Development and Evaluation of a Lamprey Passage Structure in the Bradford Island Auxiliary Water Supply Channel, Bonneville Dam, 2004

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EXECUTIVE SUMMARY

The serpentine weirs near the top of the Bonneville Dam fishways are obstacles to upstream passage of adult Pacific lamprey *Lampetra tridentata*. Radiotelemetry studies have indicated that lamprey are delayed and fall back in this area and often enter the adjacent auxiliary water supply (AWS) channels, which provide no ready outlet to the dam forebays. In 2002-2003, we developed and installed a bypass collector and determined that lamprey could be bypassed into the Bonneville Dam forebay from the Bradford Island AWS channel. In these studies, lamprey were collected from the AWS channel and carried to the dam forebay for release. In 2004, our objective was to extend the Lamprey Passage Structure (LPS) so that lamprey could volitionally move from the collector in the AWS, through a series of rest boxes, and into the forebay of Powerhouse 1.

The LPS was constructed of aluminum and achieved a total elevation gain of 10 m over a distance of 36 m. It featured four rest boxes that served as “one-way valves” to prevent lamprey from backing downstream, while affording a low-velocity area for lamprey to rest. To evaluate lamprey movement through the LPS, we installed a half-duplex passive integrated transponder (PIT) detector immediately downstream from each rest box. In addition, we installed a video monitoring system and lamprey-activated counter immediately downstream from the LPS exit to allow enumeration of lamprey that used the structure. We surgically implanted 1,493 adult Pacific lamprey with PIT tags and released them either directly into the LPS or into the Bradford Island AWS channel.

After extensive testing, an accurate lamprey-activated counter was developed, and we estimated that nearly 7,500 lamprey passed through the LPS from mid-June to mid-September (about 21% of the estimated number of lamprey that used the Bradford Island fishway during the testing period). The LPS was nearly maintenance-free, and the individual PIT detectors had detection efficiencies of 0.94-0.97.

Using the PIT-tag detectors, we determined that of the tagged lamprey released in the AWS channel, 25% entered the LPS. In addition, of the lamprey that were released into the LPS and fell back, 15% subsequently re-entered the structure. PIT-tagged lamprey negotiated the LPS rapidly, spending relatively little time in the rest boxes. The median travel time from the first rest box to the LPS exit was about 1 h, and after initiating upstream movements, very few lamprey fell back downstream in the structure. At the LPS exit, we detected 92% of the lamprey released directly into the LPS and 96% of those that had volitionally entered the LPS after release in the AWS channel. The results of this work indicate that bypass devices of this type can aid lamprey passage at obstacles throughout the Columbia River Basin.

CONTENTS

INTRODUCTION

Restoring migration corridors for anadromous Pacific lamprey *Lampetra tridentata* has been identified as one of the most important needs for recovery of declining populations in the Columbia and Snake Rivers (CRLTW 2005). Adult lamprey must negotiate four mainstem hydropower dams to reach the confluence of the Columbia and Snake Rivers, and to attain spawning areas in headwater streams, they must pass up to five additional dams. Radiotelemetry studies have determined that adult lamprey passage at lower Columbia River dams is poor relative to that of salmonids, and have identified particular fishway structures that are obstacles to lamprey passage (Bjornn et al. 2002a, 2000b; Moser et al. 2002a,b, 2005c).

At Bonneville Dam, adult lamprey are obstructed or delayed at fishway entrances, collection/transition areas at the bottom of the fishways, and count-station 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 the 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. Lamprey exhibit relatively higher passage efficiency and are delayed less at The Dalles than at Bonneville Dam (Moser et al. 2002b, 2005).

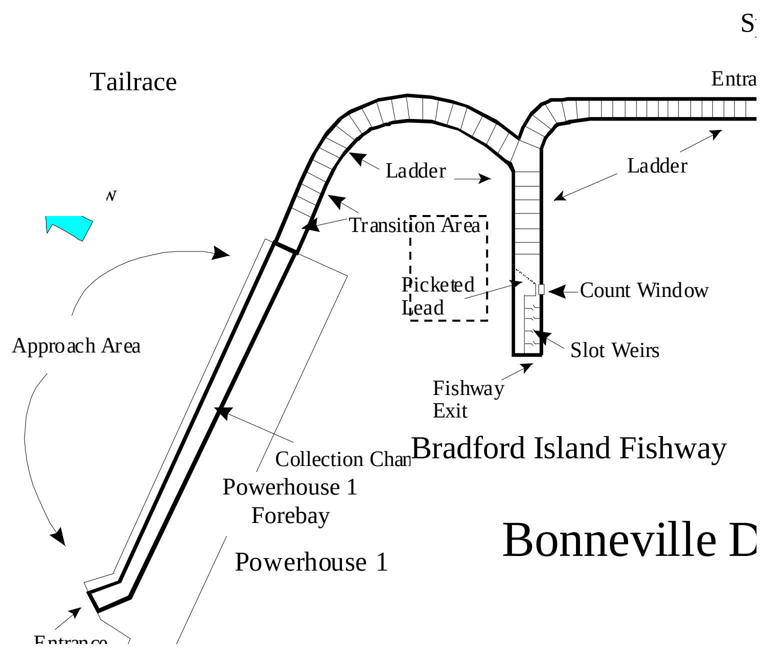

Figure 1. Schematic drawing of the Bradford Island fishway system at Bonneville Dam. The top of the fishway is indicated in the dashed box.

Construction differs between Bonneville and The Dalles Dams in the flow-control section at the top of the fishways. At Bonneville Dam, this part of the fishway has serpentine weirs (Figure 2, top), whereas at The Dalles Dam there are overflow weirs at the top of fishways. At the top of Bonneville Dam fishways, adult Pacific lamprey are routinely delayed and/or obstructed by the serpentine weirs located immediately upstream from the count stations at both the Bradford Island and Washington-shore fishways (Moser et al. 2002c, 2003b, 2005a). In contrast, at the Dalles Dam from 1997 to 2002, 99% of radio-tagged lamprey that approached the top of fishways passed successfully over the dam (Moser et al. 2005a).

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

At Bonneville Dam, lamprey that are obstructed by the serpentine weirs can move into the adjacent auxiliary water supply channel (AWS) through connecting diffuser gratings. In addition, some lamprey move into the AWS channel via the picketed lead downstream from the count stations (Figure 3). There is no ready access to the forebay of Bonneville Dam from the AWS channel, and radiotelemetry indicated that lamprey delay in the channel for an average of 4 d, and then typically fall back downstream.

In 2002 and 2003, we designed, installed, and tested lamprey collectors in the Bradford Island AWS to see if lamprey could be attracted into a lamprey-specific fishway. The results of this work were encouraging. Up to 18% of the lamprey that we marked and released into the AWS were collected in an “open ramp” type of collector. By the end of 2003, over 5,400 lamprey had been collected from AWS channels during the course of the experiments. These fish were released above Bonneville Dam by placing them into a chute that emptied into the forebay upstream from Powerhouse 1 (Figure 1).

