Technical Report 2019-1

ADULT PACIFIC LAMPREY PASSAGE AT THE FOUR LOWER COLUMBIA RIVER DAMS AND LAMPREY BEHAVIORS IN RELATION TO NIGHTTIME FISHWAY VELOCITY REDUCTIONS AT BONNEVILLE AND THE DALLES DAMS AND THE NEW UMTJ-LPS AT BONNEVILLE DAM - 2018

Study Code: LMP-P-17-1

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For

U.S. Army Corps of Engineers
Portland District

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Acknowledgements

Many people assisted in the field work and data compilation for this report. We are grateful for the assistance from the U.S. Army Corps of Engineers (USACE) Portland District and project biologists. They include Brian Bissell, Robert Cordie, Andrew Derugin, Eric Grosvenor, Ben Hausmann, Erin Kovalchuck, Jeffrey Randall, Jon Rerecich, Sean Tackley, Ricardo Walker, Nathan Zorich, and Miro Zyndol. Others at the Bonneville Lock and Dam that supported the project include the electrical and crane crews. We also thank Bobby Johnson (Walla Walla District) for project support and coordination at McNary Dam. Breanna Graves and Sarah Hanchett (University of Idaho) assisted with fish collection, tagging, and fish transport. Successful setup of the radio-telemetry and PIT-tag array was made possible by the assistance of Lotek Wireless and the Pacific States Marine Fisheries Commission (PSMFC): Darren Chase (PSMFC), Roger Clark (PSMFC), Travis Dick (UI contract), Matt Knoff (Lotek), and Nicole Tancreto (PSMFC). We thank the Columbia River Tribal Fish Commission (CRITFC) for their assistance in tag coordination, lamprey collection, and recapture information: Gerald Ellenwood, Spencer Lejins, Brian McIlraith, Laurie Porter, and Brian Sharp. Staff at other agencies also provided lamprey detection data Andy Johnsen and Shay Workman (Confederated Tribes of Warm Springs Reservation of Oregon), Julie Harper (Blueleaf Environmental for Grant County Public Utility District), Mike Clement (Grant County Public Utility District), and Steven Hemstrom (Chelan County Public Utility District). We also thank Ralph Lampman (Yakima Nation) for detailed information on furunculosis. Successful completion of this work was also made possible with help from Steve Corbett and Kinsey Frick at NOAA Fisheries. State permits were facilitated by Bruce Baker and Anita Victory (Washington Department of Fish and Wildlife). Use of AQUI-S 20E was approved under INAD protocol number 11-741 and administered by Bonnie Johnson (U.S. Fish and Wildlife Service). The University of Idaho Institutional Animal Care and Use Committee approved the collection and tagging protocols used for this study, which were facilitated by Blair Ehlert and Craig McGowan. The USACE, Portland District, provided funding for the study (project number LMP-P-17-1) under Cooperative Ecosystems Study Unit (CESU) agreement CESU W912HZ-16-2-0013with the assistance of Sean Tackley, Sherry Whitaker, and Deberay Carmichael.

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Executive Summary

Declines in abundance of Pacific Lamprey (*Entosphenus tridentatus*) and low passage rates at lower Columbia River dams have prompted a series of modifications to fishway structures and operations. In 2018, our adult lamprey research and monitoring project addressed two recent structural and operational modifications at lower Columbia River dams: (1) experimental reductions in nighttime fishway velocity at Bonneville and The Dalles dams; and (2) construction of a new Lamprey Passage Structure (LPS) inside the Washington-shore fishway at Bonneville Dam.

Adult lamprey sample summary

In 2018, 595 adult Pacific Lampreys were collected and double-tagged with a radio transmitter and HD-PIT tag and another 578 lampreys were tagged with only HD-PIT tags at the adult fish facility (AFF) at Bonneville Dam and released downstream. Movements of radio-tagged lampreys were monitored with fixed-site aerial and underwater antennas attached to radio receivers deployed in the tailraces and at the four lower Columbia River dams. HD-PIT and dual-PIT (PTAGIS) antennas in dam fishways, lamprey passage systems (LPSs), and in some tributaries were used to monitor movements of the HD-PIT tagged sample and augment movement histories of radio-tagged lampreys. Lamprey behaviors and passage metrics from 2018 were compared to those from previous studies.

Fishway entrance velocity reductions at Bonneville and The Dalles dams

Fishway head was experimentally manipulated at night to reduce water velocity at the Bonneville A- and B-branch fishway openings (i.e., the fishway entrances) and at The Dalles east fishway openings. Radio-tagged lampreys that approached fishways were significantly more likely to enter the three fishways during the reduced velocity treatment than during the 'normal' treatment. Lamprey entrance times were also faster during the reduced treatment. In proportional hazards regression models, the instantaneous likelihood of fishway entry by lampreys was higher during the reduced treatment by ~2.1 times at the Bonneville A-branch fishway, by ~2.8-3.3 times at the Bonneville B-branch fishway, and by ~2.2-2.3 times at The Dalles east fishway. While the reduced velocity conditions increased both the proportion of lampreys that entered fishways and the rate at which they entered, the reduced treatment did not substantively affect lamprey passage success after they entered a fishway because many fish turned around upstream from the head control points. Fishway passage success (the number of lamprey entrance events that resulted in dam passage) did not statistically differ by velocity treatment at the time of fishway entry at either dam.

Lamprey behavior near the UMTJ-LPS at Bonneville Dam

A dual-ramp lamprey passage structure (LPS) was recently installed in the Washington-shore fishway at Bonneville Dam near the upstream migrant tunnel junction (UMTJ) with the overflow-weir section of the fish ladder. Behaviors of radio-tagged and PIT tagged lampreys near the UMTJ-LPS indicated that 4% of radio-tagged and 6% of PIT-tagged lampreys passed the dam via the UMTJ-LPS. PIT-only fish were more likely to pass the dam via the combined

UMTJ and auxiliary water supply (AWS) LPSs, whereas radio-tagged lamprey were more likely to pass via the serpentine weir section of the fishway. Route passage was 9.4% UMTJ-LPS, 46.5 % AWS-LPS, and 44.0% ladder for PIT-tagged lampreys and was 6.5%, 32.3 %, and 61.3%, respectively, for radio-tagged lampreys. In the radio-tagged group, fish with shorter dorsal distance were more likely to use the UMTJ-LPS.

Lamprey behavior near count stations and serpentine weirs at Bonneville Dam

Serpentine weir sections of the fish ladders presented significant challenges to lamprey passage in 2018. Movements of radio-tagged lampreys near the count windows, serpentine weirs, and AWS channels of the Washington (WA)-shore and Bradford Island (BI) fishways at Bonneville Dam indicated that 35-38% of fish that reached these areas did not pass the dam, consistent with findings from previous years. Among non-passing lampreys 64% (WA-shore) and 80% (BI) had their highest ascensions (and turnaround points) in the serpentine weirs.

Fishway approach and entry rates

On average, lampreys approached Bonneville fishway openings 15.6 times per fish, entered fishways 2.3 times per fish among entrants, and of those that exited fishways into the tailrace 2.4 times per fish (1.8 times per fish among unique fishway entrants). At Bonneville Dam, the largest numbers of fishway approaches, entries, and exits were at Powerhouse 2 (PH2). Means at The Dalles Dam were 3.1 approaches, 1.6 entries among entrants, and 1.8 exits per fish among fish that exited (0.9 exits per fish among unique fishway entrants). Most approaches and entries at The Dalles occurred at the West powerhouse and East fishway openings, respectively. At John Day Dam lamprey approached 1.6 times, entered 1.8 times and exited 2.1 times per fish on average. Means at McNary Dam were 1.5 approaches, 1.2 entries, and 1.2 exits per fish.

Fishway and dam passage efficiency and effectiveness estimates

Dam passage efficiency (the number of tagged lampreys that passed the dam divided by the number that approached a fishway) were 43-44% (*n* = 517-532 approached) at Bonneville Dam (first number excludes 15 recaptured fish). Dam passage efficiency was ~72% (*n* = 152) at The Dalles Dam, 69% (*n* = 68) at John Day Dam, and 87% (*n* = 23) at McNary Dam. Fishway passage efficiencies (the number of tagged lampreys that passed a dam divided by the number that entered a fishway) were 50-52% at Bonneville Dam (*n* = 442-457 entered), 77% (*n* = 142) at The Dalles Dam, 76% (*n* = 62) at John Day Dam and 87% (*n* =23) at McNary Dam.

Fishway entrance efficiencies (the number of tagged lampreys recorded entering a fishway divided by the number recorded approaching the same site) at Bonneville Dam were highest at the Cascades Island (CI) spillway entrance (~81%) and were lowest at PH2 north entrances (~31%). Entrance efficiencies at The Dalles Dam were highest at the north entrance (99%) and lowest at the west powerhouse entrance (46%). Entrance efficiencies at John Day Dam ranged from 78% at the north entrance to 50% at the south-shore entrance. At McNary Dam site-specific fishway entrance efficiencies ranged from 100% at the north and south entrances to 67% at the north powerhouse entrance.

Fishway and dam passage times

Median dam passage times (i.e., the interval between first tailrace record and last detection at the ladder top) were 6.7 d at Bonneville, 3.3 d at The Dalles, 2.0 d at John Day, and 0.9 d at McNary dams. Median times from first fishway entrance to exit from the top of a ladder were 2.9 d at Bonneville, 1.1 d at The Dalles, 1.0 d at John Day, and 0.4 d at McNary dams. Many lampreys passed quickly through collection channels, transition pools, and ladders, but some took several days or weeks to pass.

Lamprey fallback

Fallback percentages (number of unique lamprey that fell back at a dam divided by the unique number that passed a dam) were ~2% at Bonneville Dam, 5% at The Dalles Dam, and 13% at John Day Dam. No tagged fish were detected falling back at McNary Dam. Two of four lamprey reascended fishways after falling back at Bonneville, one of five did so at The Dalles Dam, and four of six reascended after falling back at John Day Dam.

Introduction

Populations of Pacific Lamprey *(Entosphenus tridentatus*) have declined throughout much of their native range (Close et al. 2002; Moser and Close 2003; Luzier et al. 2011; Clemens et al. 2017). Dam passage can be difficult for adult migrants and upstream passage failure is believed to have contributed to population declines (e.g., Beamish and Northcote 1989; USFWS 2004; 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. 2009; Keefer et al. 2009a, 2009b, 2011, 2012, 2013a, 2013b, 2014; Clabough et al. 2015). These and other studies have identified many locations where lamprey have difficulty passing Columbia River dams, including fishway entrances, transition pools, count stations, 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. 2010a; Keefer et al. 2010; USACE 2014), and reduction of fishway water velocities (Boggs et al. 2010; Johnson et al. 2010, 2012).

In 2018, our adult lamprey research and monitoring project addressed two recent structural and operational modifications at lower Columbia River dams: (1) experimental reductions in nighttime fishway velocity at Bonneville and The Dalles dams; and (2) construction of a new LPS (UMTJ-LPS) inside the Washington-shore fishway at Bonneville Dam. 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 (reduced water velocities) and by providing separate lamprey passage routes.

A series of radiotelemetry and experimental fishway studies have shown that adult lampreys have difficulty entering fishway openings (Moser et al. 2002a; Keefer et al. 2010, 2013b). High water velocities at the entrances designed to attract adult Pacific salmonids (*Oncorhynchus* spp) appear to restrict adult lamprey entry (Moser et al. 2002b; 2005; Daigle et al. 2005). Fishway entrances often have water velocities that exceed 2.0 m•sec^{-1}, which are considerably higher than the estimated critical adult lamprey swimming speed of 0.8 m•sec^{-1} (Mesa et al. 2003), and are higher than velocities found to impede lamprey passage in experimental studies (> 1.2 m•sec^{-1}, Keefer et al. 2008). In response, entrance velocity was experimentally reduced at night at Bonneville Dam Powerhouse 2 entrances in 2007, 2008, and 2009. Johnson et al. (2012) reported that lamprey entrance efficiency was significantly higher in the reduced-velocity treatment (26-29%) than in the control (13-20%) or standby (5-9%) treatment. Subsequently, reduced nighttime head (velocity) was incorporated into the fish passage plan for Powerhouse 2. Similar experimental reductions in nighttime velocities were conducted at Bonneville's Bradford Island fishways (Powerhouse 1 and B-branch entrances) and at The Dalles east fishway in 2018.

Construction and installation of LPS systems to provide a bypass route has been a core component of fishway improvements for Pacific Lamprey. In the winter of 2016-2017, U.S. Army Corps of Engineers (USACE) installed a new LPS in the Washington (WA)-shore fishway at Bonneville Dam. The LPS was built with two ramps extending into the WA-shore fishway downstream from the adult count station and upstream from the upstream migrant tunnel (UMT) junction with the main WA-shore fishway. The new structure, named the UMTJ-LPS, connects to an existing LPS in the adjacent auxiliary water supply channel (AWS). The combined system allows adult lamprey to bypass the adult count station and the serpentine weir section of the WA-shore fishway. At Bonneville Dam, the serpentine weir sections of the fishways have been identified as particularly challenging areas for adult lamprey passage. In recent studies, approximately one-fifth to nearly one-third of radio-tagged lampreys that were detected reaching the serpentine weirs failed to pass (Keefer et al. 2013b, 2014; Clabough et al. 2015). Additionally, improved passage would likely reduce poorly understood milling behavior near the adult count stations and serpentine weirs that contributes to enumeration uncertainty in these locations (Clabough et al. 2012).

We used radiotelemetry and HD-PIT telemetry to adress several complimentary objectives in 2018. In this report, we present results on: (1) the fishway velocity experiments at Bonneville and The Dalles dams; (2) lamprey use of the new UMTJ-LPS at Bonneville Dam; (3) lamprey behavior near the count windows, serpentine weirs and AWS channels at Bonneville Dam, and (4) lamprey dam passage and fishway use metrics at the four lower Columbia River dams. Results were compared to previous fishway use and dam passage studies (e.g., Keefer et al. 2012; Clabough et al. 2015). System-wide summaries of lamprey behaviors, escapement, and distribution are reported separately (see Keefer et al. 2019). Results from experimental flume studies and a pilot accelerometer tag evaluation will also be provided in a separate report (see Hanchett and Caudill 2019).

1. Lamprey Collection, Tagging, and Monitoring

Tagging and monitoring

Adult lamprey used in this study were collected at Bonneville Dam (Columbia River kilometer [rkm] 235). Fish were collected in two traps located at the Washington shore fishway: (1) the trap near the Adult Fish Facility (AFF) and (2) the Lamprey Flume System (LFS). The AFF trap was installed in May 2018 and consists of a climbing ramp leading to terminal trap box on the upper fishway deck (Figure 1). The ramp gained ~6.1 m (~20 ft) in total elevation from the fishway floor and was ~5.8 m (~19 ft) long, with a slope of ~55 degrees. The LFS is located outside of the north downstream entrance (NDE) of the Washington-shore fishway and served as an entrance modification to provide a lamprey-specific entrance and passage route from the tailrace. The LFS is comprised of two large lamprey-specific entrances, one along the bottom of the fishway floor and another higher up in the water column, neither of which can be entered by adult salmonids. Lamprey then ascend an LPS to a trap at the tailrace deck of the dam.

In 2018, a total of 1,499 lamprey were tagged at Bonneville Dam for four study groups. The first group included 599 tagged with radio transmitters (RT) and half-duplex passive integrated transponder (HD-PIT) tags in which 595 were released downstream from Bonneville Dam near Hamilton Island (*n* = 305; rkm 232.5) and near Tanner Creek (*n* = 290; rkm 232.0). Three radio-tagged lamprey died before release (0.2% of the tagged samples) and were censored from all analyses. One radio-tagged fish was accidentally released at the Stevenson boat ramp and was also excluded from all analyses. The second group had 578 (n=265 Tanner Creek, n= 313 Hamilton Island) that were tagged with HD-PIT tags only and were released downstream from the dam for general migration evaluations. The third group had 309 lampreys that were PIT tagged, used in experimental flume studies, and released upstream from Bonneville Dam at Stevenson boat launch (rkm 242.7). The fourth group was a pilot accelerometer tag evaluation that included 13 fish that were released from the AFF back into the Washington-shore fishway. Results from the experiments and pilot study were reported separately (see Hanchett and Caudill 2019). The PIT-tagged lamprey were randomly sampled from collected lamprey. However, we note that it was unknown whether lamprey collected inside Bonneville fishways were representative of the run at large.

All lamprey 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). 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). Lamprey selected for radio tagging had a girth circumference > 9 cm (at the insertion of the dorsal fin) and received uniquely-coded radio transmitters following protocols described in Moser et al. (2002a) and Johnson et al. (2012). We used Lotek NTC-4-2L (167 MHz) radio transmitters (18.3 mm length, 8.3 mm diameter, and 2.1 g in air) with a burst rate of 5.1-6 s and an expected tag life of 69 d (Lotek Wireless Inc. Newmarket, Ontario). All radio-tagged fish were also tagged with a uniquely-coded, glassencapsulated HD-PIT tag (Texas Instruments, 4×32 mm, 0.8 g). HD-PIT only fish had tags surgically implanted in the body cavity 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.

Figure 1. Overhead view of Adult Fish Facility (AFF) lamprey trap in the Washington shore fish ladder at Bonneville Dam.

In 2018, we tagged and released 595 radio and HD-PIT tagged adult Pacific Lamprey (May 17-Sep 11) and 578 HD-PIT lamprey (May 17-Sep 10) (Figure 2) downstream from Bonneville Dam. The total ‘corrected’ adult Pacific Lamprey count at Bonneville Dam including night and LPS passage estimates through 31 December 2018 was 131,268 (Zorich et al. 2019). Downstream-released PIT-tagged lamprey represented ~0.44% of the total corrected count and double-tagged lamprey represented ~0.45% of the count at the dam in 2018.

