Technical Report 2015-10-FINAL

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For

U.S. Army Corps of Engineers
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Acknowledgements

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Executive Summary

Bonneville and John Day fishway modifications

In 2014, we monitored the passage behavior of radio-tagged adult Pacific lamprey (*Entosphenus tridentatus*) at Bonneville and John Day dams to evaluate the effectiveness of modifications made to improve their passage. At Bonneville Dam, a Lamprey Flume System (LFS) was installed at the north downstream entrance (NDE) of the powerhouse 2 (PH2) fishway in the winter of 2012-2013. A variable-width entrance weir and bollards were installed at the Cascades Island (CI) entrance at Bonneville Dam in 2008-2009. 2014 was the first year evaluating the PH2 modifications and the fifth year evaluating the CI modifications. At John Day Dam, we evaluated lamprey passage behavior at the north entrance (JDN), where modifications similar to CI fishway were made in 2009-2010. Our analytical approach was to compare lamprey passage times and behaviors from pre-modification years to those from post-modification years using a set of five quantitative passage metrics while considering inter-annual variation in environmental and operational conditions. The metrics included: fishway entrance efficiency, fishway exit ratio, fishway approach-to-entry time, entry-to-ladder base time, and proportion of adults requiring > 1 hour to pass these segments. In addition to calculating passage metrics, we summarized general passage behavior at Bonneville, The Dalles, John Day, and McNary dams.

A total of 600 adult Pacific lamprey were collected and double-tagged with a radio transmitter and HD-PIT tag and another 900 lamprey were only HD-PIT tagged at the adult fish facility (AFF) at Bonneville Dam in 2014. An additional 100 lamprey were collected from the John Day lamprey passage structure (LPS), HD-PIT tagged, and released into the John Day forebay. Movements of radio-tagged lamprey were monitored with fixed-site, aerial and underwater antennas attached to radio receivers deployed in the tailraces and at the dams. HD-PIT antennas in dam fishways and in some tributaries were used to monitor movements of the HD-PIT tagged sample and augment movement histories of radio-tagged lamprey. Lamprey behaviors and passage times from 2014 were compared to those from the 2007-2010 lamprey radiotelemetry studies.

Lamprey behavior at the Bonneville Dam modified fishway entrances

Comparison of lamprey behaviors in 2014 to those from pre-modifications years indicated an increase in entrance efficiency, faster approach-to-entrance times, and fewer lamprey with extended passage times from entrance to the base of ladder in 2014. Little variation was observed in the proportion of radio-tagged lamprey that approached PH2 NDE at Bonneville Dam across all study years. NDE entrance efficiency was higher ($P < 0.001$) in 2014 (0.59) than in pre-modification years (2007-2010 *mean* = 0.11). Lamprey approach-to-entrance times at the NDE were also faster (P < 0.001) in 2014 than in pre-modification years. Across all years, lamprey had faster ($P < 0.05$) fishway approach-to-entry times during nighttime hours and as water temperatures increased. Proportionately fewer lamprey ($P = 0.004$) had extended approach-to-entrance times (> 1 h) in 2014 than in pre-modification years. Fishway exit ratios and passage times from the PH2 NDE to the base of the ladder were similar between pre- and post-modification years. Only ten HD-PIT tagged lamprey (0.8% of ~1,200

PIT-tagged fish released downstream) were recorded on the HD array in the Washington-shore LFS. One of the ten reached the LFS terminus with a passage time of 15.3 minutes through the lower LFS.

Comparisons of passage metrics from Cascades Island indicated increased entrance efficiency during the post-modification period, but higher exit ratios and slower passage times in the lower ladder. Entrance efficiencies in post-modification years were higher (P = 0.006) than in pre-modification years. Fishway exit ratios were higher (P = 0.017) in post-modification years (*mean* =0.65) than in the two pre-modification years (*mean* = 0.45). Approach-to-entry times at the CI opening were not different (P = 0.39) between pre-and post-modification years. However, passage times in 2014 were faster (P = 0.014) than in 2010. Across all study years, approach-to-entry times were faster (P = 0.02) at night than during the day. Times from entrance to the ladder base were higher and more fish took longer than 1 h to reach the base of the ladder in post-modification years. Fourteen radio-tagged lamprey were recorded in the CI auxiliary water supply (AWS) channel in 2014. Six (43%) of the 14 fish eventually passed the dam.

Lamprey behavior at the Bonneville count windows

Movements of radio-tagged lamprey near the count windows, serpentine weirs, and AWS channels of the Washington (WA)-shore and Bradford Island (BI) fishways at Bonneville Dam indicated that 30-43% of fish that reached these areas did not pass the dam, consistent with findings from previous years. Similarly, the serpentine weir section of the fish ladders presented significant challenges to lamprey passage in all years. Among tagged lamprey that passed the count windows, 87% and 92% of non-passing fish in the WA-shore and BI fishways, respectively, had their highest ascensions (and turnaround points) in the serpentine weirs.

John Day north entrance

We had no pre-modification data with which to compare 2014 results but entrance efficiencies and fishway passage efficiencies at the John Day north entrance (JDN) in 2014 were relatively high based on other dam passage studies. Specifically, entrance efficiency at the JDN for the single post-modification year (2014) was relatively high (84%, n = 25) and the exit ratio was 19%. The four fish that did not pass the dam turned around upstream from, or near the transition pool. Movements of 154 HD-PIT lamprey detected at the north entrance HD array indicated that the highest percentage of lamprey were detected only on a single, outside antenna on the south side of the fishway (34%), followed by a group with detections on multiple antennas (23%), and then a group at both outside antennas only (14%). Evaluation of the north entrance HD-PIT array for fish that fell back yielded similar results to those from radiotelemetry studies.

General passage at Bonneville, The Dalles, John Day, and McNary dams

General patterns of lamprey behavior and resulting passage metrics calculated at multiple scales were broadly similar to those observed in previous years. Of the 599 radio-tagged lamprey released, 473 (79%) approached a Bonneville Dam fishway, 437 (73%) entered a Bonneville fishway, and 224 (37%) volitionally passed the dam. Another 20 lamprey (3%) were recaptured in the Bonneville fishway traps. At upstream dams, 157 (26%) lamprey were recorded at The Dalles Dam, 48 (8%) were recorded at John Day Dam, and 7 (1%) were recorded at McNary Dam.

On average, lamprey approached Bonneville fishway openings 4.1 times per fish, entered fishways 2.3 times per fish, and of those that entered, lamprey exited fishways into the tailrace 2.4 times per fish. At Bonneville Dam, the largest numbers of fishway approaches, entries, and exits were at PH2. Means at The Dalles Dam were 2.4 approaches, 1.5 entries, and 1.8 exits per fish. Most approaches and entries at The Dalles and John Day dams occurred at the north-shore entrances. Lamprey approached, entered, and exited John Day fishway openings once, on average.

Median dam passage times (i.e., the interval between first tailrace record to last detection at the ladder top) were 5.7 d at Bonneville Dam, 1.3 d at The Dalles Dam, and 1.6 d at John Day Dam. Median times from first fishway entrance to exit from the top of a ladder were 2.1 d at Bonneville, 0.9 d at The Dalles, and 0.8 d at John Day dams. Many lamprey passed quickly through collection channels, transition pools, and ladders, but some took several days or weeks to pass.

Dam passage efficiency (the number of tagged lamprey that passed the dam divided by the number that approached a fishway) were 49-52% (n = 453-473 approached) at Bonneville Dam (first number excludes 20 recaptured fish). Dam passage efficiency was 47% (n = 157) at The Dalles Dam, 83% (n = 48) at John Day Dam, and 100% (n = 7) at McNary Dam. Fishway passage efficiencies (the number of tagged lamprey that passed a dam divided by the number that entered a fishway) were 54-56% at Bonneville Dam (n = 417-437 entered), 67% (n = 111) at The Dalles Dam, 87% (n = 46) at John Day Dam and 100% (n =7) at McNary Dam.

Fishway entrance efficiencies (the numbers of tagged lamprey recorded entering a fishway divided by the numbers recorded approaching the same site) at Bonneville Dam were highest at the PH2 north downstream entrance (~63%) and were lowest at Powerhouse 1 (PH1) south entrances (~12%). Entrance efficiencies at The Dalles Dam were highest at the north entrance (98%) and lowest at the east shore and west powerhouse entrances (33%). Entrance efficiencies at John Day Dam ranged from 85% at the north entrance to 50% at the south-shore entrance.

Fallback percentages (number of unique lamprey that fell back at a dam divided by the unique number that passed a dam) were 1% at Bonneville Dam, 3% at The Dalles Dam, and 35% at John Day Dam. No tagged fish were detected falling back at McNary Dam. Few lamprey reascended fishways after falling back at Bonneville or John Day dams but all fish that fell back at The Dalles reascended and passed.

Introduction

Populations of Pacific lamprey *(Entosphenus tridentatus*) have declined throughout much of their range (Renaud 1997; Close et al. 2002; Kostow 2002; Moser and Close 2003). Dam passage can be difficult for adult migrants and upstream passage failure is believed to be contributing to population declines (e.g., Beamish and Northcote 1989; USFWS 2004; Keefer et al. 2009c; Mesa et al. 2009). In the Columbia River basin, a multi-year series of radiotelemetry and PIT-tag studies have described lamprey passage behavior, passage efficiency, and passage bottlenecks at dams (Moser et al. 2002a, 2002b, 2005; Boggs et al. 2009; Johnson et al. 2009b; Keefer et al. 2009a, 2009b, 2011, 2012, 2013a, 2013b). These and other studies have identified many locations where lamprey have difficulty passing Columbia River dams, including fishway entrances, transition pools, count windows, and serpentine weirs. A variety of steps have been taken to improve lamprey passage, These include development of lamprey-specific passage structures (LPS, Moser et al. 2006, 2011), physical modifications to fishway entrances and fishway floors (Clabough et al. 2010; Keefer et al. 2010), and manipulations of fishway water velocities (Johnson et al. 2010, 2012; Boggs et al. 2010).

The primary objective of this study was to evaluate several major and minor fishway modifications intended to improve passage of adult Pacific lamprey at Bonneville and John Day dams. These modifications were implemented as part of the Pacific Lamprey Passage Plan 2008-2018 (USACE 2014) and were designed to provide easier passage routes for adult Pacific lamprey via improvements to existing entrances (e. g. rounded corners, reduced water velocities, etc.) and by providing separate lamprey passage routes.

During winter 2012-2013, a prototype lamprey flume system (LFS) was installed at the Washington-shore fishway North Downstream Entrance (NDE) of Powerhouse 2 (PH2) at Bonneville Dam (Figure 1). Design elements for this structure were drawn from experience with the Bonneville Dam Lamprey Passage Structure (LPS collectors; Moser et al. 2011) and from behavioral observations in the experimental fishway (Keefer et al. 2010, 2011). The flume system included two alternative entrances with lower entrance velocities and a duct system leading to a LPS collector (Washington Shore Fishway LPS: WSFLPS) that terminated on the tailrace deck. A primary research objective at PH2 in 2014 was to assess behavior and use of the LFS by lamprey as they approached NDE after the LFS was installed.

A variable-width entrance weir and bollards were installed at the Cascades Island (CI) entrance at Bonneville Dam in 2008-2009 (Figure 2; also see Clabough et al. 2010) to improve the passage of adult salmonids and Pacific lamprey. The variable-width weir is thought to improve attraction flows for salmonids while providing a wider opening at the bottom of the weir with reduced entrance velocities for lamprey. The design eliminated lower bulkheads that may have interfered with adult lamprey entering the fishway and it reduced operation and maintenance costs. The modifications also included installation of bollards (a.k.a. “artificial rocks” fabricated as 18” high × 12” diameter stainless steel columns set on 24” centers; Figure 2) designed to reduce near-floor water velocity for entering lamprey, and a new LPS inside the fishway opening that allowed lamprey volitional passage to the the dam forebay.

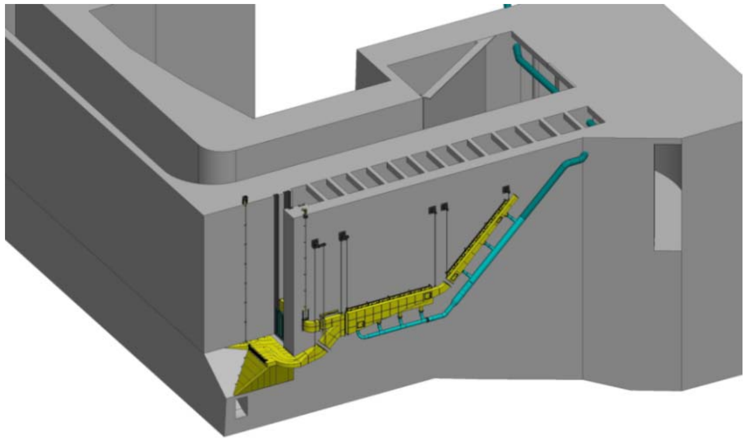

Figure 1. Lamprey flume system (LFS) designed for the Washington-shore NDE.

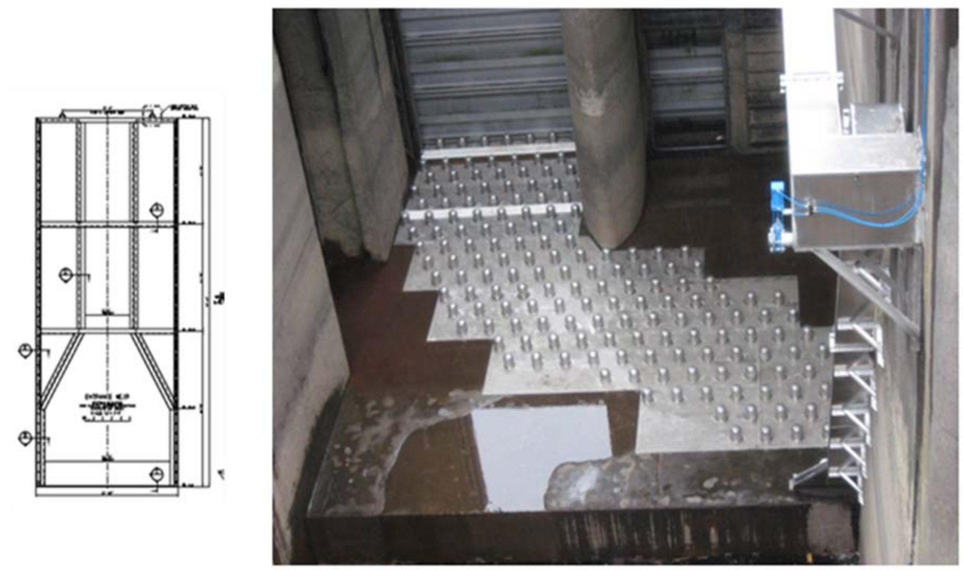

Figure 2. Variable-width entrance weir (line drawing, left) and Bonneville Dam Cascades Island entrance during installation of bollards, Lamprey Passage System (LPS, ascending wall to right in photo), and HD-PIT antennas (white bars spanning opening near entrance bulk head).

Several recent modifications have been made to the north fishway at John Day Dam (JDN). The upper section of JDN was reconstructed during winter 2009-2010. Specific modifications included: 1) removal of existing concrete weirs and the existing sill gates and actuators; 2) construction of new concrete weirs; 3) modification of existing concrete baffles in the transition section located in the non-overflow portion of the fishway; 4) modifications to the floor, diffuser, and the fish counting building; 5) replacement of the existing bulkhead, picket leads, crowder, and light box and the addition of a window washer for the fish counting building (USACE solicitation at http://www.dgmarket.com/tenders/np-notice.do~4109482). In the winters of 2011-2012 and 2012-2013, additional north-fishway modifications were made to facilitate the upstream passage of adult salmonids and adult Pacific lamprey. These modifications included: 1) installation of a variable width entrance weir; 2) closure of one of the two fishway entrance slots; 3) installation of velocity-reducing bollards on the fishway floor just inside the entrance; 4) installation of a lamprey passage structure (LPS) on the north wall just upstream from the entrance; and 5) removal of the first two concrete overflow weirs to increase attraction velocities in the transition area (Figure 3).

Our primary objective at both Bonneville NDE PH2 and CI was to compare fish performance metrics from pre-modification years to those from post-modification years while simultaneously considering interannual variation in environmental and operational conditions. At JDN, our objective was to qualitatively evaluate lamprey passage metrics in 2014 because no pre-modification data were available for comparison. Below we describe variation in environmental parameters and the detailed results of lamprey passage behavior at the modified Bonneville PH2 NDE, Cascades Island, and JDN locations. A second goal of the study was to summarize passage at fishways in an effort to build on a long time series of migration behavior through the hydrosystem (e.g., Keefer et al. 2012). The second component of this report provides general summaries and metrics of adult lamprey passage of fishways at Bonneville, The Dalles, John Day, and McNary dams.

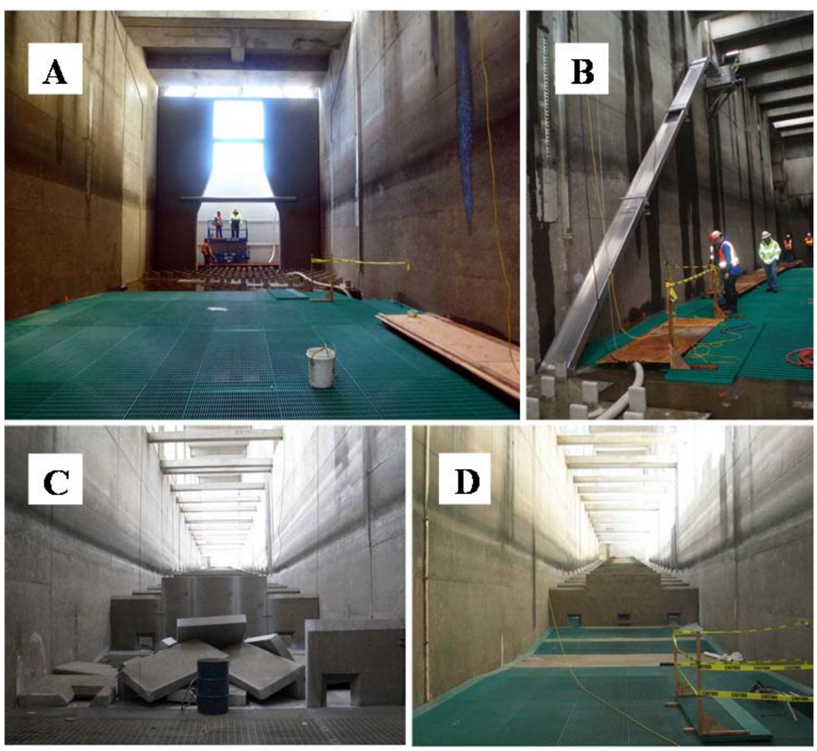

Figure 3. Modifications to the John Day Dam north fishway entrance area: A) variable-width entrance weir, bollard field, and closed entrance slot (new concrete on left wall); B) lamprey passage structure (with bollard field in foreground); C) removal of concrete weirs; and D) completed fishway with concrete weirs removed.

Methods

Tagging and monitoring

Adult lamprey used in this study were collected at Bonneville (Columbia River kilometer [rkm] 235) and John Day dams (rkm 346.9). At Bonneville Dam, they were collected in traps located in the fishway near the AFF. At John Day Dam, fish were collected from the LPS trap box in the north fish ladder. In 2014, 1000 lamprey (900 at Bonneville and 100 at John Day) were tagged with half-duplex passive integrated transponder (HD-PIT) tags only, and 600 collected at Bonneville Dam were tagged with radio transmitters (RT) and HD-PIT tags. Lamprey were randomly PIT tagged (i.e., those that were tagged on any given day were a random sample of the fish that were collected the previous night) at Bonneville Dam. However, it was unknown whether lamprey collected inside Bonneville fishways were representative of the run at large. Tagged lamprey were released downstream from Bonneville Dam near Hamilton Island at rkm 232.5 (n = 898), near Tanner Creek at rkm 232.0 (n = 300), or near the Stevenson boat ramp at rkm 242.7 (n = 299). The latter group was used in experimental flume studies and was not used in Bonneville fishway evaluations. HD-PIT tagged lamprey from JDN were released to the forebay near the south navlock guide wall (rkm 347.0). Three lamprey tagged (2 HD-PIT and 1 RT+HD-PIT) at Bonneville Dam died before release (0.2% of the tagged samples) and were censored from all analyses.

Lamprey with a girth circumference > 9 cm (at the insertion of the dorsal fin) were anesthetized in ~60 ppm (3 mL×50 L^{-1}) of AQUI-S 20E (AquaTactics, Kirkland, WA), measured for length (mm), distance between dorsal fins (mm), weight (g), and girth (mm), and evaluated for muscle lipid content (% fat) with a non-invasive Distell fish fat meter (Distell Inc., West Lothian, Scotland). Lamprey were tagged with uniquely-coded radio transmitters following protocols described in Moser et al. (2002a) and Cummings (2007). While under anesthesia, lamprey were placed ventral side up in a wetted, 12-cm diameter polyvinyl chloride (PVC) cradle with a T-end. A portion of the pipe was cut away to allow access to the ventral surface of the animal for surgery. The PVC cradle and surgery tank were disinfected prior to use each day (15 min submersion in chlorinated water solution of 7.8ml●L). We used Lotek NTC-4-2L radio transmitters (18.3 mm length, 8.3 mm diameter, and 2.1 grams in air) with a burst rate of 8 s and an expected tag life of 130 d (Lotek Wireless Inc. Newmarket, Ontario). All radio-tagged fish were also tagged with an HD-PIT tag (Texas Instruments, 4×32 mm, 0.8 g). HD-PIT only fish were outfitted with a uniquely-coded, glass-encapsulated HD-PIT tag. HD-PIT tags were surgically implanted in the body cavity of anesthetized fish through a small incision (< 1 cm) along the ventral midline and in line with the anterior insertion of the first dorsal fin as described in Moser et al. (2006). Collection and tagging protocols were reviewed and approved by the University of Idaho Institutional Animal Care and Use Committee.