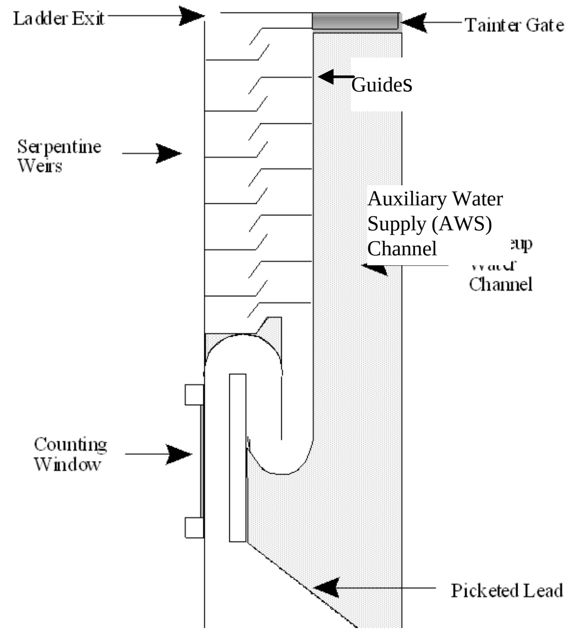

Figure 3. Detail of the top of the Bradford Island fishway.

Our objective in 2004 was to extend the lamprey passage structure (LPS) so that lamprey could move volitionally from the Bradford Island AWS channel into the forebay of Bonneville Dam. The goal was a relatively maintenance-free that lamprey could pass through rapidly and with minimal exertion. In addition, accurate daily counts of the number of lamprey that used the LPS were needed to evaluate the structure. We used half-duplex passive integrated transponder (PIT) technology to monitor lamprey passage events, determine rates of passage through the LPS, and estimate overall passage efficiency of the LPS.

METHODS

Structure Tested

In previous years, the LPS collector was positioned on the west wall at the upstream end of the Bradford Island AWS channel (Figure 3). Guides were installed during winter dewatering and were placed so that the entrance to the passage structures was approximately 15 m downstream from the Tainter gate at the upstream end of the AWS channel. In 2004, the same guides were used, and the collector ramp was installed at this location (see Moser et al. 2005a for details of collector construction).

The 0.5-m wide collector ramp was made of schedule-40 aluminum and extended from the bottom of the AWS channel to the level of the first rest box (3.3-m elevation, Figure 4). Lamprey could enter the collector ramp at any depth in the water column. A heavy rubber flange was used to create a seal against the wall and floor of the AWS channel and to help guide lamprey onto the ramp (see Moser et al. 2005a).

Figure 4. Photo of the Bradford Island LPS collector. Arrow points to a lamprey that is moving up the ramp near the water surface.

After ascending the 4.4-m long ramp (slope = 1:1), lamprey entered a 1.1-m long open, horizontal, rectangular chute (15.2-cm high H 20.3-cm wide) that emptied into Rest Box 1 (Figures 5 and 6). The end of the chute was fitted with a funnel made of 1.2-cm plastic mesh to prevent lamprey from passing back down the structure after entering the rest box. This “one-way valve” design was incorporated into each LPS rest box.

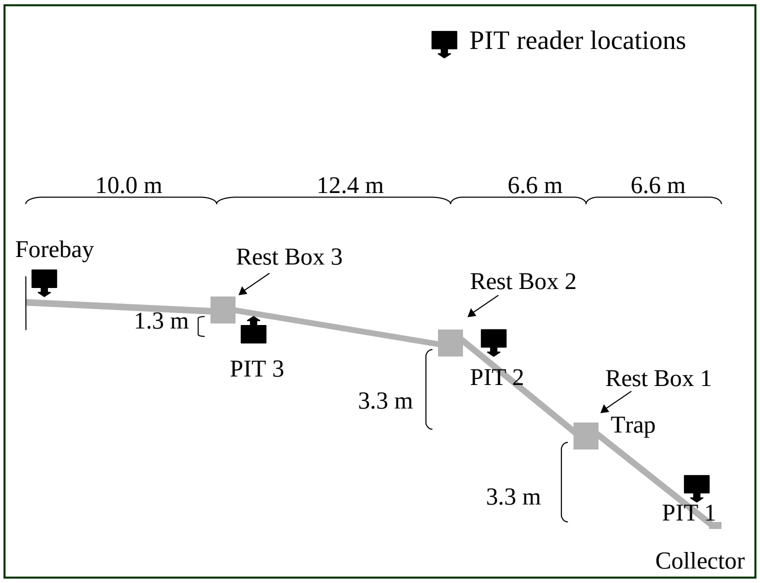

Figure 5. Schematic drawing of the Bradford Island LPS in side view. The light gray squares represent rest boxes and the black boxes indicate the location of PIT readers.

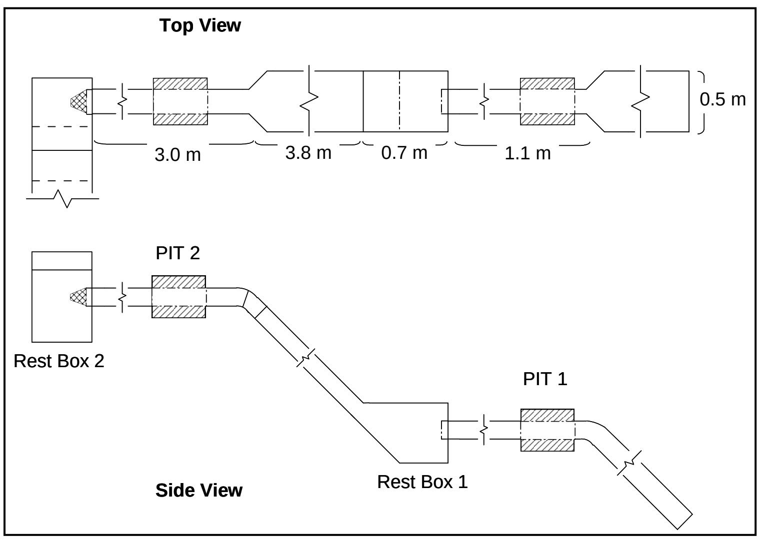

Figure 6. Top and side schematic views of the LPS section from Rest Box 1 to Rest Box 2.

Rest Box 1 held approximately 0.5 m^3 of water and was lined with a perforated aluminum plate. Lamprey could exit Rest Box 1 via a ramp of the same basic construction as the collector ramp (1:1 slope).

This ramp (referred to as the "steep ramp") was 3.8 m long and terminated in an open chute, similar to that at the upstream end of the collector (Figure 6). Lamprey passed through the chute and dropped into Rest Box 2.

From Rest Box 2, the LPS turned 90° to the east (up to this point, the LPS was oriented north-south, Figure 7). Lamprey entered at the north end of the rest box and could exit only to the east. Upon exiting Rest Box 2, they started up a 3.7-m, shallow (0.3:1) ramp (hereafter referred to as "shallow ramp"). At the top of this ramp, they entered a straight tube (8.1-m-long H 15.2-cm high H 20.3-cm wide), dubbed "straightaway," before dropping into Rest Box 3 (Figure 8). The straightaway was fitted with a hinged lid to allow observation of lamprey passing through it while protecting the lamprey from avian predators.

At Rest Box 3, the LPS turns 90° to the south (i.e., lamprey entered from the west and exited to the south, Figure 7). Upon exiting Rest Box 3, lamprey negotiated a 1-m long, 45° ramp up to a 9.6-m long closed tube ("home stretch"). At the end of this tube the lamprey passed through a plastic mesh funnel and dropped into an exit slide (30-cm diameter PVC pipe) that was lined with plastic mesh to prevent lamprey attachment (Figure 9). The 3-m long slide dropped the lamprey into the forebay of Powerhouse 1 approximately 10 m upstream from the Bradford Island fishway exit.