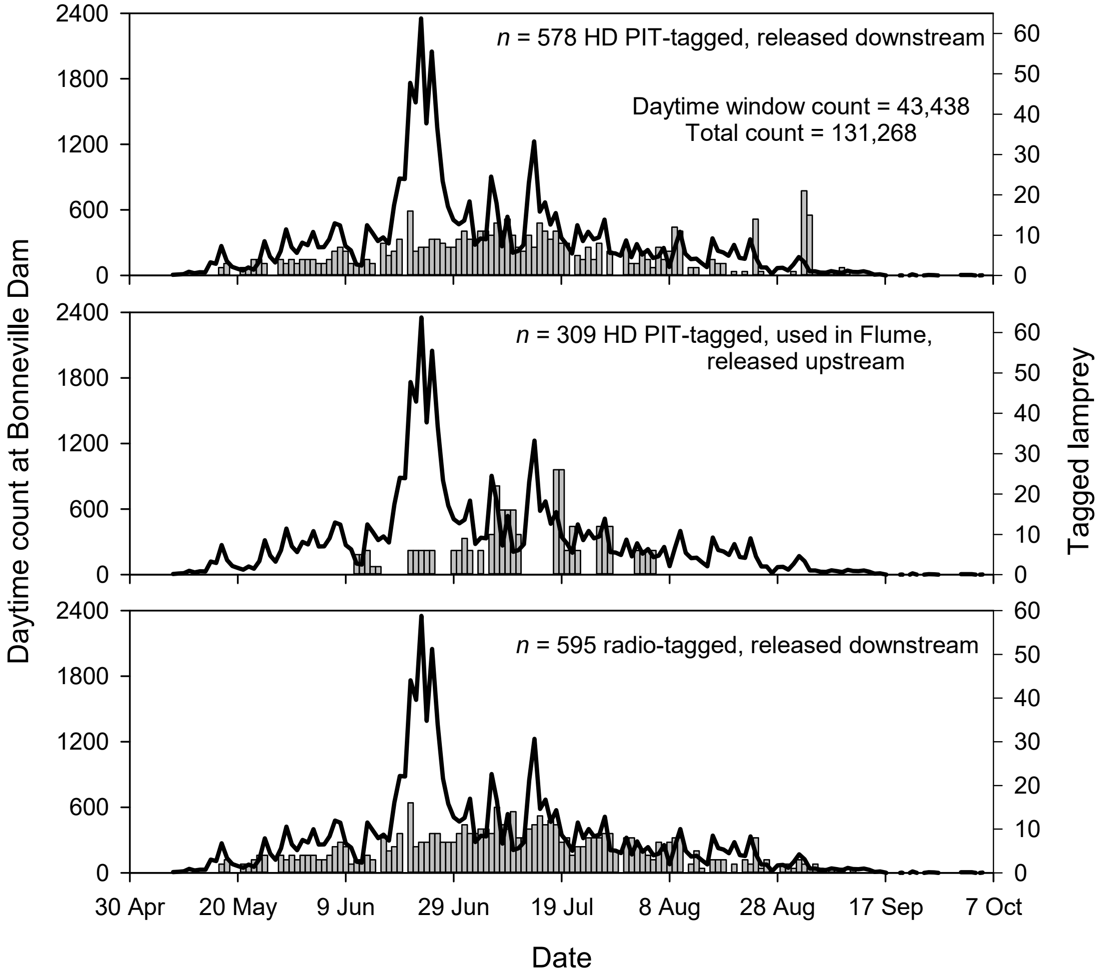

Figure 2. Number of adult Pacific Lampreys counted passing Bonneville Dam during the day (solid lines) and the numbers that were collected and tagged (bars) in 2018. 'Total count' is the corrected total from daytime counts at windows, night video at windows, and LPS passage estimates through 31 December. Top panel shows fish released downstream from Bonneville Dam with HD PIT tags only. Middle panel shows fish that were HD PIT-tagged, used in experimental flume trials, and then released upstream from the dam near Stevenson, Washington. Bottom panel shows fish that were double-tagged (HD PIT and radio) and released downstream from the dam near Hamilton Island or Tanner Creek. Radio-tagged fish used in the accelerometer tag pilot study are not shown.

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 3-7). 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 (except McNary). One or more underwater coaxial cable antennas were positioned at fishway entrances (also referred to as fishway 'openings') 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. It is important to note that the

Powerhouse 1 (PH1), Powerhouse 2 (PH2) and Cascades Island (CI) entrances at Bonneville Dam were monitored using an aerial Yagi antenna in 2014 and 2018 (due to limited access to underwater locations in winter 2012-2013) whereas these sites were monitored using underwater antenna arrays historically (Figures 3 and 4). Data from previous evaluations at entrance locations with both underwater and aerial Yagi antennas in 2009-2010 indicated qualitatively similar resolutions between antenna types. Radiotelemetry monitoring at McNary Dam in 2018 only included fishway entrances and top-of-the-ladder-exits.

HD PIT tag monitoring – We monitored lamprey movements at Bonneville, The Dalles, and John Day dams with half-duplex antennas (Table 1). Additional PIT data was queried from dual (full and half) PIT tag sites on The Columbia Basin PIT Tag Information System (PTAGIS) (See October 2018 PTAGIS newsletter for specific site list: https://www.ptagis.org/docs/default-source/ptagis-newsletter-archive/vol-16-no-2-october-2018.pdf?sfvrsn=4).

Table 1. Half-duplex PIT tag interrogation sites (antennas) used to monitor lamprey passage at lower Columbia River dams in 2018. Note: additional HD monitoring sites were operated at Priest Rapids, Wanapum, and Rocky Reach dams (by Public Utility Districts) and in Hood River, Mill Creek, Fifteenmile Creek, and Deschutes River (Confederated Tribes of Warm Springs) and at Lower Columbia and Snake river dams (PTAGIS).

Site	Location	Number of antenna(s)
Bonneville Dam	PH 2, WA-shore LFS	5
	PH 2, WA-shore ladder	4
	PH 2, WA-shore UMT Junction channel	1
	PH 2, WA-Shore UMTJ-LPS	4
	PH 2, WA-Shore AWS-LPS	2
	PH 2, WA-shore exit	1
	Cascades Island entrance	4
	Cascades Island lamprey LPS	1
	Cascades Island AWS	1
	PH 1, Bradford Island lamprey AWS-LPS	4
	PH 1, Bradford Island exit	1
The Dalles Dam	East ladder below count window	4
	North ladder exit	3
John Day Dam	South fish ladder trap near count station	1
	South ladder exit	1
	North ladder entrance	4
	North ladder exit	2

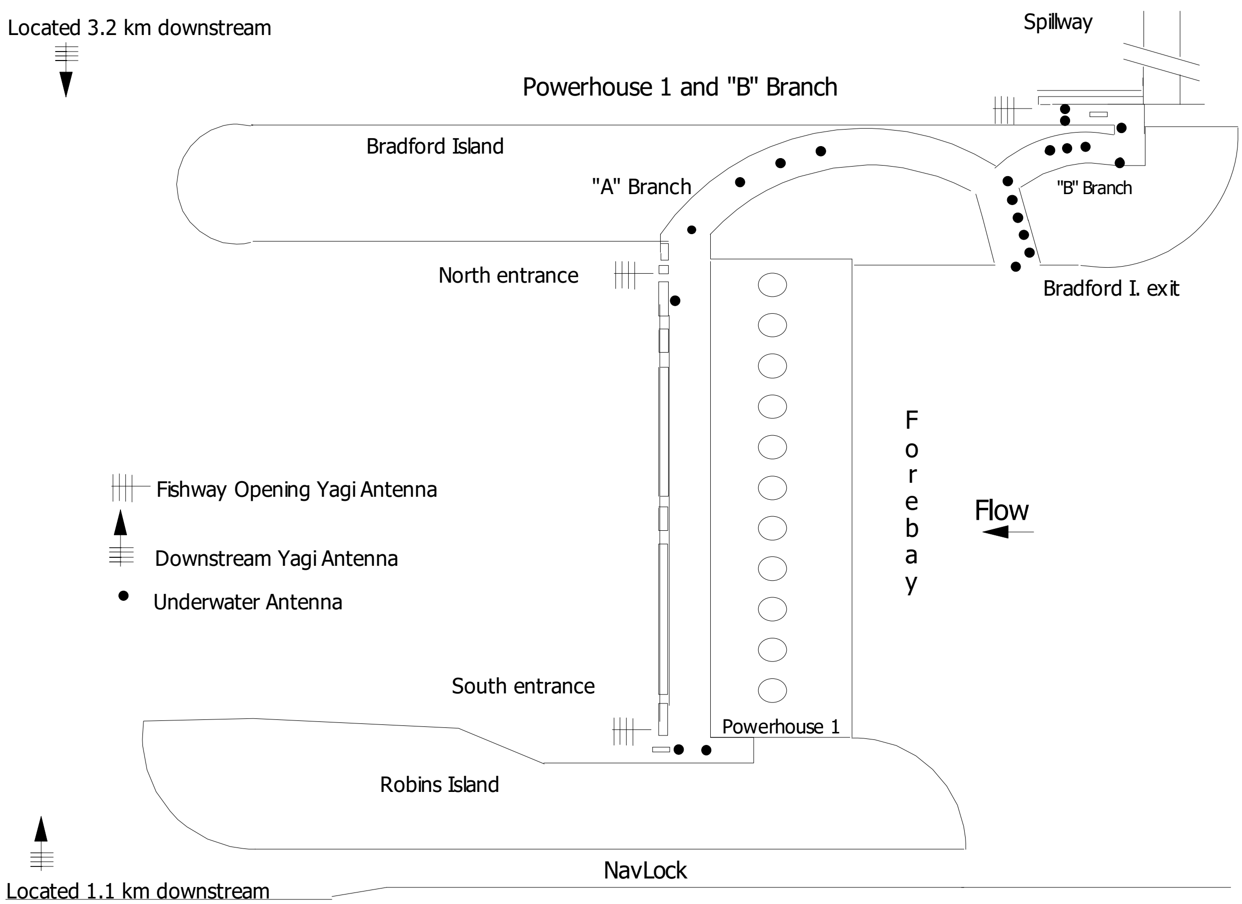

Figure 3. Diagram showing radio antenna deployments at Bonneville Dam Powerhouse 1 and B-Branch fishways in 2018 (not to scale).

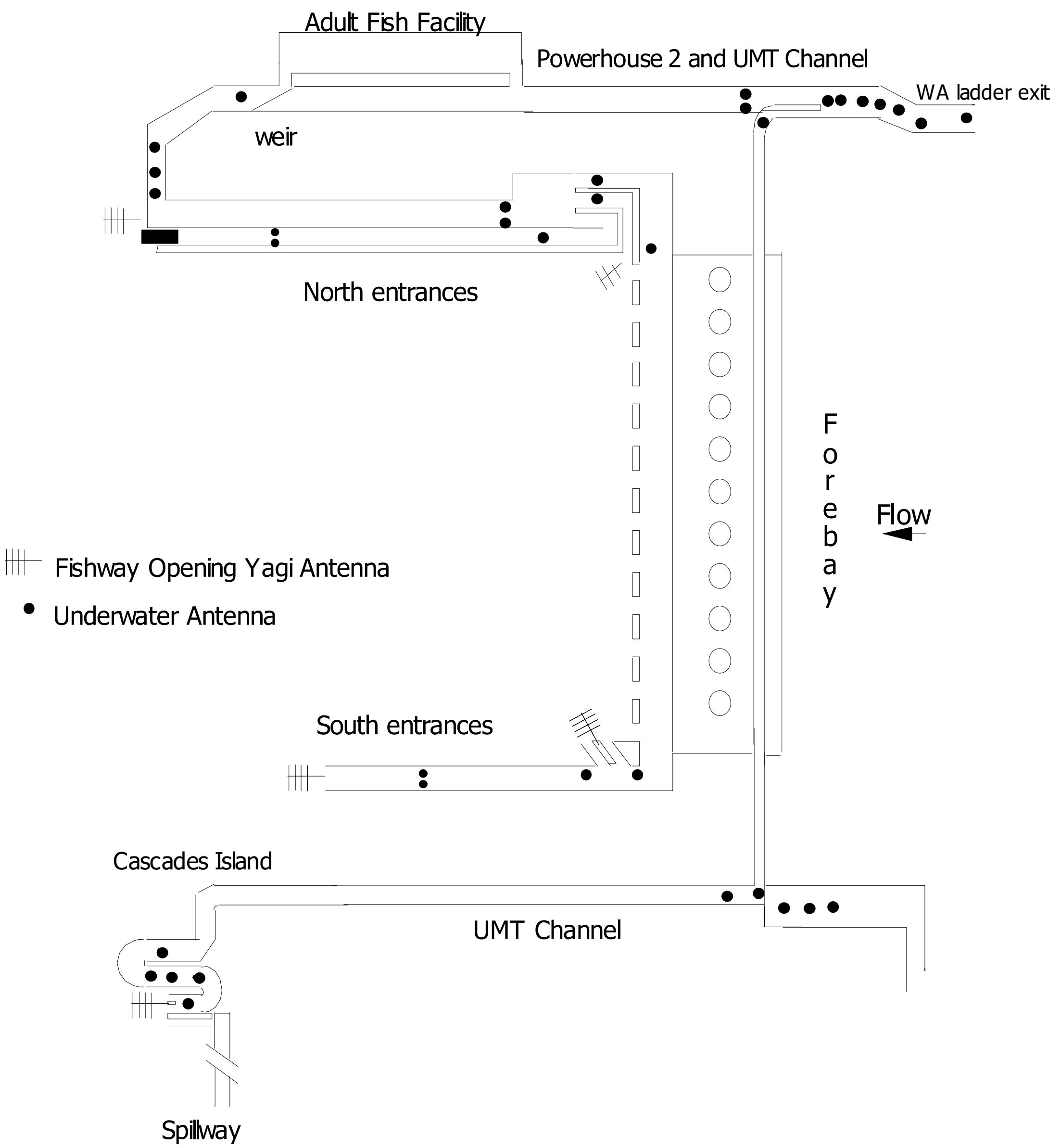

Figure 4. Diagram showing radio antenna deployments at Bonneville Dam Powerhouse 2 and Cascades Island fishways in 2018 (not to scale).

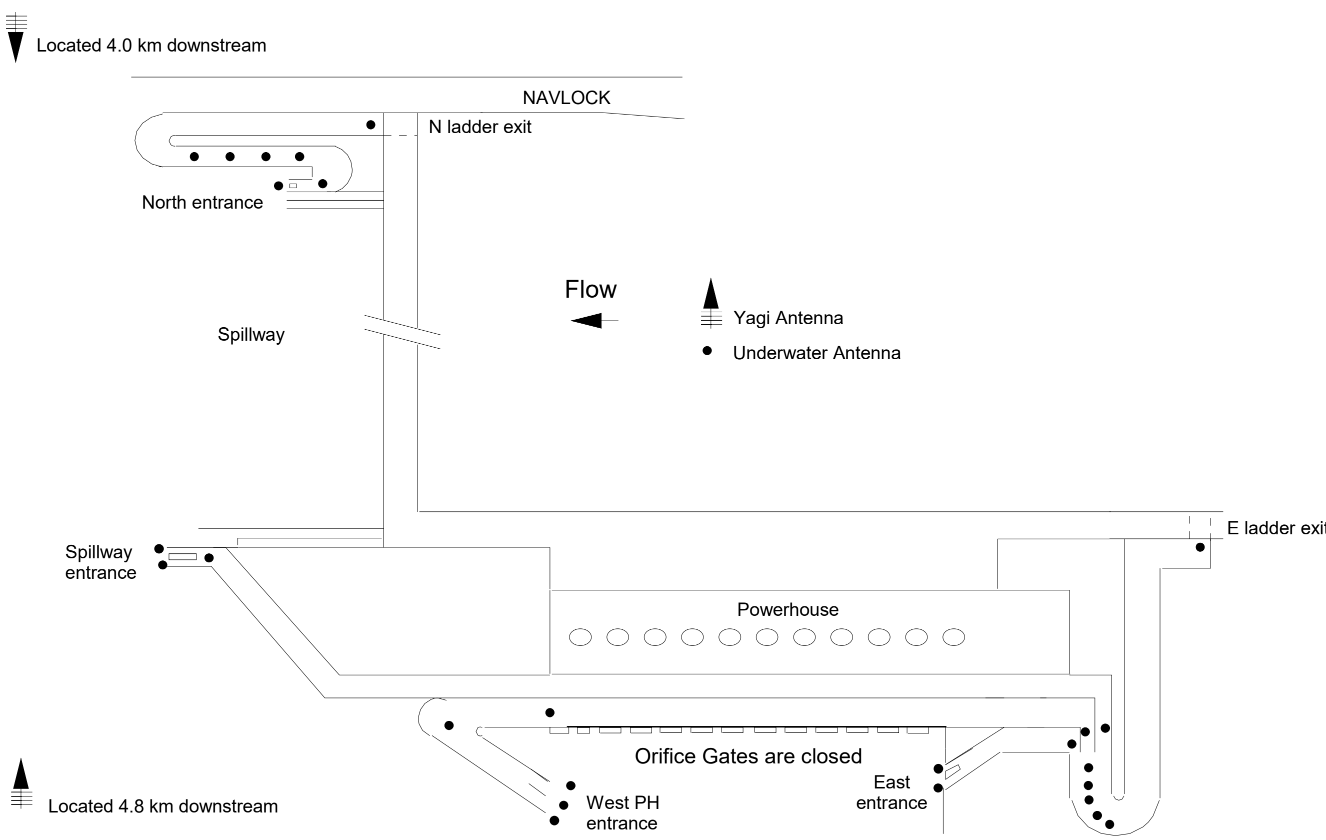

Figure 5. Diagram showing radio antenna deployments at The Dalles Dam in 2018 (not to scale).

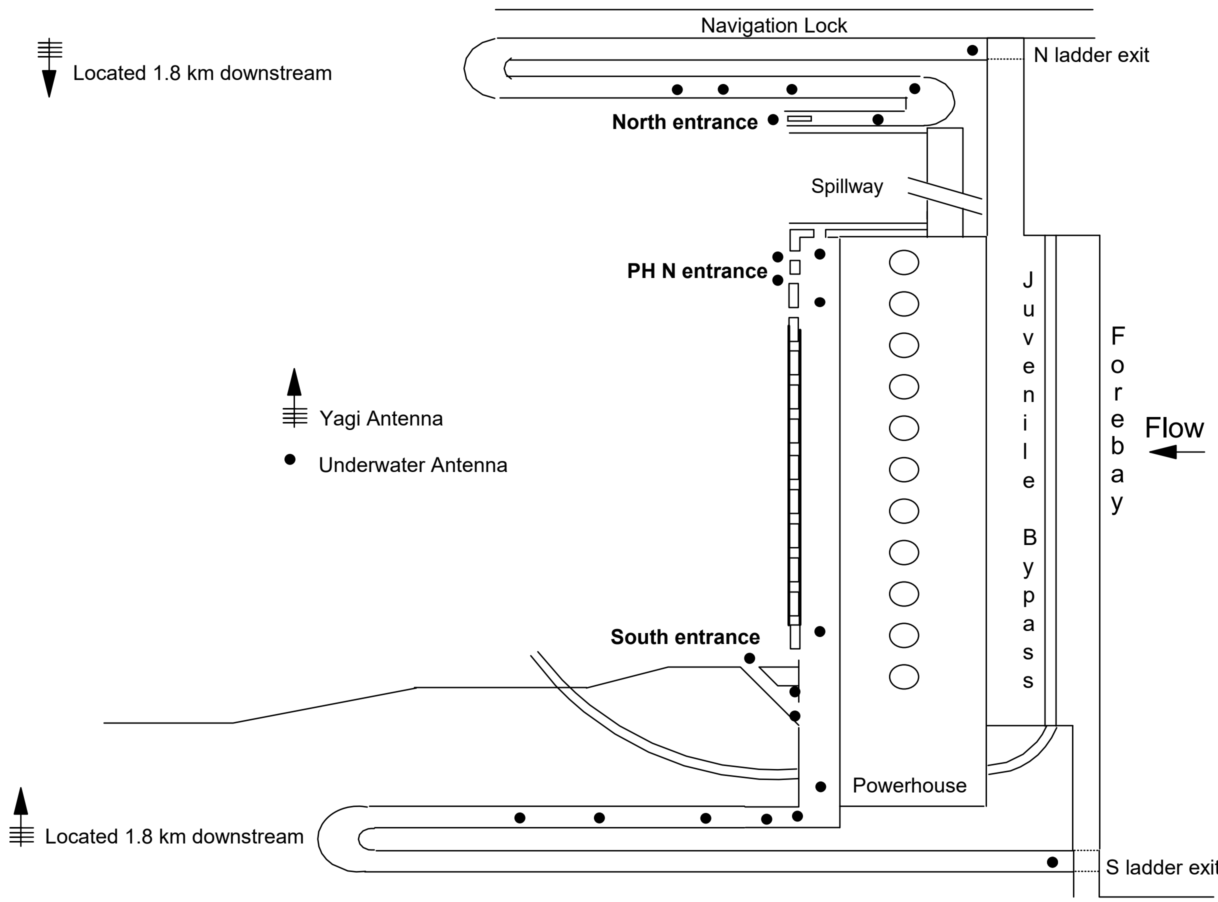

Figure 6. Diagram showing radio antenna deployments at John Day Dam in 2018 (not to scale).