Monitoring Sites

Radiotelemetry monitoring – Radio-tagged lamprey movements were monitored using arrays of fixed-site antennas and receivers at Bonneville, The Dalles, John Day, and McNary dams (Figures 4-8). Receivers were equipped with digital spectrum processors (DSPs) to receive transmissions on multiple frequencies simultaneously. Aerial antennas were used to monitor tailraces at each dam. One or more underwater coaxial cable antennas were positioned at fishway entrances and inside fishways, transition pools and fish ladders to detect when lamprey approached a fishway entrance, entered a fishway, moved within a fishway, and exited a fishway. Receivers were installed to intensively monitor movements at the modified areas: the BON PH2/ Washington- shore north downstream entrance (NDE), the Cascades Island (CI) fishway, and John Day north fishway. It is important to note that the PH2 NDE and CI entrances were monitored using an aerial Yagi antenna in 2014 (due to limited access to underwater locations in winter 2012-2013) whereas these sites were monitored using underwater antenna arrays historically (Figure 5). Data from previous evaluations at entrance locations with both underwater and aerial Yagi antennas in 2009-2010 indicated qualitatively similar resolutions between antenna types. Data collected in 2014 were compared to passage performance metrics collected during previous passage evaluations (2007-2010).

HD PIT tag monitoring – We monitored lamprey movements in the Washington-shore LFS with four half-duplex antennas (Figure 9) that were installed in May 2014. An array of four antennas arranged in two plates (one outside the entrance and one inside the entrance) at the north fishway (installed winter 2011) at John Day was used to monitor lamprey movements (Figure 10). An analysis of HD detections on the CI entrance was not conducted because the prototype antenna array installed in 2008-2009 was not fully operational in 2014.

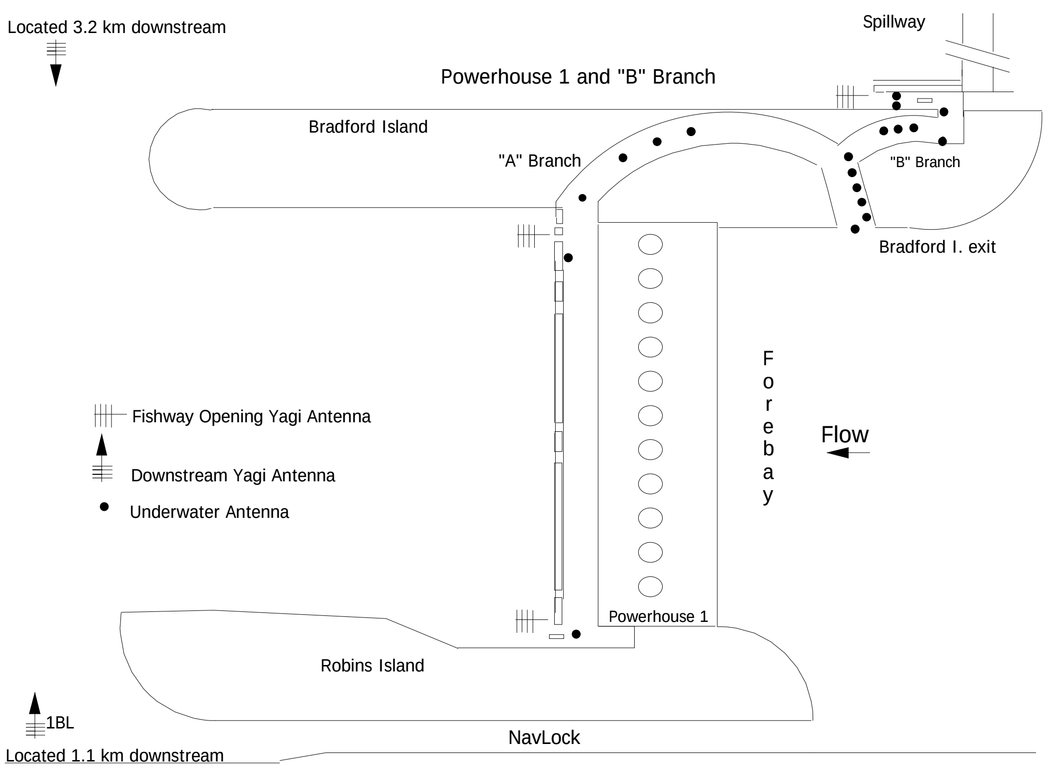

Figure 4. Diagram showing radio antenna deployments at Bonneville Dam PH1 and B-Branch fishways in 2014 (not to scale).

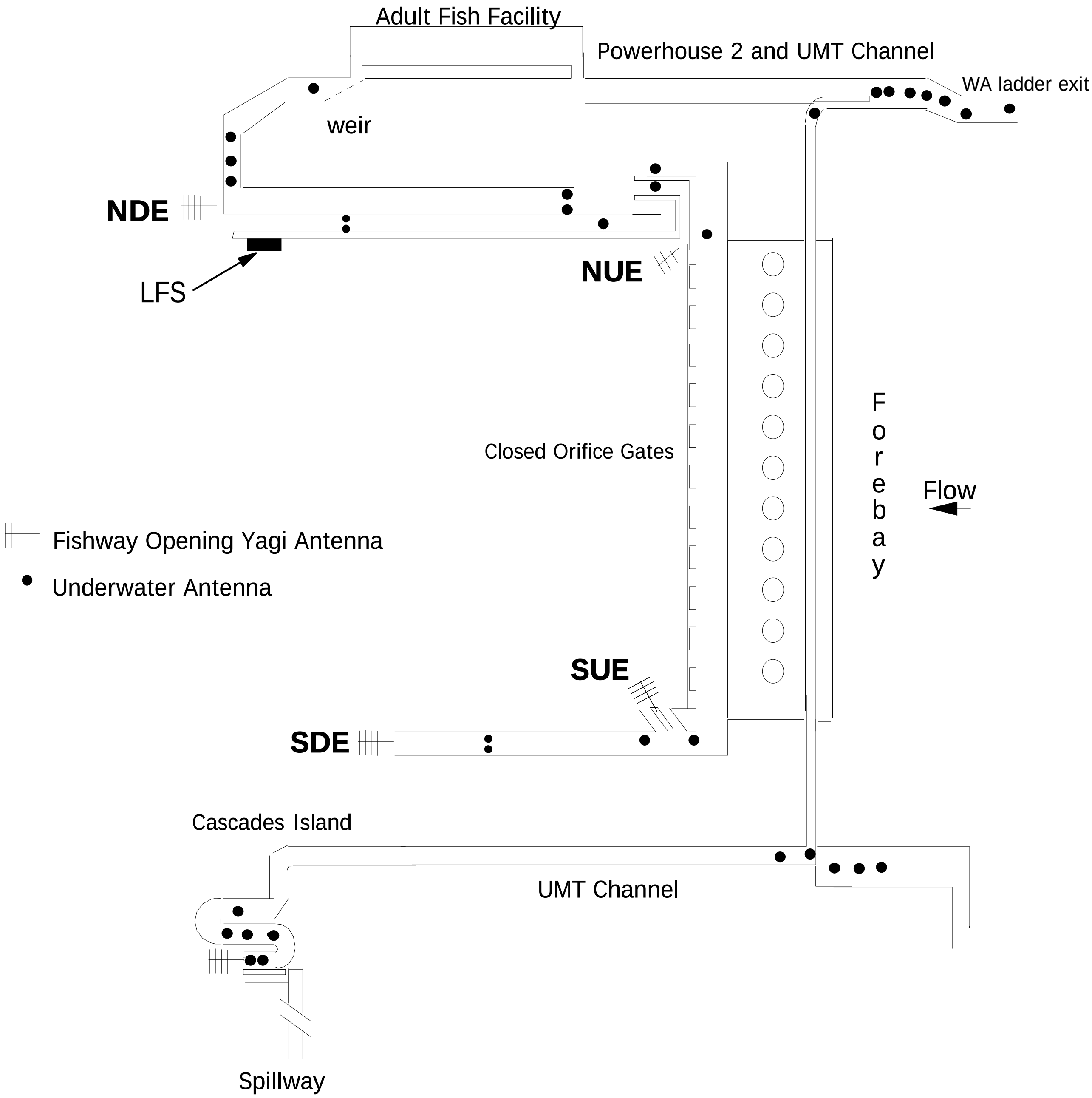

Figure 5. Diagram showing radio antenna deployments at Bonneville Dam PH 2 and Cascades Island in 2014 (not to scale). See Figure 9 for LFS details.

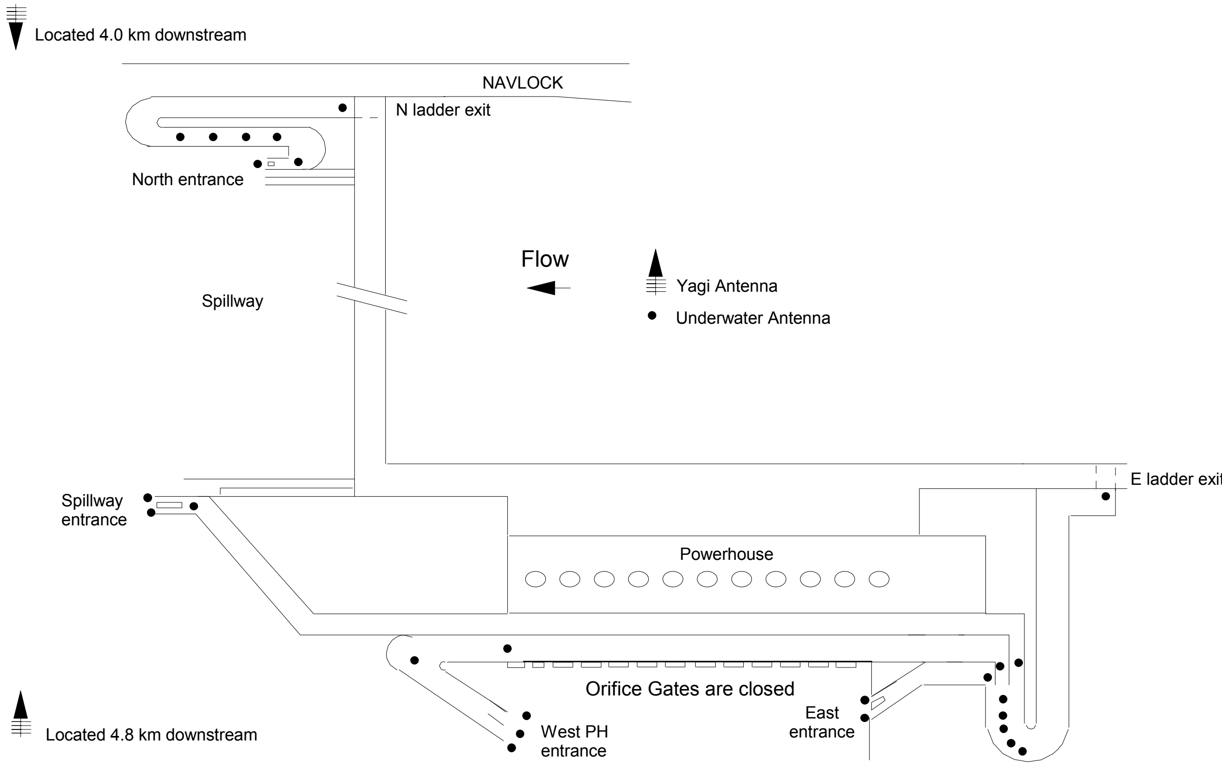

Figure 6. Diagram showing radio antenna deployments at The Dalles Dam in 2014 (not to scale).

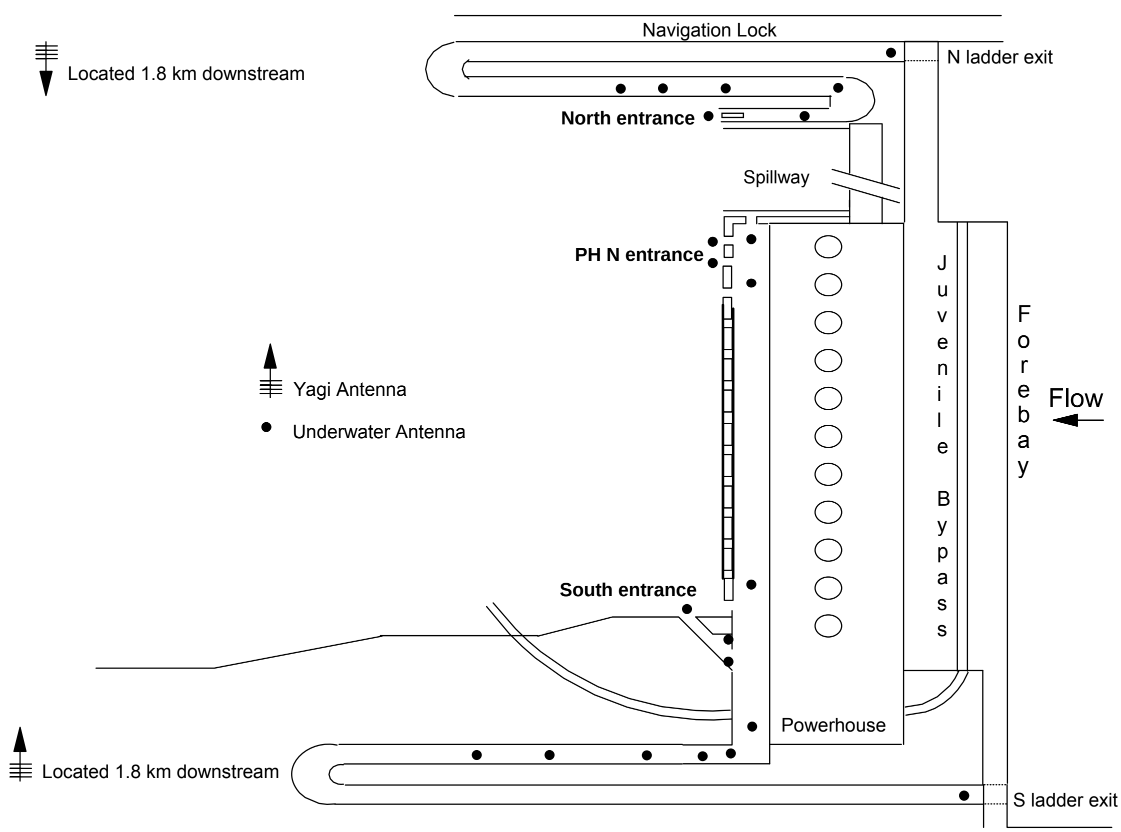

Figure 7. Diagram showing radio antenna deployments at John Day Dam in 2014 (not to scale).

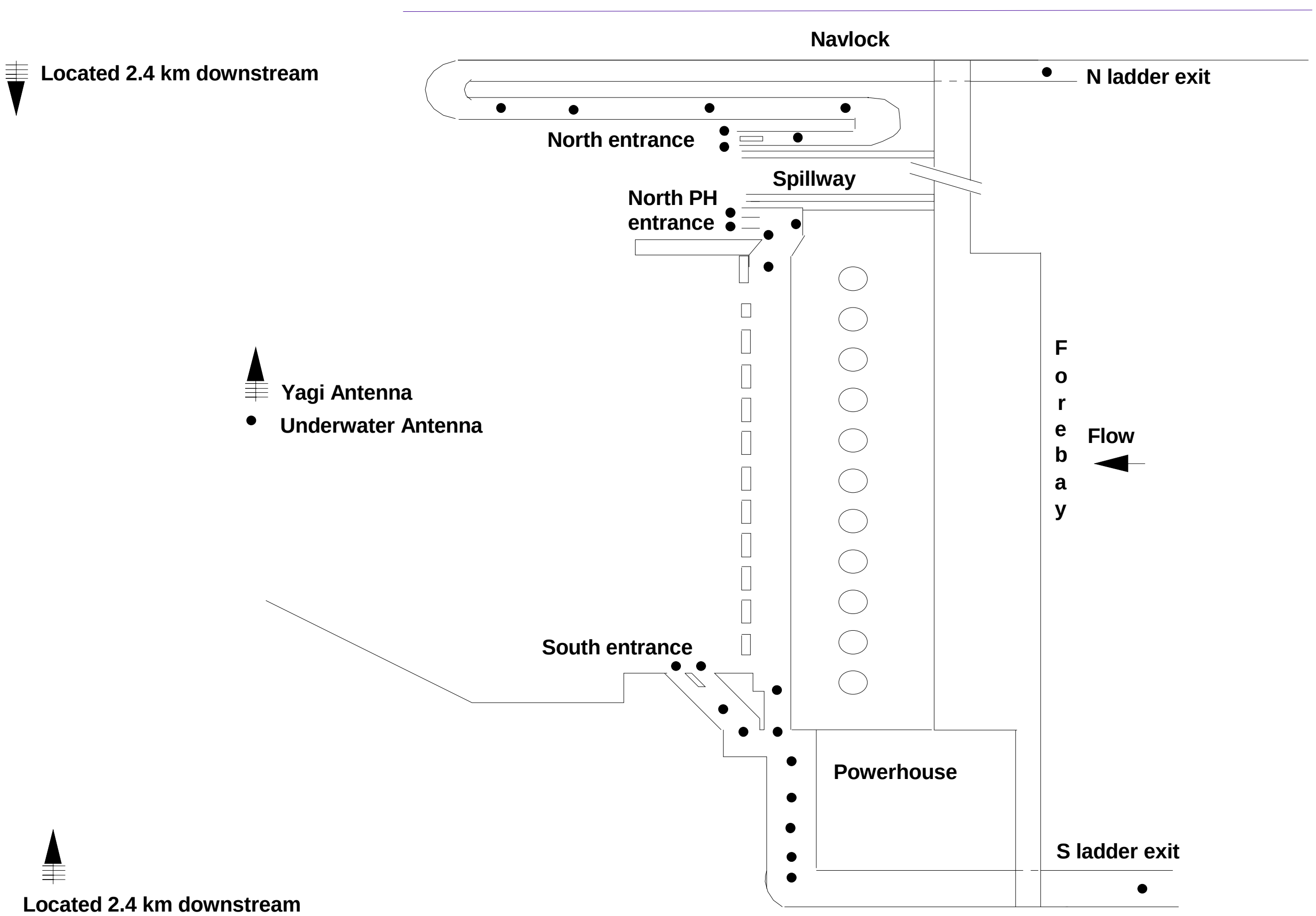

Figure 8. Diagram showing radio antenna deployments at McNary Dam in 2014 (not to scale).

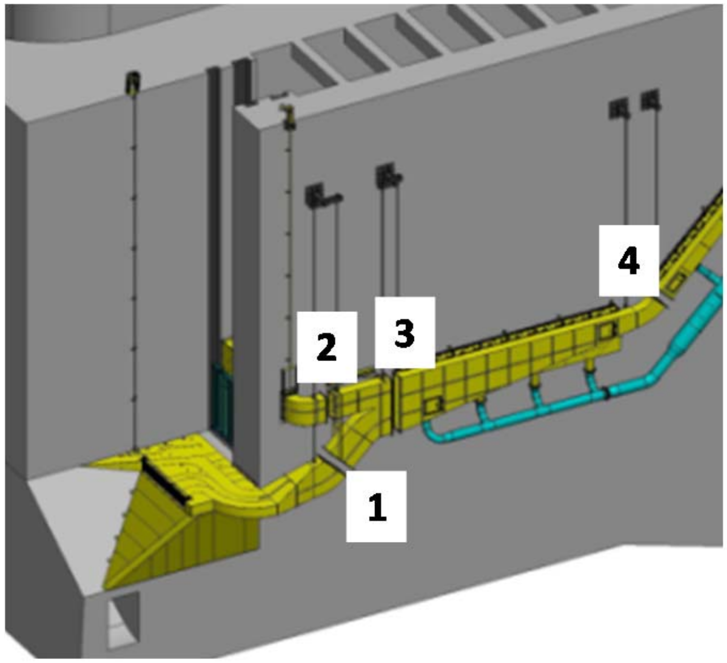

Figure 9. Location of Bonneville Dam WA-shore LFS HD-PIT half duplex antennas in 2014.

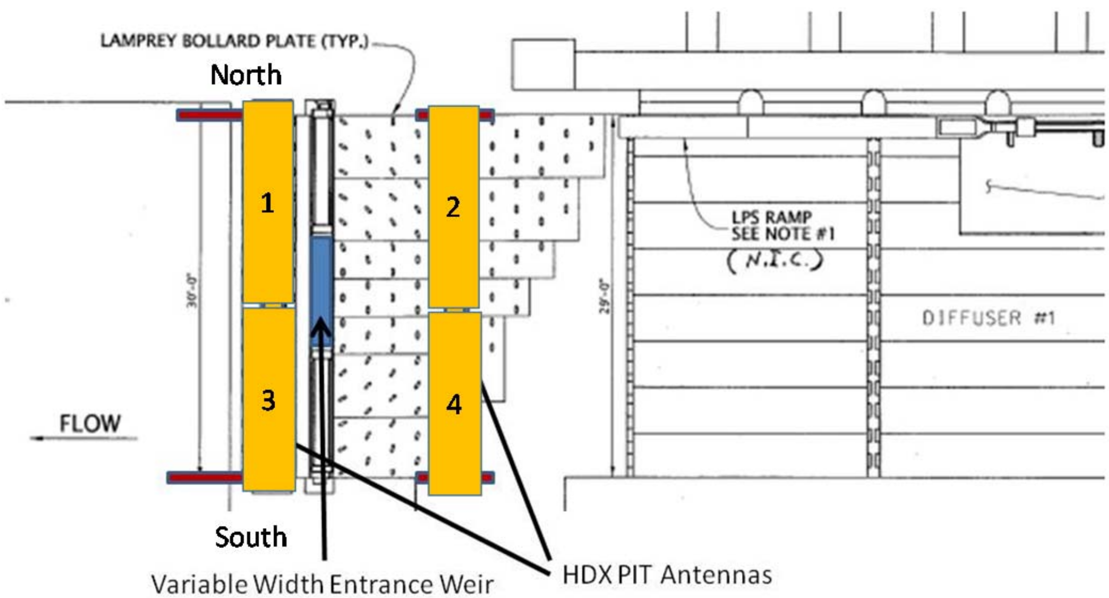

Figure 10. Location of John Day North entrance HD-PIT half duplex antennas in 2014.

Data Analyses

A variety of passage time and efficiency metrics were calculated to evaluate whether the fishway modifications may have affected lamprey behaviors. For this evaluation, we report metrics that are consistent across the previous five study years using similar tag sizes, protocols, and monitoring arrays, which included 2007-2010 and 2014. We compared 2014 passage metrics from locations with major modifications at Bonneville Dam to corresponding values from previous years.

