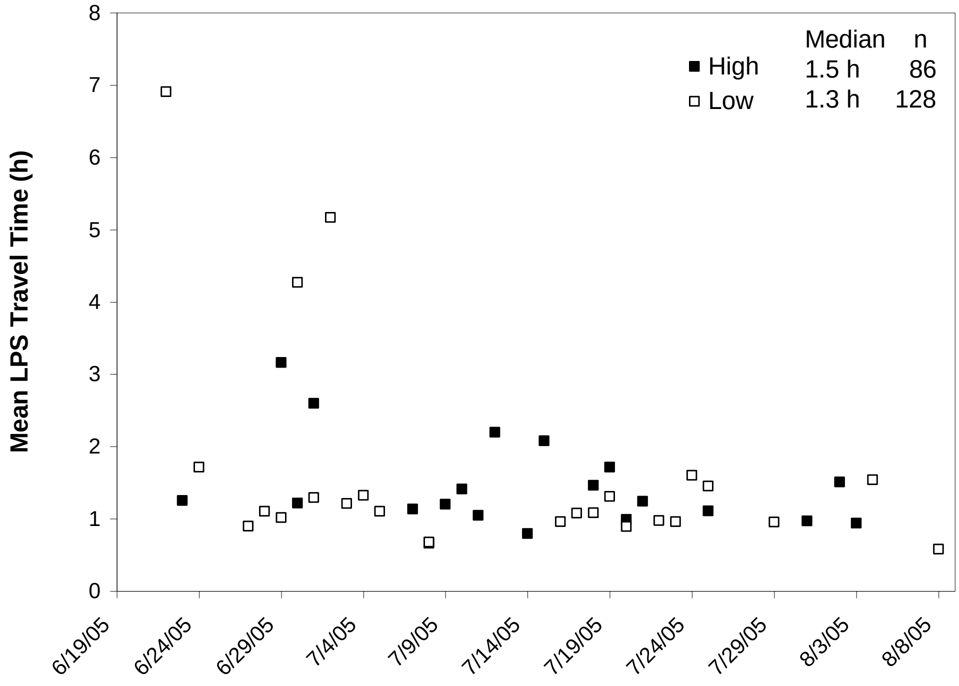


Figure 19. Mean time lamprey required to pass through the LPS during high (closed squares) and low (open squares) flow treatments.

Releases Downstream from Bonneville Dam

Of the 78 fish released downstream from Bonneville Dam, 2 were detected in the LPS and 4 in the AWS channel; surprisingly, none of these fish were detected at both locations. The two fish detected in the LPS required 3.6 and 4.6 d to reach PIT 1 after release below the dam. Both fish detected in the LPS were detected at PIT 4, indicating that they successfully passed through the LPS. The 4 lamprey detected in AWS channel required 4.5, 4.6, 6.8, and 13.5 d to reach the channel after release downstream from Bonneville Dam.

One of these 4 fish was detected at the Bradford Island fishway exit 1.1 d after passing the antenna in the downstream end of the AWS channel. In addition to detections of lamprey released in 2005, we detected 3 lamprey in the LPS that had been tagged and released in 2004. Interestingly, two of these fish were detected in the LPS on the same day (23 June) and the other was detected in the LPS on 4 August. All three succesfully passed from the LPS to the dam forebay. However, the fish that passed in August apparently fell back downstream and into the fishway: it was detected at the Bradford Island fishway exit just 15 min after passing through the LPS.

DISCUSSION

The number of lamprey that used the Bradford Island AWS LPS was higher in 2005 than in 2004, the first year of its operation. Almost 1,400 (19%) more lamprey used the LPS in 2005 than in 2004 (Moser et al. 2006). This was surprising in light of the fact that lamprey numbers at the Bradford Island count station in 2005 were down 14% from those made in 2004. Thus, it appears that a higher percentage of the lamprey at the top of the Bradford Island fishway used the AWS LPS in 2005 than in 2004.

Based on numbers at the Bradford Island count station, we estimated that 29% of the lamprey using the top of the Bradford Island fishway passed through the AWS LPS. A total of 9,242 lamprey exited the Bradford Island AWS LPS and passed into the Bonneville Dam forebay. Of these, 353 were PIT-tagged fish that had been introduced experimentally into the AWS channel. To avoid biasing the estimate of LPS efficiency, we omitted the PIT-tagged fish for this calculation.

During the period that the LPS was operated, 10,257 lamprey were counted at the Bradford Island count station. These counts were not made during the night, when 67% of the lamprey were likely to pass (Moser and Close 2003). Therefore, we estimated that the total number of lamprey at the Bradford Island count station was 30,771. Based on this estimate, LPS efficiency in 2005 (8,889/30,771 = 0.289) was higher than a similar estimate made in 2004 (0.21, Moser et al. 2006).

Detections of PIT-tagged lamprey in the LPS also indicated higher collection efficiency in 2005 than in 2004. Of the PIT-tagged lamprey released into the AWS channel in 2004, 25% were detected on LPS antennas (Moser et al. 2006). In contrast, 42% of the AWS releases in 2005 were detected in the LPS. In both years, it is likely that LPS collection efficiency was underestimated because lamprey released into the AWS channel could move downstream and out of the study area. In 2005, we operated PIT antennas at both the downstream end of the AWS channel and at the Bradford Island fishway exit.