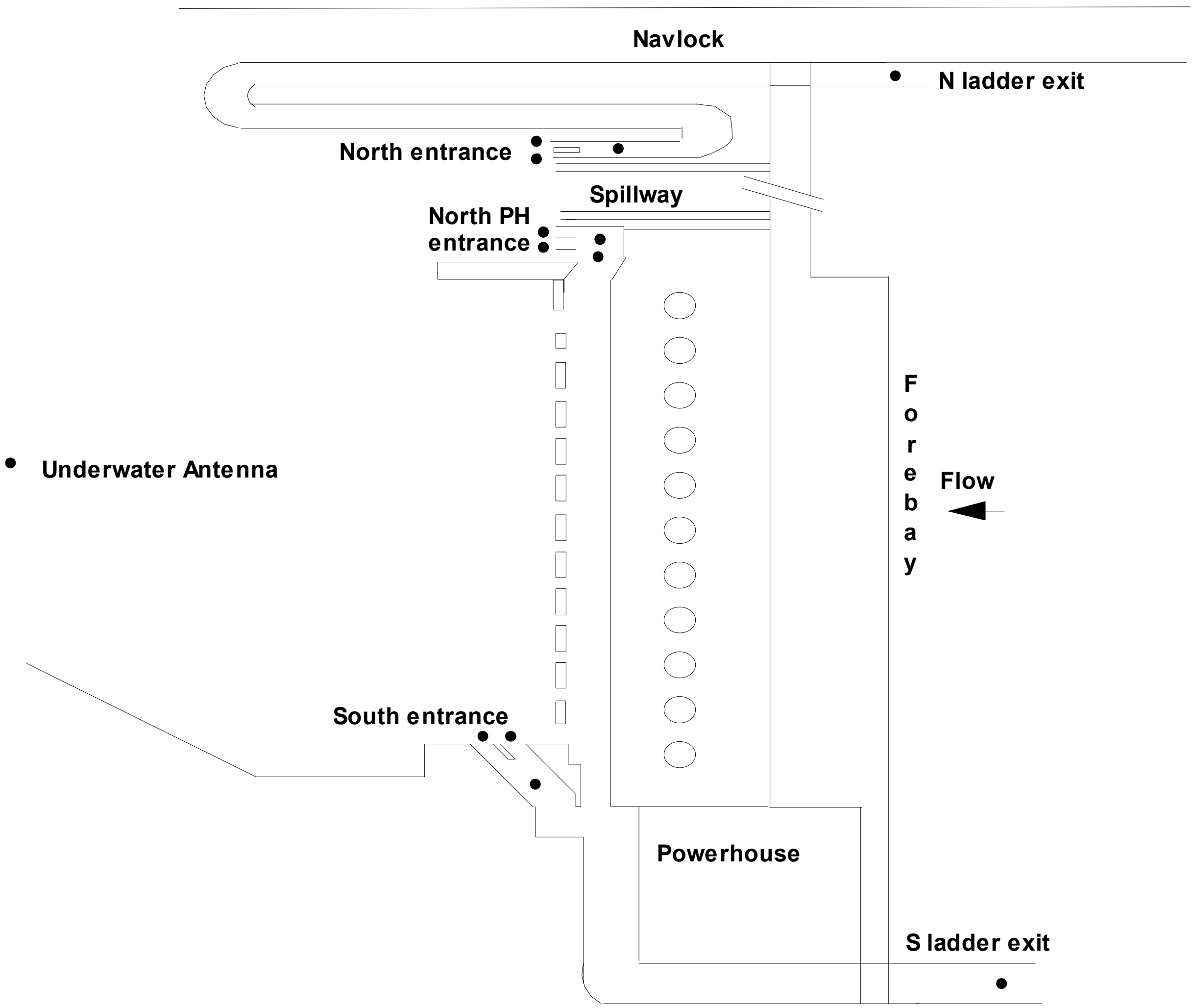

Figure 7. Diagram showing radio antenna deployments at McNary Dam in 2018 (not to scale).

Environmental conditions at Bonneville Dam

Environmental conditions at Bonneville Dam during the 2018 lamprey migration were characterized by above average flow and spill in May compared to the 10-year average and near-average flow and spill thereafter (Figure 8). Water temperatures at the water quality monitoring (WQM) site in 2018 were slightly warmer than the 10-year average in July and August. A maximum water temperature of 23.1 °C occurred on 9 August and was 1.4 °C warmer than the 10-year average maximum.

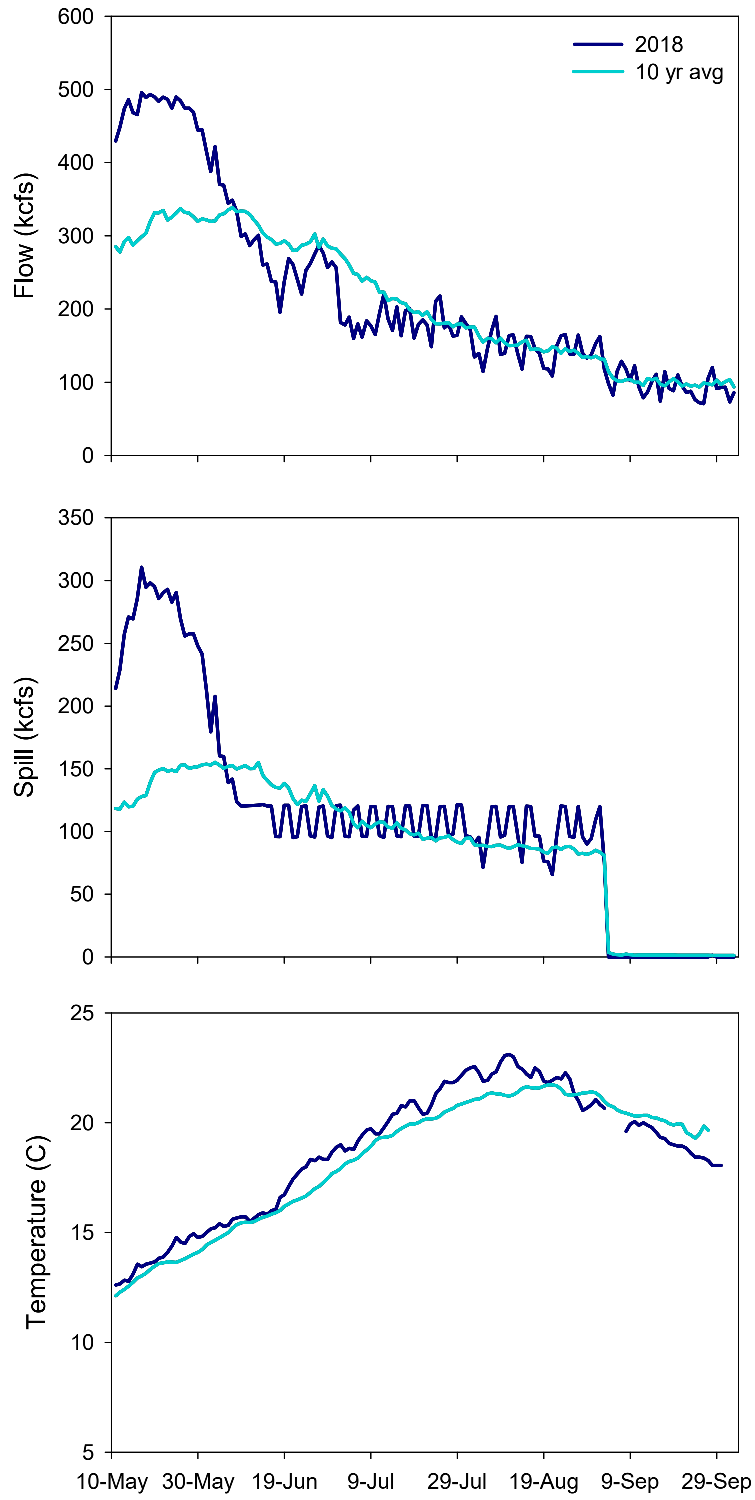

Figure 8 Mean daily Columbia River discharge (flow, kcfs), spill (kcfs), and water temperature (C) at Bonneville Dam in 2018 and the ten-year average (source: http://www.cbr.washington.edu/dart/query /river_daily).

2. Nighttime fishway velocity experiments

Methods

Fishway operations

Nighttime entrance water velocities were altered between 'normal' and 'reduced' conditions in a randomized block design from 1 June through 31 August in 2018 at the Bradford Island fishways (Powerhouse 1 and B-Branch) at Bonneville Dam and from 4 June to 31 August at The Dalles east fishway (Figures 10-11). Water velocities through fishway entrances were manipulated by adjusting the difference in elevation (head) between the inside of the fishway (e.g., the collection channel) and the tailrace. The two target head differences were 0.45 m for the control condition (normal) and 0.15 m for the treatment condition (reduced) at Bonneville Dam and 0.45 m and 0.21 m, respectively at The Dalles Dam. In a previous study by Johnson et al. (2012), head differentials in this range at Bonneville Dam corresponded to mean fishway entrance velocities of >1.96, and 1.2 m sec^{-1}, respectively. On nights when the reduced treatment occurred, the operation was for six hours from 22:00 h to 04:00 h.

Changes in head at fishway entrances at Bonneville PH1 and B-branch (spillway entrance) were achieved by altering operation of fish valves that controlled discharge through diffusers at the north end of the PH1 collection channel (FV1-1), in the transition area of the A-branch fishway (FV3-8), and near the turnpool at the base of the B-branch fishway (FV4-3 and FV4-4). No changes were made to the discharge from two valves near the top of the Bradford Island fish ladder (FV3-7 and FV3-9). Consequently, experimental effects were limited to the lower sections of the Bradford Island fishways and lamprey encountered 'normal' operational conditions from the transition areas to the top-of-ladder exit (similar to conditions in Johnston et al. 2012 at PH2). In addition to the records of fishway operations maintained by the Corps, we tracked the experimental changes in fishway head using four water level loggers (Hobo U20-001-02 and HOBO U20L-01; Onset, Bourne, MA) at Bonneville Dam. Loggers were deployed in the B-Branch tailrace, inside the B-Branch fishway below the turn pool, in the PH1 tailrace, and in the PH1 collection channel. At The Dalles Dam, the east entrance weirs were adjusted to adjust nighttime entrance head (i.e., there were no changes in discharge and the experimental effects were restricted to the entrance areas). Two water level loggers (Hobo U20-001-04) were installed at The Dalles Dam, one in the tailrace outside the east entrance and one downstream of the junction pool inside the east ladder. All level logger data was collected at a five minute interval.

Data analyses

We used several methods to evaluate the effects of the fishway head (e.g., velocity) reduction on radio-tagged lamprey behaviors. The principal objectives of the head reductions were to increase the proportion of lampreys that enter the fishways and to reduce the amount of time between fishway approach and fishway entry events. The analyses required several elements because lamprey behaviors around the fishway openings were sometimes complex, with many individual lampreys approaching, entering, and exiting the fishways multiple times. In addition, individual fish and individual passage attempts, or 'events', could potentially include lamprey exposure to both fishway velocity treatments. We therefore structured most of the analyses at the event scale (e.g., Keefer et al. 2012, 2013b), which incorporated treatment conditions at the start and end of each event as well as event duration (Figure 9).

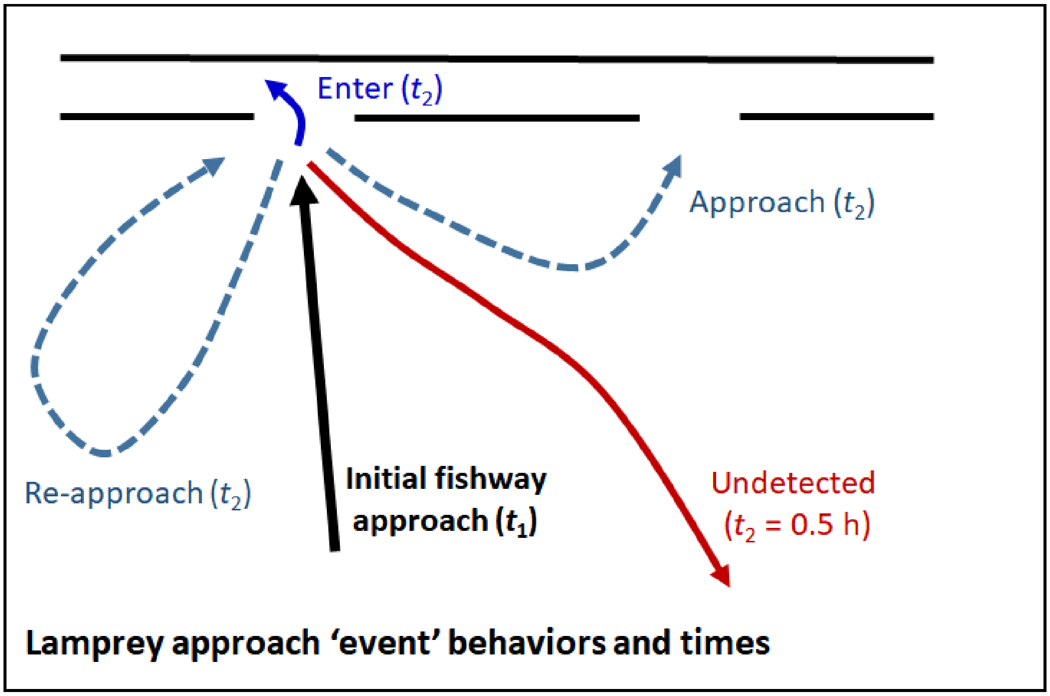

Figure 9. Schematic of a lamprey approaching a fishway opening and subsequent behaviors. Each approach event could be followed by one of four behaviors: 1) fishway entry; 2) fishway approach at another opening at the same fishway; 3) re-approach at the original opening; and 4) no further detection at the fishway. 'Event' duration was calculated from each approach time (t_1) to the subsequent detection time (t_2, entry, re-approach, approach); duration was censored at 30 min (a conservative value near the median approach-to-entry time for successful entrants) for the undetected category. Experimental treatments and environmental covariates could change between t_1 and t_2.

To test for effects of the reduced treatment on entry proportions we calculated two metrics: 1) the number of unique lampreys that were detected entering a fishway divided by the number of unique fish detected approaching a fishway opening, by treatment; and 2) the proportion of fishway entry events divided by the number of fishway approach events, by treatment. The individual-based metric has been reported in many previous lamprey studies (e.g., Keefer et al. 2012), but was somewhat less appropriate for the experimental design. The events-based metric better captured the overall behavior of lampreys around the fishways openings; we note that all approach events that could be assigned to a fishway were included, including those where the first detections were on antennas inside the fishway (i.e., when detections on outside antennas were missed). We tested for treatment effects using 2-way contingency tables and χ^2 tests.

While the proportions of lampreys entering during each treatment are useful metrics, the rate (or instantaneous probability) of fishway entry is also important (Castro-Santos and Perry 2012). We therefore used time-to-event analysis, also known as Cox proportional hazards regression

(Therneau and Grambsch 2013), to analyze lamprey event passage times in relation to the experimental treatments and other potential covariates. Time-to-event analysis was appropriate because it can account for time-varying covariates like the changes in treatment that some lampreys encountered as well as changes in river environment during events.

We used PHReg in SAS v.9.2 (SAS Institute, Cary, North Carolina) to compare a series of models that included combinations of fishway treatment, event date, river discharge, spill, water temperature, tailrace elevation, and lamprey weight at the start and end of each approach event. Event start and end times were rounded to the nearest 5 min and matched with fishway treatment. We used mean daily environmental data at the dams (source: Columbia River DART) for the other environmental covariates, as these conditions varied very little within day. Because the experimental focus was on treatment effects, all models included treatment at either the event start or end time. In addition to treatment-only models, we evaluated models that included treatment plus date, treatment plus lamprey weight, treatment plus individual environmental covariates, and several 3-term models with treatment, date, weight, or an environmental term. More complex models were discarded after exploratory analysis indicated little improvement in model fit. In addition, models with event time-of-day were excluded because time was confounded with nighttime treatment. Because individual lampreys could make multiple attempts, events were potentially not independent and we therefore also tested models where fish identification was included as a random effect.

The fishway head manipulations affected water velocities only in the most downstream fishway segments. Therefore, we expected that impacts on lamprey behaviors would also manifest mainly near the fishway entrance areas, as occurred in previous experiments (e.g., Johnson et al. 2012). We did, however, assess the proportions of entry events that resulted in dam passage and identified where lampreys that did not pass the dam (i.e. "non-passers") turned around inside fishways in relation to treatment at the time of fishway entry.

Results

Experimental treatments

The randomized manipulation of fishway entrance head levels was successful at all three study sites (Figures 10 and 11). During the experimental period at Bonneville Dam (22:00 – 04:00, 1 June – 31 August), the reduced treatment occurred 41% (Powerhouse 1) and 38% (B-Branch) of the time (Table 2). When daytime hours were included, the reduced condition at Bonneville occurred 10-11% of the time. Reduced treatments were less frequent at The Dalles Dam, occurring on 20% of the nighttime experimental period and 6% of the combined day and night.

The water level logger data indicated that conditions near the B-Branch entrance at Bonneville Dam were more seasonally variable than at the Powerhouse 1 entrances, likely reflecting effects of spillway discharge and higher turbulence in the spillway tailrace. Water levels also fluctuated somewhat at the east fishway opening at The Dalles Dam, where some reduced treatment conditions were less pronounced than others. The variation added some uncertainty to the treatment assignments and experimental evaluation (Figure 11).

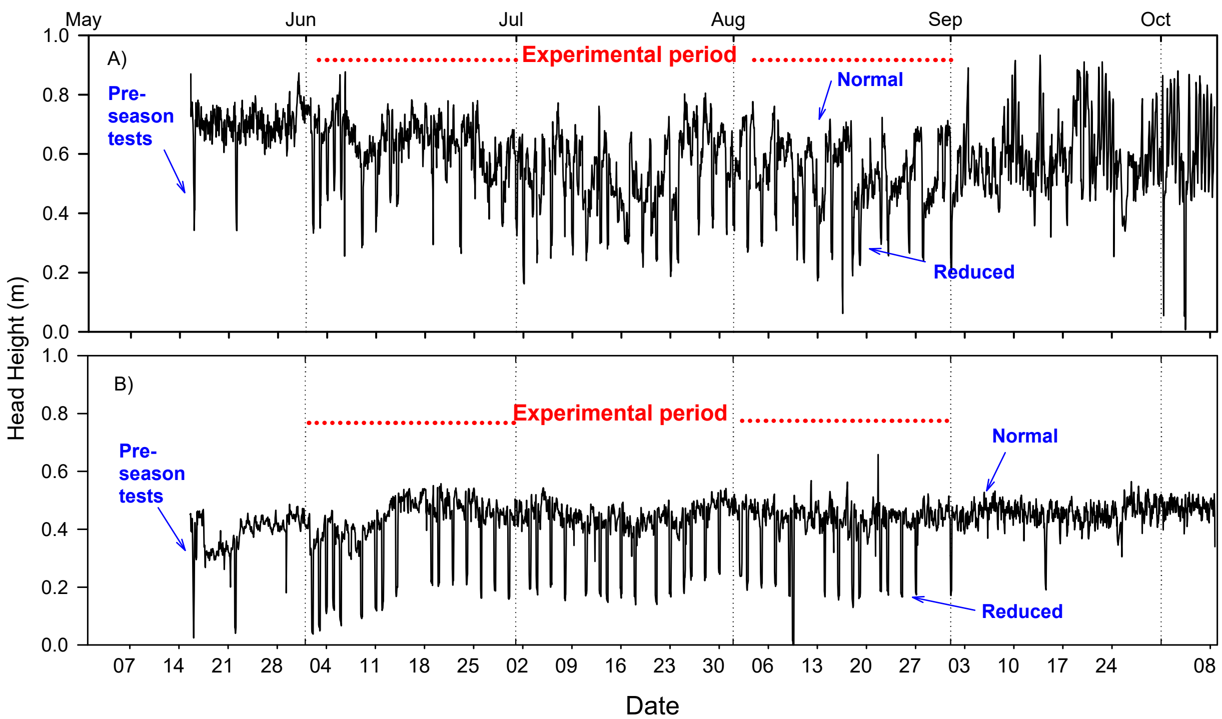

Figure 10. Head height (m) measured with water level loggers (mean hourly) inside and outside the A) Bradford Island B-Branch and B) Bradford Island Powerhouse 1 entrances during the randomized normal and reduced velocity conditions throughout the experimental period (1 June to 31 August) at Bonneville Dam in 2018.