We performed several statistical analyses to test for differences in passage metrics across study years. Pearson's chi-square (χ^2) tests were used to determine whether lamprey entrance efficiencies and exit ratios differed between pre- and post- modification years. Statistical tests of between-year effects in entrance and lower ladder passage times were performed using a General Linear Model (GLM) and *a priori* contrast statements to specifically test hypotheses that fishway entrance and lower ladder passage times were not different between pre- and post- modification years (Zar 1999). Predictor covariates used in the model included: year, fishway approach date, and mean daily flow, spill, temperature and tailwater elevation on the approach date, and whether fish approached or entered during the day or night. Tukey's HSD tests were used to compare the difference among annual mean passage times. Passage time data were consistently right-skewed because some fish had long passage times; data were $\log_{ln}$-transformed to improve normality. We additionally used a logistic regression model to evaluate if longer passage times (> 1 hr) were associated with the fishway modifications. Potentially confounding factors in our multi-year comparisons were the variations in spill patterns, orifice gate closures, reduced nighttime flow evaluations from 2007-2010 at PH2 entrances that included reduced and full velocities during nighttime versus only reduced velocities at night during 2014, and the switch from underwater to aerial antennas at the NDE fishway opening. Note nighttime velocities were not reduced in 2008 and normal operations occurred and are included in our analyses.

Passage Metrics

We calculated several passage time and efficiency metrics to evaluate potential effects of the PH2 NDE, CI, and John Day north entrance modifications on lamprey behavior. The metrics estimate different elements of fishway approach and entry behaviors and passage times.

1) ***Entrance efficiency***. The ratio of the total number of fishway entry events at a site divided by the total number of fishway approaches at the same site. Each event was reviewed manually and multiple events by individuals were included. A drop in entrance efficiency would suggest that the environment near the entrance became less attractive to lamprey.

2) ***Exit ratio***. The number of exit events (fish recorded exiting the fishway into the tailrace) divided by the number of entrance events (fish recorded entering the fishway). Each event was reviewed manually and multiple events by individuals were included. An increase in the exit ratio would suggest that conditions inside the fishway entrance became less favorable.

3) ***Entrance time***. The passage time from first approach to first entrance. An increase in entrance time would suggest that passage conditions at the entrance have degraded.

4) ***Entrance to base of ladder time***. The passage time from the entrance antenna to the antenna located in the transition pool at the base of the ladder. An increase in passage time through this section would suggest that the modifications had a negative effect on adult lamprey behavior inside the fishway at or near the lamprey modifications. Vibration related to pumps at the LFS is of concern at NDE and the bollards may have affected hydraulic conditions inside the entrance at CI.

5) ***Extended passage times***. Lamprey passage times are strongly right-skewed. We used the percentage of fish that require > 1 h to pass through the lower fishway (entrance to base of ladder) as a standardized metric of slowed passage. Increases in this metric would suggest that passage became more difficult.

Fishway use

Lamprey use of fishway entrances at Bonneville, The Dalles, John Day, and McNary dams was evaluated by assessing where fish first approached, entered, and exited fishways. We also described the distributions of total fishway approaches, entries, and exits per site. In the spatial distribution summaries, some movements were inferred using upstream records when downstream records were missing. The latter occurred most often during receiver power outages and when lamprey were detected on antennas inside fishway openings without being detected on antennas outside the same opening (i.e., when they entered via unmonitored routes like orifice gates or missed the antenna outside an opening).

Transition pools at the junctions of fishway collection channels and the overflow sections of fish ladders were monitored at Bonneville, The Dalles, John Day and McNary dams. Detailed behavioral summaries were also generated for serpentine weir and count window areas in the upper sections of the Bonneville Dam fishways. Lamprey passage in these sections has been poor in the past (e.g., Keefer et al. 2010a, 2013b). As part of our evaluation of potential lamprey passage bottlenecks, we identified the fishway turn-around locations for all lamprey that failed to pass each of the study dams.

Passage times

Lamprey passage times were calculated for a variety of tailrace, fishway, and full-dam passage segments. These included times from release or first tailrace detection to first approach at a fishway, first entry at a fishway, and to pass the dam. Additional passage times were calculated from first fishway approach to first fishway entry, from first fishway entry to first transition pool entry, and to pass a dam, between first and last transition pool records (only for fish that eventually passed a dam), and from transition pool exit (upstream) to pass a dam.

In all passage time calculations, only radiotelemetry records with known location and time were included (this contrasts with the spatial distribution summaries described above). In most cases, passage times were calculated from each lamprey's first record at the start of a passage segment to the first record at the start of the next upstream segment.

Passage efficiency

We calculated dam passage and fishway passage efficiency metrics for several segments and spatial scales. These metrics can be used to evaluate broad-scale differences in lamprey passage success among dams as well as more detailed comparisons of the relative effectiveness of different fishways or fishway segments for lamprey passage.

The most basic efficiency metric was dam passage efficiency. This was calculated by dividing the number of unique lamprey that passed a dam by the total number of unique fish recorded approaching a fishway at the dam. A similar metric, fishway passage efficiency, was calculated by dividing the total number of unique fish that passed a dam by the total number of unique fish that entered a fishway at the dam.

The fishway entrance efficiency metric was calculated by dividing the number of unique fish that entered a specific fishway opening by the total number of unique fish recorded approaching the same opening. Similar calculations based on unique fish detections were used to estimate passage efficiencies for specific fishway segments (i.e., through transition pools, past count windows, etc.).

Fallback

Lamprey fallback at dams was estimated using records at top-of-ladder antennas and subsequent records in tailraces or at fishways downstream from the fallback location.

Results

Radio and HD-PIT tagging

Bonneville Dam – In 2014, we collected and then radio and HD-PIT tagged 600 adult Pacific lamprey (May 23-Sep 12) and HD-PIT tagged 900 lamprey (May 15-Sep 23) at the AFF (Figure 11). The total 'corrected' adult Pacific lamprey count at Bonneville Dam including night and LPS passage estimates through 18 November 2014 was 120,099 (N. Zorich, USACE, *personal communication*). HD-only PIT lamprey represented ~0.75% of the total corrected count and double-tagged lamprey represented ~0.49% of the count at the dam in 2014.

John Day Dam – In 2014, 100 adult Pacific lamprey were collected from the JDN LPS structure, HD-PIT tagged, and released in the forebay. Of these fish, 41 unique lamprey fell back one or more times and were subsequently used in the John Day north entrance HD evaluation. HD-PIT only tagged lamprey (*n* =282) from Bonneville Dam had records at John Day Dam between June 7 and October 2 (Figure 12). Forty-eight double-tagged lamprey from the Bonneville sample were recorded approaching John Day Dam between June 18 and September 27.

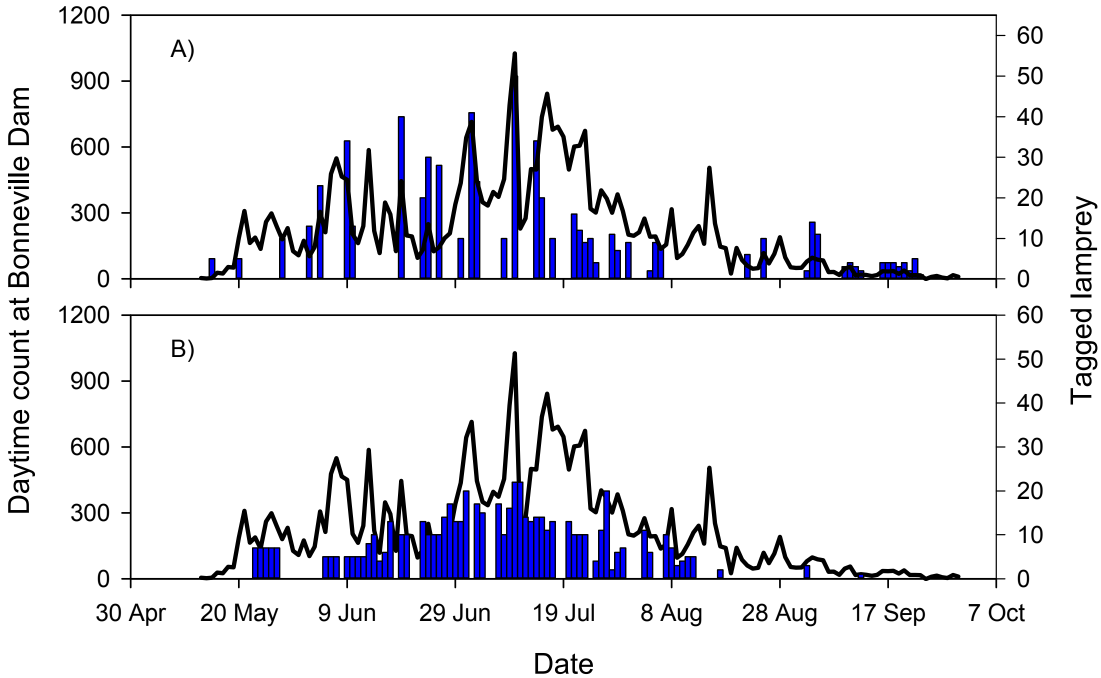

Figure 11. The number of adult Pacific lamprey A) HD-PIT only tagged and B) radio and HD-PIT tagged and released downstream from Bonneville Dam and the daytime count of lamprey passing the dam in 2014. Note 299 HD-PIT only tagged lamprey released in forebay are not shown.

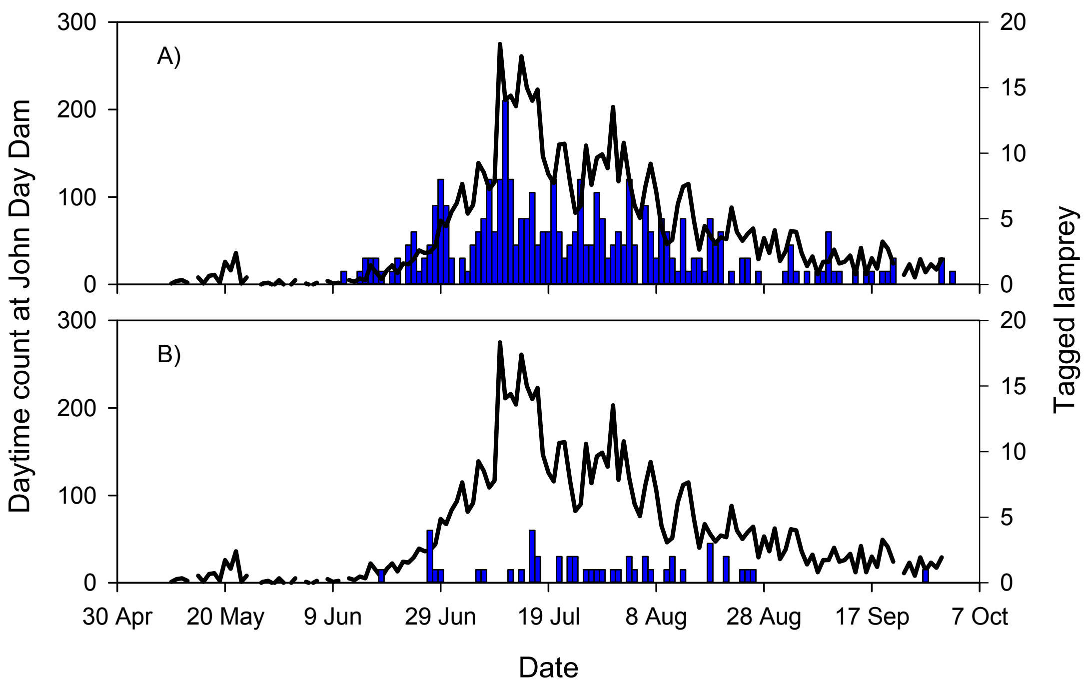

Figure 12. The number of adult Pacific lamprey that were: A) HD-PIT only tagged (*n* =282) and B) radio and HD-PIT (*n* =48) tagged at Bonneville Dam and were subsequently recorded at John Day Dam in 2014. Solid lines show daytime Pacific lamprey counts at John Day Dam.

Environmental Data

Columbia River discharge, spillway discharge, and river temperatures at Bonneville Dam varied during the lamprey runs over the five study years (Figure 13). This likely contributed to the inter-annual variation in lamprey passage behaviors. For example, total river discharge ('flow') and spill ranged from low levels in 2007 (flow mostly < 250 kcfs [7,080 cms]) to higher levels (flow mostly > 346 kcfs [9,798 cms]) in 2008 (Figure 13).

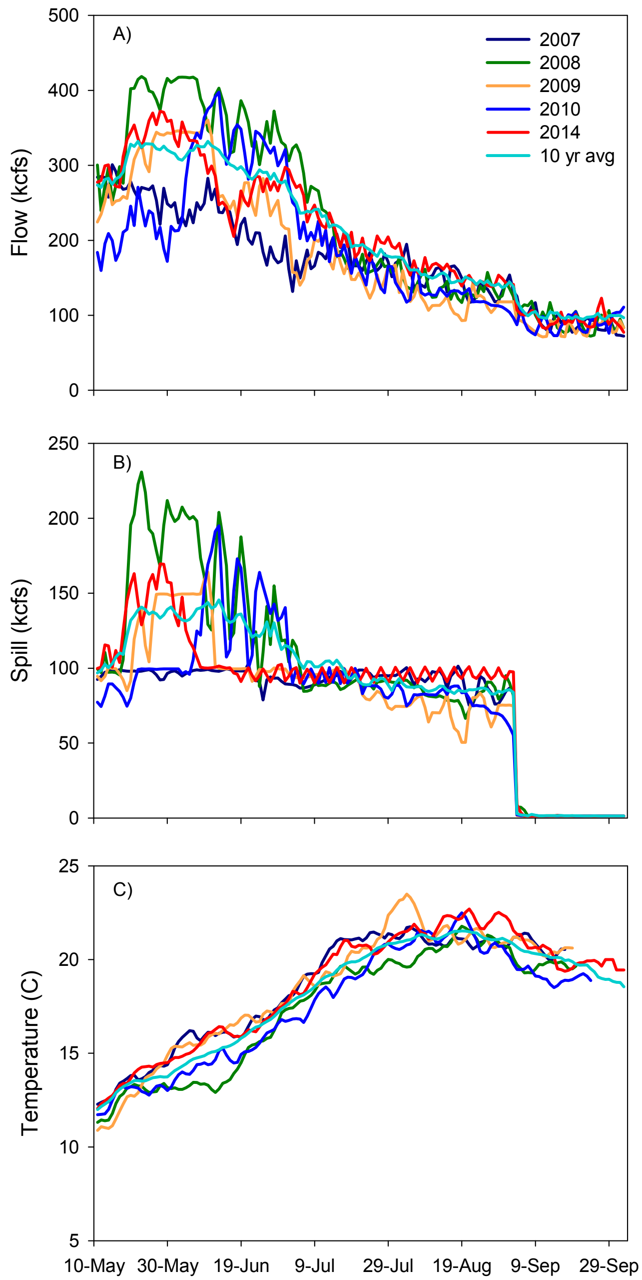

Figure 13. Mean daily A) flow, B) spill, and C) water temperature (WQM) at Bonneville Dam in 2007-2010 and 2014.

Environmental conditions at Bonneville Dam during the 2014 lamprey migration were characterized by average flows, near average spill, and above average water temperatures compared to the 10-year average (Figure 13; Note: flow and spill hereafter reported in English units). Environmental conditions at John Day Dam in 2014 were near the 10-year average for flow and spill and were warmer than the 10-year average for temperature. The maximum temperature at John Day in 2014 (22.7 ºC) occurred on 11 August.

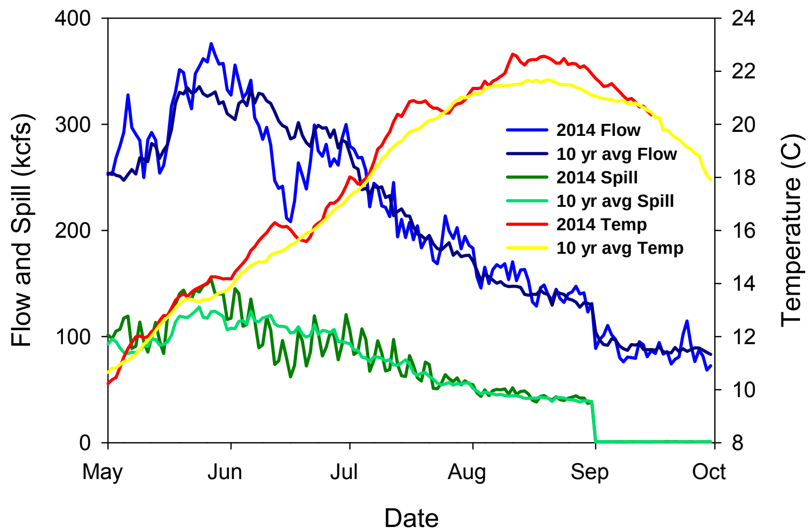

Figure 14. Mean daily flow, spill and water temperature (WQM site) in 2014 and the 10-year averages at John Day Dam.

Bonneville Dam PH2 NDE Results

Radiotelemetry

Radio-tagged lamprey used all of the primary fishway entrances at Bonneville PH2 in all years (Figure 15). The highest among-year variability in proportion of all approaches occurred at the south downstream entrance (SDE) and ranged from 1-44%. There was less among-year variation in the proportion of all approaches at NDE (16-31%) across study years; the 21% that approached NDE in 2014 was near average.

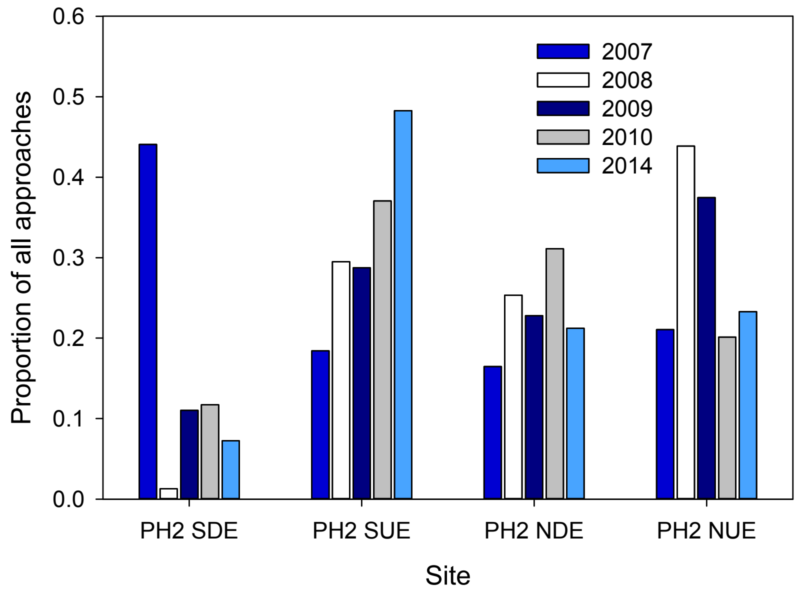

Figure 15. Proportion of all approaches by radio-tagged lamprey at Bonneville Dam PH2 entrances in 2007-2010 and 2014.

Of the 599 adult lamprey released in 2014, 124 (21%) were recorded approaching and 95 (16%) were recorded entering the NDE (Figure 16). The 2014 approach and entrance percentages were higher than the means from pre-modification years, which were 19% and 5%, respectively. The number of fish detected approaching the NDE remained fairly consistent with decreasing tailwater (Figure 17).

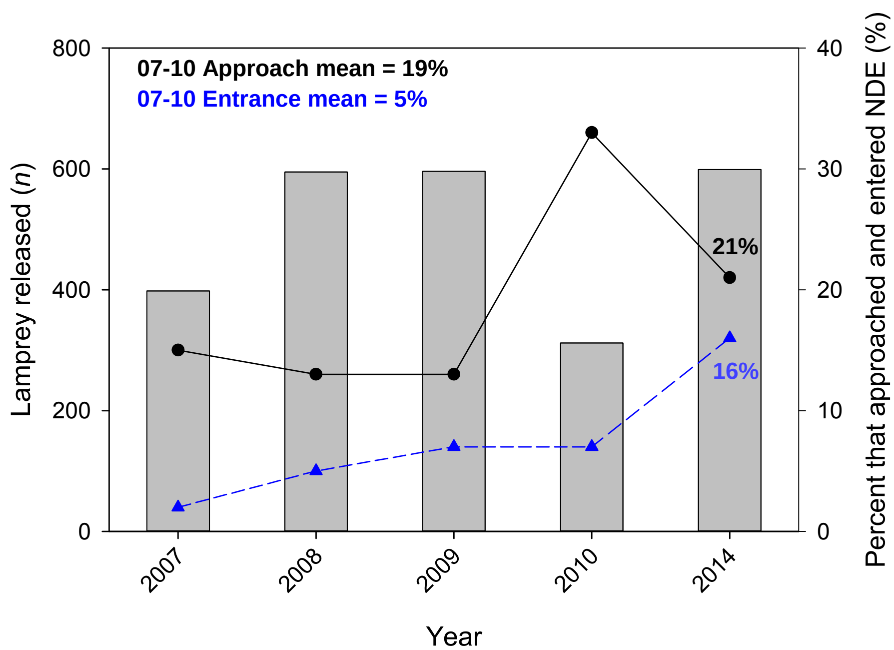

Figure 16. Number of adult lamprey that were radio-tagged (bars) and the percentages that were recorded approaching (circles and solid line) and entering (triangles and dashed line) the PH2 NDE in 2007-2010 and 2014.

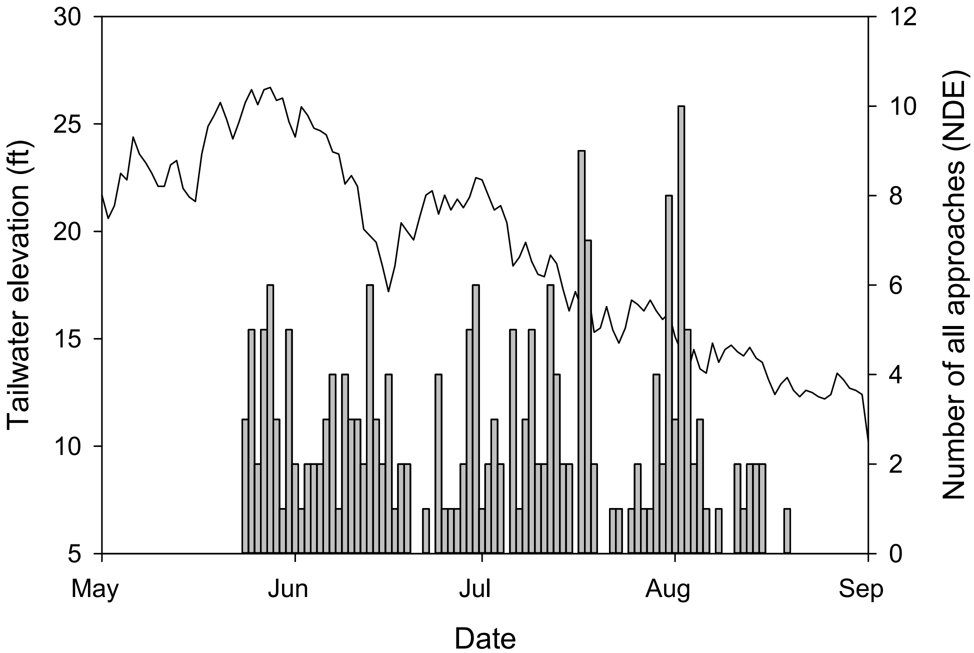

Figure 17. Number of all individual fishway approach events by radio-tagged lamprey at Bonneville NDE in 2014 in relation to tailwater elevation (ft).