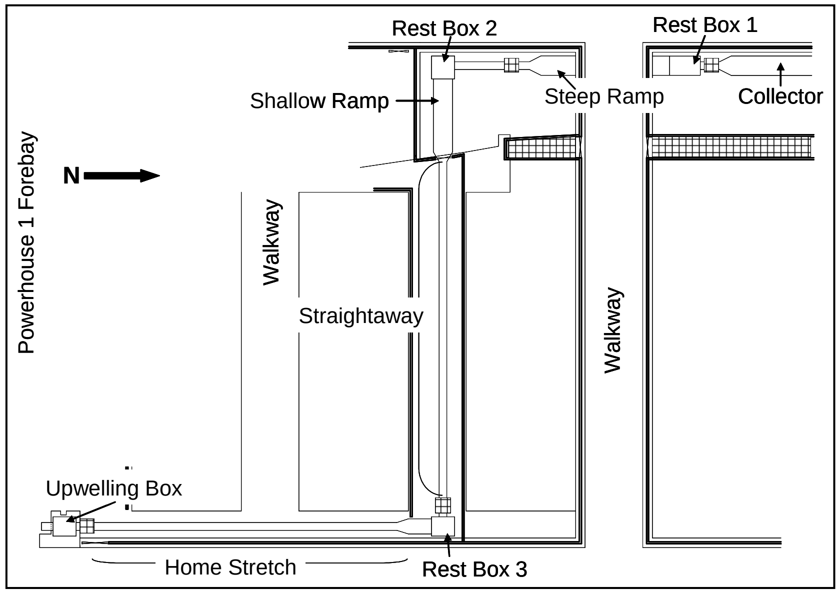

Figure 7. Top view of entire LPS structure.

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. This flow regulation was achieved using an upwelling box at the top of the LPS (Figure 9). In this way, lamprey were stimulated to move onto the exit slide, even though water was passing down the slide. Water velocity through each section of LPS was estimated by floating a drogue down the LPS four times and computing mean velocity.

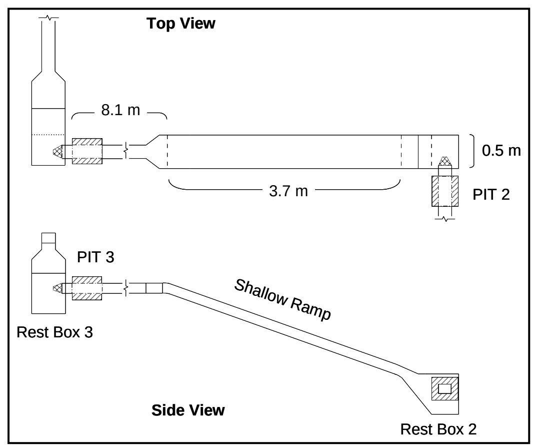

Figure 8. Schematic showing top and side views of the LPS section from Rest Box 2 to Rest Box 3.

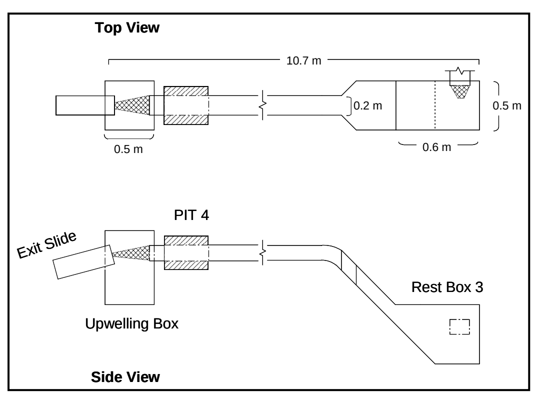

Figure 9. Schematic showing top and side views of the upstream LPS section from Rest Box 3 to the exit slide.

A series of four half-duplex PIT readers was integrated into the LPS design (Figure 4). A rectangular schedule-40 PVC sleeve was seamlessly inserted into the chutes leading to each rest box and to the exit slide (Figure 7). This was necessary because the aluminum chute itself would attenuate the PIT signal. Each reader was comprised of the following elements: 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 that interrogated the antenna; and a palmtop computer that logged the time and date of each detection to a 256-mB memory card. We synchronized the detectors by wiring them together.

Several different methods were tested to obtain counts of lamprey as they exited the LPS. In the chute leading to the exit slide, we installed infrared lighting and a video camera to allow visual enumeration of lamprey passing through the chute. The camera was connected to a time-lapse video cassette recorder and a monitor. In addition, we attempted to obtain lamprey counts via two types of lamprey activated switches: a mechanical lever and an infrared beam.

The first iterations of the lamprey activated switches were installed in the upwelling box located at the top of the exit slide. As the lamprey entered the box, they passed through a plastic mesh funnel that forced them to move through a narrow opening (approximately 5 cm). We tested a variety of limit switch sensitivities and positions near this constriction point. Next, we tested an infrared detector installed in the same location. The lamprey's body interrupted an infrared beam and thereby triggered the switch.

Figure 10. Lamprey activated switch at the terminus of the LPS exit slide.

In each case, these devices were wired to an event recorder so that the number of lamprey that activated the switch could be recorded. Ultimately, we attached the limit switch to a large paddle, which was fitted into the slide near its terminus (Figure 10). As the lamprey fell through the slide, they contacted the paddle, and the switch was activated. The switch was connected to a digital event recorder that recorded the number of lamprey passing the switch.

We were concerned that water temperature in the LPS might be elevated in summer due to direct solar radiation and high air temperature. To monitor LPS water temperature, we installed a temperature logger (Onset Hobo) in the middle of Rest Boxes 2 and 4 (Figure 4). The loggers recorded water temperature every 15 min throughout the study.

Testing Protocol

Lamprey passage through the LPS was determined by reviewing and recording passage events captured on videotape. The daily counts of lamprey from the videotape recordings were then compared to counts from the event recorder to assess the accuracy of the different types of counters. We also made visual observations of lamprey use of the LPS, during which we recorded passage time for each LPS section and any fallback events (downstream movement in the LPS).

Passage times were also obtained using detection data from PIT-tagged lamprey. For these experiments, we collected lamprey using 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 running Columbia River water.

After anaesthetizing lamprey using 60-ppm clove oil, we measured the weight of each to the nearest g, total length to the nearest 0.5 cm, and girth at the insertion of the anterior dorsal fin to the nearest 0.1 cm. 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 × 23 mm) was inserted into the body cavity.

Prior to PIT-tagging work, we experimented with three different incision treatments: closed with sutures, closed with cyanoacrylic cement (glued), and not closed. All treatment groups were held in the laboratory for one week. The incisions from all treatment groups healed at the same rate, and there was no evidence of tag loss. Based on these results, we made no attempt to close the incision of PIT-tagged fish and thereby minimized handling stress. Tagged lamprey were allowed to recover from the anesthetic and were released on the day of tagging.

Most PIT-tagged lamprey were released directly into the LPS by carefully lowering them onto the steep ramp, so that they could slide into Rest Box 1 (Figure 4). To avoid crowding in the rest box on a given day, half of the lamprey were released in the morning (0800-1200) and half were released in the evening (1800-2300).

Figure 11. PIT-tagged lamprey being lowered into the Bradford Island AWS.

Some PIT-tagged lamprey were also released directly into the AWS to obtain estimates of LPS efficiency. To help lamprey acclimate upon release, they were lowered into the AWS in an open aluminum release box (Figure 11). 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 detected in the LPS by the total number of AWS releases. However, the study area was not closed. Lamprey could leave the AWS by falling back downstream through the picketed lead and into the Bradford Island fishway (Figure 3). This would result in an underestimate of LPS efficiency.