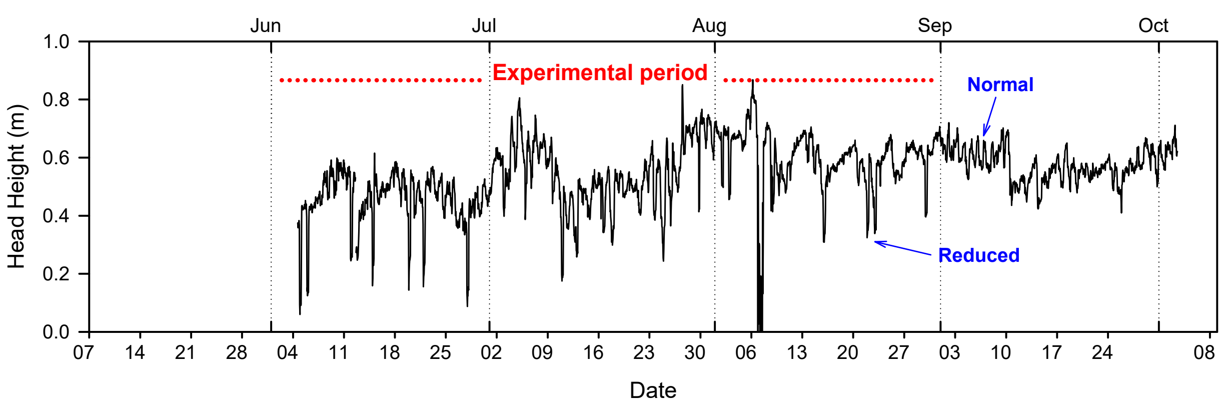

Figure 11. Head height (m) measured with water level loggers (mean hourly) inside and outside the Dalles east fishway entrance during normal and reduced velocity conditions throughout the experimental period (4 June to 31 August) at The Dalles Dam in 2018.

Table 2. Total number of days that normal, reduced, and transition conditions occurred at Bonneville and The Dalles dams during the reduced entrance velocity experiment at night (22:00-04:00 h) and 24 h period (day and night) from 1 June (Bonneville) an 4 June (The Dalles) through 31 August.

Time period	Location	Normal (d)	Reduced (d)	Transition[1] (d)
Night	Bonneville Dam			
	Powerhouse 1	15.7 (58%)	11.0 (41%)	0.1 (1%)
	B-Branch	15.4 (58%)	10.2 (38%)	1.2 (4%)
Day and night	Bonneville Dam			
	Powerhouse 1	80.3 (87%)	11.1 (12%)	0.8 (1%)
	B-branch	79.9 (87%)	10.2 (11%)	1.9 (2%)
Night	The Dalles Dam			
	East entrance	20.2 (78%)	5.0 (20%)	0.5 (2%)
Day and night	The Dalles Dam			
	East entrance	80.7 (91%)	5.1 (6%)	2.5 (3%)

[1] transition conditions occurred during treatment switching and included some unusually high or low values.

Lamprey approach and entry behaviors

Lampreys approached and entered fishways at the three study sites throughout the experimental period, though activity tapered off in August (Figure 12). Substantial majorities of the lamprey activity near the fishway entrances occurred at night (Figure 13). At Bonneville Dam, 117 unique lampreys approached the Powerhouse 1 entrances a total of 348 times (~3.0 times per fish, on average) and 200 unique fish approached the B-Branch 729 times (~3.7 times per fish) across all treatments (Table 3). At The Dalles Dam, 89 unique fish approached the powerhouse openings a total of 296 times (~3.3 times/fish) (Table 3).

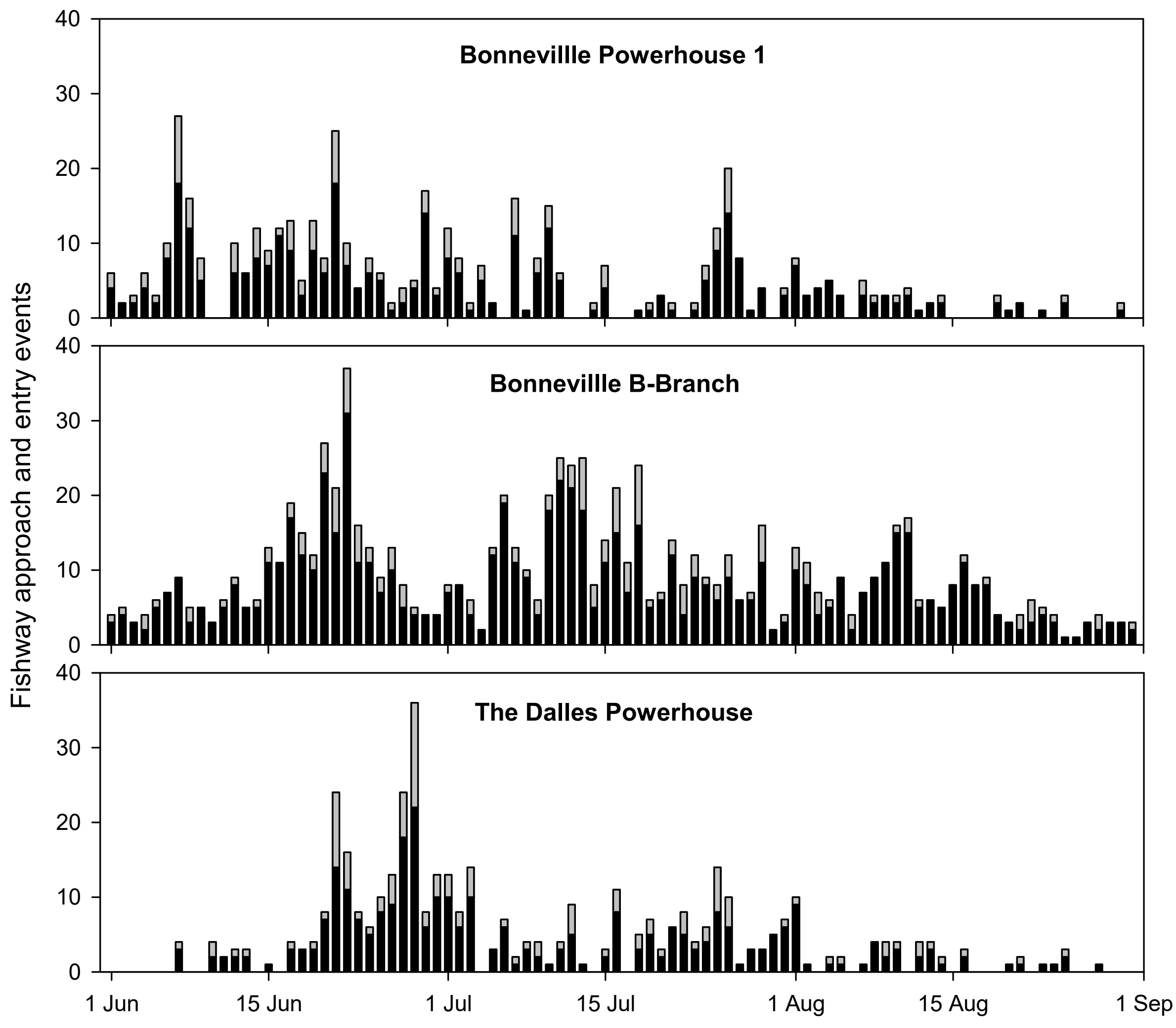

Figure 12. Numbers of fishway approach (black shaded area of bars) and fishway entry (gray shaded area of bars) events by radio-tagged adult Pacific Lampreys during the nighttime fishway velocity experiments at Bonneville and The Dalles dams in 2018.

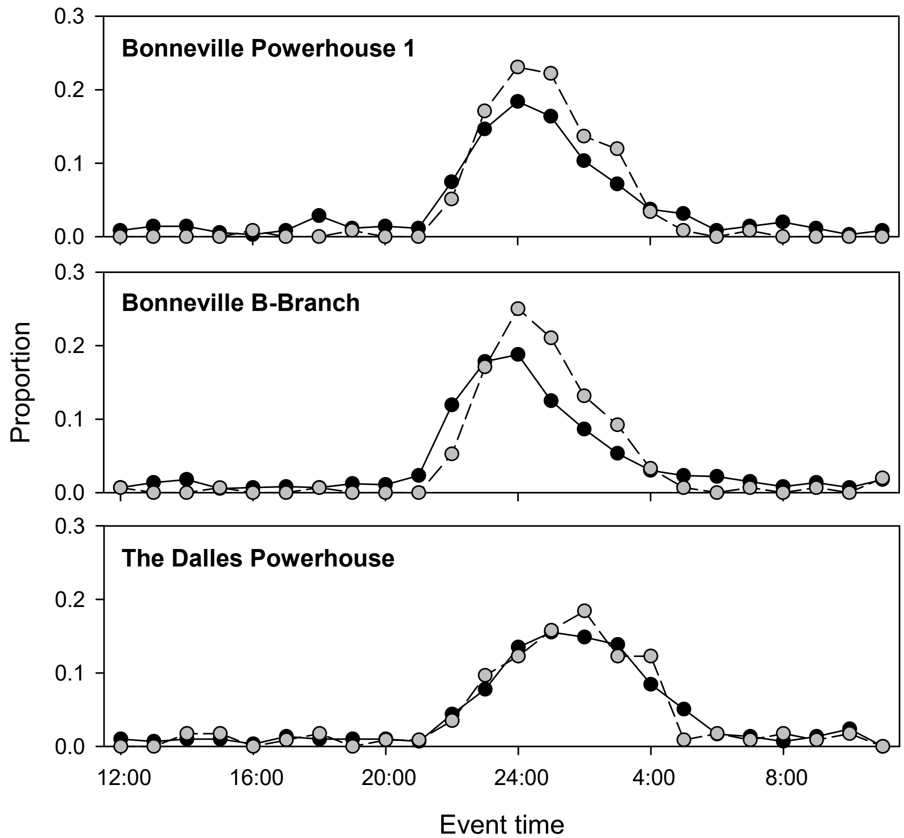

Figure 13. Distributions of the times that radio-tagged adult Pacific Lampreys approached (black circles) and entered (gray circles) fishways during the velocity experiments at Bonneville and The Dalles dams in 2018.

Lamprey fishway approach events were more likely to be followed by fishway entries during the reduced treatment at all three study sites (Table 3). Using the event start time (i.e., the time of each approach), event-based entry ratios were ~1.75-2.48 times higher during the reduced treatment than during the normal treatment ($14.1 < \chi^2 < 42.1$, $P < 0.001$). Most events had the same start and end treatment condition, but some fish did experience changed conditions over the course of an event. Using the event end time, event-based entry ratios were ~1.69-2.80 times higher during the reduced treatment ($12.1 < \chi^2 < 55.0$, $P < 0.001$). Differences in entry ratios for unique lampreys that encountered each treatment had less statistical support (all $P \geq 0.070$), but ratios were higher for those that encountered the reduced treatment in all comparisons (Table 3).

Table 3. Summary of fishway approach and entry events by radio-tagged adult Pacific Lampreys during the nighttime velocity experiments at Bonneville and The Dalles dams in 2018. ‘Unique’ is the number of unique individuals detected in each treatment category and ‘Events’ is the number of attempts as some fish made multiple approaches and entries and individuals could be exposed to more than one treatment condition. ‘Start’ refers to the time that fish began each approach event and ‘End’ refers to the end of the event, which could include fishway entry, another approach event, or a censor event if the fish was not detected again.

		BON Powerhouse 1		BON B-Branch		TDD Powerhouse	
Event:Treatment	Metric	Unique	Events	Unique	Events	Unique	Events
All	Approached	117	348	200	729	89	296
	Entered	90	117	111	152	75	114
	Entered/Approached	0.769	0.336	0.555	0.209	0.843	0.385
Start:Normal	Approached	81	239	167	519	76	222
	Entered	50	65	66	76	57	72
	Entered/Approached	0.617	0.272	0.395	0.146	0.750	0.324
Start:Reduced	Approached	62	109	132	210	41	74
	Entered	44	52	66	76	33	42
	Entered/Approached	0.710	0.477	0.500	0.362	0.805	0.568
	χ^2	*1.33*	*14.11*	*3.28*	*42.06*	*0.45*	*13.87*
	P	*0.249*	***<0.001***	*0.070*	***<0.001***	*0.502*	***<0.001***
End:Normal	Approached	79	240	149	494	74	220
	Entered	50	65	56	65	56	72
	Entered/Approached	0.633	0.271	0.376	0.132	0.757	0.327
End:Reduced	Approached	57	108	125	235	41	76
	Entered	44	52	74	87	32	42
	Entered/Approached	0.772	0.481	0.592	0.370	0.780	0.553
	χ^2	*3.00*	*14.81*	*12.74*	*54.95*	*0.08*	*12.11*
	P	*0.083*	***<0.001***	***<0.001***	***<0.001***	*0.774*	***<0.001***

On median, lamprey events lasted 30-76 minutes between the time they approached a fishway opening and the subsequent fishway entry, a new fishway approach, or the 30-minute censoring time for those that neither entered nor approached again. Median times between approach events and successful entry times were faster, at 2-35 min at each study site. Mean times were considerably higher in each category because some lampreys took several hours or days between event start and end times.

The Cox regression models revealed lampreys were much more likely to enter a fishway during the reduced treatment, with generally larger effect size for the treatment condition at the event end times than at event start times (Table 4). Event start and end treatments produced qualitatively similar effect sizes, as indicated by the hazard ratios and the cumulative hazard plots (Figures 14-16).

In the models using data at Bonneville Powerhouse 1, hazard ratios indicated that the instantaneous likelihood of lampreys entry to the fishway were ~2.1 times higher during the reduced treatment. The most parsimonious model at Powerhouse 1 included the event end treatment (χ^2 = 13.35, P < 0.001) and tailrace elevation (χ^2 = 5.40, P = 0.022), with higher hazard as tailrace elevation increased. Including fish identification as a random effect had little impact on the treatment hazard ratio (fish id χ^2 = 25.70, P = 0.177). In the models for Bonneville B-Branch, treatment hazard ratios were ~2.8-3.3, indicating much higher entry likelihood during the reduced condition (Table 4). The most parsimonious model included event end treatment (χ^2 = 49.59, P < 0.001) and a non-significant lamprey weight effect (χ^2 = 2.44, P = 0.118). As at Powerhouse 1, including the individual random effect had little impact on the treatment hazard ratio, but some support for a subject effect (fish id χ^2 = 50.69, P = 0.075).

At The Dalles Dam, hazard ratios for the reduced treatment effect were ~2.2-2.3 and the most parsimonious model included only the event start treatment (χ^2 = 16.22, P < 0.001). The treatment hazard ratio was similar in the model with individuals treated as a random effect.

Table 4. Summary of Cox proportional hazards regression models at Bonneville (BON) and The Dalles (TDD) dams. Three models are shown for each study location: 1) treatment condition at event start time; 2) treatment condition at event end time; and 3) the most parsimonious model from the set that included a treatment variable or a treatment variable plus lamprey weight, discharge, spill, water temperature, or tailrace elevation[1].

Site	Parameter	Parameter estimate	SE	Hazard Ratio	95% CI	χ^2	P
BON Powerhouse 1	Treatment:Start	0.734	0.187	2.083	1.444-3.004	15.41	**<0.001**
	Treatment:End	0.764	0.187	2.146	1.487-3.097	16.65	**<0.001**
	Treatment:End[1]	0.984	0.190	2.002	1.381-2.905	13.35	**<0.001**
	Elevation:End[1]	0.050	0.022	1.052	1.007-1.098	5.40	**0.022**
BON B-Branch	Treatment:Start	1.040	0.162	2.830	2059-3.891	41.03	**<0.001**
	Treatment:End	1.194	0.164	3.301	2.393-4.554	52.91	**<0.001**
	Treatment:End[1]	1.163	0.165	3.201	2.315-4.424	49.59	**<0.001**
	Weight[1]	0.002	0.001	1.002	1.000-1.004	2.44	0.118
TDD Powerhouse	**Treatment:Start**	0.822	0.195	2.275	1.552-3.335	17.75	**<0.001**
	Treatment:End	0.778	0.195	2.176	1.485-3.190	15.90	**<0.001**

[1] tailrace elevation tested at Bonneville Dam only

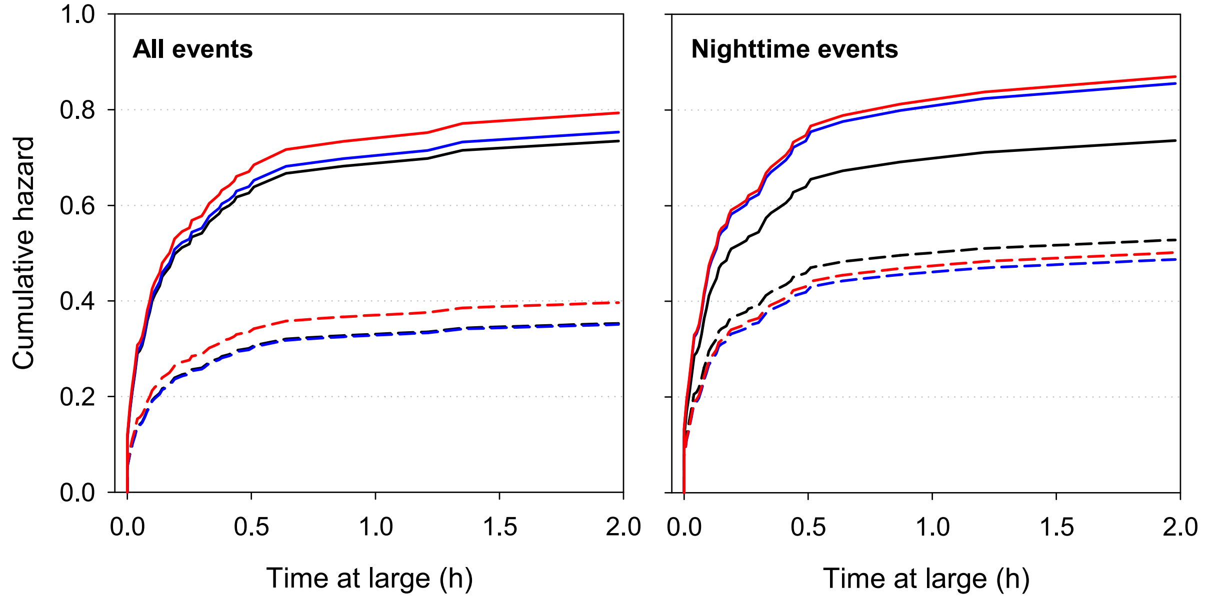

Figure 14. Cumulative hazards of fishway entry by radio-tagged Pacific Lampreys at the Powerhouse 1 fishway at Bonneville Dam during the reduced velocity experiment. Solid lines show hazards for the reduced velocity condition and dashed lines are for the normal condition. Left panel includes all fishway approach events (day and night) and right panel shows approach events during the 22:00-04:00 experimental period only. Hazards were generated using three models: treatment condition at the start of each event (i.e., at fishway approach, black lines); treatment condition at the end of each event (blue lines); and from the most parsimonious model for all events (end treatment + tailrace elevation, red lines).