Of the PIT-tagged lamprey that we released into the AWS channel in 2005, 26% were detected downstream from the release site at the AWS channel. In addition, 5% (40 fish) were detected at the Bradford Island fishway exit and were not detected either in the LPS or AWS channel. Together these data suggest that around 30% of the lamprey released into the AWS channel left the study area and were not available to the LPS. Nevertheless, the proportion of lamprey using the LPS was greater in 2005 than in 2004.

There are several potential reasons that more lamprey seemed to use the LPS structure in 2005 than in 2004. Our previous work with lamprey-specific structures has indicated that lamprey may be repelled when a metal structure is new. After the metal has been "seasoned" by repeated exposure to flowing water and growth of algae, lamprey seemed more likely to accept and attach to it.

Another possible explanation is that flow conditions attracted more lamprey into the AWS channel in 2005. Lamprey can enter the AWS channel via the downstream picket lead or through grates in the wall between the AWS channel and the upper Bradford Island fishway (Moser et al. 2005a). Changes in flow regulation at these areas could have resulted in greater lamprey use of the AWS.

It is also possible that the presence of PIT-tagged lamprey released to the AWS channel may have somehow attracted conspecifics. However, Keefer et al. (in press) found no evidence for attraction among conspecifics during laboratory trials. PIT-tagged lamprey released into the AWS channel required less time to find and enter the LPS collector in 2005 than in previous years.

In 2004, PIT-tagged fish were detected in the LPS collector 0.5-42 d after release (median = 4 d; Moser et al. 2006). For branded fish released into the AWS in 2003 and recaptured in the LPS collector, time at large was even longer (median > 6 d; Moser et al. 2005a). However, in 2005 median time from release to first detection in the LPS collector was only 1.7 d.

While all of these measures indicated improvement in LPS performance, there was no indication that this improvement was due to low flow in the LPS. Differences in the number and percent of lamprey using the LPS between high and low flow treatments were not statistically significant. In fact, slightly more fish used the structure during the high flow than during the low flow treatment. In addition, there was no evidence that during the low flow treatment lamprey passed through the structure significantly faster or with greater success.

As in 2004, PIT-tagged lamprey that entered the LPS moved through it quite rapidly, had high passage success rates, and exhibited few fallbacks. In 2005, median time to pass through the LPS was 1.5 d, while in 2004 it was 1.1 h (Moser et al. 2006). In both years, lamprey took longest to traverse the steep ramp. Of the PIT-tagged fish detected in the LPS in 2005, 94% passed the PIT antenna at the exit slide, indicating successful passage through the structure. In 2004, 96% of the lamprey that entered the LPS passed to the PIT antenna at the exit slide (Moser et al. 2006). Most (95%) of the fish that did not successfully pass the LPS fell back at the steep ramp.

Fish that were not detected at the exit slide (PIT 4) in each year may have been missed due to PIT antenna outages or tag collisions. In 2004, 60% of the presumptive fallbacks occurred on a single night (5 July), and in 2005, 75% of them occurred in the period 11-17 June, many on only one night (14 June). We noted that 17 fish attempted to climb the steep ramp, fell back downstream, and then successfully passed through the LPS several days later. Of these, 71% made their first attempt during 13-15 June. This indicates that some lamprey failed to pass the LPS during those few days in June, and that this failure was not an artifact of missed detections. The presence of predators on the LPS or human interference might have elicited this response.

Alternatively, a short-term pump failure might have periodically interrupted flow on the steep ramp and reduced passage success on those nights. Of the PIT-tagged lamprey that passed through the LPS, 6% were subsequently detected at the Bradford Island fishway exit. The exit slide drops lamprey into the Bonneville Dam forebay approximately 10 m to the east and upstream from the Bradford Island fishway exit.

Lamprey may become disoriented during passage through the exit slide and fall back downstream after landing in the forebay. The fact that 95% of these fish were detected at the exit less than 25 min after passing PIT 4 lends credence to this hypothesis. Two of these fish were later detected at upstream dams, indicating that they were able to resume upstream passage after their foray into the fishway exit. Efforts to provide a less abrupt exit from the LPS may help to reduce the fallback behavior we observed in 2005.

There was evidence that some lamprey that passed through the LPS ultimately migrated upstream past The Dalles Dam. PIT antennas operated at both McNary and Ice Harbor dams detected lamprey we had tagged and released at Bonneville Dam; however, the relatively low detection efficiency at these antennas made it difficult to estimate true escapement above The Dalles Dam (Keefer et al. in press). Some PIT tags were also collected by tribal members during lamprey harvest at Sherar's Falls in the Deschutes River (J. Graham, Warm Springs Tribal Fisheries, personal communication); however, whether these fish had used the LPS is not known.