We also used PIT detections to compute:

1) Time from release to first detection for each fish.
2) Time to traverse the LPS sections between PIT readers (defined as the time between last detection at a reader and first detection at the subsequent reader) for each fish.
3) Direction of lamprey movement in the LPS.
4) PIT-reader detection efficiency.
5) Percentage of lamprey that successfully passed through the LPS.

For PIT-tagged lamprey that entered the LPS from the AWS channel, we used linear regression to examine the role of lamprey size and release date on passage time through the shallow, straight ramp sections between PIT 2 and PIT 4. Similarly, we tested for correlation between these continuous variables and the time lamprey required to move up the steep ramp section between PIT 1 and PIT 2.

RESULTS

Lamprey Counts

The LPS was installed by 3 June, before lamprey counts at the Bradford Island Count Station had peaked (Figure 12). We observed a lamprey using the LPS and successfully passing into the forebay of Bonneville Dam on the same day that the structure was installed. While we were able to make visual observations of lamprey use of the LPS immediately after its installation, the video system and lamprey activated counter were not fully functional until 17 June.

From 17 to 23 June, the counter consisted of a lever that the lamprey contacted as they entered the upwelling box near the exit slide. When we compared the visual observations to the number of lamprey counted, we found that the counter was detecting passage of only one in every three lamprey. To correct this problem, we moved the lever slightly closer to the exit slide, but about every other lamprey was still able to pass under it and was not detected.

From 28 to 30 June, a more sensitive lever was used so that less lamprey contact was required to activate the limit switch. However, this resulted in multiple counts of the same lamprey (2-3 times the actual number). The switch was repositioned to several different locations during 1 to 16 July, but the resulting counts still overestimated the actual number of lamprey by 2-5 times.

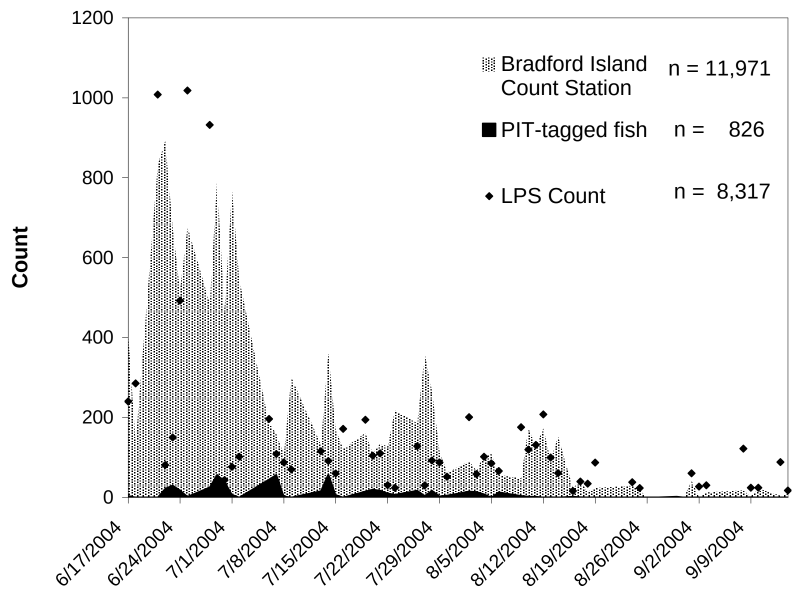

Figure 12. Numbers of lamprey counted at the Bradford Island count station, detected in LPS PIT tag readers, and counted at the upstream end of the LPS.

From 19 July until 19 August we experimented with multiple pads that the lamprey had to contact to activate the switch. This arrangement still did not produce an accurate count, and overestimated by 1.2–2.5 times the actual number of lamprey.

On 25 August we installed two completely new counters: an infrared beam counter in the upwelling box, and a mechanical limit switch at the distal end of the exit slide. Testing from 26 August to 14 September revealed that the beam counter always over-represented the number of lamprey passing. In contrast, the mechanical counter (Figure 10) produced accurate counts of lamprey falling through the exit slide.

The estimated number of lamprey that used the LPS in the period from 17 June to 14 September (based on video and corrected counter data) was 8,317, with a peak at the end of June that coincided with the peak of lamprey counts at the Bradford Island Count Station (Figure 12). This number included 826 PIT-tagged fish that were known to have exited the LPS on days when counts were estimated (Figure 12).

Water Velocity and Temperature in the Lamprey Passage Structure

Water velocity estimates ranged from 4.0 to 6.3 m/s on the steep ramp (mean 4.7 m/s) and from 2.0 to 2.4 m/s on the shallow ramp (mean 2.1 m/s). Velocity was 0.9 m/s in the straightaway and 1.1–1.3 m/s in the home stretch (mean 1.2 m/s).

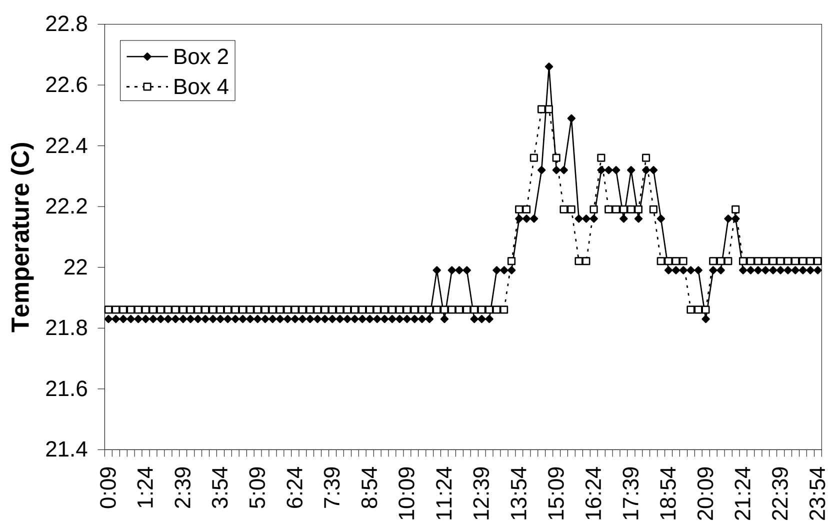

Figure 13. Water temperature recorded every 15 min in LPS Rest Boxes 2 and 4 of the Bradford Island lamprey passage structure on 7 August 2006.

In spite of relatively slow water movement through the flat stretches of the LPS, there was no evidence that water temperature increased significantly between Rest Boxes 4 and 2. Water temperature measured at 15-min intervals during a hot summer day (7 August) revealed differences in water temperature of no more than 0.2°C between the two boxes (Figure 13). The difference in water

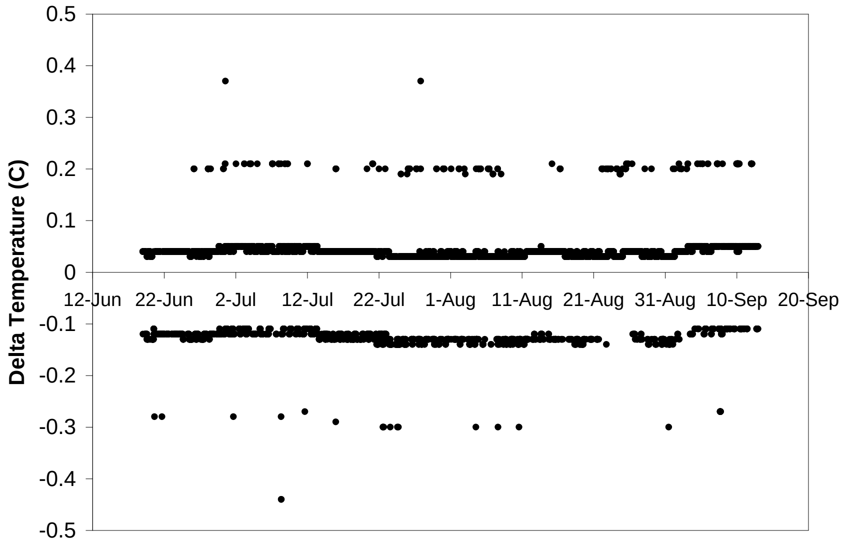

Figure 14. The difference in water temperature (Δ°C) between Bradford Island LPS Rest Box 2 and Rest Box 4 during 2006.

temperature between the two rest boxes rarely exceeded 0.2°C during the entire period of LPS deployment (Figure 14).