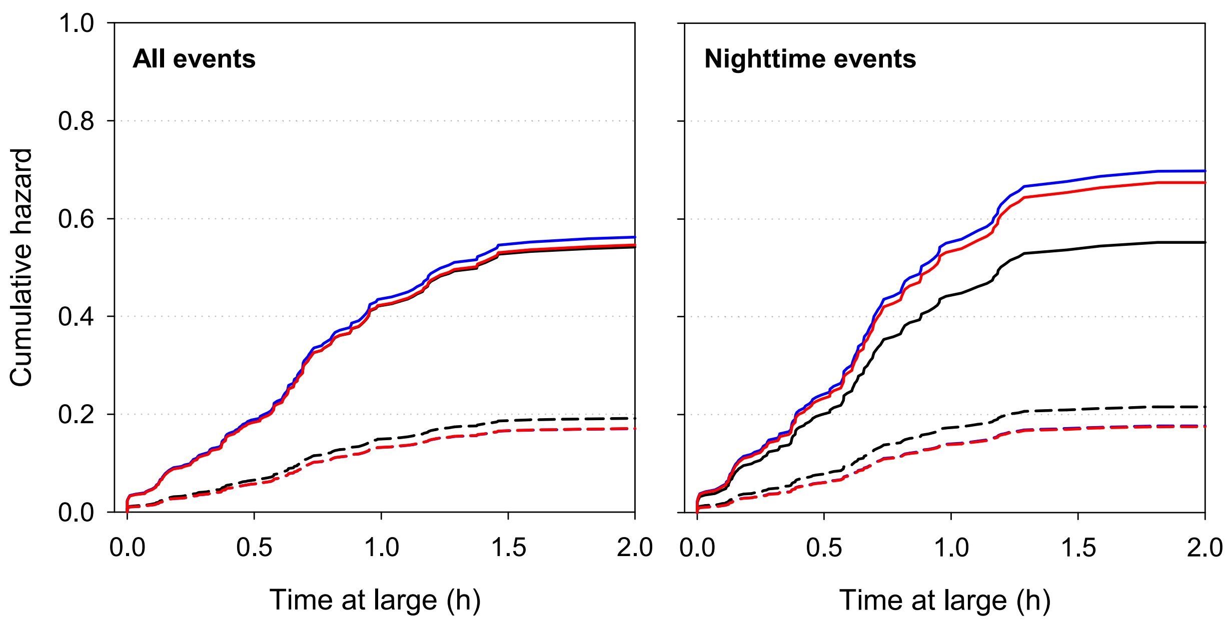

Figure 15. Cumulative hazards of fishway entry by radio-tagged Pacific Lampreys at the B-Branch fishway at Bonneville Dam during the reduced velocity experiment. Solid lines show hazards for the reduced velocity condition and dashed lines are for the normal condition. Left panel includes all fishway approach events (day and night) and right panel shows approach events during the 22:00-04:00 experimental period only. Hazards were generated using three models: treatment condition at the start of each event (i.e., at fishway approach, black lines); treatment condition at the end of each event (blue lines); and from the most parsimonious model for all events (end treatment + lamprey weight, red lines).

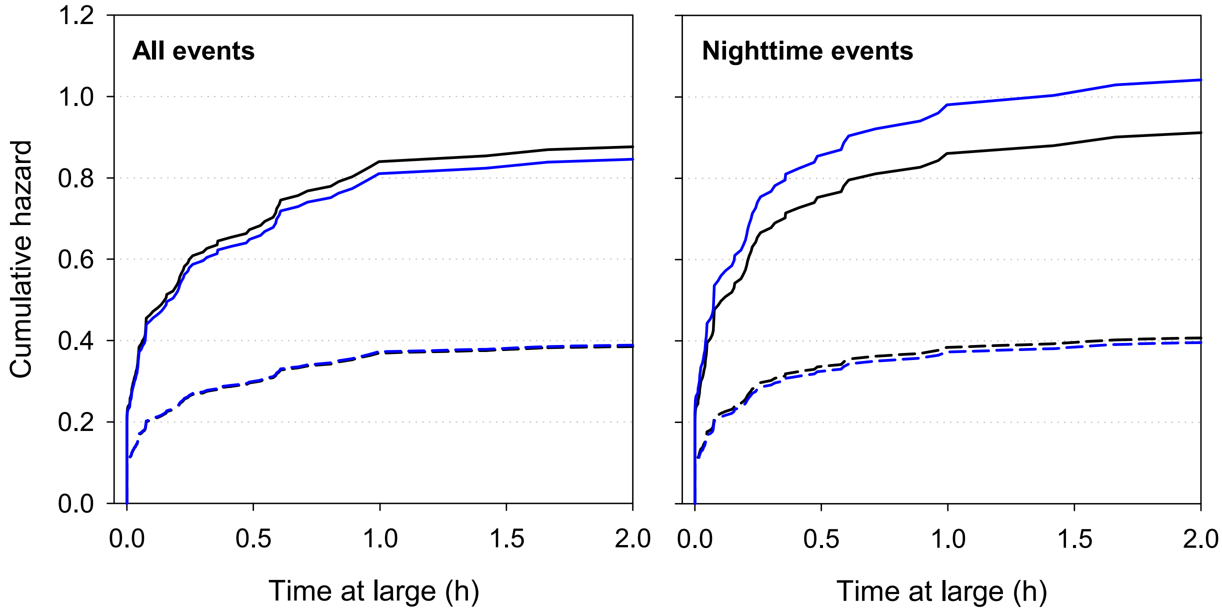

Figure 16. Cumulative hazards of fishway entry by radio-tagged Pacific Lampreys at the Powerhouse fishway at The Dalles Dam during the reduced velocity experiment. Solid lines show hazards for the reduced velocity condition and dashed lines are for the normal condition. Left panel includes all fishway approach events (day and night) and right panel shows approach events during the 22:00-04:00 experimental period only. Hazards were generated using two models: treatment condition at the start of each event (i.e., at fishway approach, black lines); treatment condition at the end of each event (blue lines). The start treatment model was the most parsimonious model.

Lamprey passage attempt outcomes

Fishway passage success did not statistically differ for lampreys that entered fishways during reduced versus normal velocity treatments at either dam (Table 5). Dam passage percentages for lampreys that entered the Powerhouse 1 fishway were 33.8% for events during the normal treatment versus 42.3% for events during the reduced treatment ($\chi^2 = 0.88$, $P = 0.348$). Passage percentages for entry events at the B-Branch fishway were 35.9% (normal) and 32.9% (reduced) ($\chi^2 = 0.15$, $P = 0.696$). At The Dalles Dam, percentages were 41.7% (normal) and 42.9% (reduced) ($\chi^2 = 0.05$, $P = 0.901$).

There was some evidence that treatment was associated with where lampreys turned around inside fishways, with fish more likely to turn around closer to the tailrace during normal treatment conditions (Table 5). At the Powerhouse 1 fishway, 40% of failed entry events during the normal treatment had fish turn around inside the fishway collection channel, 16% were in the transition area, and 44% were near the top of the fishway (i.e., serpentine weirs or AWS channel). In contrast, lamprey attempts that failed after entry during the reduced treatment had turned around in the collection channel (17%), transition area (27%), and near the top of the fishway (57%) ($\chi^2 = 4.55$, $P = 0.103$). Similarly, lampreys that failed to pass after entering the B-Branch fishway during the normal treatment were more likely to turn around near the turn pool (52%) than in the transition area (6%) or top of fishway (42%). In comparison, turn around percentages during the reduced treatment were more likely to be upstream of where discharge was reduced in the experiment, at 39% (turn pool), 22% (transition area), and 39% (top of fishway) ($\chi^2 = 5.75$, $P = 0.056$).

Table 5. Summary of passage attempt outcomes, by velocity treatment, for radio-tagged Pacific Lampreys that entered fishways at Bonneville (BON) and The Dalles (TDD) dams. Turnaround locations indicate the most upstream location where lampreys were detected before they moved downstream and exited into the tailrace.

		Normal		Reduced	
Location	Metric	*n*	%	*n*	%
BON Powerhouse 1	Entered	65		52	
	Passed	22		22	
	Entered/Passed	0.338		0.423	
	Did not pass	43		30	
	Turnaround location				
	South Powerhouse	12	27.9%	5	16.7%
	North Powerhouse	5	11.6%	-	-
	Transition area	7	16.3%	8	26.7%
	Serpentine weirs / AWS	19	44.2%	17	56.7%
BON B-Branch	Entered	78		73	
	Passed	28		24	
	Entered/Passed	0.359		0.329	
	Did not pass	50		49	
	Turnaround location				
	B-Branch turnpool	26	52.0%	19	38.8%
	Transition area	3	6.0%	11	22.4%
	Serpentine weirs / AWS	21	42.0%	19	38.8%
TDD Powerhouse	Entered	72		42	
	Passed	30		18	
	Entered/Passed	0.417		0.429	
	Did not pass	42		24	
	Turnaround location				
	West powerhouse	5	11.9%	3	12.5%
	East powerhouse	8	19.0%	6	25.0%
	Transition area	28	66.7%	15	62.5%
	Count station	1	2.4%	-	-

Discussion

The fishway head manipulations were designed to reduce velocity at the fishway openings and thereby increase both the proportion of lampreys that entered fishways and the speed at which they entered. These objectives were achieved at all three study sites in 2018. Event-based fishway entry metrics and Cox proportional hazards regression models that accounted for environmental and lamprey trait covariates indicated clear statistical improvements in lamprey entry success during the reduced head treatments. The experimental results in 2018 were consistent with the improved lamprey entrance efficiencies in a similar experiment conducted at Bonneville's Powerhouse 2 fishway in 2007-2009 (Johnson et al. 2012).

The operational effects of reduced fishway head were limited to the most downstream sections of the fishways. Consequently, the impact of the experiment on lamprey behaviors was also spatially constrained, and we found little evidence that lamprey behaviors were affected upstream from the head control points. Treatment at the time lampreys entered the fishways was not statistically associated with fishway passage success upstream from the entrance areas past the dams. As in previous radiotelemetry studies (e.g., Keefer et al. 2013b), lampreys that entered the A-branch and B-branch fishways at Bonneville Dam were most likely to turn around in transition areas (near head control points) and in the upper sections of the Bradford Island fishway (well above control points). Our finding of limited experimental effects upstream from control points was expected and was consistent with observations in the Johnson et al. (2012) experiment.

There was relatively more uncertainty in the experimental results at The Dalles Dam than at Bonneville Dam for several reasons. First, reductions in fishway entrance velocity were achieved using different methods at Bonneville (fish valve adjustments) versus The Dalles (raising and lowering weirs) and the magnitude of reductions was consequently somewhat more variable at The Dalles (compare Figures 10 and 11). Second, there were fewer reduced treatment nights at The Dalles than at Bonneville. Third, there were fewer radio-tagged lampreys at The Dalles, and fourth, there was limited lamprey use of the spillway and west powerhouse entrances at The Dalles. The treatment schedule and sample size and distribution among openings resulted in reduced statistical power at The Dalles relative to at Bonneville. Nonetheless, the reduced treatment effects on lamprey behaviors at The Dalles were very consistent with results at Bonneville, and we think a misinterpretation of effects is unlikely.

The experimental design presented several statistical challenges. These include: multiple passage attempts by individual lampreys; potential exposure of individuals to multiple treatments; treatment switching during the interval between fishway approach and fishway entry; and the selection of censoring times for lampreys that approach but subsequently leave the study area. Proportional hazards regression is frequently applied in these types of circumstances, and we think the presented regression results reasonably captured the overall treatment effects. We recommend, however, that the estimated hazard ratios be interpreted cautiously. Ratios changed slightly in models where individual lampreys were treated as random effects and in models that included different combinations of covariates. Ratios also likely would have changed somewhat had we selected a different censoring time for fish that did not enter. We conservatively selected 30-min as the censoring time because it was close to the median lamprey approach-to-entry time.

Selection of a longer censoring time may have been appropriate if we could have confirmed that lampreys spent extended times near the fishway openings before departing, but this was not possible. Nonetheless, all models supported the qualitative conclusion that reduced nighttime velocities increased fishway entry rates for Pacific Lampreys.

3. Lamprey behaviors near the new UMTJ-LPS

Methods

Monitoring sites

Movements of radio-tagged and HD PIT-tagged (only) lamprey were monitored with an array of antennas near the UMT junction channel (downstream of the UMTJ-LPS), near the entrance to and inside of the UMTJ-LPS, and upstream of the structure in the serpentine weirs, AWS channel, and at the top of the ladder (Figures 17-18). Lampreys that entered the study area (from the UMT junction to the top of the fishway) were categorized by route of passage (UMTJ-LPS, AWS-LPS, or traditional fishway) or non-passage based on their detections at radio and PIT antennas. Individual fish behaviors for lampreys that used the UMTJ-LPS were further summarized based on upstream and downstream movement in the study area before entering the UMTJ-LPS. Passage times (total passage) were calculated for the three passage routes (UMTJ-LPS, AWS-LPS, and traditional fishway) from first detection at the UMT junction to last detection at the top of an LPS or the fishway. Time to pass through the UMTJ-LPS was calculated from the first to last detection for each fish on antennas inside the structure.

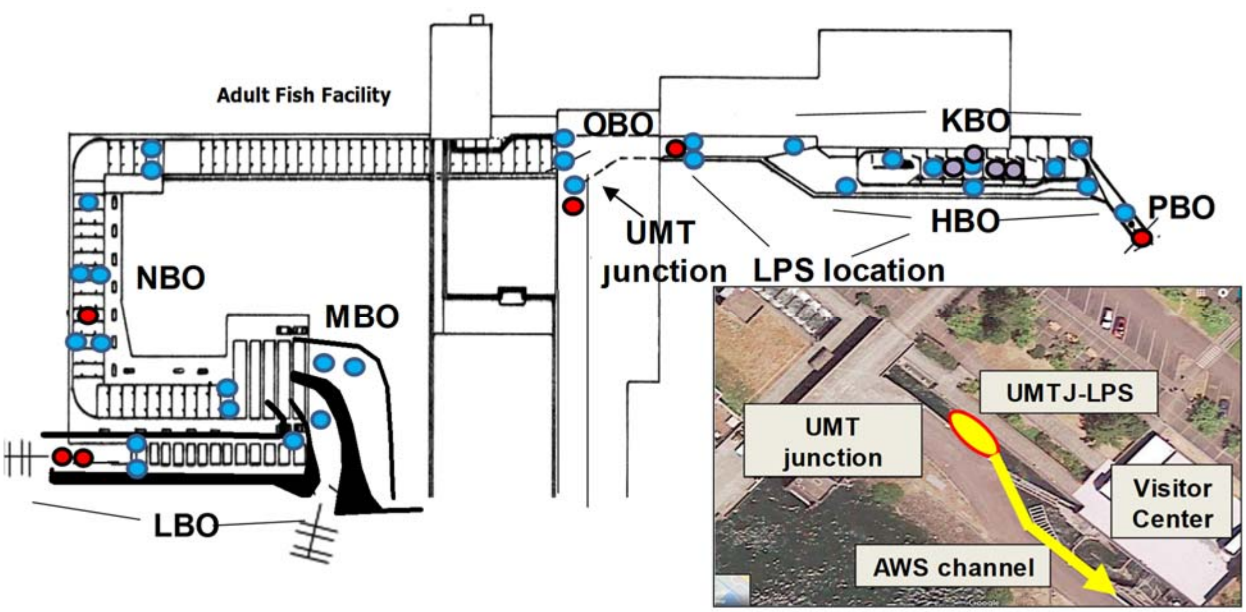

Figure 17. Map of aerial and underwater radio antennas (blue), University of Idaho (UI) HD PIT antennas (red), and PTAGIS dual PIT antennas (grey) in the Washington shore fish ladder and AWS channel used to monitor fish behavior. Sites upstream from the UMT Junction were used to evaluate movements near the UMTJ-LPS in 2018.

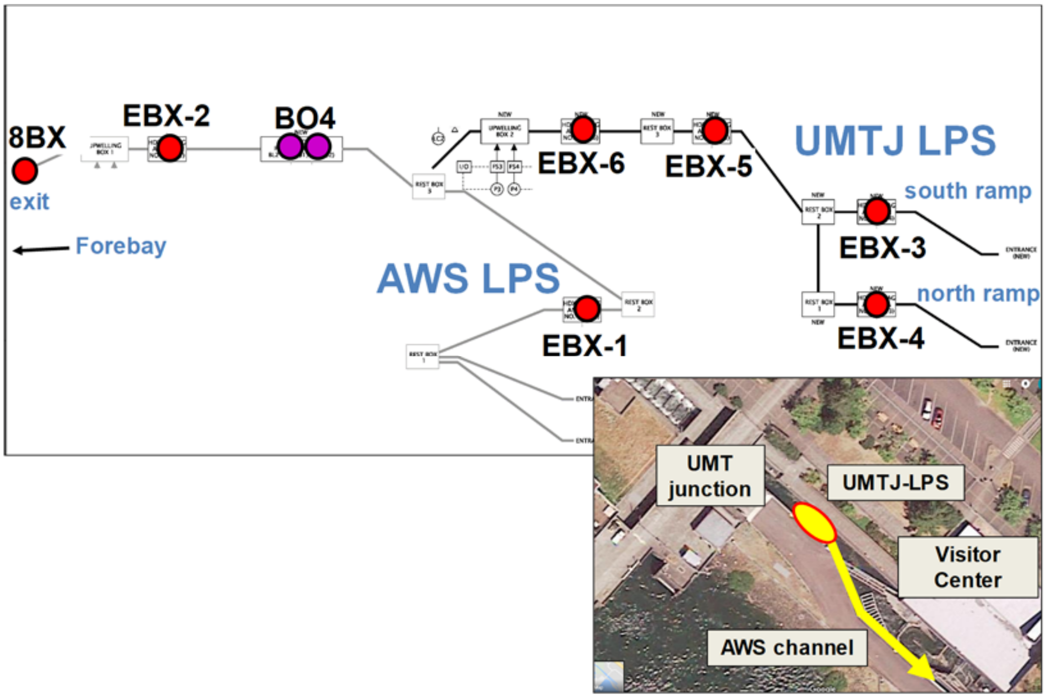

Figure 18. Map of UI (●), and PTAGIS HD PIT antennas (●) in the Washington-shore LPSs (UMTJ-LPS and AWS-LPS) in 2018.

Data analyses

We used Pearson's chi-square (χ^2) tests and analysis of variance (ANOVA) in SAS v.9.2 (SAS Institute, Cary, North Carolina) to test whether differences in lamprey size metrics (weight, length, girth, and dorsal distance), migration date (first detection), or tag type (radio, HD-PIT) were associated with passage route and dam passage success. Lampreys that were recaptured at the AFF were censored from all analyses.

Results

Lamprey behaviors

PIT-tagged (only) lamprey – In total, 234 unique PIT-tagged lampreys were recorded at one or more antennas near the WA-shore UMTJ-LPS (from the UMT channel junction upstream). Of the 234, 15 (6%) passed through the UMTJ-LPS, 74 (32%) passed via the AWS-LPS, 70 (30%) passed via the ladder, 11 (5%) were recaptured at the AFF, and 64 (27%) did not pass the dam via the WA-shore ladder. Of the 64 that did not pass the dam via the WA-shore, 8 (13%) eventually passed via the Bradford Island ladder. One of the 15 lamprey that passed through the UMTJ-LPS subsequently entered the upper ladder and then moved down the ladder to the UMT junction channel, and did not pass the dam.