In addition to the lamprey released in 2005, we detected 3 lamprey in the LPS that were tagged and released in 2004 (Moser et al. 2006). All of these fish passed successfully through the LPS during the summer of 2005, two of them on the same day. While it is unknown whether these lamprey overwintered together in the AWS channel, these data provide irrefutable evidence that lamprey will resume upstream migration in their second season in freshwater. It is possible that even more lamprey tagged in 2004 would have attempted to use the LPS in 2005 if it had been operated starting in April, when water temperatures increase and stimulate lamprey to resume migration (Robinson and Bayer 2005).

In 2005 we released some PIT-tagged lamprey downstream from Bonneville Dam to obtain estimates of overall passage route used by these fish. We found that 3% of the lamprey used the AWS LPS and another 5% entered the AWS channel but did not enter the LPS. In addition, 15% were detected at the Bradford Island fishway exit and were not detected either in the LPS or AWS channel. Thus, 23% of the PIT-tagged lamprey released below Bonneville Dam made their way to the top of the Bradford Island fishway, but only 15% used the fishway exit. This finding was similar to that of radiotelemetry studies during 2001 and 2002. In both years, an estimated 17% of lamprey released below the dam made it to the count window, but only 15% in 2001 and 12% in 2002 successfully passed through the fishway exit. (The dam was operated with Powerhouse 2 priority in both years; Moser et al. 2005a.)

Greater increases in overall lamprey passage might be achieved if passage impediments to lamprey could be successfully mitigated at Bonneville Dam fishway entrances (Moser et al. 2002a,b, 2005a). In 2005, we designed, fabricated, and installed a prototype LPS collector at the downstream north main entrance to the Washington-shore fishway. Due to difficulties encountered during installation, the structure was not operational until after the peak of lamprey migration. Nevertheless, 4 lamprey used this structure, including one very small specimen (58 cm total length, 272 g). A complete year of operation is needed to fully evaluate the efficacy of this collector. However, the fact that some lamprey found the LPS collector entrance in spite of rapid, turbulent currents, and that they were able to traverse its relatively long, steep ramp, is a promising early result.

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REFERENCES

CRLTW (Columbia River Lamprey Technical Workgroup). 2005. Critical uncertainties for lamprey in the Columbia River Basin, April 19, 2005. Report of the Columbia Basin Fish and Wildlife Authority. Available www.fws.gov/columbiariver/ lampreywg/docs.htm (March 2008).

Daigle, W. R., M. L. Keefer, C. A. Peery, and M. L. Moser. In press. Evaluation of adult Pacific lamprey passage rates and survival through the lower Columbia River hydrosystem. Report to U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Keefer, M. L., W. R. Daigle, C. A. Peery, and M. L. Moser. In press. Adult Pacific Lamprey Bypass Structure Development: Tests in an experimental fishway, 2004-2006. Report to U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Moser, M. L., and D. A. Close. 2003. Assessing Pacific lamprey status in the Columbia River Basin. Northwest Science 77:116-125.

Moser, M. L., A. L. Matter, L. C. Stuehrenberg, and T. C. Bjornn. 2002a. Use of an extensive radio receiver network to document Pacific lamprey (*Lampetra tridentata*) entrance efficiency at fishways in the lower Columbia River. Hydrobiologia 483:45-53.

Moser, M. L., P. A. Ocker, L. C. Stuehrenberg, and T. C. Bjornn. 2002b. Passage efficiency of adult Pacific lampreys at hydropower dams on the lower Columbia River, U.S.A. Transactions of the American Fisheries Society 131:956-965.

Moser, M. L., D. A. Ogden, D. Cummings, and C. A. Peery. 2006. Development and evaluation of a lamprey passage structure in the Bradford Island Auxiliary Water Supply Channel, Bonneville Dam, 2004. Report of the National Marine Fisheries Service to the U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Moser, M. L., D. A. Ogden, S. G. McCarthy, and T. C. Bjornn. 2003. Migration behavior of adult Pacific lamprey in the lower Columbia River and evaluation of Bonneville Dam modifications to improve passage, 2001. Report of the National Marine Fisheries Service to the U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Moser, M. L., D. A. Ogden, and C. A. Peery. 2005a. Migration behavior of adult Pacific lamprey in the lower Columbia River and evaluation of Bonneville Dam modifications to improve passage, 2002. Report of the National Marine Fisheries Service to the U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Moser, M. L., L. C. Stuehrenberg, W. Cavender, S. G. McCarthy, and T. C. Bjornn. 2002c. Radiotelemetry investigations of adult Pacific lamprey migration behavior: evaluations of modifications to improve passage at Bonneville Dam, 2000. Report of the National Marine Fisheries Service to the U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Moser, M. L., R. W. Zabel, B. J. Burke, L. C. Stuehrenberg, and T. C. Bjornn. 2005b. Factors affecting adult Pacific lamprey passage rates at hydropower dams: using 'time to event' analysis of radiotelemetry data. Pages 61-70 *in:* M. L. Spedicato, G. Marmulla, and G. Lembo, editors. Aquatic Telemetry: advances and applications. FAO-COISPA, Rome.

Robinson, T. C., and J. M. Bayer. 2005. Upstream migration of Pacific lampreys in the John Day River, Oregon: behavior, timing, and habitat use. Northwest Science 79:106-119.