Lamprey Tagging and Release

We PIT tagged and released 1,493 lamprey from 17 June to 12 August. We released most of these fish (1,220) directly into the LPS, with a smaller sample (269) released into the AWS channel. The four remaining tagged fish had unknown release locations. All of the AWS releases were made after 19 July, when water temperatures exceeded 20°C.

Releases to the Lamprey Passage Structure

Of the 1,220 PIT-tagged lamprey released directly into the LPS, 133 (11%) were never detected after release; 186 (15%) were detected only on PIT 1 as they exited the LPS (i.e., they fell back downstream and were not detected again); 16 (1%) were not detected upstream from PIT 2; 56 (5%) were not detected upstream from PIT 3; and the remaining 826 (68%) were detected at PIT 4 and apparently exited the LPS into the dam forebay. Therefore, of the 901 lamprey that were detected upstream from the release location, at least 92% successfully exited the LPS.

This is a conservative estimate, because some of the tagged lamprey might have been missed at PIT 4, as they were at other detectors. The detection efficiency of PIT 2 and PIT 3 was evaluated by determining the number of PIT-tagged fish that were missed by one or both of these readers but detected further upstream in the LPS. For PIT 2, detection efficiency was 0.97 (872/901), i.e., 29 passages were missed. Similarly, detection efficiency of PIT 3 was 0.94 (828/885), that is, 57 were missed by PIT 3.

Many passage events that were missed can be attributed to arbitrary power outages to all or a part of the PIT-tag detection system. For example, 17 passage events were missed by both PIT 2 and PIT 3 during a partial outage of the system on the evening of 22 July. During the same evening, 43 (77%) of the 56 fish that were not detected upstream from PIT 3 were last detected at PIT 2. At the end of the season we were able to trace the source of these random outages to a faulty power supply.

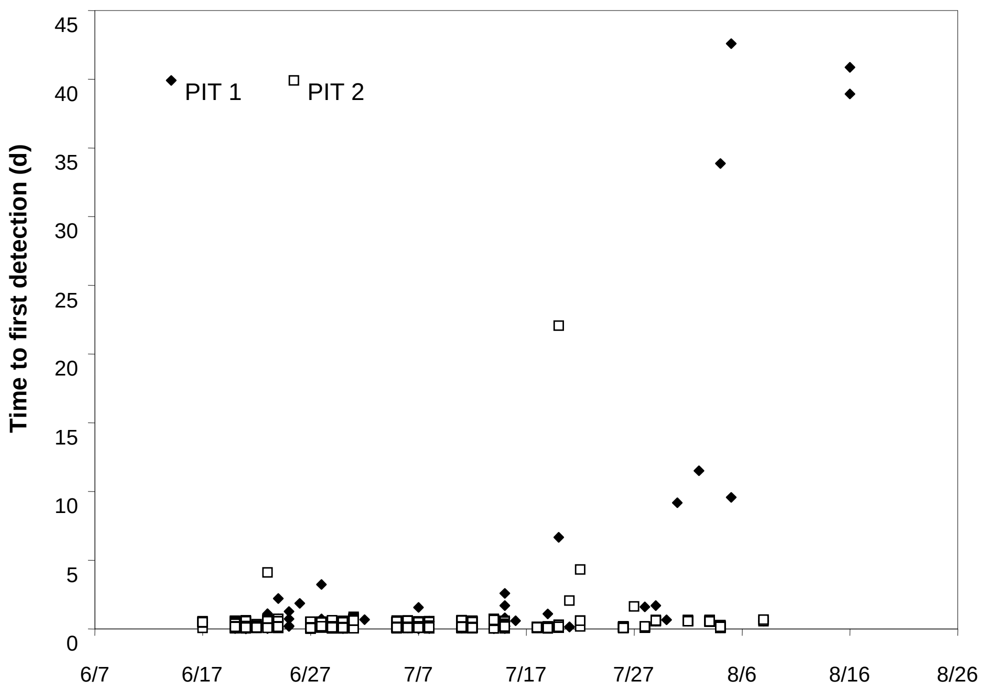

Figure 15. Days from release to first detection at PIT 1 (diamonds) and PIT 2 (squares) for PIT-tagged lamprey released into the LPS in relation to release date.

For all lamprey released into the LPS, the time from release to first detection on a PIT reader ranged from 5 min to 43 d (median 5.0 h). Of these fish, 209 (17%) were first detected at PIT 1 (downstream from the release location, Figure 4). The median time to first detection for these 209 fish was 11 h, but the range encompassed the entire range of times to first detection for all releases to the LPS (5 min to 43 d, Figure 15). The longest times to first detection occurred at the end of the study period, and fish with these longer times were those that re-ascended the LPS after initially falling back downstream and out of the structure (n = 28, Figure 15).

Fish that were not first detected at PIT 1 were either never detected after release (n = 133), had unknown first-detection times (n = 18), or were first detected upstream from their release location: 830 (68 %) at PIT 2, 13 at PIT 3 and 17 at PIT 4. The median time to first detection for fish first detected at PIT 2 was 4.6 h (range 0.5-22.1 h; Figure 15).

A bimodal distribution was apparent among the times to first detection; fish released in the evening were detected within a few hours (median = 2.7 h) of release, while those released in the morning were detected after 12-16 h (median 12.7 h; Figure 16). Three fish that were first detected at PIT 2 were subsequently detected at PIT 1 (i.e., they fell back downstream). Of these, two reascended the LPS (noted above), and one was never detected again.

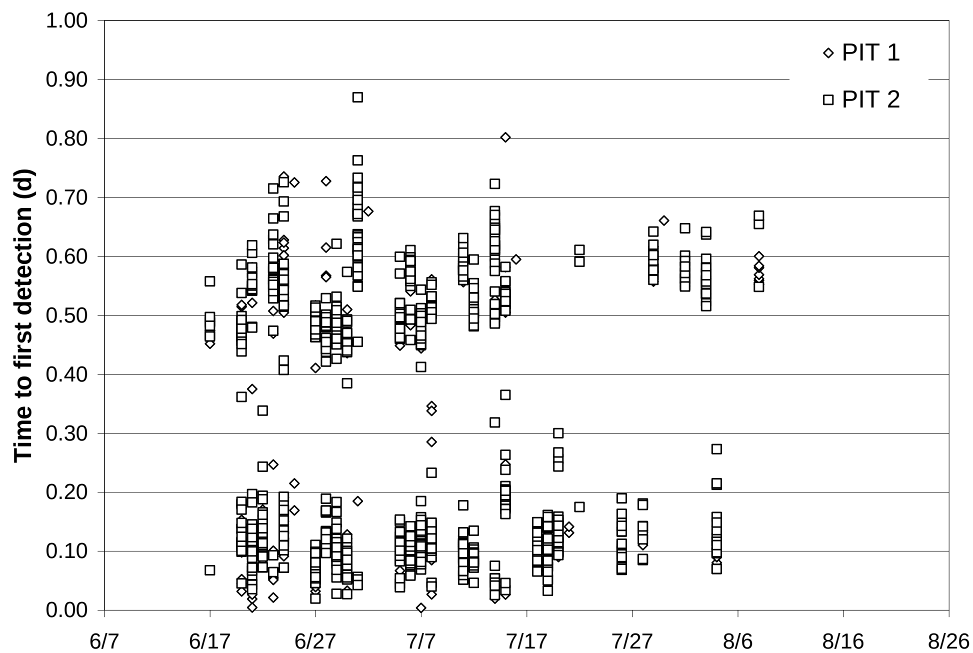

Figure 16. Days from release to first detection at PIT 1 and PIT 2 for PIT-tagged lamprey released into the LPS and first detected less than 1 day after the release date (x-axis).