Of the 15 lamprey in the study area that passed through the UMTJ-LPS, 9 (60%) entered the north ramp and 6 (40%) entered the south ramp of the LPS. All lamprey but one initially swam upstream past (i.e., bypassed) the UMTJ-LPS 1-3 times before moving back downstream and entering the UMTJ-LPS and passing the dam (Figure 19). Passage times from UMTJ-LPS entry until dam passage were 0.8 h, on median. Median times to pass from the UMT junction (below the UMTJ-LPS) to the top of the ladder were 2.5 d (*n* = 10) for fish that used the UMTJ-LPS, 2.1 d for fish that used the AWS-LPS (*n* =42), and 2.5 d for fish that used the ladder (*n* = 12).

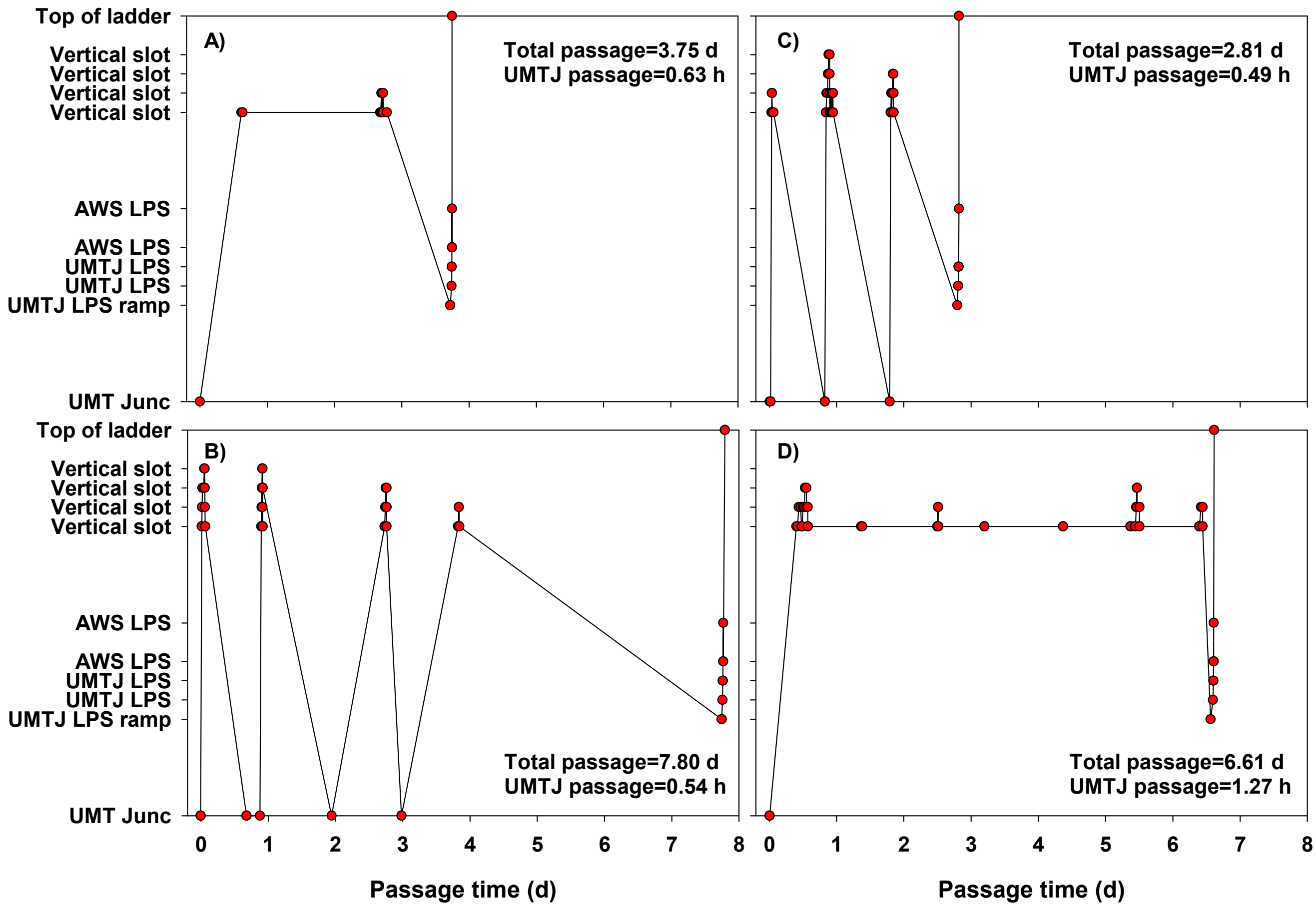

Figure 19. Examples of PIT-tagged lamprey movements and passage times inside the WA-shore fishway before they passed via the UMTJ-LPS. Passage dates were A) 15-July, B) 21-June, C) 27 July, and D) 13 June in 2018. Y-axis labels correspond to locations of individual PIT antennas, ordered from downstream to upstream and 'vertical slot' = serpentine weir.

Radio-tagged lamprey – A total of 199 unique radio-tagged lamprey were recorded at one or more antennas near the WA-shore UMTJ-LPS (from the UMT channel junction upstream). Of the 199 lamprey, 8 (4%) passed via the UMTJ-LPS, 40 (20%) passed via the AWS-LPS, 76 (38%) passed via the ladder, 6 (3%) were recaptured at the AFF, and 69 (35%) did not pass the dam via the WA-shore fishway. Two (3%) of the 69 lamprey that exited the WA-shore fishway to the tailrace eventually passed the dam via the Bradford Island fish ladder.

Of the 8 radio-tagged lamprey that passed via the UMTJ-LPS, 2 (25%) entered the north ramp and 6 (75%) entered the south ramp of the LPS. Seven initially moved upstream past the UMTJ-LPS 1-5 times before entering the UMTJ-LPS and passing the dam. Passage times from

UMTJ-LPS entry until dam passage were 1.1 h, on median. Median time to pass from the UMT junction (below the UMTJ-LPS) to the top of the ladder was 0.8 d for fish using the UMTJ-LPS (n = 8), 1.0 d for fish using the AWS-LPS (n = 31), and 0.9 d for fish using the ladder (n = 58).

PIT and radio-tagged lamprey – Similar proportions of PIT- and radio-tagged lampreys passed the dam ($\chi^2 = 2.37$, $P = 0.124$). PIT-tagged lampreys were more likely to pass the LPSs and radio-tagged lampreys were more likely to pass the dam via the ladder ($n = 283$, $\chi^2 = 8.32$, $P = 0.016$). Route passage for PIT-tagged lampreys was 9.4% UMTJ-LPS, 46.5 % AWS-LPS, and 44.0% ladder and was 6.5%, 32.3 %, and 61.3%, respectively, for radio-tagged lampreys. There were no differences in size or date among routes (UMTJ-LPS, AWS-LPS, ladder) for PIT-tagged lampreys (ANOVA, all $P > 0.05$). However, dorsal distance differed among routes for radio-tagged lampreys ($df = 2$, $F = 3.82$, $P = 0.025$) where fish with smaller dorsal distance used the UMTJ-LPS (Figure 20).

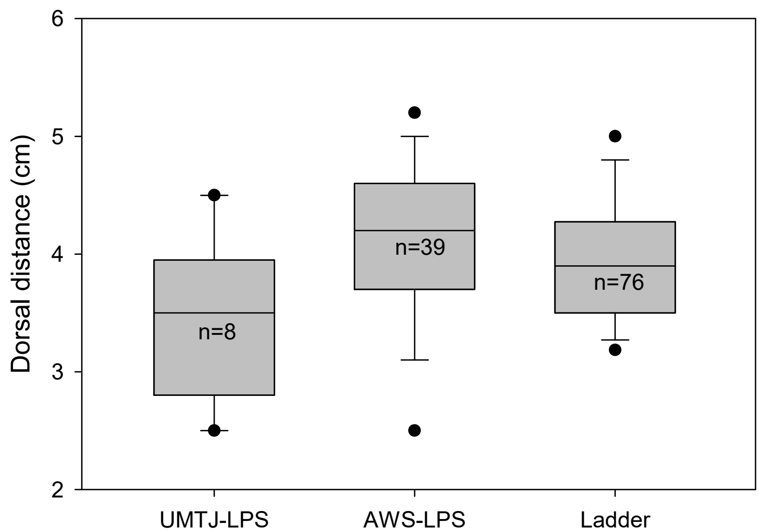

Figure 20. Box plots of dorsal distance for radio-tagged lampreys that passed Bonneville Dam via three routes at the WA-shore fishway. Distributions show 5th, 10th, 25th, 50th, 75th, 90^{th,} and 95th percentiles.

Lamprey behavior after exiting the LPSs at Bonneville

Washington-shore fishway – Eighty-two radio-tagged fish had detections on AWS radio antennas and 48 likely passed through the WA-shore LPSs (8 UMTJ-LPS + 40 AWS-LPS) based on PIT detections. One of the eight lamprey that passed through the UMTJ-LPS moved upstream and exited the AWS-LPS, but then moved downstream through the serpentine weirs and reascended through the UMTJ-LPS; this individual then passed the dam.

Another 89 PIT-tagged (only) lamprey passed via the WA-shore LPSs (15 UMTJ-LPS + 74 AWS-LPS). One of the 15 lamprey that passed via the UMTJ-LPS moved down through the serpentine weirs to the UMT junction channel and did not pass the dam.

Bradford Island fishway – Fifty-two radio-tagged fish were detected in the AWS (on radio antennas) and 41 likely passed the fishway through the LPS based on PIT detections. Two of the 41 lamprey that passed via the BI AWS-LPS fell back. One moved down the Bradford Island fish ladder 2 days after apparently exiting into the forebay; this fish was last recorded in the Bonneville tailrace. The other fish fell back 7 days after exiting into the forebay via an unknown route but reascended the Bradford Island fishway and passed the dam. Of the 41 lampreys that passed via the LPS, 9 (19.5%) also had detections on the radio antenna used to monitor the fish ladder exit area; the range of this antenna potentially included a small portion of the forebay near the LPS exit.

Another 77 PIT-tagged (only) lamprey passed via the AWS-LPS and 9 (12%) were detected on the HD PIT antenna used to monitor the ladder exit. Five of the 77 (6%) that passed via the BI AWS-LPS fell back. There were no records that indicated these fish moved down the ladder. Three of the five reascended the dam via the Bradford Island fishway (2 LPS + 1 ladder), one was recaptured at the AFF (WA-shore), and one was last detected in the Bradford Island serpentine weirs.

Discussion

Overall, a small percentage (4-6%) of tagged lampreys that reached the area of the UMTJ-LPS used it to pass the dam at the Washington-shore fishway. The low percentage was likely due to lampreys failing to initially locate the LPS ramps to the UMTJ-LPS or choosing to swim past the structure upon initial encounter. We observed that 92% (23 of 25) of tagged lamprey that used the UMTJ-LPS initially swam upstream past the UMTJ-LPS multiple times before returning downstream to enter the UMTJ-LPS and pass the dam. Finding suitable attraction flow to the UMTJ-LPS for lampreys to provide guidance is difficult because too much flow could attract salmonids at the entrance of the LPS ramps (Keefer et al. 2011; Zobott et al. 2015). We also note, however, that in our observations using DIDSON in 2017, adult salmonids were not attracted to the UMTJ-LPS ramps (Clabough et al. 2018).

Factors affecting the choice for climbing and LPS use vs. swimming may include structural and hydraulic context and fish condition/recent experience (Kemp et al. 2009; Goodman and Reid 2017). Specifically, climbing may be induced when lamprey perceive a lack of other routes (such as in the AWS channels) or when alternative passage routes have been 'sampled' and perceived to be taxing or impassable (e.g., multiple attempts in the serpentine weirs). Distinguishing between guidance and climbing motivation as mechanisms would be challenging but possible in experimental settings manipulating guidance cues and lamprey experience, specifically recent exercise history. Notably, the observation that dorsal distance was associated with LPS use implies that lamprey condition or maturation status may affect behavioral decisions and the motivation to switch from swimming to climbing.

Lamprey passage times through the UMTJ-LPS were similar between radio- (1.1 h) and PIT-tagged (0.8 h) lampreys. However, overall passage times through the upper ladder study area to exit regardless of route (UMTJ-LPS, AWS-LPS or ladder) were twice as long for PIT-tagged lampreys than for radio-tagged lampreys. This may be because radio-tagged lampreys were slightly larger than PIT-tagged lampreys and thus predicted to travel longer distances upstream

(Keefer et al. 2009c). In statistical analyses, we found similar proportions of PIT- and radio-tagged lampreys passed the dam. However, PIT-tagged fish were more likely to pass via the LPSs and radio-tagged fish were more likely to pass via the ladder. We did find that radio-tagged lampreys with smaller dorsal distance were more likely to pass thru the UMTJ-LPS, consistent with results reported by Kirk et al. (2016), who found adult Pacific Lampreys with larger dorsal distance were more likely to successfully pass vertical slot weirs, again suggesting an association between lamprey condition and behavioral decisions during passage.

A small percentage (1-6%) of lampreys that used the LPSs at Bonneville Dam backed down the ladder or fell back over the dam and approximately half of those fish reascended the dam. Backing down the ladder after exiting an LPS is possible at the Washington-shore fishway because the LPS exits into the main fishway above the serpentine weirs rather than into the dam forebay. At the Bradford Island fishway, the exit from the LPS is into the forebay and is in close proximity (~6 m; 20 ft) to the main ladder exit. Extending the Washington-shore LPS exit into the forebay could alleviate the downstream movement problem.

4. Lamprey behaviors near Bonneville count stations and serpentine weirs

Methods

Movements of radio-tagged lampreys were extensively monitored with underwater antennas near the UMT junction channel (WA-shore), near the count windows, serpentine weir sections and AWS channels of both the Washington and Bradford Island fishways in 2018 (Figure 21). Individual fish behaviors were summarized for fish that did and did not pass the dam. The most upstream detection locations were summarized for lampreys that did not pass the dam. We statistically tested for effects of fish size metrics and date using methods described in the UMTJ-LPS section.

Results

Washington-shore fishway – As described in the UMTJ-LPS section, 199 unique radio-tagged lampreys were recorded with one or more antennas at or upstream from the UMT channel junction. Of the 199, 124 (62%) passed the dam, 69 (35%) did not pass the dam via the WA-shore fishway, and six (3%) were recaptured. The six recaptured fish were excluded from the behavior summary below. We found no differences in size or date among lamprey that did and did not pass the dam via the Washington shore fishway (ANOVA, all $P > 0.05$).

Lampreys moved extensively within the study area. Of the 124 fish that passed the dam via the WA-shore, 86% (n = 107) were recorded on the antenna below the count window (KBO5) and 73% (n = 90) were recorded on the antenna above the count window (KBO4; Figure 22). About a third (n = 37, 30%) of the fish that passed the dam were recorded on antennas in both the serpentine weirs and inside the AWS channel. The majority of fish (61%) that passed the dam did so via the serpentine weirs, 32% passed through the AWS-LPS, and 7% passed through the combined UMTJ-LPS and AWS-LPS.

Of the fish that did not pass the dam via the WA-shore (n = 69), 90% were recorded on the antenna below the count window (KBO5) and 77% were recorded on the antenna above the count window (KBO4). The furthest upstream record (turn around point) for the majority (64%, n = 44) of fish that did not pass was in the serpentine weir section (Figure E). Most (n = 36, 82% of 44) of the serpentine turnarounds were estimated to have occurred at the uppermost antennas (KBO6 = 25%; KBO2 = 57%). The next largest group of non-passers, thirty-two percent (n = 22, 32% of 69) had their most upstream records in the AWS channel at the most upstream antenna (HBO3; Figure 21). None of these 22 fish were detected in the WA-shore LPSs. The remaining 3 (4%) non-passing fish were only recorded near the UMT junction channel.

Of the 69 lampreys that did not pass, 87% (n = 60) were last recorded in the Bonneville tailrace, 7% (n = 5) were in the WA-shore ladder, 4% (n = *3*) passed the dam via the Bradford Island fishway, and 1% (n = 1) was last detected in the Cascades Island fishway. A majority (53%) that were last were recorded in the tailrace traveled from the Washington-shore ladder through the UMT channel and exited the Cascades Island fishway; the other 47% exited the

Washington-shore ladder to the tailrace. Three of the 60 fish last recorded in the tailrace had exited to the tailrace after making multiple attempts ascending the WA-shore fishway.

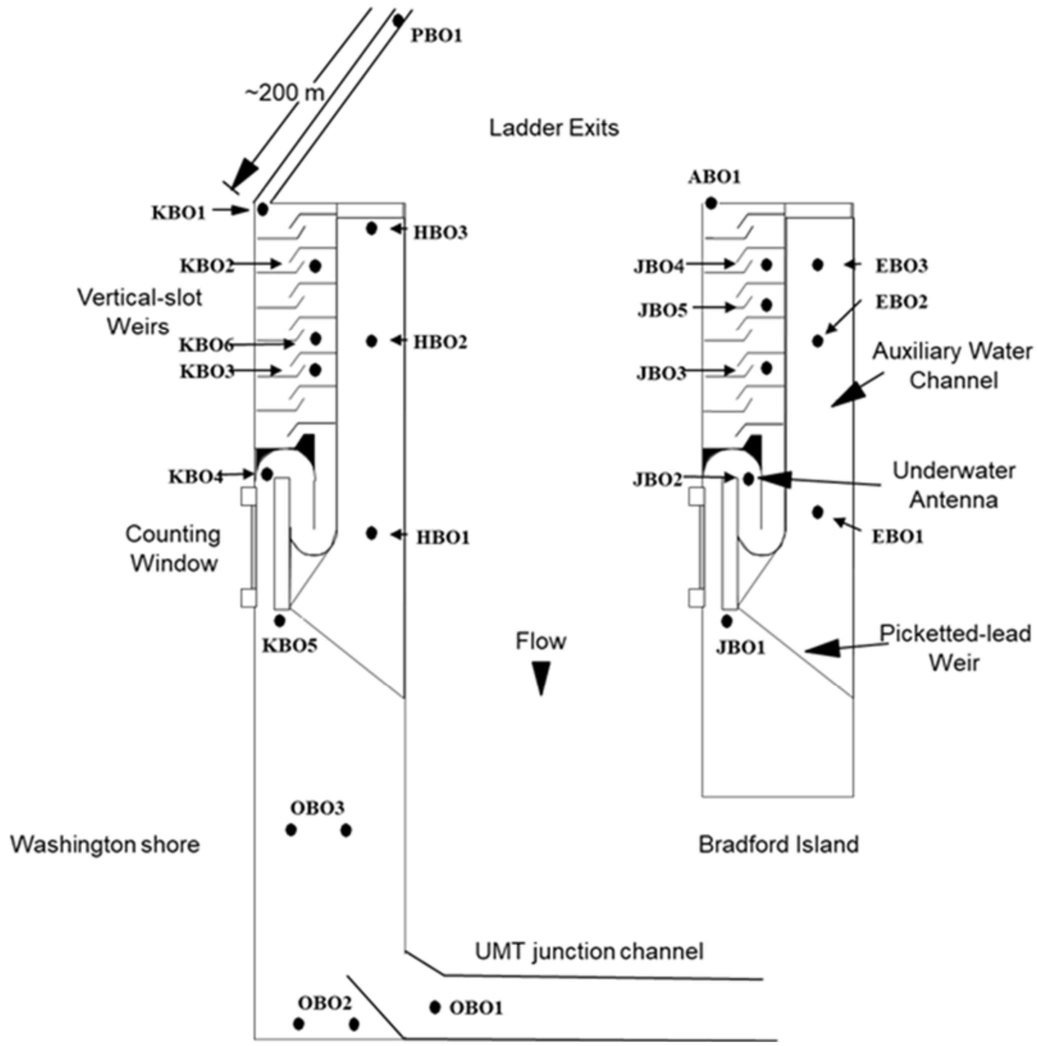

Figure 21. Overhead diagram of radio antenna deployments at Bonneville Dam UMT junction channel (WA-shore), count stations, serpentine weirs, and auxiliary water supply (AWS) channels in 2018. Note drawings are not to scale.