Metric 1: Entrance efficiency. The NDE entrance efficiency estimate for radio-tagged adult lamprey in 2014 (0.59) was much higher than the mean of estimates across pre-modification years (0.11) during nighttime reduced velocity conditions ($\chi^2 = 146.89$, $P < 0.001$) (Figure 18). In pairwise χ^2 tests, entrance efficiency in 2014 was higher than in all pre-modification years ($P < 0.001$). Overall (day and night) NDE entrance efficiency estimates were similar to those during the night reduced conditions, with the 2014 estimate (0.64) higher than the mean across the pre-modification years (0.08). Entrance efficiency at SDE in the post-modification year for lamprey (0.41) was also higher ($\chi^2 = 8.14$, $P = 0.004$) than the mean across pre-modification years (0.27) during nighttime reduced velocity conditions (Figure 18). In pairwise χ^2 tests, entrance efficiency in 2014 at SDE was higher than in 2007 ($P = 0.004$) and in 2010 ($P = 0.001$). Overall (day and night) SDE entrance efficiency estimates were similar to those during the night reduced conditions, with the 2014 estimate (0.32) higher than the mean across the pre-modification years (0.17). Notably, while entrance efficiency went up at both locations in 2014, the relative increase at NDE was higher than at SDE, with efficiency at NDE exceeding the value at SDE only in 2014 (Figure 18).

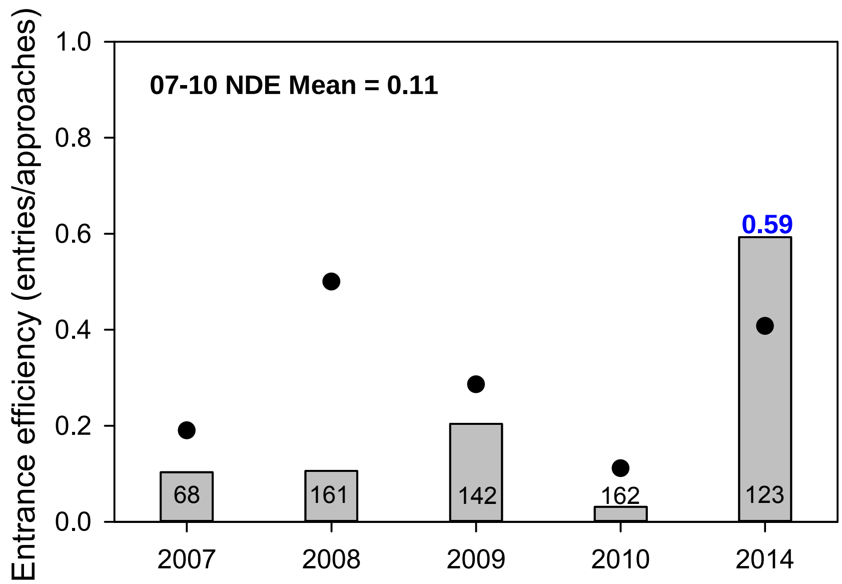

Figure 18. NDE (gray bars) and SDE (solid circles) entrance efficiency estimates (total entry events/total approach events) for radio-tagged lamprey during nighttime (22:00-04:00 h) with reduced velocity conditions (except in 2008). Samples sizes in each bar are the numbers of lamprey that approached NDE.

Metric 2: Exit ratio. Exit ratios ranged from 0.10 in 2010 to 0.67 in 2008 during the pre-modification years (Figure 19). However, the mean pre-modification exit ratio (0.48) was the same as the exit ratio in 2014 (0.48) during nighttime reduced velocity conditions. Adult lamprey exit ratios were not different in the post-modification year than in pre-modification years ($\chi^2 = 0.99$, $P = 0.319$). Overall (day and night) NDE exit ratio estimates were similar to those during the nighttime reduced velocity conditions with the 2014 estimate (0.43) similar to the mean across the pre-modification years (0.45).

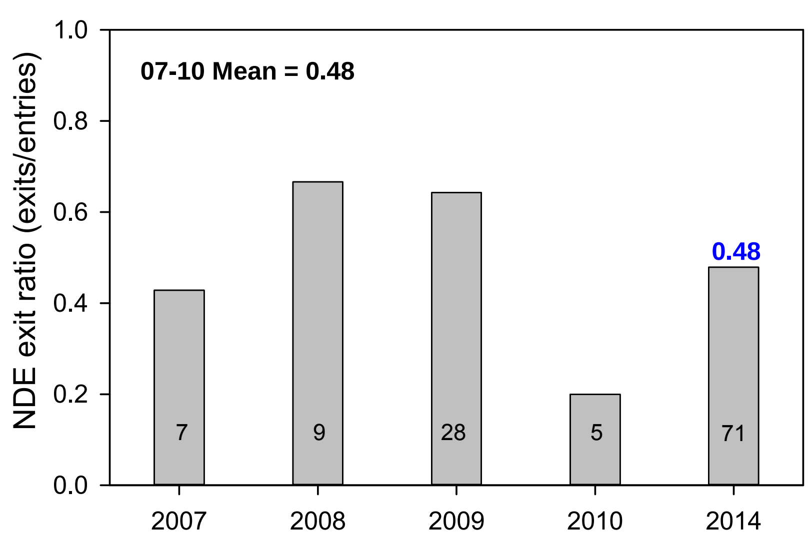

Figure 19. NDE exit ratios (total exit events/total entry events) for radio-tagged adult lamprey during nighttime (22:00-04:00 h) with reduced velocity conditions (except in 2008). Sample sizes (number of lamprey that entered) are inside each bar.

Metric 3: Entrance time. Generally, radio-tagged lamprey moved quickly into the NDE in most years, but some had long passage times when they repeatedly approached the fishway without entering, or moved to the tailrace, or to other fishways, and then returned to enter NDE. Regardless, approach-to-entrance times ranged from less than a minute to 3.8 d in 2014 with a median of 3 min (Figure 20). In comparison, the median passage times in pre-modification years ranged from <1 min in 2008-2010 to 29.1 d in 2008. Across all years, there was a significant difference in log-transformed entrance times between pre- and post- modification years (ANOVA $df = 1$, $F = 17.2$, $P \leq 0.001$). Pairwise comparisons using a Tukey's test indicated faster annual mean entrance times in 2014 compared to 2007-2010 (Figure 20). The GLM model also indicated significantly faster passage times across all years for lamprey that approached ($df = 1$, $F = 8.9$, $P = 0.003$) and entered ($df = 1$, $F = 10.1$, $P = 0.002$) NDE during nighttime hours (between 2200-0400) than during daytime and as water temperatures increased ($df = 1$, $F = 4.1$, $P = 0.043$). We observed no statistically significant associations between lamprey time to enter NDE and date, flow, or tailwater elevation in univariate comparisons (Figure 21).

Lamprey passage times at SDE, a useful comparison site for NDE, were generally faster than those at NDE for radio-tagged lamprey (Figure 22). Median SDE approach-to-entry times ranged from <1 min (in all years) to 17.1 d (2009). The fast median passage time in 2014 (~1 sec) was a result of 11 of the 19 lamprey having approach and entrance records at approximately the same time.

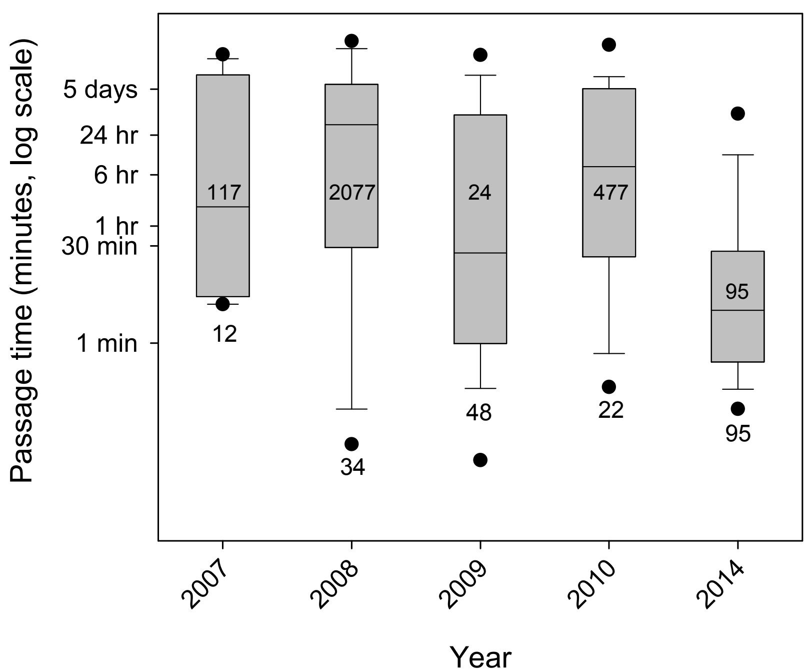

Figure 20. Radio-tagged lamprey passage time distributions (log scale) from approach to entry at the Bonneville NDE. Values inside boxes are median times in minutes. Distributions show 5th, 10th, 25th, 50th, 75th, 90th and 95th percentiles; sample sizes are shown at bottom.

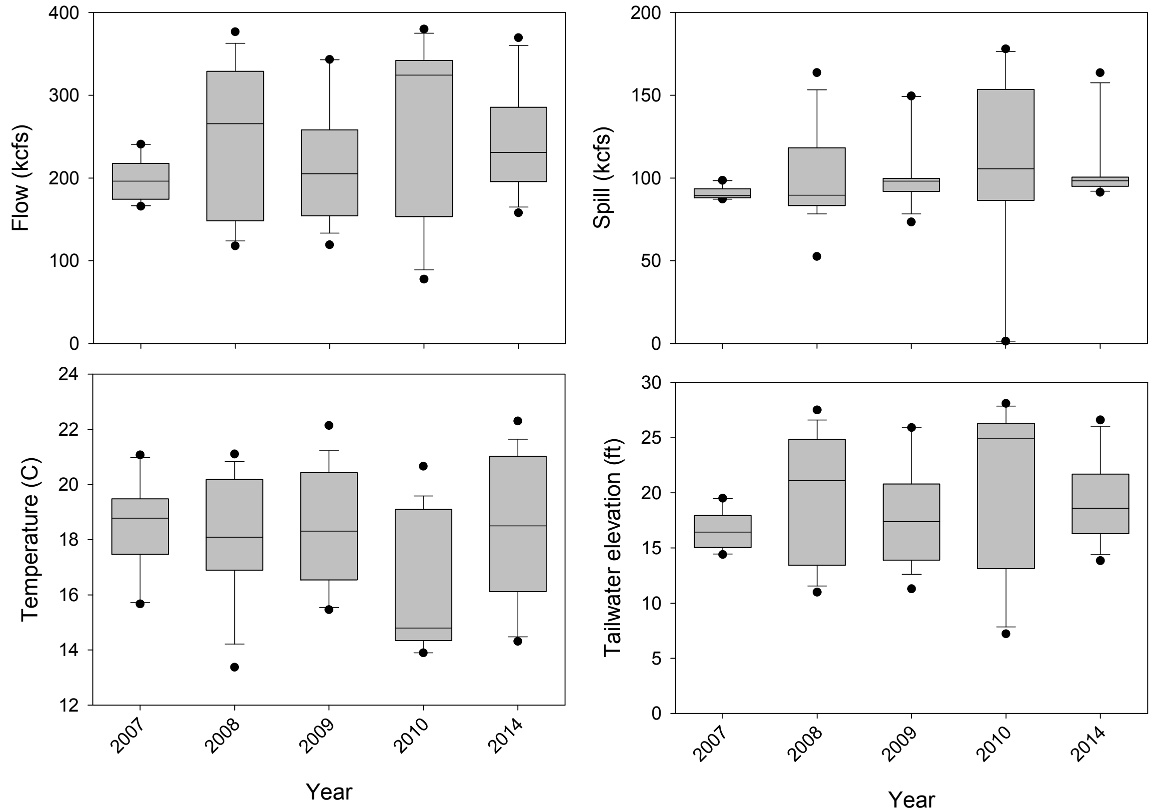

Figure 21. Box plots of the total discharge ('flow'), spill, water temperature, and tailwater elevation on the days that radio-tagged adult lamprey first approached the NDE. Distributions show 5th, 10th, 25th, 50th, 75th, 90th, and 95th percentiles.

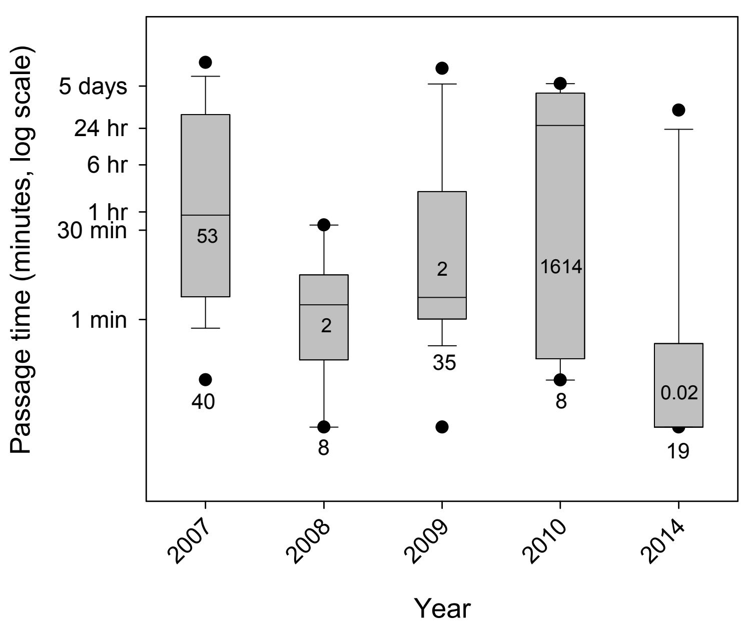

Figure 22. Radio-tagged lamprey passage time distributions (log scale) from approach to entry at the Bonneville SDE. Values inside boxes are median times. Distributions show 5th, 10th, 25th, 50th, 75th, 90th and 95th percentiles; sample sizes are shown at bottom.

Metric 4: Entrance to base of ladder time. Once tagged lamprey entered NDE, annual median times to reach the ladder base prior to installation of the LFS ranged from 7–20 min (Figure 23). The median time in 2014 (8 min) was at the faster end of that range. However, the GLM model with a linear contrast for log-transformed passage times indicated no change in passage times after the fishway modification (df =1, F = 3.0, P = 0.08).

Metric 5: Extended passage times. In years before the fishway modification, the percentage of lamprey with entrance and lower ladder passage times > 1 h at NDE ranged from 44–71% (*mean* = 58%) and from 7–23% (*mean* = 18%), respectively. Logistic regression models indicated significantly fewer lamprey took > 1 h to enter the fishway in 2014 (df = 1, χ^2 = 8.15, P = 0.004). In 2014, 19% of lamprey that entered NDE took longer than 1 h to enter and 13% took longer than 1 h to reach the first ladder antenna.

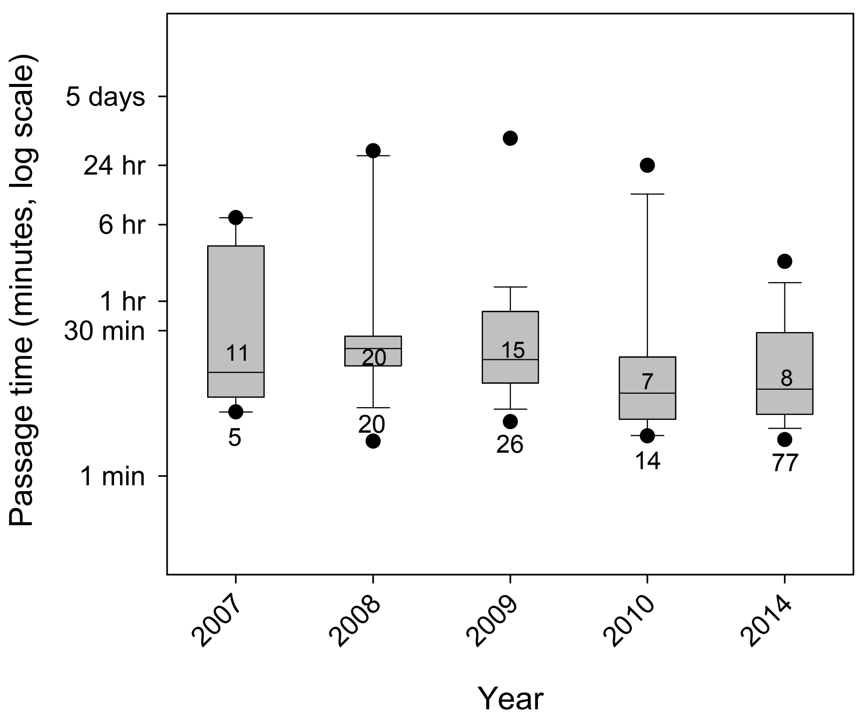

Figure 23. Lamprey passage time distributions (plotted on log-scale) from NDE to the antenna at the base of the ladder. Numbers inside boxes are median times in minutes. Distributions show 5th, 10th, 25th, 50th, 75th, 90th, and 95th percentiles; sample sizes are below boxes.

HD-PIT

Of the 1,198 HD-PIT tagged lamprey released below Bonneville Dam, 10 (0.8%, 7 HD-PIT and 3 double-tagged fish) were detected on the HD antenna array (Figure 9) in the LFS at the Washington-shore fishway. Seven of the 10 detections occurred before June 15. Ninety percent of lamprey were detected on antenna 2, 70% on antennas 1 and 3, and 30% on the most upstream antenna 4. Detection times between antennas ranged from 0.01 to 1.32 h with a median of 0.17 h. One fish was recaptured at the terminus with a lower-LFS passage time of 0.17 h. Of the other nine fish, four subsequently exited the LFS and passed the dam (1 WA shore ladder, 2 WA shore AWS LPS, 1 Bradford Island LPS), four were not recorded passing the dam, and one was recaptured in the Washington-shore AFF and released upstream at Stevenson, WA.

Bonneville Cascades Island Results

Radiotelemetry

Of the 599 adult radio-tagged lamprey released, 68 (11%) were recorded approaching and 49 (8%) were recorded entering the CI fishway opening at least once. Across all years, the percentage of radio-tagged lamprey that approached and entered the CI fishway was higher after the fishway modifications (Figure 24). In post-modification years (2009-2010, 2014), 11–29% (*mean* = 18%) of tagged lamprey were detected approaching the CI fishway one or more times and 8–18% (*mean* = 12%) were recorded entering the CI fishway, though we note the post-modification mean for both metrics was strongly influenced by results from a single year (2010).

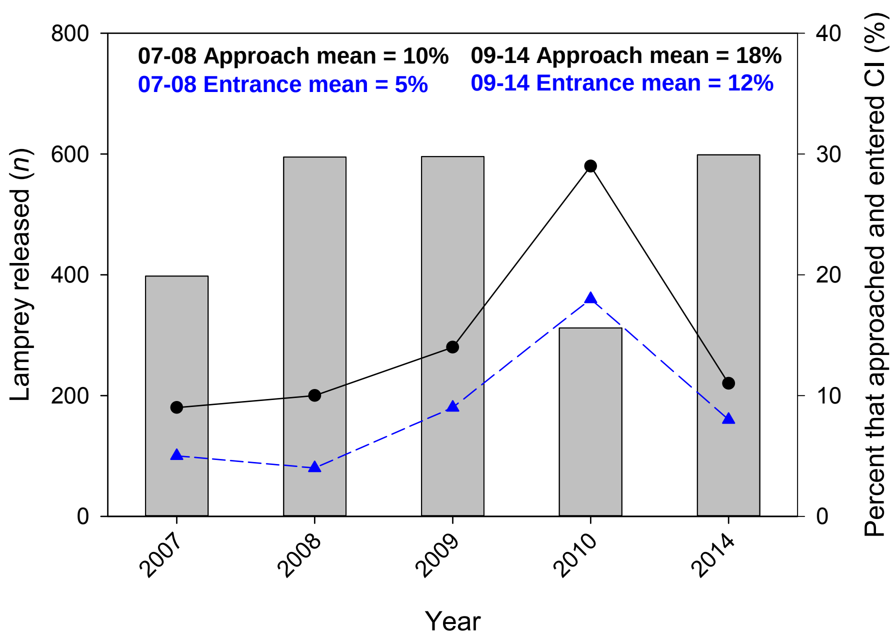

Figure 24. Number of lamprey that were radio-tagged (bars) and the percentages that were recorded approaching (circles and solid line) and entering (triangles and dashed line) the Cascades Island fishway. Fishway modifications occurred prior to the 2009 migration.

Metric 1: Entrance efficiency. The CI entrance efficiency estimates prior to the fishway modification ranged from 0.23–0.45 for radio-tagged adult lamprey (*mean* = 0.34, Figure 25). The mean entrance efficiency after the modification was 0.47 (range 0.31-0.60) and the estimate in 2014 was 0.60, the highest of all study years. In a χ^2 test, the post-modification entrance efficiency was higher than in the pre-modification years ($\chi^2 = 7.45$, $P = 0.006$). In pairwise χ^2 tests among years, 2010 ($P < 0.001$) and 2014 ($P < 0.001$) entrance efficiencies were higher than 2008. There were also differences among pre-modification years, with 2007 having a higher ($P = 0.014$) entrance efficiency than 2008. In the post-modification years, 2010 ($P = 0.002$) and 2014($P < 0.001$) efficiencies were higher than in 2009.