We computed the time it took for lamprey released into the LPS to travel upstream between PIT-detectors. For this analysis, we included only fish that did not fall back downstream and that had known first and last detection times at each detector. From PIT 2 to PIT 3 (Rest Box 2, shallow ramp, and straightaway section) median time was 0.4 h (range 0.1-22.4 h; n = 741). From PIT 3 to PIT 4 (Rest Box 3, short ramp, and home stretch) the median time was 0.1 h (range 0.04-18.0 h; n = 757). Median time to traverse the entire distance from PIT 2 to PIT 4 was 0.6 h (range 0.2-22.5 h; n = 797).

Releases to the Auxiliary Water Supply Channel

Of the 269 PIT-tagged fish released into the auxiliary water supply (AWS) channel, 68 were detected in the LPS (25%); all but 2 of these fish were detected at PIT 4. In addition to the fish released directly into the AWS, 186 fish that were released into the LPS fell back downstream and into the AWS. Of these, 28 (15%) re-ascended the AWS and all but 2 were detected at PIT 4. Therefore, of the 96 fish that volitionally entered the LPS from the AWS channel, at least 92 (96%) successfully passed through the LPS.

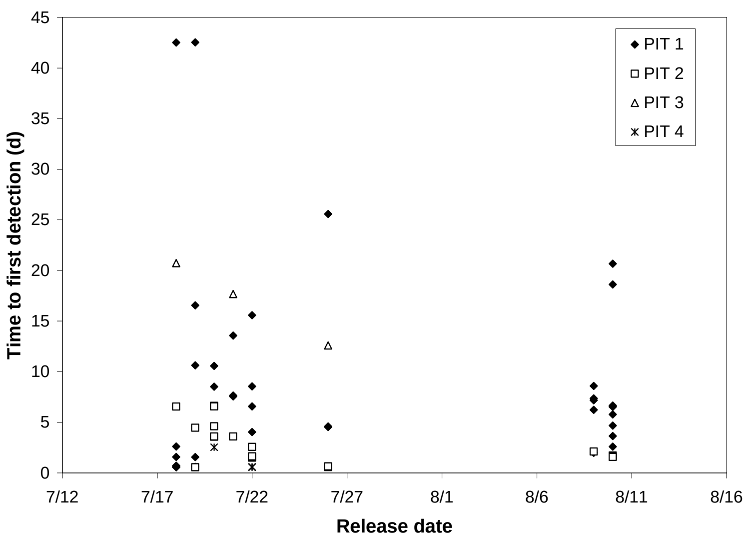

Figure 17. Days from release to first detection at PIT 1, PIT 2, PIT 3, and PIT 4 for PIT-tagged lamprey released into the AWS.

For fish released directly into the AWS channel, time from release to first detection ranged from 0.5 to 42.5 d (median 4.2 d; Figure 17). Most of these fish were first detected at PIT 1 (n = 39); however, 22 were first detected at PIT 2, 4 at PIT 3, and 3 at PIT 4 (Figure 17). Lamprey from 8 of the 9 AWS release groups were detected in the LPS (no lamprey from the last AWS release group was detected in the LPS; Figure 17).

For fish that volitionally entered the LPS, we computed the time required to travel upstream between PIT-detectors. For this analysis, we included only fish that did not fall back downstream and that had known first and last detection times at each detector. From PIT 1 to PIT 2 (Rest Box 1 and steep ramp) median passage time was 0.54 h (range 0.3-25.9 h; n = 55). From PIT 2 to PIT 3, the median travel time was 0.41 h, and from PIT 3 to PIT 4 median travel time was 0.16 h (Table 1). Median passage time over the entire distance from PIT 1 to PIT 4 was 1.14 h (range 0.7-26.4; n = 57; Table 1).

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

	PIT 1 to 2	PIT 2 to 3	PIT 2 to 4	PIT 3 to 4	PIT 1 to 4
N	55	51	83	71	57
			Passage time (h)		
Median	0.54	0.41	0.58	0.16	1.14
Min	0.29	0.25	0.35	0.06	0.73
Max	25.94	5.27	5.41	0.48	26.38

Regression analysis indicated no relationship between release date and the time to traverse the shallow sections (PIT 2 to PIT 4), the steep section (PIT 1 to PIT 2), or the entire LPS (PIT 1 to PIT 4, Figure 18). Lamprey length and girth were not significant factors in any of the regression analyses. However, heavier lamprey took longer to ascend the LPS from PIT 1 to PIT 4, and the effect of weight was most apparent when regressed against the time to ascend the steep ramp (PIT 1 to PIT 2, Figure 19). Lamprey weight had no significant effect on the travel times in the shallow and straight sections of the LPS (PIT 2 to PIT 4, Figure 20).

We made visual observations of lamprey at night as they ascended the LPS and recorded the time that an individual took to traverse a specific area (collector ramp, steep ramp, shallow ramp, straight tube, and home stretch). For lamprey that we saw on the collector ramp (above the water line) median time to climb up that part of the ramp was 6.5 min (range 1.3–26.1 min; n = 44).

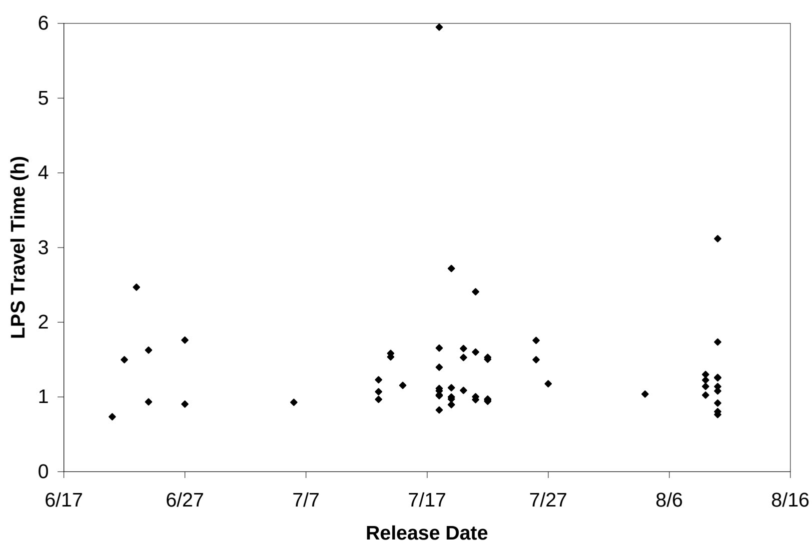

Figure 18. Time (h) that PIT-tagged lamprey took to travel through the LPS (PIT 1 to PIT 4) after entering from the AWS channel.