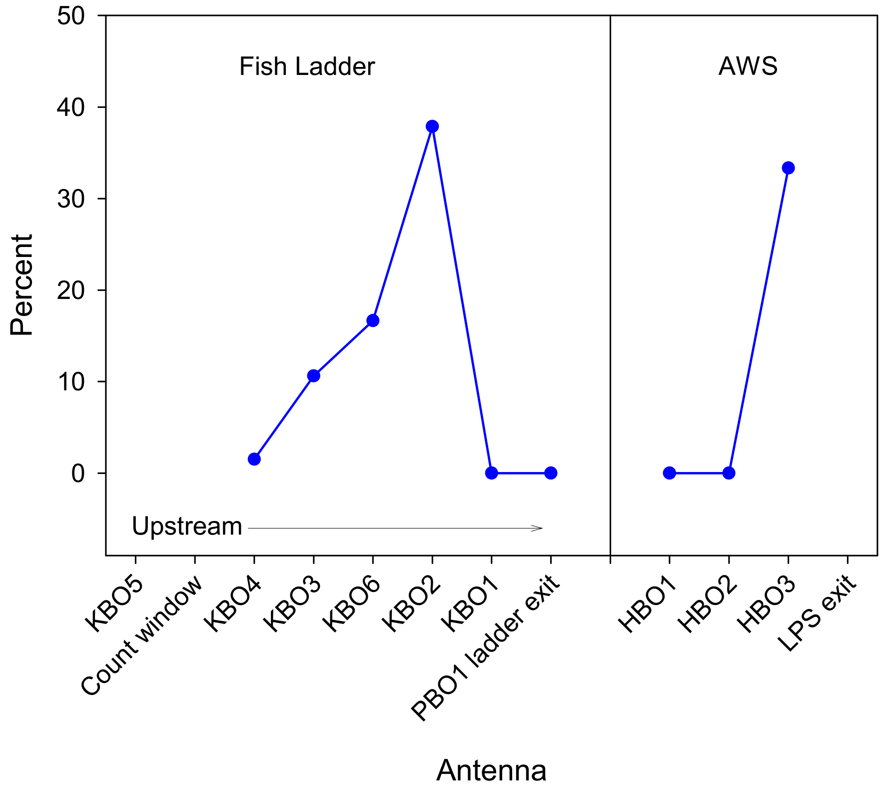

Figure 22. Distribution of furthest upstream detections, by antenna, for 69 radio-tagged lampreys that did not pass Bonneville Dam via the Washington-shore fishway or LPSs. AWS = auxiliary water supply channel.

Bradford Island fishway – In total, 157 unique radio-tagged lamprey were recorded at one or more antennas upstream from the Bradford Island junction pool. Of the 157 lamprey, 97 (62%) passed the dam and 60 (38%) did not pass the dam via the Bradford Island fishway or LPS. We found no differences in size or date among lamprey that did and did not pass the dam at Bradford Island fishway (ANOVA, all $P > 0.05$).

Of the 97 fish that passed the dam, 94% (n = 91) were recorded on the antenna below the count window (JBO1) and 91% (n = 88) were recorded on the antenna above the count window (JBO2; Figure 21). More than a third (n = 37, 38%) of the fish that passed were recorded on antennas in both the serpentine weir section of the ladder and the AWS channel. The majority (58%) passed the dam through the ladder and 42% passed through the AWS-LPS.

Of the 60 fish that did not pass the dam via the Bradford Island fishway, 98% were recorded on the antenna below (JBO1) and above (JBO2) the count window. The furthest upstream record (turn around point) for the majority (80%, n = 48) of fish that did not pass the dam was in the serpentine weirs. Of the 48 fish that ultimately turned around in the serpentine weir section, 39 (81%) were at the uppermost antennas (JBO5 = 56%; JBO4 = 25%; Figure 23). Eight fish (13%) were detected at the top-of-ladder exit antenna (ABO1) before turning around and moving downstream. The other 7% (n = 4) of the fish that did not pass had their most upstream records in the AWS channel; all 4 were detected at the most upstream antenna (EBO3) and none were detected in the AWS-LPS.

The last recorded locations for 60 fish that did not pass the dam via Bradford Island included 92% (n = 55) in the tailrace, 5% (n = 3) that eventually passed the dam via the WA-shore ladder, and 3% (n = 2) that were last detected inside the BI fishway. Of the 55 fish last recorded in the tailrace, 62% (n = 34) moved downstream via the B-branch and 38% (n = 21) via the A-branch. Eight of the 55 fish last recorded in the tailrace attempted to ascend the Bradford Island fishway multiple times.

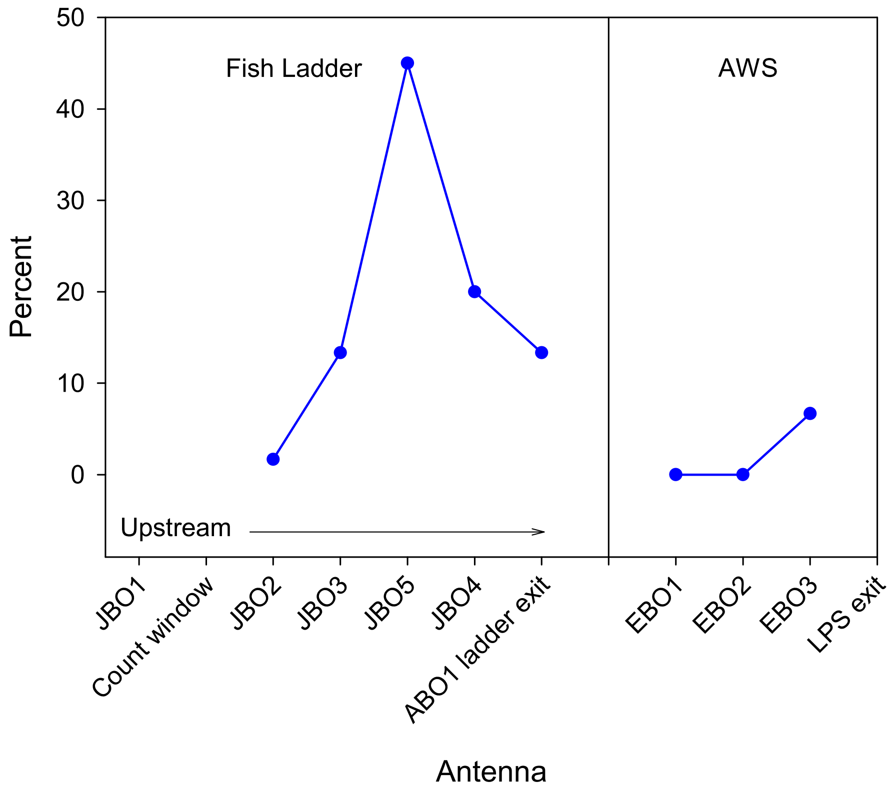

Figure 23. Distribution of furthest upstream detections, by antenna, for 60 radio-tagged lampreys that did not pass Bonneville Dam via the Bradford Island fishway or LPSs. AWS = auxiliary water supply channel.

Discussion

Although orifices for lamprey passage were installed in the first three serpentine weirs above the Washington-shore count window in the winter of 2016-2017, we still observed high turnaround rates for non-passers in the serpentine weir section of the ladder. Approximately 34% of the lamprey detected near the WA-shore count station or AWS channel did not pass the dam. This was the second highest turnaround percent compared to previous studies (2008-2010 and 2014) which ranged from 21% in 2010 to 37% in 2008 (Johnson et al. 2009; Clabough et al. 2010b, 2011, 2015). Lamprey that did not pass the dam at Bradford Island that were detected near the count station or AWS channel in 2018 was 38%. This was also the second highest non-passer rate compared to the previous passage studies: 16% (2008), 27% (2009), 26% (2010) and 43% (2014) (Johnson et al. 2009; Clabough et al. 2010b, 2011, 2015).

The majority 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 2018, 64% of non-passers turned around in the WA-shore serpentine weirs compared to 71% in 2014 (Clabough et al. 2015). At Bradford Island fish ladder, we observed 80% of non-passers turning around in the serpentine weirs compared to 92% in 2014 (Clabough et al. 2015). In 2018, at Bradford Island fish ladder we observed more non-passers turning around after reaching the antenna at the top-of-the-ladder in 2018 (13%, $n = 8$) compared to 2014 (4%, $n = 2$). In the WA-shore ladder, fewer fish were detected on the antenna above the count window (KBO4; Figure 21) in 2018 (77%) than in 2014 (92%) which may have been due to fish using the new lamprey orifices and not being detected in 2018.

5. General fishway and dam passage metrics

Methods

General fishway and dam passage metrics were only evaluated for radio-tagged lamprey which were released downstream from Bonneville Dam.

Fishway use

Lamprey use of fishway entrances at Bonneville, The Dalles, John Day, and McNary dams was evaluated by assessing where radio-tagged fish first approached, entered, and exited fishways. We also summarized the distributions of total fishway approaches, entries, and exits by fishway entrance 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 lampreys were detected on antennas inside fishway openings without being detected on antennas outside the same opening or when they entered via unmonitored routes like orifice gates.

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 a 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. Two exceptions included: 1) 'first transition pool to last transition pool' estimates, which were calculated only for lamprey that passed a dam (i.e., they may have made multiple trips through a transition pool(s)), and 2) 'last ladder top' records, which were assigned only when a lamprey passed a dam, independent of how many detections at a ladder top may have preceded the final passage event.

Passage efficiency

Dam-wide fishway entrance, fishway passage, and dam passage efficiencies

We calculated dam passage and fishway passage efficiency metrics for several segments and spatial scales following methods in Keefer et al. (2012). 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. Dam-wide entrance efficiency was an estimate of lamprey passage success at all fishway openings and was calculated by dividing the number of unique lampreys that entered any fishway by the unique number of lampreys that approached any fishway.

Dam-wide dam passage efficiency was calculated by dividing the number of unique lamprey that passed a dam by the total number of unique fish recorded approaching a fishway opening at the dam. A similar metric, dam-wide 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.

Site-specific fishway entrance efficiency

Site-specific entrance efficiency was an estimate of lamprey passage success at individual fishway openings. Two metrics were calculated for each opening: 1) the number of unique lampreys that entered at a site divided by the number of unique lampreys that approached the same site (i.e., individual-based metrics); and 2) the total number of fishway entry events at a site divided by the total number of fishway approach events at the same site (i.e., event-based metrics).

Route-specific fishway passage efficiency

Route-specific fishway passage efficiency was an estimate of lamprey passage success through individual fishways from fishway entry to a top-of-ladder-exit. Two metrics were calculated for each route: 1) the number of unique lampreys that passed the dam divided by the number of unique lampreys that entered at a site; and 2) the total number that passed the dam divided by the total number of fishway entries at a site.

Most upstream point recorded by lamprey that did not pass dams

At each dam, we reviewed the detection histories for each unique radio-tagged lamprey that entered a fishway but failed to pass the dam. 'Turnaround' locations were defined as the most upstream antenna where each fish was detected before moving back downstream into the tailrace. At Bonneville Dam, we additionally assigned specific turnaround locations inside fishways for each fishway entry event that did not result in dam passage. Turnaround events at some adjacent antennas were combined within fishway segments to simplify analyses and interpretation. In total, 20 fishway segments were identified at Bonneville Dam (see Figures 26 and 27), following the methods described in Keefer et al. (2013b).

Lamprey fallback at dams

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

Results

Bonneville fishway use

Fishway approaches – Of the 595 radio-tagged lampreys released downstream from Bonneville Dam, 532 (89%) approached a Bonneville Dam fishway. The highest percentage first approached at Powerhouse 2 (PH2) fishway openings (59%), followed by Powerhouse 1 (PH1, 21%), and the combined B-Branch and Cascades Island opening adjacent to the spillway (19%; Figure 24). Four first approach events were at unknown PH2 locations (< 1%). The highest percentage of all approach events was at PH2 (82%), followed by the spillway (11%), and PH1 (5%). On average, lamprey approached fishways 15.6 times per fish (*median* = 7; *range* = 1-263). Two lampreys had more than 200 approaches, but it was not clear whether they had died or simply remained stationary, with intermittent detections at antennas outside a fishway.

Fishway entries – A total of 457 lampreys were recorded inside Bonneville Dam fishways (77% of 595 released and 86% of 532 that approached a fishway). Many lampreys first entered at PH2 (23% at south entrances and 22% at north entrances) and the fewest first entered the PH1 north entrance (5%; Figure 24). Among the 62 first entry events where both time and location were unknown, 58 (94%) occurred at PH2. This was due in part to unmonitored routes along the face of the powerhouse. These 62 first unknown entry events represented ~14% of all 457 first entry events. The distribution of total fishway entries was generally similar to the distribution of first entries (Figure 24). Lampreys that entered a fishway did so 2.3 times per fish, on average (*median* = 2; *range* = 1-15).

Fishway exits – A total of 341 lampreys exited a Bonneville fishway to the tailrace, 75% of the 457 that entered. Most of the fishway exits (52% of first and 55% of total) were from PH2 openings, most frequently from the south-shore entrances (Figure 24). Approximately 23% of first and total exits were from each of the two fishways adjacent to the spillway and 12% of first exits and 8% of all exits were from PH1 openings. Lampreys 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* = 1-14).

Bonneville passage times

Fishway approach, fishway entry, and dam passage – Median passage times from lamprey release to first fishway approach, first fishway entry, and to pass the dam were 0.2 d (4.4 h), 1.1 d (25.6 h), and 6.2 d (148.7 h), respectively (Table 6). Mean times were substantially longer than medians 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 0.2 d (4.3 h), 0.5 d (12.9 h), and 6.9 d (164.9 h), respectively. Lamprey release sites were near the aerial tailrace antennas at Bonneville Dam in 2018.

Lampreys entered a fishway after their first recorded approach in a median of 0.9 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* = 1.2 h). Passage times were much longer and more variable from the transition pool exit to the top-of-ladder exit (*median* = 26.6 h).

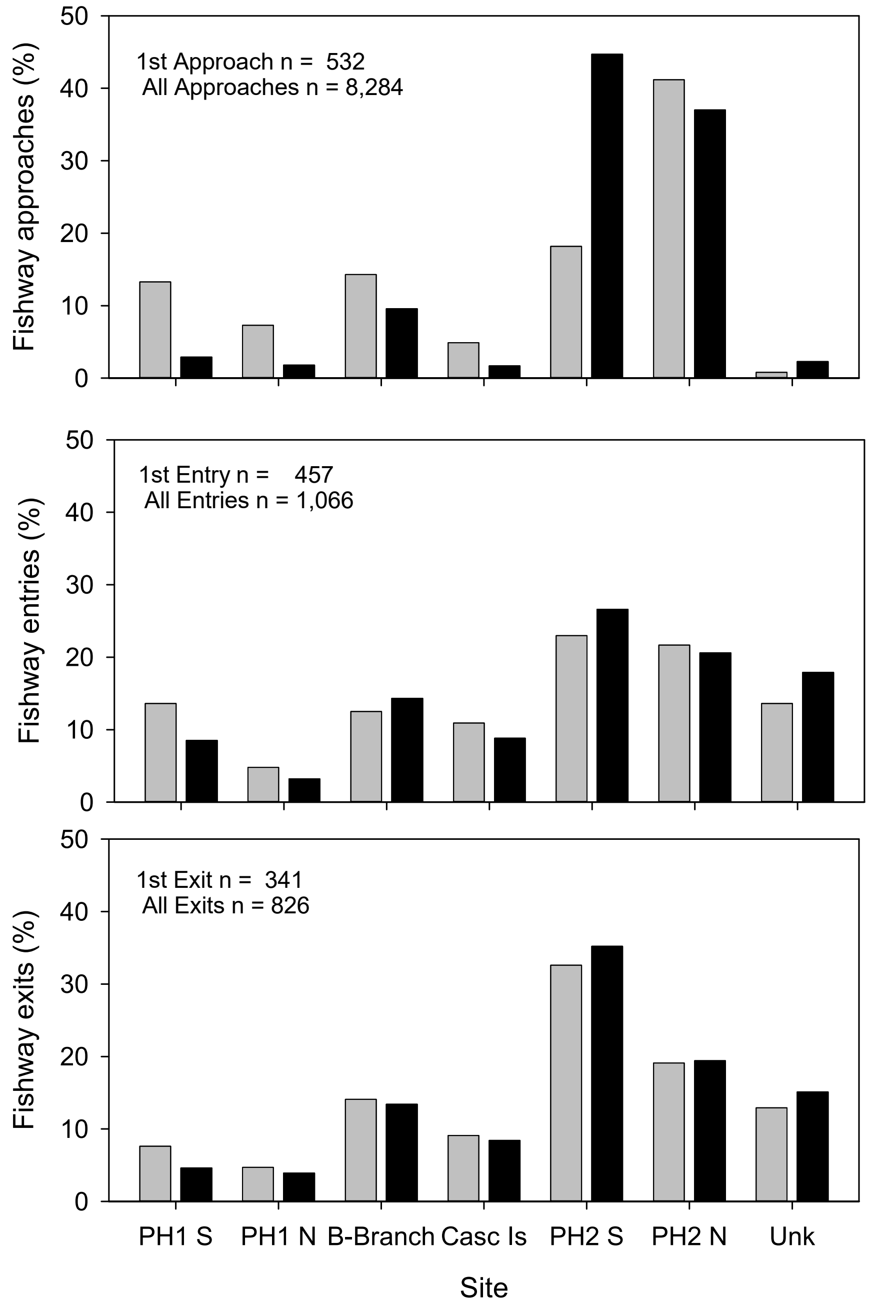

Figure 24. Distributions of first (gray bars) and total (black bars) fishway approaches, fishway entries, and fishway exits among sites by radio-tagged adult Pacific Lamprey at Bonneville Dam in 2018. The Unknown (Unk) category includes fish recorded inside a fishway without a clear fishway approach, entry, or exit record.

Table 6. Summary of radio-tagged adult lamprey passage times at Bonneville Dam in 2018. Q1 and Q3 are first and third quartiles, respectively. (Includes data from fish that were recaptured in the AFF in the passage segments where estimates could be calculated).

Passage segment			Passage time (h)			
Start	Finish	*n*	Median	Mean	Q1	Q3
Release	First approach	518	4.4	56.7	3.2	47.9
Release	First entrance	371	25.6	75.3	4.1	79.4
Release	Past dam	233	149.1	223.1	57.1	341.2
Tailrace	First approach	469	4.3	55.4	3.0	30.8
Tailrace	First entrance	343	12.9	71.3	3.7	79.4
Tailrace	Past dam	200	161.9	230.8	58.6	343.2
First approach	First entrance	371	0.9	34.9	0.2	24.2
First entrance	Transition pool entry	347	0.1	12.5	<0.01	0.5
First entrance	Past dam	174	70.3	125.3	26.1	159.9
Transition pool entry	Transition pool exit[a]	199	1.2	65.9	0.4	73.8
Transition pool exit	Past dam	207	26.6	54.3	21.8	71.2

[a] includes only fish that passed the dam.