Metric 2: Exit Ratio. Exit ratios at the CI opening for radio-tagged adult lamprey prior to modifications ranged from 0.43–0.47 (*mean* = 0.45; Figure 26). Post-modification exit ratios were higher, ranging from 0.62-0.67 (*mean* = 0.65). The exit ratio estimate in 2014 (0.62) was the lowest of the three post-modification years. In a χ^2 test, the post-modification exit ratios were higher than in pre-modification years ($\chi^2 = 5.74$, $P = 0.017$). In pairwise χ^2 tests among years, the exit ratio in 2009 was higher than in 2008 ($P = 0.049$); no other pairwise comparisons were significant.

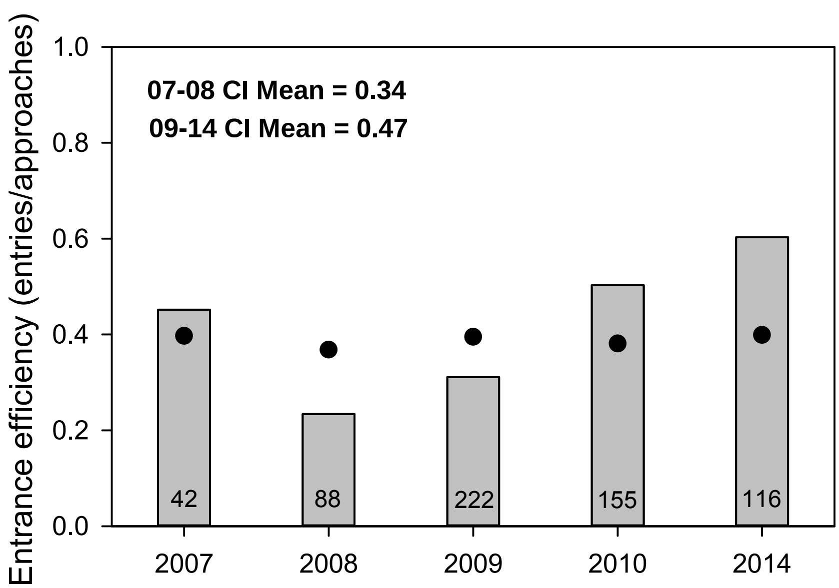

Figure 25. Cascades Island (gray bars) and Bradford Island (solid circles) entrance efficiency (total entrance events/total approach events) for radio-tagged lamprey. Sample sizes (number of approaches to CI) are inside each bar. Modifications occurred prior to the 2009 migration.

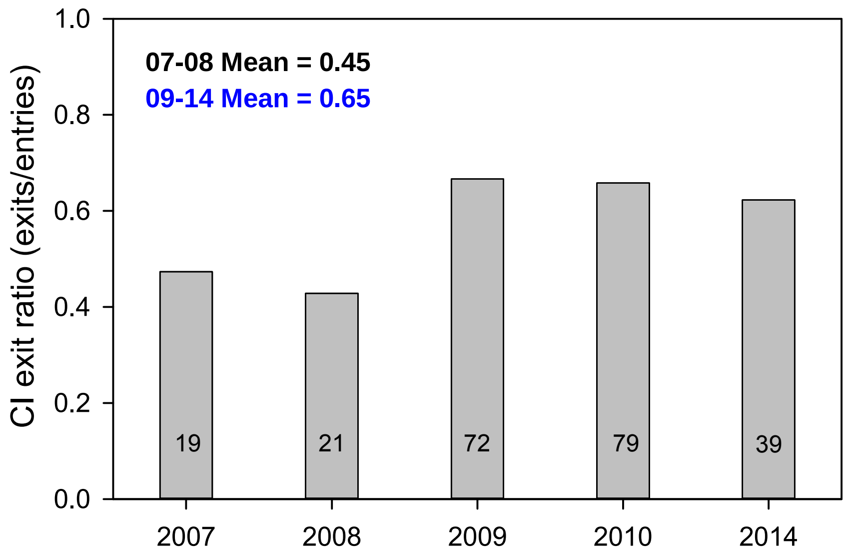

Figure 26. Cascades Island fishway exit ratios (total exit events/total entry events) for radio-tagged lamprey. Sample sizes (number of entries) are inside each bar. Modifications occurred prior to the 2009 migration.

Metric 3: Entrance time. Passage times for lamprey from first CI approach to first CI entry were strongly right-skewed in all study years (Figure 27). Generally, the majority of fish moved rapidly into the fishway, but a few had long passage times when they repeatedly approached the fishway without entering or moved to the tailrace or to other fishways and then returned to enter. Annual median approach-to-entrance times ranged from 9 to 74 min in years prior to fishway entrance modifications. Post-modification, the medians ranged from 22 min in 2014 to 40 min in 2009. There was not a significant difference in entrance times between pre- and post-modification years (ANOVA df =1, F = 0.74, $P = 0.39$); however, significant among-year differences were identified (ANOVA df =4, F = 3.23, $P = 0.014$). Pairwise comparisons using the Tukey's test indicated significantly faster lamprey passage in 2014 compared to 2010 (Figure 20). The GLM model also indicated faster passage times across years for lamprey that approached (df =1, F = 5.36, $P = 0.02$) CI at night (between 22:00-0400). We observed no statistically significant associations between date, flow, temperature, tailwater elevation and lamprey time to enter (Figure 28).

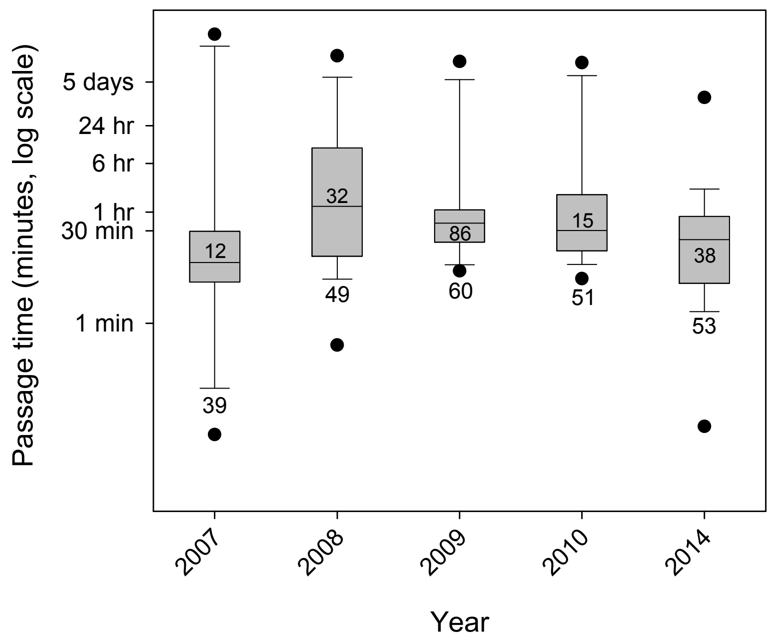

Figure 27. Lamprey passage time distributions (plotted on log scale) from approach to entry at Cascades Island fishway. Values inside boxes are median times in minutes. Distributions show 5th, 10th, 25th, 50th, 75th, 90th and 95th percentiles; sample sizes are shown at bottom.

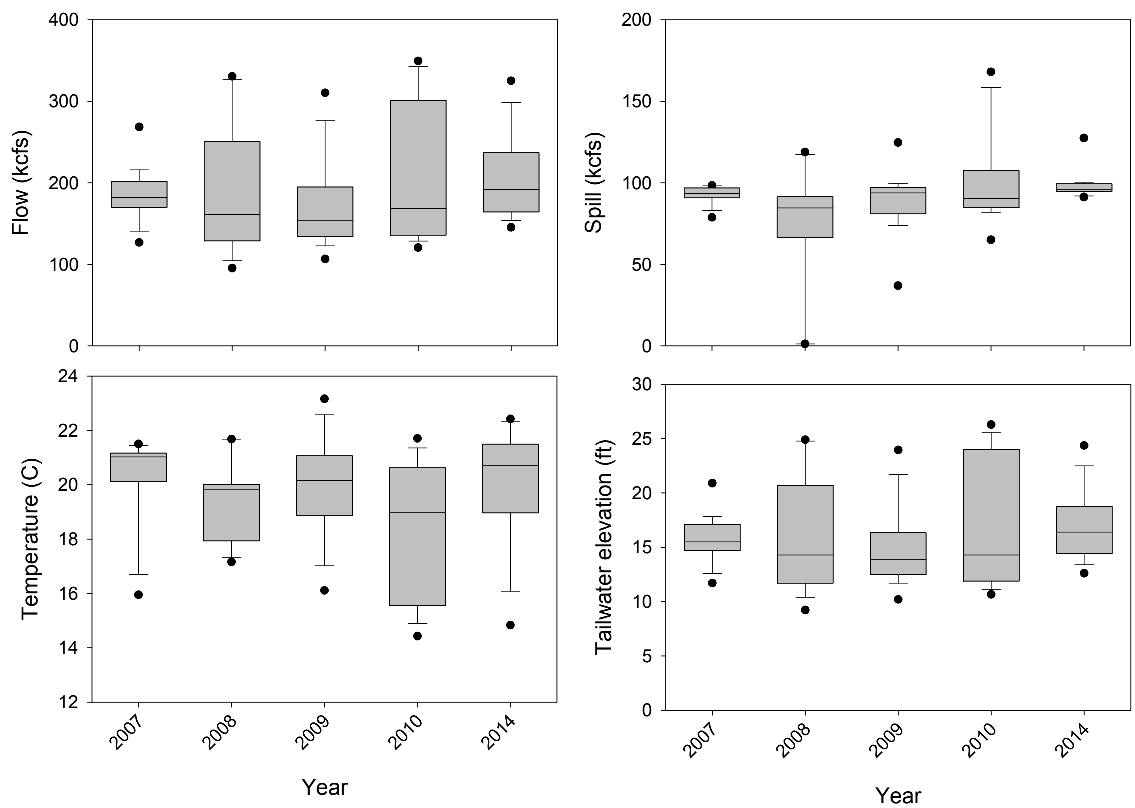

Figure 28. Box plots of the total discharge ('flow'), spill, temperature, and tailwater elevation on the days that radio-tagged adult lamprey first approached the CI. Distributions show 5th, 10th, 25th, 50th, 75th, 90th, and 95th percentiles.

Similar to the comparisons of lamprey behavior at NDE and SDE, we compared fish passage times at CI with those from the Bradford Island Fishway entrance (BI) on the south side of the spillway channel. Lamprey had median approach-to-entry times at the BI fishway opening that were lower than those at the CI fishway opening in 2008 and that were slightly higher than at the CI fishway opening in 2007 (Figure 29). In contrast, the median approach-to-entry time (86 min) for lamprey at BI in 2009 was more than two times higher than the 2009 CI median time (40 min). The CI median in 2010 (30 min) was also higher than its respective BI value (15 min). However, in 2014 the median approach-to-entry passage time at CI was lower than at BI (Figure 30).

Metric 4: Entrance to base of ladder time. After radio-tagged lamprey entered the CI fishway, the median time to reach the ladder base ranged from 7–9 min in pre-modification years (Figure 31). Median times in post-modification year were slightly higher and ranged from 14 min (2010) to 23 min (2014). GLM results for log-transformed passage times indicated a significant difference between pre- and post-modification groups ($df = 1$, $F = 8.3$, $P = 0.005$). Tukey's pairwise comparisons indicated significantly slower passage times in 2014 compared to 2007.

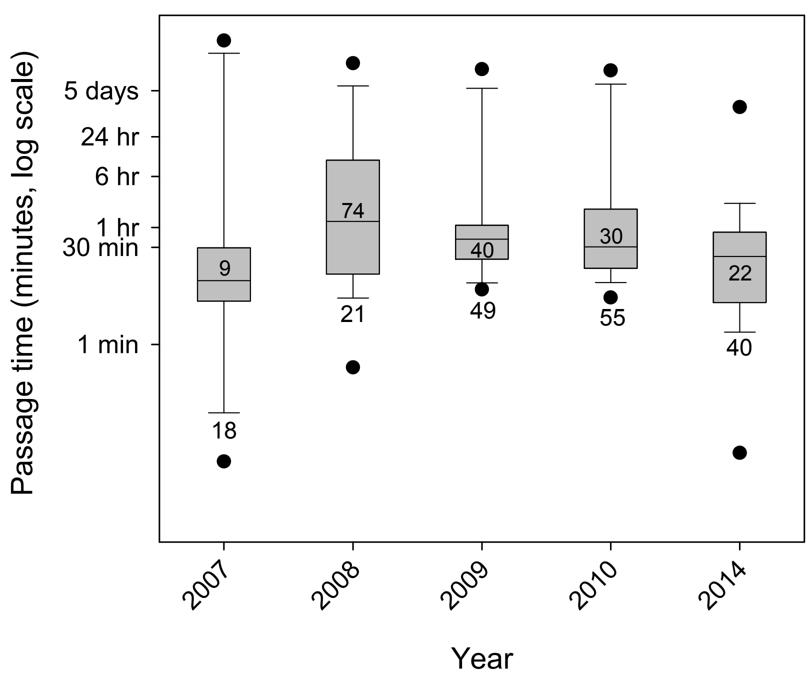

Figure 29. Lamprey passage time distributions (plotted on log scale) from approach to entry at the Bradford Island fishway. Values inside boxes are median times in minutes. Distributions show 5^{th}, 10^{th}, 25^{th}, 50^{th}, 75^{th}, 90^{th}, and 95^{th} percentiles; sample sizes are listed at bottom.

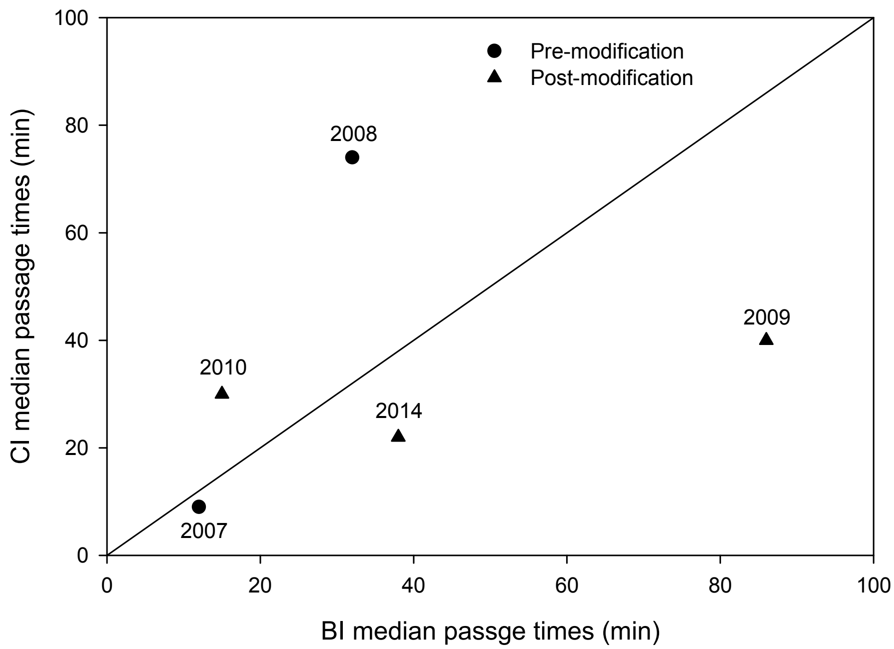

Figure 30. Scatterplot of annual median first approach to first entry times (min) at the Bradford Island and Cascades Island fishway entrances for radio-tagged lamprey during pre-and post-modification years.

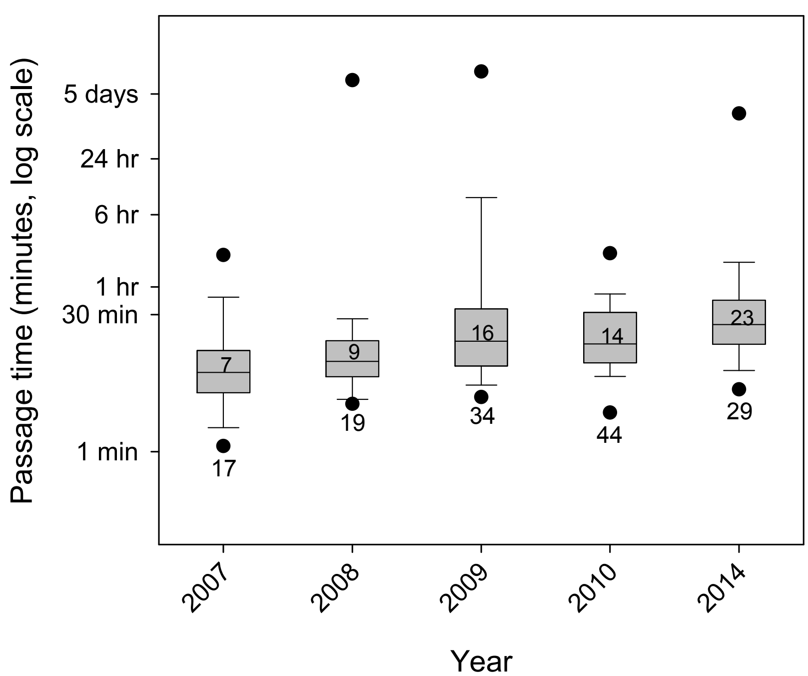

Figure 31. Lamprey passage time distributions (plotted on log-scale) from Cascades Island fishway entry to the antenna at the base of the ladder. Numbers inside boxes are median times in minutes. Distributions show 5th, 10th, 25th, 50th, 75th, 90th, and 95th percentiles; sample sizes are below boxes.

Metric 5: Extended passage times. In pre-modification years, the percentage of adult lamprey with long passage times (> 1 h) ranged from 17–52% (*mean* = 35%) from CI approach to CI entrance and from 5–6% (*mean* = 6%) for CI entrance to the first base-of-ladder antenna. The mean approach-to-entry percent in post-modification years was 28% and ranged from 23% in 2014 to 33% in 2010. Logistic regression models indicated no differences in fish taking > 1 h to enter the fishway between pre- and post- modification years ($df = 1$, $\chi^2 = 0.11$, $P = 0.74$). In contrast, the percentage of lamprey with > 1 h entry-to-base of ladder times was higher (*mean* = 13%) after the fishway was modified and ranged from 7% in 2010 to 18% in 2009.

Lamprey in Cascades Island AWS

A total of 14 radio-tagged lamprey were recorded in the CI auxiliary water supply (AWS) channel in 2014. Nine fish moved into the CI AWS via the upstream migrant tunnel (UMT) channel from the WA shore fishway (i.e., they moved down the UMT) and the other 6 had entered the CI fishway. Based on radiotelemetry records, 6 of the 14 fish eventually passed the dam (5 via the WA shore ladder and 1 via an unknown route). Six fish exited the fishway to the tailrace (5 via the CI fishway and 1 via the WA-shore fishway). Of the two remaining fish, one was last recorded in the CI AWS and other was in the UMT channel.

Lamprey behavior near count window/serpentine weirs and AWS channels at Bonneville

Movements of radio-tagged lamprey were extensively monitored with underwater antennas near the count windows and serpentine weir sections and AWS channels of both the Washington and Bradford Island fishways in 2014 (Figure 32).

Washington-shore fishway – Two hundred and sixteen radio-tagged lamprey were recorded at one or more antennas at the top of the Washington-shore fish ladder (upstream from the UMT channel junction). Of the 216 lamprey, 148 (69%) passed the dam, 65 (30%) did not pass the dam, and 3 (1%) were recaptured. The three recaptured fish were excluded from the following behavior summary.

Of the 148 fish that passed the dam, 81% (*n* = 120) were recorded on the antenna below the count window (KBO5) and 82% (*n* = 121) were recorded on the antenna above the count window (KBO4; Figure 31). Thirty-three percent (*n* = 49) of the fish that passed the dam were recorded on antennas in both the serpentine weirs and in the AWS. The majority of fish (63%) that passed the dam did so through the serpentine weirs and 37% passed through the AWS channel.

Of the fish that did not pass the dam (*n* =65), 94% were recorded on the antenna below the count window (KBO5) and 92% were recorded on the antenna above the count window (KBO4). The furthest upstream record (turn around point) for the majority (71%, *n* = 46) of fish that did not pass the dam occurred in the serpentine weirs (Figure 33). Eighty-seven percent (*n* = 40) of the serpentine turn-arounds were estimated to have occurred at the upper most antennas (KBO6 = 44%; KBO2 = 41%; KBO1 = 2%). One fish (1%) made it to the top-of-ladder exit antenna (PBO1) before turning around and moving back downstream. The other 28% (*n* =18) of the fish that did not pass the dam had their most upstream records in the AWS channel, with the majority occurring at the most upstream antenna (HBO3 = 94%, n = 17; Figure 33).

The last recorded locations of 65 fish that did not pass the dam via the WA-shore fishway included 92% (n = 60) in the tailrace. The majority of fish (55%) that were last were recorded in the tailrace traveled from the Washington-shore ladder through the UMT channel and exited the Cascades Island fishway and the other 45% exited the Washington-shore ladder to the tailrace. The last recorded locations for the remaining 7% (n = 5) of the fish that did not pass the dam were: 3% in CI AWS, 3% passed the dam via the BI fish ladder, and 1% was last detected in the WA-shore AWS.