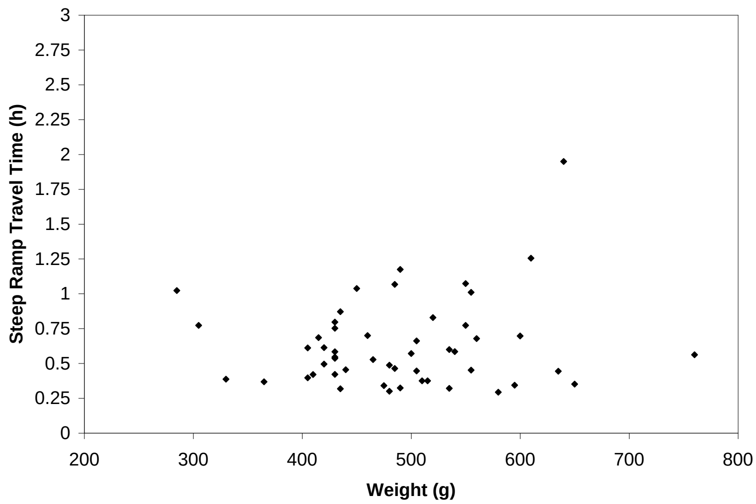

Figure 19. Time (h) that PIT-tagged lamprey took to ascend the steep ramp (PIT 1 to PIT 2) in relation to lamprey weight (g).

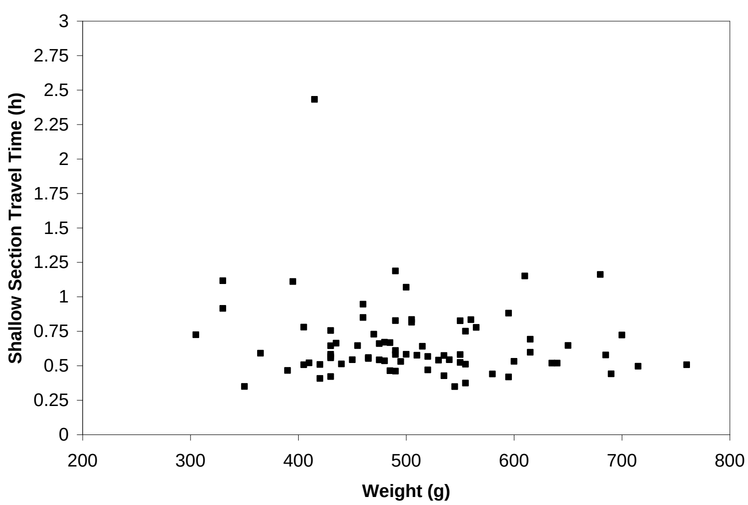

Figure 20. Time (h) PIT-tagged lamprey took to travel from PIT 1 to PIT 2 (shallow section) after entering from the AWS channel in relation to lamprey weight (g).

We were able to view the entire steep and shallow ramps, but it was difficult to keep track of individual lamprey because there were often more than 10 individuals moving up each ramp at the same time. We were able to distinguish and time 31 individuals climbing the steep ramp. The median time of these fish from initial movement onto the ramp to passage into Rest Box 2 at the top was 18.1 min (range 7.5-50.1 min). In contrast, median time to climb the shallow ramp was 6.1 min (range 1.4-9.9 min; n = 13).

Visual observations of lamprey in straight tubes indicated that they could move very rapidly through these sections. After climbing the shallow ramp, the median time to pass through the next straight tube and into Rest Box 3 was 0.4 min (range 0.1-3.4 min; n = 13). Similarly, median time for lamprey to move through the home stretch and exit slide was 1.5 min (range 0.9-21.9 min; n = 6). Visual observations indicated that median passage time from first appearance on the collector ramp to exit into the forebay was 1.6 h (range 0.5-2.5 h; n = 5).

DISCUSSION

An estimated 7,490 untagged fish used the LPS and volitionally passed into the Bonneville Dam forebay from the AWS channel. The LPS was installed in early June, just prior to the peak of adult lamprey migration (as indicated by visual counts at the Bradford Island count station, Figure 8), and lamprey were observed using the structure immediately after installation. The LPS counts were started on 17 June, and the estimated number of untagged lamprey that passed through the LPS was over 60% of the Bradford Island visual count after that date (Figure 12).

We were able to expand the visual counts to estimate the total number of lamprey that passed the Bradford Island count station after 17 June. In previous studies, 33% of the radio-tagged lamprey that passed the Bradford Island count station would have been counted (the remainder passed during the night when counts were not made, Moser and Close 2003a). Using this value, we estimated that the expanded Bradford Island count during the 2004 study period was 35,949. During radiotelemetry studies in 2001 and 2002, the Bradford Island count station area was intensively monitored. In 2001, only 3 (4%) of 73 radio-tagged lamprey entered the AWS without passing the count window (i.e., via the picket lead, Moser et al. 2003b). In 2002, none of the 52 radio-tagged lamprey entered the AWS without having passed the count window (Moser et al. 2005a). Therefore, we assumed that the expanded count (35,949) represented all lamprey at the top of the Bradford Island fishway during the 2004 study. Consequently, an estimated 21% of these fish were counted in the LPS.

The LPS allowed lamprey to volitionally move from the AWS channel into the dam forebay, resulting in higher numbers of LPS lamprey passed in 2004 than in 2003. In 2003, lamprey were collected in a trap at the top of the LPS collector and physically transported to the dam forebay. The LPS was therefore not operated on holidays and weekends. In addition, very high numbers of lamprey in the trap could result in reduced collector efficiency (Moser et al. 2005b). The 37% increase in the number of lamprey passed using the LPS probably reflected the benefits of extending the LPS to the forebay.

Our development of a lamprey-activated counter for the LPS indicated that the simplest design worked best. A mechanical lamprey-activated limit switch in the LPS upwelling box was not successful because the lamprey were able to either pass under the switch without being detected, or were detected multiple times when the switch sensitivity was increased. Similarly, use of an infrared beam to detect lamprey passage was plagued by multiple counts of the same individual. A mechanical limit switch positioned in the LPS exit slide produced reliable counts of lamprey exiting the LPS.

The only potential miscount that could occur with the exit slide counter would result if more than one lamprey hit the paddle at the same time, thus producing an underestimate. The LPS channel at the upwelling box (near the LPS exit) narrows to permit only one lamprey to enter the exit slide at a time. While it is possible that multiple lamprey could simultaneously slide down, we did not observe any instances of this during either video or visual observations.

The LPS was nearly maintenance-free. However, LPS operation required the use of electrical pumps that can fail. On 27 July at 2100, we discovered that the power to water supply pumps was off. Bonneville Dam control room personnel indicated that the power outage had only lasted a short time and the temperature record showed no excessively elevated water temperature on that day. In fact, water temperature between the upper and lower rest boxes rarely differed by more than 0.2°C.

During periods of no flow, oxygen in the rest boxes could become limited. On 10 August during a routine inspection of the downstream-most rest box, the decomposed remains of 6 lamprey were found, along with two PIT tags lying in the bottom of the box. During all other examinations of the rest boxes, no signs of dead lamprey were found. We speculate that the lamprey died during the 27 July power outage. This highlights the need for regular monitoring of pump operations.