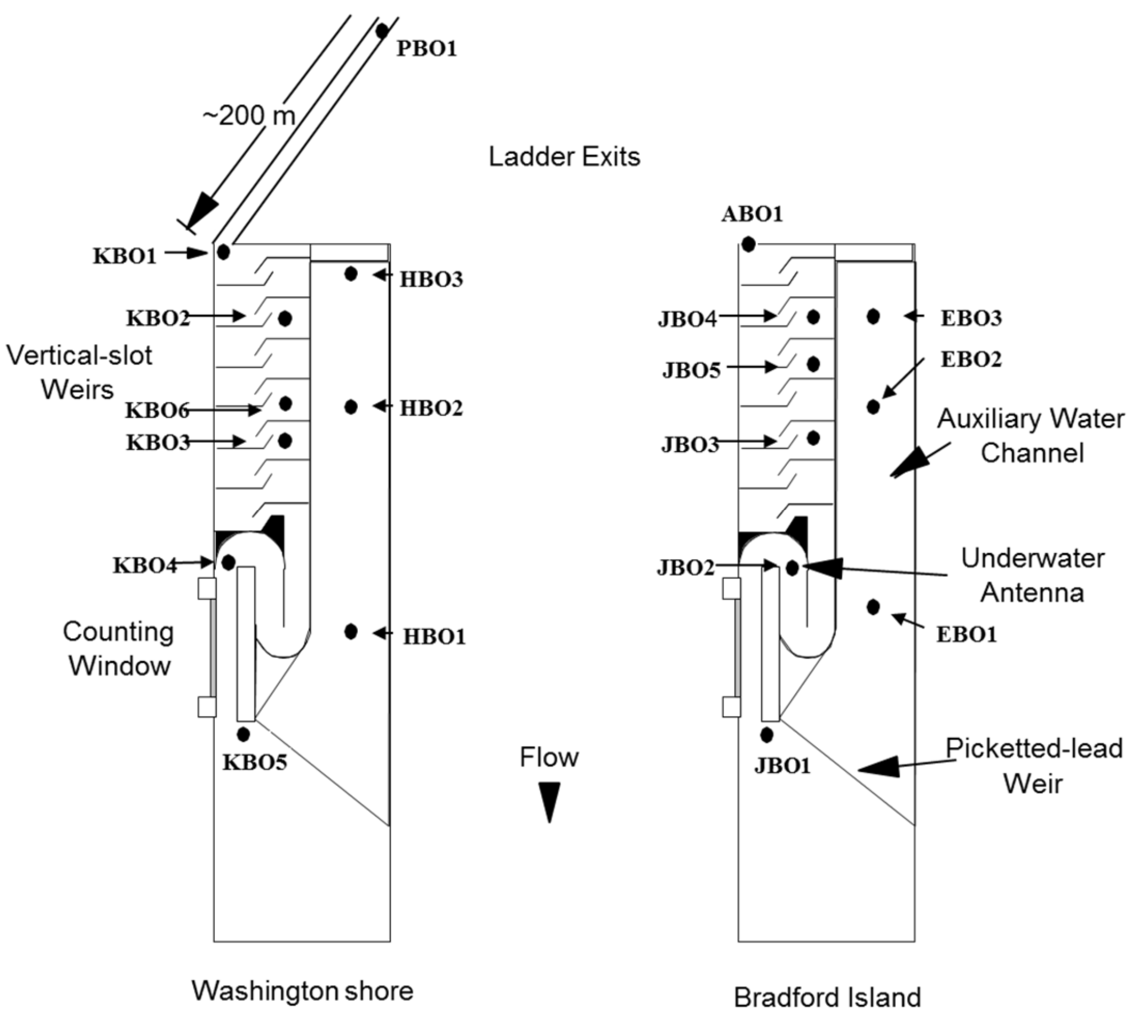

Figure 32. Overhead diagram of radio antenna deployments at Bonneville Dam count stations, serpentine weirs, and auxiliary water supply (AWS) channels in 2014.

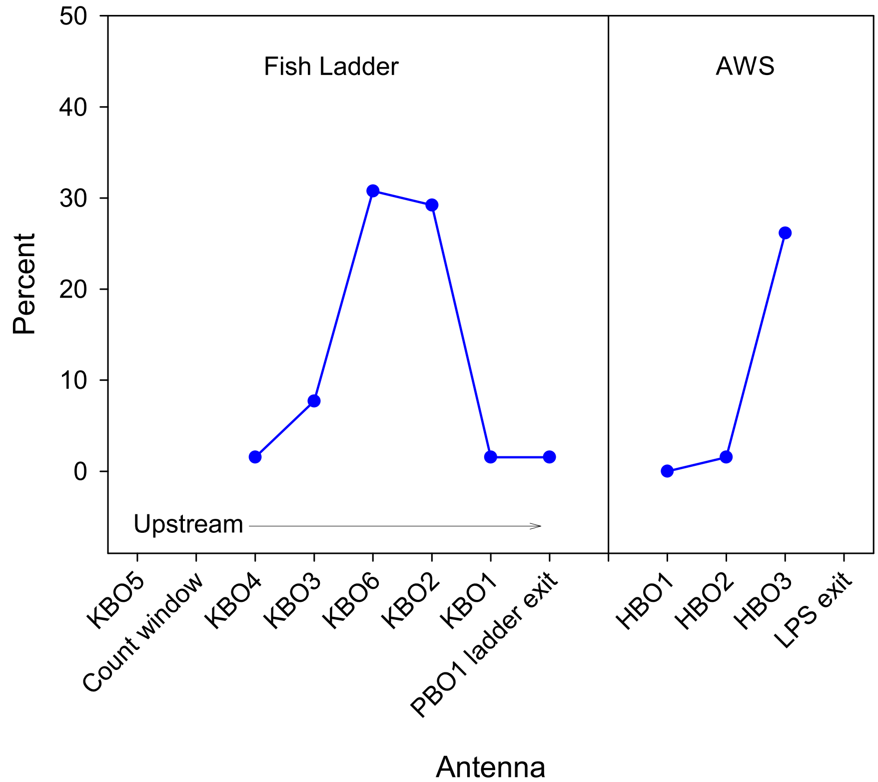

Figure 33. Percent of furthest upstream detections by antenna for lamprey that did not pass the dam in 2014 at Washington-shore fish ladder and auxiliary water supply (AWS) channel.

Bradford Island fishway – One hundred and fifteen radio-tagged lamprey were recorded at one or more antennas at the top of the Bradford Island fish ladder (upstream from the junction pool). Of the 115 lamprey, 65 (56%) passed the dam, 49 (43%) did not pass the dam, and 1 (1%) was recaptured. The recaptured fish was excluded from the following behavior summary.

Of the 65 fish that passed the dam, 92% (n = 60) were recorded on the antenna below the count window (JBO1) and 88% (n = 57) were recorded on the antenna above the count window (JBO2; Figure 31). Twenty-eight percent (n = 18) of the fish that passed the dam were recorded on antennas in both the serpentine weir section of the ladder and the AWS. The majority of fish (66%) that passed the dam did so through the serpentine weirs and 34% passed through the AWS channel and LPS.

Of the fish that did not pass the dam via the BI fishway (n =49), 100% were recorded on the antenna below the count window (JBO1) and 100% were recorded on the antenna above the count window (JBO2). The furthest upstream record (turn around point) for the majority (92%, n = 45) of fish that did not pass the dam occurred in the serpentine weirs. Fifty-six percent (n = 25) of the turn-arounds in the serpentine weir section occurred at the uppermost antennas (JBO4 = 36%; JBO5 = 20%; Figure 31). Two fish (4%) made it to the top of the ladder exit (antenna ABO1) before turning around and moving back downstream. The other 4% (n = 2) of the BI fish that did not pass the dam had their furthest upstream records in the AWS channel with both fish detected at the most upstream antenna (EBO3 = 100%, n = 2).

The last recorded locations for fish that did not pass the dam included 80% (n = 39) in the tailrace, 16% in the PH1 collection channel (n = 8) and 4% in the "A-branch" transition pool (n = 2).

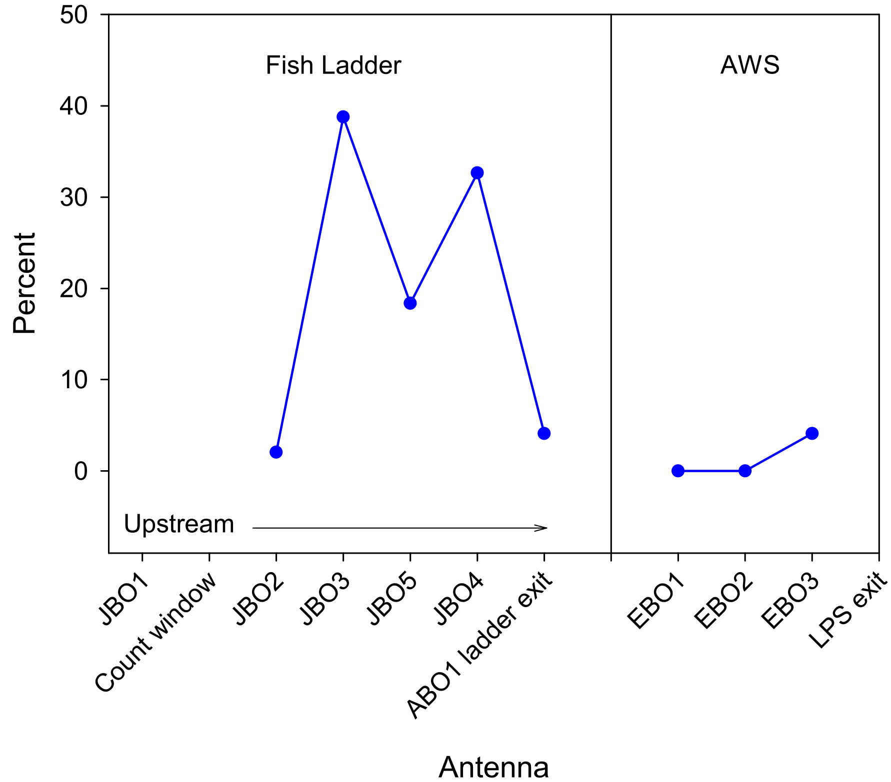

Figure 34. Percent of furthest upstream detections by antenna for lamprey that did not pass the dam in 2014 at Bradford Island fish ladder and auxiliary water supply (AWS) channel.

Lamprey behavior after exiting the AWS LPSs at Bonneville

Washington-shore fishway – Ninety-nine radio-tagged (RT + HD) fish had detections on AWS radio antennas and 28 likely passed through the WA LPS based on HD PIT records. After passing the WA LPS, 1 of the 28 lampreys (3.6%) moved back down the adult fishway through the serpentine weirs and past the count window and exited to the tailrace via the Cascades Island fish ladder; this fish did not reascend the dam. No downstream movement was detected for the other 27 radio-tagged lamprey that passed the dam via the WA LPS. Another 44 HD PIT (only) lamprey passed via the WA LPS and none was detected moving downstream into the fish ladder (note, however, that the only potential downstream HD PIT detection sites were in lamprey rest boxes or near fishway entrances).

Bradford Island fishway – Twenty-four radio-tagged (RT + HD) fish had detections in the AWS and 17 likely passed the ladder through the BI LPS based on HD PIT records. Of the 17 that passed via the LPS, 9 (52.9%) also had detections on the radio antenna used to monitor the adult fish ladder exit area; the range of this antenna potentially included a small portion of the forebay near the BI LPS exit. Importantly, none of the 17 radio-tagged fish were detected on antennas used to monitor the serpentine weirs or the area near the count station after LPS exit, indicating that these fish did not move downstream into the fish ladder. Another 24 HD PIT (only) lamprey passed via the BI LPS and 3 (12.5%) were detected on the HD PIT antenna used to monitor the ladder exit. None of the HD PIT lamprey was detected moving downstream into the fish ladder, but there were no downstream HD PIT antennas.

John Day North Entrance Results

Radiotelemetry

In 2014, lamprey entrance efficiency at the JDN was 84%. Of the 26 entry events (by 25 fish), 5 exit events were recorded to the tailrace for an exit ratio of 19%. The median time from fishway approach to entry was 11 min and ranged from < 1 min to 6 h. After radio-tagged lamprey entered the north fishway, the median time to reach the base of the ladder was 10 min (*range* = 6-66 min). The percentage of adult lamprey at the John Day north entrance with long approach-to-entry times (> 1 h) was 29% and 1 lamprey that entered had >1 h passage times from entrance to the first ladder antenna. Of the 25 unique fish that entered JDN, 21 successfully passed the dam (84%). Three of the four fish that did not pass the dam turned around just above the transition pool and the other fish turned around in the lower transition pool.

HD-PIT

Movements of 154 HD-PIT tagged lamprey were detected with the HD PIT antenna array at the north John Day entrance (two antennas outside the variable width weir and two inside the entrance upstream from the variable width weir, Figure 35). The 154 tagged lamprey that first approached the John Day north entrance consisted of 18 double-tagged fish (12%, released below Bonneville), 72 HD-PIT tagged fish released below Bonneville Dam (47%), and 64 HD-PIT tagged fish released upstream from Bonneville near Stevenson (41%).

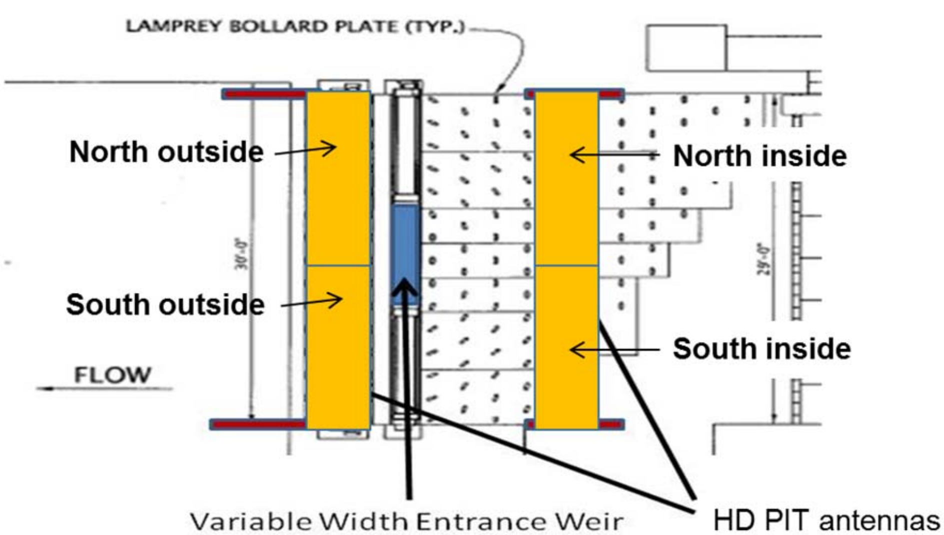

Figure 35. Overhead diagram of HD-PIT antenna array at the John Day north entrance in 2014.

There were several types of HD-PIT detections histories. The most common (34%, n = 53) history included lamprey that were only detected at the outside antenna. Seventy percent of these 53 fish moved upstream and passed the dam via the north ladder and one fish was recaptured at the LPS trap box (Figure 36). Twenty-percent (n = 31) of the 154 lamprey at the north entrance were detected on multiple antennas (3 or more). Forty-five percent (n = 14) of the 31 moved upstream and passed the north ladder; 1 fish had an unknown dam passage route and two were recaptured in the John Day north ladder. The third most common detection history was for lamprey recorded on both outside antennas: (14%) 67% of these fish moved upstream and passed the north ladder along with one fish that was recaptured in the LPS trap box. With all detection histories combined (Figure 36), 65% of the lamprey detected at the north entrance passed the dam via the north ladder, 5% passed the dam via an unknown route, 5% passed via the south fishway, 3% were recaptured in the LPS trap box (4 first detected on south outside antenna and 1 on north outside antenna), and 22% did not pass the dam.

Movements of 45 of lamprey that fell back one or more times at John Day were evaluated at the John Day north entrance HD-PIT antenna array. The 45 fallback lamprey that were detected at the John Day north entrance consisted of 6 double-tagged (13%, released below Bonneville), 12 HD-PIT fish released below Bonneville Dam (27%), 8 HD-PIT fish released upstream from Bonneville (18%), and 19 HD-PIT released upstream from John Day Dam (42%). Overall fallback percentages for Bonneville-tagged lamprey that passed John Day were 35% for double-tagged fish and 15% for HD-PIT fish. Forty-one percent of HD-PIT fish released upstream of John Day fell back.

Detection histories at John Day north for 45 lamprey that appeared to fall back at John Day Dam were similar to those of fish that first encountered the John Day north entrance array before passing the dam. The highest percentage (49%, n = 22) were detected only at the south outside antenna (Figure 36). The second highest detection history occurred at the south inside antenna (11%, n = 5) followed by detection at both outside antennas (9%, n = 4). Of all fallback lamprey detected at the north entrance array, 64% eventually passed the dam via the north ladder, 13% were recaptured in the LPS trap box, 9% passed via the south ladder, and 14% were not detected reascending a John Day fishway (Figure 33).

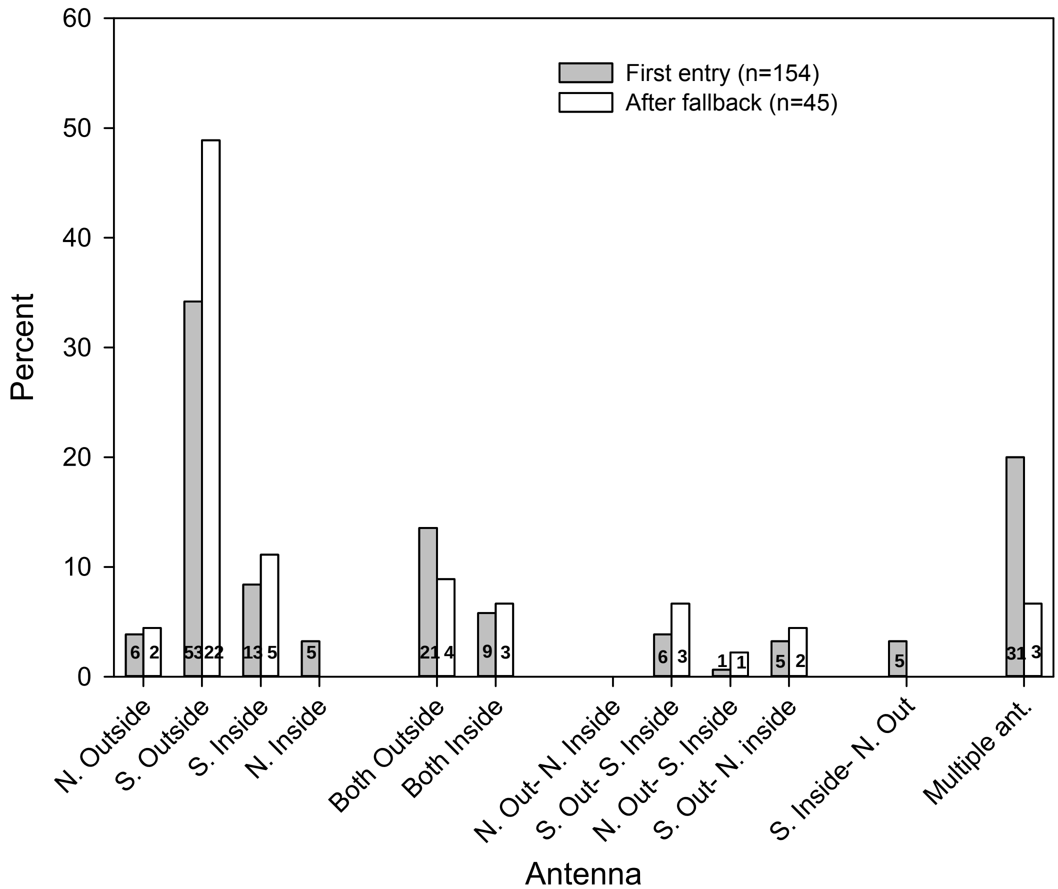

Figure 36. Detection histories of HD-PIT tagged lamprey at the John Day north entrance HD-PIT antenna array in 2014 before and after fallback at John Day Dam. Numbers indicate number of unique fish with each history.

General passage at Bonneville, The Dalles, John Day, and McNary dams

Bonneville fishway use

Fishway approaches – Of the 599 lamprey released, 473 (79%) approached a Bonneville Dam fishway. The highest percentage first approached at PH2 fishway openings (44%) followed by PH1 (21%), and the spillway (11%),B-Branch and Cascades Island combined (Figure 34). Twenty-four percent of first approaches were at unknown locations with the majority of unknown approaches occurring at PH2 (96%) and the rest at PH1 (4%). The distribution of total fishway approaches was generally similar to first approaches, with the exception of a higher percentage of the total observed approaching at the spillway (17%) and PH2 S (29%). On average, lamprey approached fishways 4.1 times per fish (*median* = 2; *range* = 1-40).

Fishway entries – A total of 437 lamprey were recorded inside Bonneville Dam fishways (73% of 599 released and 92% of 473 that approached a fishway). Many lamprey first entered at PH2 (22% at north entrances and 15% at south entrances) and the fewest first entered the PH1 south entrances (4%) and the spillway CI entrance (5%, Figure 37). Forty percent of first fishway entries were at unknown locations and mainly occurred at PH2 (89%) followed by PH1 (11%). The distribution of total fishway entries was similar to the distribution of first entries except for a higher proportion of the total was at the BI spillway B-branch entrance and PH2 entrances (Figure 37). Lamprey that entered a fishway did so 2.3 times per fish, on average (*median* = 1; *range* = 1-18).

Fishway exits – A total of 308 lamprey exited a Bonneville fishway to the tailrace (70% of 437 that entered). Most of the fishway exits (45% of first and 47% of total) were from PH2 entrances, most frequently from the north-shore entrances (Figure 37). Approximately 22-24% of first and total exits were from each of the two entrances adjacent to the spillway and less than 5% were from PH1 entrances. Lamprey that entered a fishway at least once and subsequently exited to the tailrace did so 2.4 times per fish, on average (*median* = 2; *range* = 1-17).

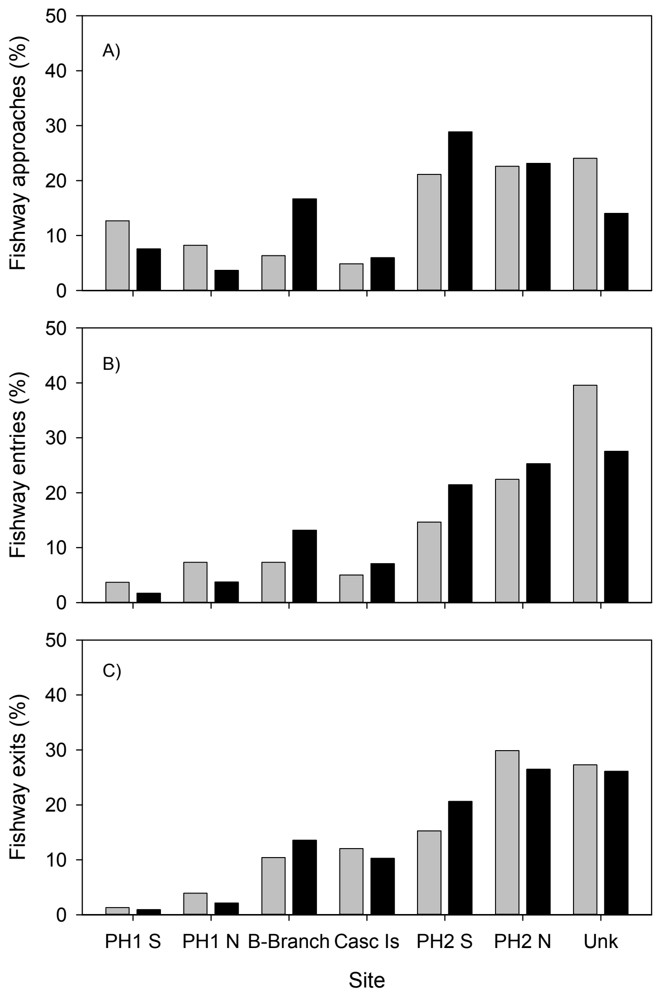

Figure 37. Site-specific distributions of first (gray bars) and total (black bars) fishway approaches (A), fishway entries (B), and fishway exits to the tailrace (C) by radio-tagged adult Pacific lamprey at Bonneville Dam in 2014. Unknown (Unk) category includes fish recorded in a transition pool without clear fishway approach, entry, or exit record.

Bonneville passage times

Fishway approach, fishway entry, and dam passage – Median lamprey passage times from release to first approach a fishway, first enter a fishway, and pass the dam were 1.1 d (26.0 h), 1.2 d (28.1 h), and 6.1 d (145.2 h), respectively (Table 1). Mean times were substantially longer because some fish took more than a week to pass. Median passage times from the first tailrace record to first approach a fishway, first enter a fishway, and pass the dam were 1.0 d (23.9 h), 1.2 d (27.9 h), and 5.7 d (137.5 h), respectively. (Note: lamprey release sites were near aerial tailrace antennas at Bonneville Dam.)

Most lamprey entered a fishway after their first recorded approach in a median of 1.5 h. Passage times were also relatively rapid from first fishway entry to first transition pool entry (*median* = 0.1 h), but were slower through transition pools (*median* = 2.0 h). Passage times were much longer and more variable from the transition pool exit to the top-of-ladder exit (*median* = 24.5 h).

Table 1. Summary of radio-tagged adult lamprey passage times at Bonneville Dam in 2014. Q1 and Q3 are first and third quartiles, respectively.

Passage segment			Passage time (h)			
Start	Finish	*n*	Median	Mean	Q1	Q3
Release	First approach	337	26.0	61.7	3.3	74.9
Release	First entrance	231	28.1	78.7	4.4	98.9
Release	Past dam	191	145.2	197.4	53.3	255.9
Tailrace	First approach	271	23.9	59.2	3.0	74.8
Tailrace	First entrance	188	27.9	75.5	4.0	97.8
Tailrace	Past dam	158	137.5	188.9	51.8	239.9
First approach	First entrance	139	1.5	37.0	0.3	23.6
First entrance	Transition pool entry	215	0.1	10.5	0.01	0.4
First entrance	Past dam	100	51.1	124.7	24.7	177.4
Transition pool entry	Transition pool exit	226	2.0	72.9	0.5	72.1
Transition pool exit	Past dam	189	24.5	44.1	20.2	48.9

Bonneville passage efficiency

Dam and fishway passage efficiency – Of the 599 released lamprey, 473 (89%) were recorded approaching Bonneville Dam fishway entrances and 437 (73%) entered a fishway. When the 20 recaptured lamprey were excluded from the analyses, dam passage efficiency was 49.4% (224 passed the dam/453 approached the dam) and fishway passage efficiency was 53.7% (224 passed/417entered). When the 20 recaptured fish were treated as passing the dam (i.e., assuming that all recaptured individuals would eventually pass, a maximum estimate), dam passage efficiency was 51.6% (244/473) and fishway passage efficiency was 55.8% (244/437).

Fishway passage efficiency was higher for lamprey that first entered the openings adjacent to the spillway (54.9%), followed by those that first entered at PH2 openings (50.5%) (Table 2). Excluding the recaptured lamprey produced similar results.

Table 2. Route-specific fishway passage efficiency calculated as the number of unique radio-tagged lamprey that passed Bonneville Dam divided by the unique number first recorded entering each main fishway entrance. (Note: fish could pass via any route and fish with unknown fishway entry location and time were excluded.)

Location[1]	Receiver	Antenna	Number of lamprey (*n*) First entered	Passed dam	Fishway passage Efficiency
Powerhouse 1 south	4BO	1	17	9	52.9
Powerhouse 1 north[2]	8BO	1	37	17	45.9
Powerhouse 1[2]	**Total**	**Total**	**54**	**26**	**48.0**
Powerhouse 1[3]	**Total**	**Total**	**53**	**25**	**47.0**
Spillway south[2]	BBO	1	73	40	54.8
Spillway south[3]	BBO	1	71	38	53.5
Spillway north[2]	CBO	1	49	27	55.1
Spillway north[3]	CBO	1	47	25	53.2
Spillway[2]	**Total**	**Total**	**122**	**67**	**54.9**
Spillway[3]	**Total**	**Total**	**118**	**63**	**53.4**
Powerhouse 2 south[2]	DBO	1,4	107	58	54.2
Powerhouse 2 south[3]	DBO	1,4	101	52	51.5
Powerhouse 2 north[2]	LBO	1,4	168	81	48.2
Powerhouse 2 north[3]	LBO	1,4	165	78	47.2
Powerhouse 2[2]	**Total**	**Total**	**275**	**139**	**50.5**
Powerhouse 2[3]	**Total**	**Total**	**266**	**130**	**48.9**

[1] Entries at known locations, but with unknown times, were included
[2] 14 recaptured fish treated as passing the dam
[3] 14 recaptured fish excluded
[*] Note 6 recaptured fish with and unknown entry location and time were excluded from this table

Entrance and fishway segment passage efficiency – We used several metrics to evaluate lamprey entrance efficiency at Bonneville Dam. Differences among metrics were related to the timing of fishway approaches and entries (i.e., first event or attempt versus total attempts). At the broadest scale, 437 unique lamprey entered a Bonneville fishway out of 473 unique lamprey that approached a fishway, for a dam-wide fishway entrance efficiency of 92%.

At individual fishway openings, lamprey entrance efficiency estimates using unique fish that approached and entered at the same site were relatively high at Cascades Island (60-72% efficiency for first entries and total entries) and at NDE (63-77%). Entrance efficiency estimates were relatively low at PH1 south (12-23%), and were intermediate at PH2 south (32-60%), BI (40-66%), PH1 north (52-59%), and PH2 north upstream (48-64%) entrances (Figure 38).

Additional efficiency metrics were calculated after lamprey entered the PH1, PH2, and spillway fishways separately (Table 3). Unique fish passage efficiencies from fishway entry to collection channels were highest at PH2 (94%) and were slightly higher at spillway entrances (77%) than at PH1 (60%) entrances. Collection channel passage efficiencies (collection pool to base of transition area) were lowest at the spillway sites (86%, CI and BI) and highest at PH1 (92%). Transition pool passage efficiencies were lowest at PH2 (83%), slightly higher at the spillway (85%), and highest at PH1 (100%). Ladder passage efficiencies ranged from 66% at the spillway to 87% via PH1. Passage efficiencies were also relatively high past the two count windows (96-99%) (Table 3).

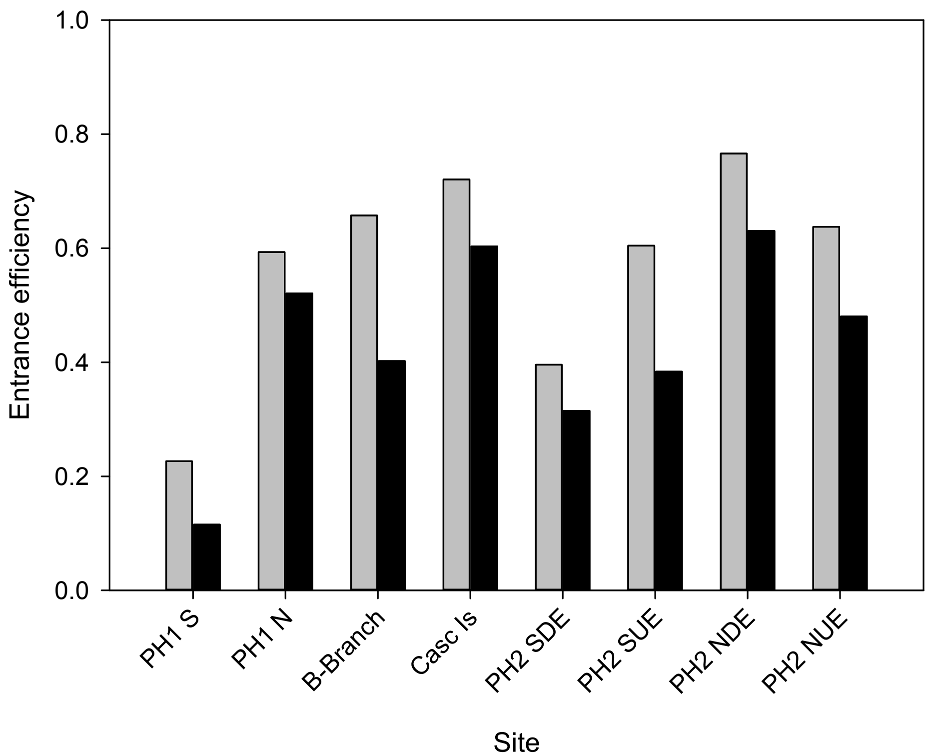

Figure 38. First (gray bars) and total fishway (black bars) entrance efficiency estimates calculated for radio-tagged adult Pacific lamprey at Bonneville Dam, by entrance site. First entrance efficiency was defined as the proportion of unique fish that first entered a fishway opening at the same location where they first approached. Total entrance efficiency was defined as the total number of fish recorded entering at each fishway opening divided by the total number of fish recorded approaching at the same site.

Table 3. The number of unique radio-tagged lamprey that passed through each area within each fishway at Bonneville Dam in 1997-2002 (Moser et al. 2005), 2007-2008 (Johnson et al. 2009a and 2009b), 2009-2010 (Keefer et al. 2015) and 2014. Passage efficiency (number of unique lamprey that passed through the area/number of unique lamprey that approached the beginning of the segment × 100) is in parentheses. Note: all efficiencies are for inside fishways (i.e., after lamprey entered) and the entrance area is from just inside the fishway opening to the collection channel or transition pool antenna.

	Year										
Segment*	1997	1998	1999	2000	2001	2002	2007	2008	2009	2010	2014
PH1											
Entrance	47 (60%)	78 (80%)	63 (72%)	97 (74%)	71 (74%)	54 (76%)	40 (71%)	105 (67%)	79 (65%)	74 (69%)	70 (60%)
Collection	36 (77%)	63 (81%)	55 (87%)	85 (88%)	59 (83%)	41 (76%)	36 (88%)	86 (82%)	75 (95%)	68 (92%)	70 (100%)
Transition	32 (89%)	61 (97%)	50 (91%)	82 (96%)	58 (98%)	38 (93%)	34 (97%)	79 (92%)	73 (97%)	66 (97%)	70 (100%)
Ladder	27 (78%)	59 (97%)	49 (98%)	71 (86%)	52 (90%)	35 (92%)	29 (85%)	69 (87%)	70 (96%)	53 (80%)	61 (87%)
Count station	21 (78%)	37 (63%)	38 (78%)	63 (89%)	45 (86%)	25 (71%)	26 (90%)	62 (90%)	63 (90%)	50 (94%)	59 (97%)
PH2											
Entrance	50 (69%)	78 (81%)	87 (80%)	109 (78%)	100 (85%)	157 (77%)	118 (67%)	160 (60%)	233 (81%)	117 (86%)	256 (94%)
Collection	30 (60%)	50 (64%)	79 (79%)	63 (72%)	94 (60%)	84 (77%)	66 (56%)	104 (65%)	191 (82%)	95 (81%)	232 (91%)
Transition	25 (83%)	32 (64%)	43 (54%)	43 (68%)	72 (77%)	54 (64%)	42 (64%)	79 (76%)	135 (71%)	68 (72%)	192 (83%)
Ladder	24 (96%)	29 (91%)	43 (100%)	38 (88%)	71 (99%)	52 (96%)	37 (88%)	73 (92%)	111 (82%)	61 (90%)	128 (67%)
Count station	21 (88%)	25 (86%)	35 (81%)	32 (84%)	57 (80%)	42 (81%)	37 (100%)	67 (92%)	111 (100%)	61 (100%)	127 (99%)
Spillway (Cascades Island + Bradford Island B-Branch)											
Entrance	33 (54%)	35 (44%)	41 (57%)	69 (60%)	55 (65%)	66 (62%)	56 (49%)	74 (44%)	99 (55%)	100 (65%)	116 (77%)
Collection	19 (58%)	21 (60%)	22 (54%)	63 (91%)	53 (96%)	59 (89%)	56 (100%)	73 (99%)	93 (94%)	79 (79%)	100 (86%)
Transition	14 (74%)	12 (57%)	11 (50%)	37 (59%)	39 (74%)	37 (63%)	33 (59%)	52 (71%)	56 (60%)	66 (52%)	85 (85%)
Ladder	11 (79%)	11 (92%)	10 (91%)	32 (86%)	36 (92%)	35 (95%)	33 (100%)	45 (87%)	51 (91%)	26 (50%)	56 (66%)
Count station	6 (54%)	9 (82%)	8 (80%)	24 (75%)	26 (72%)	25 (71%)	31 (94%)	43 (96%)	51 (100%)	26 (100%)	54 (96%)

* Entrance efficiency = total # unique entries / total # unique approaches.
* Collection efficiency = total # unique detections in base of transition area/ total # unique entrances.
* Ladder efficiency = total # unique fish detected at count windows / total # that exited the transition pool.
*Count station efficiencies = the number detected on the antenna above the count window / number detected on the antenna downstream of the count window.
*Note 'count station' for the spillway group is for fish that passed the Washington-shore and Bradford Island fishway count stations.

Most upstream point reached by lamprey that did not pass – A total of 355 lamprey did not pass Bonneville Dam, 59% of the 599 released (the 20 that were recaptured were excluded from this summary). The most upstream site recorded for the 355 non-passing fish included 18 (5%) downstream from the release sites, 104 (29%) in the tailrace, 35 (10%) outside a fishway entrance, and 198 (56%) inside a fishway (Table 4).

The 35 lamprey that were recorded approaching but not entering a fishway were recorded outside most of the primary fishway entrances. These included PH1 south (29% of 35), B-Branch (23%), PH2 south (17%), PH1 north (14%), CI (9%), and PH2 north (9%).

Table 4. The most upstream detection locations recorded for 355 radio-tagged lamprey that did not pass Bonneville Dam in 2014, including specific fishway locations for the 198 that entered a fishway but did not pass the dam. (Note: 20 fish that were recaptured and released upstream were excluded.)

	n	Percent of 355	Percent of 198
Did not pass dam	**355**		
Downstream from the release sites	18	5.1	
Tailrace only	104	29.3	
Approach fishway	35	9.9	
Entered fishway	198	55.8	
Entered fishway	**198**		
Bradford Island fishway			
B-Branch transition pool	7	2.0	3.5
Ladder between transition pool & window	5	1.4	2.5
Serpentine weirs	35	9.9	17.7
Serpentine weirs / auxiliary water channel	2	0.6	1.0
Auxiliary water channel	8	2.3	4.0
Top of ladder exit area	2	0.6	1.0
Washington-shore fishway			
Cascades Island entrance	4	1.1	2.0
Cascades Island transition pool	2	0.6	1.0
Cascades Island / UMT junction	2	0.6	1.0
PH2 collection channel	13	3.7	6.6
PH2 transition pool	51	14.4	25.8
Ladder between transition pool & window	7	2.0	3.5
Serpentine weirs	37	10.4	18.7
Serpentine weirs / auxiliary water channel	17	4.8	8.6
Auxiliary water channel	4	1.1	2.0
Top of ladder exit area	2	0.6	1.0

The most upstream locations for the 198 lamprey that entered a fishway were distributed throughout the fishways, with the majority (n = 139, 70%) in the WA-shore fishway (Table 4). Among individual locations, the largest numbers of fish turned around in the Washington-shore transition pool (n = 51, 26% of 198), followed by the Washington-shore serpentine weirs above the count window (n = 37, 19%), BI serpentine weirs (n = 35, 18%), and BI serpentine weirs/auxiliary water channel (n = 17, 9%). Combining similarly-configured sites, a total of 51

(26% of 198) lamprey turned around in one of the four transition pools at the dam and 91 (46% of 198) turned around in serpentine weir sections of fish ladders (Table 4). Of the 91 fish that turned around in the serpentine weirs , 17 fish at Washington-shore and 2 at Bradford Island fishway had records in both the serpentine weir section and the AWS channel at the top of the before moving downstream to the tailrace.

Bonneville fallbacks

We recorded 2 unique lamprey (1% of the total that passed the dam) falling back over the dam. Both fish fell back after passing the Washington-shore fishway and did not reascend the dam. They were last recorded in the tailrace.

The Dalles fishway use

Fishway approach, entry, and dam passage – Of the 157 radio-tagged lamprey detected approaching a fishway in 2014, 111 entered, and 50 subsequently exited back into the tailrace one or more times. The highest percentage of the tagged fish was first recorded approaching the east entrance (*n* = 74, 47%), followed by the north-shore entrance (*n* = 35, 22%), west powerhouse entrance (*n* = 33, 21%), and south spillway entrance (*n* = 14, 1%). First entries were highest at the north-shore entrance (*n* = 42, 38%) followed by the east entrance (*n* = 28, 25%), the south spillway entrance (*n* = 20, 18%), and west powerhouse entrance (*n* =18, 16%).

Distributions of total fishway approaches and entries were generally consistent with first approaches and entries, with the highest percentage of total approaches (43%) and total entries (45%) occurring at the north-shore entrance. Lamprey approached fishways a median of 2 times (*mean* = 2.4 times) per fish. Lamprey entered fishways a median of 1 time (*mean* = 1.5 times) per fish. Those that exited to the tailrace did so a median of 1 time (*mean* = 1.8 times). The north entrance was exited most frequently (*n* = 52 times), followed by the south spillway entrance (*n* = 17 times), the west powerhouse entrance (*n* = 12 times), and the east-shore entrance (*n* = 11 times).

The Dalles passage times

Fishway approach, entry, and dam passage – A total of 163 lamprey were detected at antennas at The Dalles Dam and/or in The Dalles tailrace. Detection efficiency at the tailrace antennas was low, with only 18% of the 163 tagged fish recorded at the tailrace sites on their first apparent approach to the fishways; 6 of the 29 (21%) lamprey recorded in the tailrace were not recorded upstream from the tailrace. Median passage times from the first tailrace record to first approach a fishway, first fishway entry, and to pass the dam were 18.6, 20.5, and 30.4 h, respectively (Table 5). Most lamprey moved quickly into a fishway after their first recorded approach (*median* = 1.5 h, *n* = 102), from first fishway entry into a transition pool (*median* = 0.1 h, *n* = 100), and through transition pools (*median* = 0.5 h, *n* = 62). In contrast, passage time variability was much higher for the segment between first fishway entrance and exit from the top of a ladder (*median* = 21.8 h, *n* = 70) in part due to time spent exiting and re-entering the fishways and transition pools. Lamprey took a median of 20.3 h (*n* = 60) to pass from final transition pool exit to exit from the top of a ladder.

Table 5. Summary of radio-tagged adult lamprey passage times at The Dalles Dam in 2014. Q1 and Q3 are first and third quartiles, respectively.

Passage segment			Passage time (h)			
Start	Finish	*n*	Median	Mean	Q1	Q3
Tailrace	First approach	23	18.6	22.4	4.2	22.3
Tailrace	First entrance	17	20.5	51.4	4.9	32.7
Tailrace	Past dam	9	30.4	121.2	27.0	122.0
First approach	First entrance	102	1.5	38.7	0.1	46.6
First approach	Past dam	70	36.2	98.0	20.6	124.7
First entrance	Transition pool entry	100	0.1	8.3	0.01	0.5
First entrance	Past dam	70	21.8	59.9	10.6	41.4
Transition pool entry	Transition pool exit	62	0.5	28.0	0.3	1.0
Transition pool exit	Past dam	60	20.3	23.4	24.7	24.7

The Dalles passage efficiency

A total of 157 lamprey were recorded approaching fishways at The Dalles Dam and 74 passed the dam for a dam passage efficiency of 47%. A total of 111 fish entered a fishway and the fishway passage efficiency was 67% (74/111). Estimated passage efficiencies through fishway segments of the fishways were similar to those calculated at The Dalles Dam in previous radiotelemetry studies, except that entrance efficiency was lower (39%) at the east-shore entrance and collection channel (75%) than in previous years (Table 6). Passage efficiencies were also lower in 2014 through the transition pool at the north-shore (49%) than in previous years.

Unique fishway entrance efficiency was highest at the north entrance (98%, *n* = 45 fish recorded approaching). Efficiencies were 81% (*n* = 26) at the south spillway entrance, 33% (*n* = 70) at the east shore entrance, and 33% (*n* = 97) at the west powerhouse entrance.

Most upstream point reached by fish that did not pass – Eighty-three fish recorded in the tailrace or at fishways at The Dalles Dam did not pass the dam. The most upstream site recorded for these fish included 47 (57%) outside a fishway entrance, 2 (2%) inside the north-shore fishway, 3 (4%) in the east-shore collection channel, 20 (24%) at antennas monitoring the north-shore transition pool, and 11 (13%) at antennas monitoring the east-fishway transition pool. About 45% of the 31 fish that reached transition pool antennas and that did not pass were recorded at the most upstream antennas in these areas (i.e., in weirs that were not submerged throughout the migration). This indicates that some lamprey turned around at unmonitored sites in the ladder upstream from transition pools but downstream from top-of-ladder exit antennas.

Table 6. The number of unique radio-tagged lamprey that passed through each area within each fishway at Bonneville Dam in 1997-2002 (Moser et al. 2005), 2007-2008 (Johnson et al. 2009a and 2009b), 2009-2010 (Keefer et al. 2015) and 2014. Passage efficiency (number of lamprey that passed through the area/number that approached the beginning of the segment × 100) is in parenthesis.