There were several outages of the half-duplex PIT detection system. These occurred randomly during the course of the study, and the cause was therefore very difficult to diagnose. Eventually, we found that a faulty power supply unit to the detectors was causing the outages and it was replaced. The less-than-perfect PIT detection rates (0.94 to 0.97) at the detectors probably resulted in large part from these power outages. In fact, 58% of the missed detections at PIT 2 and 30% of the missed detections at PIT 3 could be ascribed to a single power failure on 22 July.

Of the lamprey released directly into the LPS, 11% were not detected after release and 15% were detected only at PIT 1 as they fell downstream and out of the LPS. Fish that were not detected could have: 1) fallen off the LPS ramp during release and directly into the AWS, 2) fallen back downstream and were not detected at PIT 1, or 3) moved through the LPS but were not detected due to outages at all detectors. Over 90% of the fish that were never detected had been released during just four time periods, suggesting that they were missed due to power outages.

The fish released into the LPS and detected only at PIT 1 apparently fell downstream and never re-ascended the LPS. These fish were released by lowering them onto the steep ramp so that they slid down and into Box 1 (located at the top of the collector, Figure 4). There was a mesh fyke between Box 1 and PIT 1. We were surprised that so many lamprey were able to move downstream through this "one-way" valve. The fact that the lamprey were disoriented and undoubtedly milling excitedly after release may have increased the probability of exiting Box 1 going downstream.

Lamprey that were released into the LPS in the evening initiated upstream movement within a few hours of release (median 2.7 h), indicating that they recovered quickly after tagging. Fish released in the morning did not initiate upstream movement until much later after release (median 12.7 h). This was probably because adult Pacific lamprey are primarily nocturnal. Experiments with the LPS collector in 2003 clearly indicated that lamprey only entered the collector at night (Moser et al. 2005b), and radiotelemetry studies confirm that lamprey activity peaks at around midnight (approximately 3 h after most evening releases and 14 h after most morning releases were made) (Moser et al. 2002a).

Of the lamprey released directly into the AWS channel, 25% were detected as they ascended the LPS. In addition, 15% of the lamprey that were released in the LPS and fell downstream past PIT 1 were detected as they re-ascended the LPS. These results are similar to the collector efficiency we estimated in 2003 for the same ramp collector design (18%, Moser et al. 2005b). In that study, lamprey were branded and released into the AWS in the same way that fish were released into the AWS in 2004. A higher percentage of the AWS releases in 2004 used the LPS than in 2003, suggesting that the PIT-tagging procedure had no more negative effect than branding.

As in 2003, we noted that the times at large for marked lamprey released into the AWS were variable (0.5 to 42 d) and that the fish typically did not enter the LPS for several days after release in the AWS (median 4 d in 2004 and 6 d in 2003; Moser et al. 2005b). Radiotelemetry also suggested that lamprey can reside in the AWS for extended periods and can fall back downstream and out of the AWS channel (Moser et al. 2005a). Thus, the collector efficiency was probably under-estimated because marked fish could leave the AWS channel study area.

When the PIT-tagged lamprey started moving upstream in the LPS, they reached the exit slide rapidly (about 1 h) and exhibited little fallback behavior (i.e., downstream movement). At the top of the exit slide, we detected 92% of the lamprey released directly into the LPS and 96% of those that had volitionally entered the LPS after release in the AWS channel. Many of the lamprey that were not detected at the exit slide after initiating upstream movement were probably missed during detector outages. This is supported by the fact that over 60% of the missed fish were last recorded on a single night (5 July). In addition, only 3% of the missed fish were detected moving downstream through the LPS.

The lamprey moved most rapidly through the shallow (18°) ramp and straight sections of the LPS and spent little time in the rest boxes. The median time to pass through Rest Box 2, climb a 4-m long shallow ramp, and pass through an 8-m long straight tube was 24 min. Visual observations indicated that about 6 min was spent on the shallow ramp and only 24 seconds in the straight tube. Thus, lamprey ground speed in the tube was 0.3 m/s, and estimated swim speed (ground speed + current velocity) was 1.5 m/s (2.2 body lengths/s). Similarly, we estimated that lamprey ground speed through the short ramp, home stretch, and exit slide was 0.14 m/s, with an estimated swimming speed of 1 m/s or 1.5 body lenghts/s.

Both visual observations and PIT detections indicated that more than half of the time lamprey took to ascend the LPS was spent traversing the steep ramps. Median times to climb the collector (above the water line) and steep ramps were 26 and 18 min, respectively. Therefore, reducing the time required to ascend the steep ramps would be the best way to reduce overall LPS passage time.

Lamprey ascended both steep and shallow ramps in a saltatory fashion by thrusting forward a few centimeters at a time and then re-attaching with their oral disc. This was repeated several times in a given climbing bout. Climbing bouts were interspersed with long periods of "resting," whereby a lamprey would hang motionlessly on the ramp. However, it is not clear how much energy lamprey expend while hanging vertically in current velocities of over 4 m/s.

The only factor tested that significantly affected lamprey LPS passage time was their weight. Regression analyses of PIT data indicated that time of year/temperature, lamprey length, and lamprey girth had no significant effects on passage times through specific sections or the entire LPS. The heaviest lamprey took longer to pass through the entire LPS, and this effect was most pronounced on the steep LPS sections. Interestingly, lamprey weight did not significantly affect passage times through the shallow and straight sections of the LPS.

The fact that lamprey weight was positively correlated with the time to traverse the steep sections is intuitive. Larger body mass results in both greater drag and requires a larger effort to counteract the effects of gravity, particularly when ramp angles approach vertical. This observation also indicates that tag effects were minimal, as the PIT tag was a proportionately larger burden for small fish.

In summary, the LPS at the Bradford Island AWS channel was relatively maintenance-free, produced a reliable count of lamprey exiting the LPS into the forebay, and provided a rapid and apparently lamprey-friendly passage route for fish that entered the AWS channel. Whether the LPS at this location significantly increases overall passage rates of lamprey at Bonneville Dam is not known.

We estimated that over 20% of all lamprey that approached the top of the Bradford Island fishway eventually found their way into the LPS. However, this estimate assumes that: 1) counts at the Bradford Island count station are accurate, 2) only a third of the lamprey passed the count station during count periods, and 3) no lamprey entered the AWS without passing the count station. If these assumptions are correct, then the 2004 data indicates that nearly all of the lamprey that approached the top of the Bradford Island fishway eventually made their way into the AWS channel (i.e., collector efficiency was also around 20%).

Our mark recapture studies in 2003 produced similar results (Moser et al. 2005b). Based on the same assumptions, we estimated that nearly all of the lamprey that approached the top of Bradford Island must have entered the AWS. Yet, this contradicts radiotelemetry results, which indicate that only 6-17% of the radio-tagged lamprey that passed the Bradford Island count station in 2000-2002 were detected in the AWS (Moser et al. 2002c, Moser et al. 2003b, Moser et al. 2005a). The only way to test overall improvement in lamprey passage efficiency will be to release PIT-tagged lamprey below Bonneville Dam and determine the percentage of these that pass over the dam via the LPS.

Even though the lamprey PIT-tagged in 2004 bore no external marks, we still obtained evidence that they eventually made it to the spawning ground, or at least further upstream. Two PIT tags were found in lamprey that were captured in the Deschutes River tribal fishery (J. Graham, Warm Springs Tribal Fishery Program, personal communication). A third PIT tag was turned in by a member of the Yakama Nation, however, the location of this capture was not known (D. Marvin, Pacific States Marine Fisheries Commission, personal communication). While these data are further testimony to the benefits of providing passage alternatives for lamprey, absolute efficiency estimates of this LPS are needed to determine whether it significantly improves overall lamprey passage at Bonneville Dam.

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