	Year									
	1997	1998	2000	2001	2002	2007	2008	2009	2010	2014
Area	East Fishway									
Entrance	41 (85%)	22 (73%)	52 (87%)	71 (89%)	46 (78%)	18 (83%)	78 (82%)	57 (81%)	87 (54%)	195 (39%)
Collection	34 (83%)	21 (95%)	47 (90%)	67 (94%)	43 (93%)	20 (100%)	64 (83%)	46 (100%)	47 (91%)	77 (75%)
Transition	27 (79%)	12 (57%)	41 (87%)	52 (78%)	29 (67%)	17 (76%)	53 (92%)	46 (91%)	43 (81%)	58 (71%)
Ladder	24 (89%)	12 (100%)	37 (97%)	48 (96%)	28(100%)	n/a	n/a	n/a	n/a	n/a
Count station	24(100%)	12 (100%)	37 (97%)	48 (96%)	28(100%)	n/a	n/a	n/a	n/a	n/a
	North Fishway									
Entrance	18 (67%)	15 (94%)	44 (94%)	34 (77%)	32(100%)	15 (75%)	32 (72%)	55 (89%)	47 (94%)	45 (98%)
Collection	14 (78%)	15 (100%)	42 (95%)	34 (100%)	32(100%)	13 (100%)	23 (100%)	49 (96%)	44 (91%)	44 (98%)
Transition	11 (79%)	13 (87%)	36 (86%)	24 (71%)	25 (78%)	13 (62%)	23 (57%)	47 (53%)	40 (83%)	43 (49%)
Ladder	11(100%)	12 (92%)	33 (92%)	22 (92%)	18 (72%)	n/a	n/a	n/a	n/a	n/a
Count station	11(100%)	12 (100%)	33 (100%)	22 (100%)	18(100%)	n/a	n/a	n/a	n/a	n/a

Note: entrance efficiency estimates in 2008 were not strictly comparable to estimates in other years because aerial antennas were used in 2008 to monitor 3 of the 4 main entrances instead of underwater antennas.

The Dalles fallbacks

Two of the 74 lamprey that passed the The Dalles Dam (2.7%) fell back over it. Both fish fell back after passing the north-shore fishway. Both fish reascended the dam, one via the north-shore fishway and one via the east fishway.

John Day fishway use

Fishway approach, entry, and dam passage – At John Day Dam, 48 lamprey approached fishway entrances in 2014, 46 entered , and 11 subsequently exited to the tailrace one or more times. The highest percentage of the tagged fish was first recorded approaching the north-shore entrance (*n* = 23, 48%), followed by the south-shore entrance (*n* = 8, 15%), and the north PH entrance (*n* = 6, 13%). Twenty-five percent of first approaches were by fish with unknown approach locations near the south fishway (likely at the unmonitored collection channel orifice). First entries were highest at the north-shore entrance (*n* = 23, 50%) followed by north PH (*n* = 5, 11%), the south-shore entrance (*n* = 2, 4%), and 35% had unknown entrance locations at the south fishway (*n* =16).

Distributions of total fishway approaches and entries were generally consistent with first approach and entry locations, with the highest percentage of total approaches (46%) and total entries (48%) occurring at the north-shore entrance. Lamprey approached fishways a median of 1 time (*mean* = 1.4 times) per fish. Lamprey entered fishways a median of 1.2 times (*mean* = 1 time) per fish. Those that exited back to the tailrace did so a median of 1 time (*mean* = 1.3 times). The north PH entrance was exited most frequently (*n* = 8 times), followed by the north-shore entrance (*n* = 6 times).

John Day passage times

Fishway approach, entry, and dam passage – A total of 48 lamprey were detected at John Day Dam. Detection efficiency at the tailrace antennas was low, with only 33% (16 of 48) of the tagged fish recorded at the tailrace sites; 3 of the 16 (19%) recorded in the tailrace were not recorded upstream from the tailrace. Median passage times from the first tailrace record to first fishway approach, first fishway entry, and to pass the dam were 24.0, 24.1, and 29.8 h, respectively (Table 7). Most lamprey moved quickly into a fishway after their first recorded approach (*median* = 0.2 h, *n* = 10), from first fishway entry into a transition pool (*median* = 0.1 h, *n* = 12), and through transition pools (*median* = 0.2 h, *n* = 18). In contrast, passage time variability was much higher for the segment from first fishway entry to exit from the ladder top (*median* = 20.0 h, *n* = 12). This was partially due to the time spent exiting and re-entering the fishways and transition pools. Lamprey took a median of 16.1 h (*n* = 18) to pass from transition pool exit to exit from the top of a ladder.

Table 7. Summary of radio-tagged adult lamprey passage times at John Day Dam in 2014. Q1 and Q3 are first and third quartiles, respectively.

Passage segment			Passage time (h)			
Start	Finish	*n*	Median	Mean	Q1	Q3
Tailrace	First approach	3	24.0	27.0	13.3	39.2
Tailrace	First entrance	3	24.1	27.1	13.4	39.3
Tailrace	Past dam	7	37.5	75.0	27.7	85.0
First approach	First entrance	10	0.2	3.2	0.1	0.8
First approach	Past dam	15	22.6	23.6	13.6	29.6
First entrance	Transition pool entry	12	0.1	2.2	0.01	0.3
First entrance	Past dam	12	20.0	20.2	10.9	22.9
Transition pool entry	Transition pool exit	18	0.2	0.4	0.1	0.3
Transition pool exit	Past dam	18	16.1	17.8	5.6	22.7

John Day passage efficiency

A total of 48 lamprey were recorded approaching fishways at John Day Dam and 40 passed the dam for a dam passage efficiency of 83%. Forty-six fish entered a fishway and fishway passage efficiency was 87% (40/46). Route-specific fishway passage efficiency was highest for lamprey that first entered the north PH entrance (100%, *n* = 5), followed by those that entered the north fishway entrance (84%, *n* = 25), and the south-shore entrance (50%, *n* = 4).

Fishway entrance efficiency at individual openings was highest at the north entrance (85%, 23 entered of 27 unique fish that approached). Entrance efficiencies were 71% (*n* = 7) at the north PH entrance and 50% (*n* = 10) at the south-shore entrance.

Most upstream point reached by fish that did not pass – Eight fish recorded in the tailrace or at John Day Dam did not pass the dam. The most upstream locations included: 3 just upstream from the north fishway transition pool and 1 inside the north transition pool, 2 in the south fishway transition pool, and 1 in the south fishway collection channel. The single remaining lamprey never entered a fishway and was last recorded outside the south-shore entrance.

John Day fallbacks

Fallback rates were much higher at John Day Dam than at Bonneville or The Dalles dams. Of the 40 unique, radio-tagged lamprey that passed John Day Dam, 14 (35%) had records that suggested they fell back at the dam at least once. Four fish fell back twice for a fallback rate of 45% (*n* = 18 events / 40 past the dam). Of those that fell back once, 60% did so after ascending the south fishway and 40% after ascending the north fishway. Of those that fell back twice, 2 passed the north ladder twice, 1 passed the south ladder twice, and 1 fish passed each ladder once before falling back. Last detections of the 14 fallback fish included 36% upstream from John Day Dam, 21% outside a John Day fishway entrance, 29% in the tailrace, and 14% recorded downstream in the Deschutes River.

McNary summary

Seven lamprey were recorded at McNary Dam and all were recorded at fishway sites. All seven first approached the south-shore fishway, with 43% at the south-shore opening, 29% at the north powerhouse opening, and 28% at unknown south fishway sites. Four of the seven first entered the south-shore opening and passed through the south-shore transition pool. The one fish that first approached the north powerhouse also entered there.

All seven lamprey passed the dam via the south-shore fishway. Five of seven fish with recorded first fishway approach and first fishway entry times entered McNary fishways within minutes of approaching. Lamprey moved rapidly from first fishway entry to first enter the transition pool (*median* = 0.2 h). Lamprey took a median of 19.8 h (*n* = 7) to pass from transition pool exit to exit from the top of a ladder. No lamprey were recorded falling back at McNary Dam.

Discussion

Bonneville passage metrics

The primary objectives of this report were to evaluate whether the structural modifications made to the Bonneville PH2 NDE in 2013, the CI fishway in 2009, and the John Day north entrance in 2011-2013 were associated with increased or decreased passage success of adult Pacific lamprey. We also used the radiotelemetry data to look at lamprey behaviors at other locations with known passage problems (i.e., the count stations, AWS channels and serpentine weir sections at Bonneville Dam) and to evaluate lamprey fallback behavior. Our multi-metric approach was designed to capture important elements of lamprey passage behavior at the modified fishways, including entrance attraction and selection, success and duration of entrance attempts, lamprey behavior in the lower fishway segments, and fishway exits to the tailrace. Results for individual metrics at Bonneville Dam indicated that the modifications have likely had a mix of negative, neutral, and positive effects on adult lamprey passage behavior and success (Table 8). A lack of directly comparable pre-modification data at John Day Dam NFE prevented a similar comparison, but qualitative comparison of metrics from 1997-1998 and 2000-2002 indicated relatively high entrance and fishway passage efficiency, and similar exit ratios in 2014 versus in earlier telemetry years.

Averaging across all metrics, the weight of evidence suggests the following at Bonneville Dam:

● Lamprey entrance efficiency, approach-to-entry times, and percentage of fish taking > 1 h from fishway approach to fishway entry indicated improved lamprey passage in 2014 at PH2 NDE compared to prior years. There appeared to be no net change in fishway exit ratio or passage time from fishway entry to the base of the ladder. We caution that this study is based on only one year of post-modification data and additional data would be needed to corroborate or refute these results.

● All but two passage metrics at CI had post-modification means that were higher or near those estimated in pre-modification years. However, exit ratios were ~20% higher on average in post-modification years and lamprey had slower passage times (7-16 min longer) from fishway entry to the base of the ladder. Of the post-modification years, 2014 had the highest entrance efficiency, fastest approach–to-entry time, and lowest percentage of fish with extended passage times from approach to entry.

Table 8. Qualitative classification of each post-modification passage metric compared to values from pre-modification years at the Bonneville north downstream entrance (NDE) at PH2 and at the CI entrance. Green indicates improved post-modification performance, white indicates no evidence of change, yellow indicates somewhat reduced performance, and red indicates substantially lower post-modification performance.

Metric	NDE lamprey	CI lamprey
1) Entrance efficiency	High	High
2) Exit ratio	Near average	High
3) Approach-Entry time	Fast[1]	Near average
4) Entry-Ladder base time	Near average	Slow
5a) Approach-Entry > 1 h	Low[1]	Near average
5b) Entry-Ladder base > 1 h	Near average	Near average

[1] Some estimates in 2014 were potentially longer due to use of aerial Yagi antennas at PH2

Bonneville LFS HD-PIT detections

There were very few detections of HD-PIT tagged lamprey at the LFS in 2014. In total, 10 fish (0.8% of 1,198 released with a PIT tag, including 3 double-tagged fish) were detected. Hypotheses for the low percentage detected have focused on attraction efficiency and attraction volume, as well as conditions near and inside the LFS associated with entrained air. With such a small number of fish detected at the structure, making inferences about cause and effect is difficult. However, we note that 7 of the 10 HD lamprey detections occurred before June 14, when the valve setting was 25% (1 fps). The 25% operation was conducted from 16 May to 26 July. Fewer fish were detected when the valve setting was 25-60% (~1-3 fps) from 27 July through 18 August, or at 30% (1.25 fps) from 19 August through September.

Lamprey behavior near the Bonneville count windows, serpentine weirs, and AWS channel

The picket lead gates, adjacent to the count windows and leading into the AWS in the WA-shore and BI fishways, were raised to increase lamprey access to the LPSs. Nevertheless, a high percentage of radio-tagged lamprey remained in the primary fishway channels and moved past the count stations. Approximately 30% of the lamprey detected near the WA-shore count station or AWS channel and 43% of those detected near the BI count station or AWS channel did not pass the dam. Large majorities (92-97%) of the non-passing fish turned around in the serpentine weirs. This area has been previously identified as a difficult area of passage for lamprey due to high water velocity and turbulence (Clabough et al. 2012; Keefer et al. 2013b). In a companion 2014 project, underwater video collected in the Bradford Island fishway indicated extensive milling behavior by lamprey and reduced lamprey abundance at the upstream versus downstream serpentine weirs (Kirk et al. 2015aR). Both the video data and the telemetry data suggest that lamprey may reach an exhaustion threshold in these fishway segments and/or that serpentine weir design directly contributes to lamprey passage failure.

John Day north entrance

Entrance efficiency of radio-tagged lamprey at the JDN in 2014 was the highest (84%) relative to previous estimates. Early radiotelemetry studies at the John Day north entrance, although not directly comparable due to larger transmitter sizes, small sample sizes, and possible differences in antenna coverage, produced lower efficiency estimates than in 2014; over 6 previous years (1997-1998, 2000-2002, and 2009), the median estimate was 50% (Keefer et al. 2012). Fishway passage efficiency was also high for the John Day north fishway in 2014 at 84%, which was higher than all previous estimates from available years ($n = 4$, *median efficiency* = 19%) (Keefer et al. 2012).

Detections of HD-PIT tagged lamprey at the John Day north entrance indicated that most fish were detected only on the south outside antenna in 2014. Even though these fish were not detected on either of the two inside antennas, a majority of these fish (74%) entered and passed the dam. We speculate that the ‘missed’ detections on the HD array were caused by lamprey swimming higher in the water column, beyond the antenna detection range (~0.5 m), after they entered the fishway.

Preliminary computational fluid hydrodynamics (CFD) model results (Figure 36; also see Yin et al. 2010) indicated higher velocities outside and near the John Day north entrance but reduced velocities upstream from the entrance. The reduced water velocities, attributable in part to the bollard field, may have allowed lamprey to travel higher in the water column. It is also possible that high turbulence near the bollard field and fishway floor prompted lamprey to avoid the near-floor area.

Returns to Bonneville Dam

The percentage of radio-tagged lamprey that were detected at Bonneville Dam after release in 2014 (79%) was near the 10-year average of 80% (Keefer et al. 2012). Returns to the dam were higher in the 1997-2002 studies (87-96%), when radio-tagged fish were significantly larger (on average), transmitters were larger, and antenna arrays monitored a larger proportion of the dam face and fishway (i.e., orifice gates were open and monitored at both Powerhouses). Lamprey not detected at Bonneville Dam in 2014 could have shed transmitters, may have abandoned upstream migration, may have died from tagging effects or predation (pinnipeds and white sturgeon), or could have avoided detection at fishway entrance antennas which are positioned high in the water column. Transmitter failure was relatively unlikely (except for possible overwintering fish) based on previous tag testing in 2009, when tag life ranged from 123-145 d ($n = 5$).

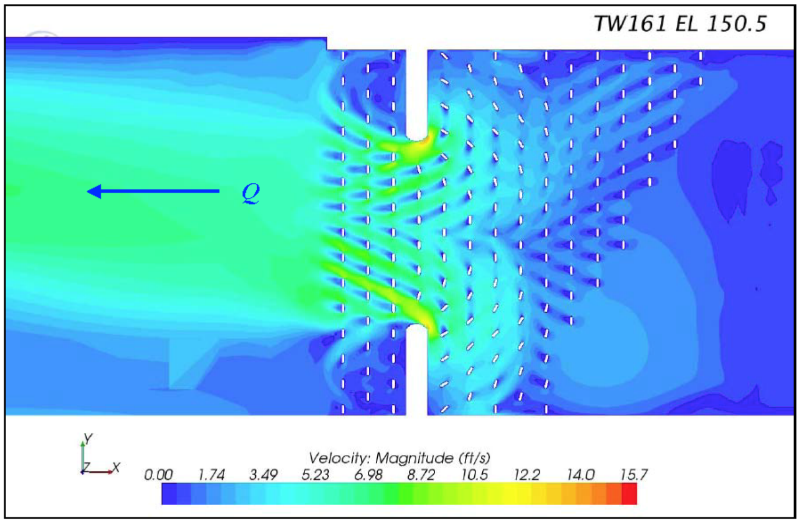

Figure 36. Velocity contours on horizontal plane (6" above invert) with elongated, rotated bollard configuration at the John Day north entrance. Q = flow direction (Source: Yin et al. 2010).

Dam and fishway passage efficiency

Dam passage efficiency (fishway approach to top of ladder) at Bonneville Dam was higher in 2014 (49% with recaptured fish excluded and 52% with recaptured fish treated as passing the dam) than in most recent lamprey radio-telemetry studies (*median* = 39%, *range* =31-46%, 2007-2010) (Keefer et al. 2012). The 2007-2010 studies used similar methods to those used in 2014 and lamprey body sizes were representative of the run at large (in contrast to radiotelemetry studies in 1997-2002, when only large-bodied fish were tagged). In a companion report on reach-scale behavior and upstream escapement, Keefer et al. (2015) showed a similar increase in apparent Bonneville passage success over the longer time series of radiotelemetry and HD-PIT studies (note: the analysis accounted for fish size and migration timing effects). There are several potential explanations for the apparent increase in Bonneville Dam passage efficiency. Operational and structural factors include the positive effects of the modified NDE entrance, reduced fishway velocity on lamprey entry behavior at the PH2 fishway (Johnson et al. 2010, 2012), increased use of the LPSs (Moser et al. 2011), raising of the WA-shore AWS picket lead, and incremental effects of recent fishway modifications at Bonneville Dam (Keefer et al. 2010; Clabough et al. 2010). Other factors include potential effects of river environment, tailwater elevation, and biological factors affecting lamprey performance.

Dam passage efficiencies in 2014 were 47% at The Dalles Dam, 83% at John Day Dam, and 100% at McNary Dam. The 2014 estimate for The Dalles Dam was low compared to the 2007-2010 estimates (*range* =66-75%) and to the median across all radiotelemetry study years (68%, *range* 55-79%) (Keefer et al. 2012). We currently do not have a clear understanding why dam passage efficiency was relatively low at The Dalles Dam in 2014.

In contrast to results from The Dalles Dam, the 2014 John Day Dam passage efficiency was high (83%) compared to the most recent study (52% in 2009) and the 6-year median (46%) (Keefer et al. 2012). The apparent increase at John Day Dam may be attributed to the modifications to the north entrance (i.e. installation of variable with weir, bollards, LPS, etc.). However, we note that radio-tagged sample sizes have been quite small across years. Sample sizes have also been limiting at McNary Dam in all years, though we note that the 2014 estimate (100%) falls within the range of the available data (67-100%, n = 6 years) (Keefer et al. 2012). The 2014 estimate at McNary Dam was also higher than estimates generated from fish that were collected and radio-tagged at McNary Dam in 2005-2010 (dam passage efficiency *range* = 0.50-0.80; Keefer et al. 2013a).

Fishway entrance efficiency results were quite variable among fishway openings at individual dams and among dams, suggesting differences in structure or operation have important effects on adult lamprey passage. At The Dalles Dam, for example, entrance efficiency ranged from 33% for lamprey that approached the west Powerhouse and east shore fishways to 98% for those that approached the north ladder entrance. At Bonneville Dam, first and total entrance efficiencies were lowest at the PH1 south entrance (12-23%) and were highest at the PH2 NDE (63-77%). Entrance efficiency differences among sites may be related to the configuration of fishway openings, the distribution of attraction flow, entrance velocity, or other factors such as the presence of predators.

Passage efficiency estimates through most sections of the fishways upstream from entrance areas were also quite variable. At Bonneville Dam, passage efficiencies were highest at PH1 (87-100%), through the collection channel, transition pool, and ladder sections in 2014. PH2 had the next highest efficiencies followed by the spillway entrances at CI and BI. Over all radiotelemetry study years (1997-2014), lamprey have had difficulty passing through the transition pool areas and the serpentine weirs, suggesting that these areas are among the critical passage bottlenecks at Bonneville Dam (for bottleneck summary, see Keefer et al. 2013b, 2014). At The Dalles Dam, entrance efficiencies were lower in 2010 and 2014 (39-54%) than in the previous 8 study years (71-87%) at the east fishway entrance. Lamprey also appeared to have had more difficulty passing through the east-shore collection channel in 2014 (75% efficiency), which was the lowest estimate in this fishway section in all study years (83-100% in previous studies). It was not clear why efficiencies were low in these areas in 2014.

Fishway use and passage times

Median lamprey passage times from tailrace to top-of-ladder exits were 5.7 d (Bonneville), 1.2 d (The Dalles), and 1.6 d (John Day) in 2014. Passage times were faster at Bonneville and The Dalles dams in 2014 than in 2010 but were generally similar to estimates from previous years (Clabough et al. 2011; Keefer et al. 2009b). At all dams, lamprey passage times were often several times longer for fish that exited a fishway to the tailrace than for fish that remained in the fishway.

Fallback

Fallback events by lamprey can be more difficult to substantiate than those by adult salmonids, in part because fewer lamprey tend to re-approach and re-ascend the fishways. Identifying lamprey fallback events often hinges on a handful of detections on aerial antennas, which are often more susceptible to radio interference and 'noise' events that receivers can interpret as tag detections.

The estimated fallback percentage at Bonneville Dam in 2014 (1%) was lower than in 2010 (3%; Clabough et al. 2011) and was much lower than in 2007-2009 (17-28%; Johnson et al. 2009a, 2009b; Clabough et al. 2010). Similarly, the 2014 estimate at The Dalles Dam (3%) was also considerably lower than in previous years (7-29% in 2007-2010). In contrast, the 2014 fallback estimate at John Day Dam (35%) was higher than in all previous years except 2010 (38%).

It is possible that the high fallback percentages reported in the early studies (2007-2009) at Bonneville and The Dalles dams may have been inflated by some false positive detections. In contrast, most of the lamprey recorded falling back at John Day Dam in 2014 were subsequently detected on underwater antennas inside fishways, and more than a third passed the dam a second time. While radio-tagged sample sizes have been small in all years at John Day Dam, the consistency of results across years suggests that a considerable proportion of the lamprey population that passes the dam falls back. Relatively high percentages of radio-tagged lamprey were also recorded falling back at John Day Dam in 2002 (35%; Moser et al. 2005) and in each of the last four study years (22-38%). The underlying causes of lamprey fallback at all sites are unknown but may be related to operational conditions and dam structures (e.g., Reischel and Bjornn 2003). Alternatively, some fallback events at John Day Dam (and other dams) may be related to lamprey searching for suitable spawning tributaries (e.g., Keefer et al. 2015). Tributary 'overshoot'-type behavior was exhibited by 14% of the lamprey that fell back at John Day Dam in 2014 and were then recorded downstream in the Deschutes River.

Conclusions

The multi-year HD PIT and radiotelemetry studies have provided a wealth of information about lamprey behavior at a range of spatial scales, from specific adult fishway segments, to individual FCRPS dams, and extending to multi-dam reaches reach and full-migrations to spawning tributaries. The resulting multi-year datasets are by far the best baseline data for evaluating changes in lamprey passage performance at dams and in the FCRPS hydrosystem as improvements are implemented. The HD PIT and radiotelemetry monitoring complement hypothesis testing in the experimental fishway (Keefer et al. 2010, 2011; Kirk et al. 2015a), passive monitoring with Dual-Frequency Identification SONAR (DIDSON, Kirk et al. 2015b), and the JSATS-tagged lamprey study results from recent years (Naughton et al. 2011; Noyes et al. 2014, 2015). This type of integrated approach, using multiple techniques at a variety of spatial and temporal scales, should continue to advance our understanding of lamprey passage at FCRPS dams and their distribution in the basin.

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