Bonneville passage efficiency

Dam-wide passage efficiency – Of the 595 lampreys released downstream from Bonneville Dam, 532 (89%) were recorded approaching a Bonneville Dam fishway, 457 (77%) entered a fishway, and 237 (40%) passed the dam (Table 7). These three estimates were equal to or slightly higher than pre-2018 median values from eleven previous study years (88%, 73%, and 40%, respectively). Eighty-six percent of tagged lamprey that approached a fishway in 2018 subsequently entered a fishway. The 2018 estimate was slightly higher than the median 85% value estimated from previous study years. Dam-wide dam passage efficiency (passed dam / approached fishway) was 45% and dam-wide fishway passage efficiency (passed dam / entered fishway) was 52% in 2018; both values were equal to the corresponding median values from previous years.

Fifteen (3%) of the 595 fish were recaptured at the dam after being released downstream. Dam-wide dam passage efficiencies ranged from ~43-44% and dam-wide fishway passage efficiencies ranged from ~50-52%, depending on the inclusion or exclusion of recaptured fish (Table 8).

Route-specific fishway passage efficiency was highest for lampreys that first entered via spillway openings (*range* = 56-63%), whereas values for fish that first entered at PH1 and PH2 openings were in the mid-40% to low-50% range (Table 9). Note, however, that not all fish passed via the same route that they initially entered, and hence comparisons should be considered qualitative given different exit rates among entrance locations. Excluding the 15 recaptured lamprey produced quantitatively similar results.

Table 7. Dam-wide passage efficiency metrics for unique radio-tagged Pacific Lamprey at Bonneville Dam in 1997-2002, 2007-2010, 2014, and 2018. At Dam = recorded in tailrace or at a fishway; Approached = approached fishway opening; Entered = entered fishway; Passed = passed dam. Fish were collected and tagged at Bonneville Dam. Sources for pre-2018 data: Keefer et al. (2012) and Clabough et al. (2015).

	1997	**1998**	**1999**	**2000**	**2001**	**2002**	**2007**	**2008**	**2009**	**2010**	**2014**	**2018**
Released (*n*)	147	205	199	299	298	201	398	595	596	312	600	595
Approached (*n*)	129	182	183	260	277	193	271	443	470	276	473	532
Entered (*n*)	102	154	162	213	240	169	201	317	384	237	437	457
Passed (*n*)	49	73	82	123	129	92	83	[1]156	[2]198	[3]128	[4]240	[5]237
Approached:Released	0.88	0.89	0.92	0.87	0.93	0.96	0.68	0.74	0.79	0.88	0.79	0.89
Entered:Released	0.69	0.75	0.81	0.71	0.81	0.84	0.51	0.53	0.64	0.76	0.73	0.77
Passed:Released	0.33	0.36	0.41	0.41	0.43	0.46	0.21	0.26	0.33	0.41	0.40	0.40
Entered:Approached	0.79	0.85	0.89	0.82	0.87	0.88	0.74	0.72	0.82	0.86	0.92	0.86
Passed:Approached	0.38	0.40	0.45	0.47	0.47	0.48	0.31	0.35	0.42	0.46	0.51	0.45
Passed:Entered	0.48	0.47	0.51	0.58	0.54	0.54	0.41	0.49	0.52	0.54	0.55	0.52

[1] *n* = 146; [2] *n* = 177; [3]*n* = 126; [4]*n* = 220; [5]*n* = 222 when trap recaptures were treated as NOT PASSING the dam

Table 8. Number of radio-tagged lampreys released downstream from Bonneville Dam in 2018, with the number detected approaching, entering, and passing the dam and with dam and fishway passage efficiencies (Eff, %) calculated with the inclusion and exclusion of 15 recaptured lamprey (Rcps.).

	Frequencies				Percentages (%)	
	Released	Approached	Entered	Passed	Dam Eff.	Fishway Eff.
Includes Rcps.	595	532	457	237	44.5	51.8
Excludes Rcps.	-	517	442	222	42.9	50.0

Table 9. Route-specific fishway passage efficiencies (%) based on first entry sites, calculated as the ratio of unique radio-tagged lamprey that passed Bonneville Dam to unique fish that first entered each main fishway opening. Efficiency estimates either censor recaptured (Rcps) fish or treat recaptured fish as passing the dam. Note: fish could pass via any route and fish with both unknown entry sites and times were excluded.

	Number of unique lampreys			Fishway passage efficiency	
First Entry Site[1]	First entered	Recaptured	Passed dam[2]	With Rcps.	No Rcps.
Powerhouse 1 South	62	1	31	50.0	49.2
Powerhouse 1 North	22	0	10	45.5	45.5
Spillway South	57	0	36	63.2	63.2
Spillway North	50	1	28	56.0	55.1
Powerhouse 2 South	105	4	47	44.8	42.6
Powerhouse 2 North	99	7	52	52.5	48.9

[1] entries at known locations, but with unknown times, were included.
[2] recaptured fish treated as passing the dam.
Note: 2 recaptured fish with unknown first entry sites at Powerhouse 2 were excluded from this table.

Site-specific fishway entrance efficiency – At individual fishway openings, the percentage of unique fish that ever approached and entered the same site was highest at the Cascades Island (81%) and PH1 South (66%) openings. The percentage of total approach events that resulted in entry events was also highest at the Cascades Island opening (69%), followed by PH1 South (38%), PH1 North (23%), the Bradford Island opening (19%) and the PH2 openings (7%) (Figure 25).

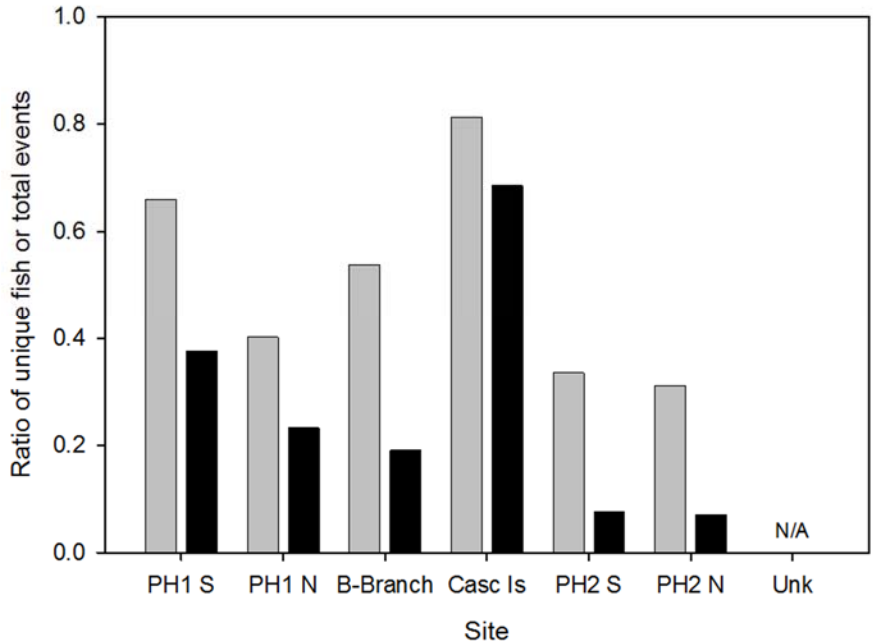

Figure 25. Ratio of unique, radio-tagged lampreys at Bonneville Dam in 2018 that entered fishway openings they approached at any time (gray bars) and the ratio of total approach events that resulted in a fishway entry (black bars).

Bonneville - most upstream point reached by lampreys that did not pass

A total of 359 lampreys did not pass Bonneville Dam, 60% of the 595 released and 62% of 580 released when the 15 recaptured fish were excluded. The most upstream site recorded for the 359 non-passing fish included 8 (2%) fish at the release site, 53 (15%) in the tailrace, 76 (21%) outside a fishway opening, and 222 (62%) inside a fishway (Table 10).

The 76 lamprey that were recorded approaching but not entering a fishway were recorded outside all of the primary fishway openings. These included PH1 south (9% of 76), PH1 North (4%), B-Branch (42%), Cascades Island (4%), PH2 south (26%), and PH2 north (14%).

The most upstream locations for the 222 lamprey that entered a fishway, but did not pass the dam, were distributed throughout the fishways, with almost two-thirds inside the WA-shore fishway (Table 10). Over half (120/222 = 54%) of the fish had their most upstream detection in the upper reaches of the Washington-shore or Bradford Island fishways, specifically in the serpentine weir sections, near the Bradford Island ladder top, or in the auxiliary water supply (AWS) channels. Approximately 19% of the 120 fish with their most upstream detections in the upper reaches of the fishways had detections in both a serpentine weir section and an AWS channel before moving downstream. Combining similarly-configured sites, 27% (61 of 222) lamprey had their most upstream detection in one of the four transition pools at the dam.

Table 10. The most upstream detection locations recorded for 359 radio-tagged lamprey that did not pass Bonneville Dam in 2018, including locations for the 222 lamprey that entered a fishway but did not pass the dam (Note: 15 fish that were recaptured and released upstream were excluded).

	n	Percent of 359	Percent of 222
Did not pass dam	**359**		
Release sites	8	2.2	
Tailrace only	53	14.8	
Approach fishway	76	21.2	
Entered fishway	222	61.8	
Did not pass dam, but entered fishway	**222**		
Bradford Island fishway			
PH1 collection channel	3	0.8	1.4
A-Branch transition pool	3	0.8	1.4
B-Branch transition pool	8	2.2	3.6
Ladder between transition pool & window	7	1.9	3.2
Serpentine weirs	43	12.0	19.4
Serpentine weirs / auxiliary water supply channel	6	1.7	2.7
Top of ladder exit area	9	2.5	4.1
Washington-shore fishway			
PH2 collection channel	23	6.4	10.4
Cascades Island transition pool	10	2.8	4.5
Cascades Island / UMT	1	0.3	0.5
PH2 transition pool	40	11.1	18.0
Ladder between transition pool & window	7	1.9	3.2
Serpentine weirs	42	11.7	18.9
Serpentine weirs / auxiliary water supply channel[1]	17	4.7	7.7
Auxiliary water supply channel	3	0.8	1.4

[1] some direct movements between the Washington-shore serpentine weirs and the auxiliary water supply channel was possible in 2018.

Bonneville - turnaround locations for each fishway entry event not resulting in dam passage

There were 183 entry events at the Bradford Island fishway that did not result in dam passage. Approximately 40% (78/183) of the turnarounds were in the serpentine weirs or in the AWS channel (section 6 in Figure 26) and 36% (65/183) were in one of the two transition pools (sections 4 & 7 in Figure 26; Table 11). There were 642 unsuccessful entry events at the Washington-shore fishway. About 54% (347/642) were near the PH2 South fishway openings or the unmonitored sluice gates (sections 12, 13, or 14) of the PH2 collection channel. Another 32% (203/642) of Washington-shore fishway turnaround events occurred in one of the two transition pools (sections 9, 16, 17, & 18 in Figure 27; Table 11). Twelve percent (74/642) were in the vertical slot weirs or AWS.

Table 11. Numbers of fishway entry events recorded for radio-tagged adult Pacific Lampreys and estimated turnaround locations inside fishways for events that did not result in Bonneville Dam passage in 2018. Turnaround locations were inferred from underwater antenna sites inside fishways. PH1, Powerhouse 1; S, south; N, north; UNK, unknown; SP, spillway; PH2, Powerhouse 2; D, downstream; U, upstream. Numbered turnaround locations correspond to the sites labeled in Figures 26 and 27.

	Entry	Turnaround location in Bradford Island fishway							
	n	1	2	3	4	5[a]	6	7	8
PH1-S	63	19	2	3	15		24		
PH1-N	19			1	5		13		
PH1-UNK	1	1							
SP-S	100						41	45	14
Total	**183**	**20**	**2**	**4**	**20**		**78**	**45**	**14**

		Turnaround location in Washington-shore fishway											
		9	10	11	12	13[b]	14[b]	15	16	17	18	19	20
SP-N	53	24	7	2									20
PH2-S-D	114				15	90			1	3	1		4
PH2-S-U	160					158					1		1
PH2-N-D	80							9	41	14	3		13
PH2-N-U	89								1	57	12	2	17
PH2-UNK	146				2	80			3	29	13		19
Total	**642**	**24**	**7**	**2**	**17**	**328**	**-**	**9**	**46**	**103**	**30**	**2**	**74**

[a] Powerhouse 1 sluice gates were closed in 2018.
[b] some segment 13 events likely occurred in unmonitored segment 14 in 2018

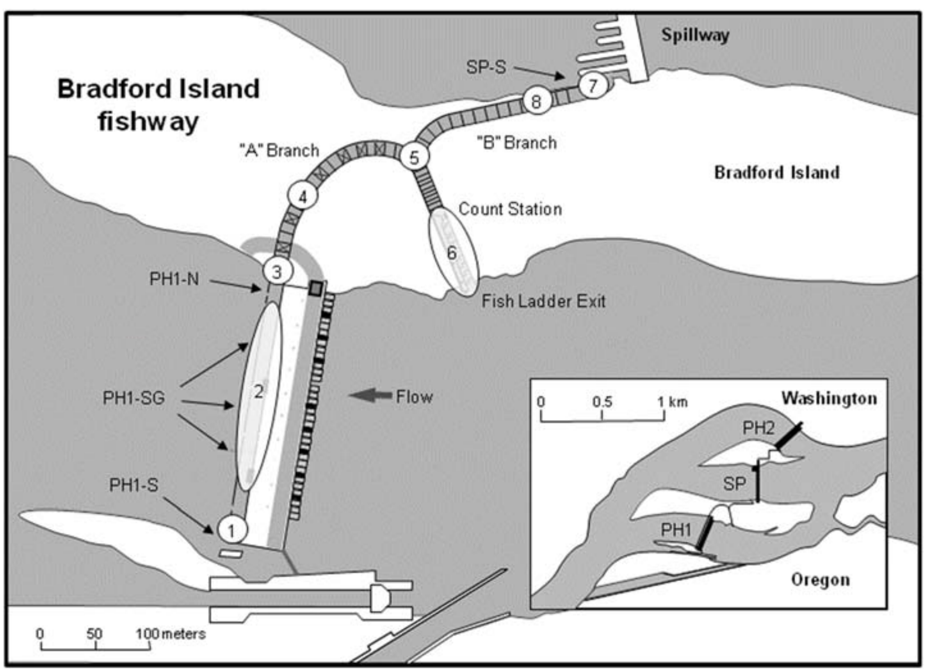

Figure 26. Map of Powerhouse 1 and the Bradford Island fishway at Bonneville Dam. Circles and ellipses show locations inside the fishway where radio-tagged lamprey turnaround events were assigned. Inset shows the configuration of Bonneville Dam, including the two powerhouses and the spillway. PH1 = Powerhouse 1; PH2 = Powerhouse 2; SP = spillway; SG = sluice gate. Note: Powerhouse 1 sluice gates were closed in 2018.

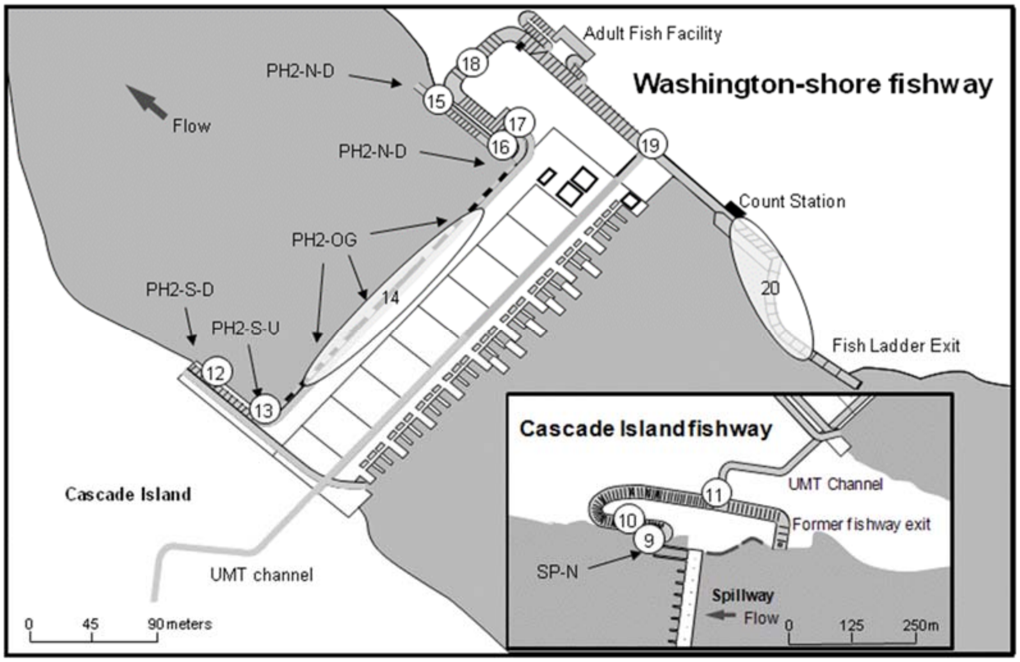

Figure 27. Map of Powerhouse 2 and the Washington-shore fishway at Bonneville Dam. Circles and ellipses show locations inside the fishway where Pacific Lamprey turnaround events were assigned. Inset shows the Cascade Island fishway, which has one entrance (SP-N) and joins the Washington-shore fishway at the terminus of the UMT channel. PH2 = Powerhouse 2; SP = spillway; OG = orifice gate. Note: Powerhouse 2 orifice gates were open and unmonitored in 2018.

Bonneville - lamprey in Cascades Island AWS

Five radio-tagged lampreys were recorded in the Cascades Island (CI) AWS channel in 2018. All five fish initially moved into the CI AWS via the upstream migrant tunnel (UMT) channel from the WA-shore fishway (i.e., they moved down the UMT). Based on radiotelemetry detections, only 1 of the 5 fish eventually passed the dam; it used the WA-shore AWS-LPS. Three fish exited the CI fishway to the tailrace (1 via the CI fishway and 2 via the WA-shore fishway). The fifth fish was last recorded in the WA-shore fishway transition area.

Bonneville fallbacks

We recorded four unique radio-tagged lampreys (~2% of the total that passed the dam) falling back past the dam. All four fish fell back after passing the Bradford Island fishway. One of the four fish passed via the BI LPS and swam down the BI fishway approximately two days after exiting the LPS. Two of the four fallback fish reascended a fishway and were last detected upstream and two were last recorded in the Bonneville tailrace.

The Dalles fishway use

Fishway approach, entry, and dam passage – Of the 152 radio-tagged lampreys detected approaching a fishway in 2018, 142 entered, and 68 subsequently exited back into the tailrace one or more times. The highest percentage of tagged fish made their first approach at the north fishway (36%), followed by the east (30%), west powerhouse (25%), and south spillway (7%) openings (Figure 28). Forty-one percent of all first entries occurred at the north-shore opening, followed by the east (36%), west powerhouse (13%), and south spillway openings (7%). There were proportionately more total approaches at the east and west openings than first fishway approaches whereas the distributions of first and total fishway entries were generally similar. Lampreys approached fishways a median of 2 times (*mean* = 3.1 times) per fish and entered fishways a median of 1 time (*mean* = 1.6 times) per fish. The 68 tagged lampreys that exited to the tailrace did so a median of 1 time (*mean* = 1.8 times). The highest percentage of fishway exits was at the east (32%), followed by the north (29%), south spillway (22%), and west powerhouse (11%) fishway openings.

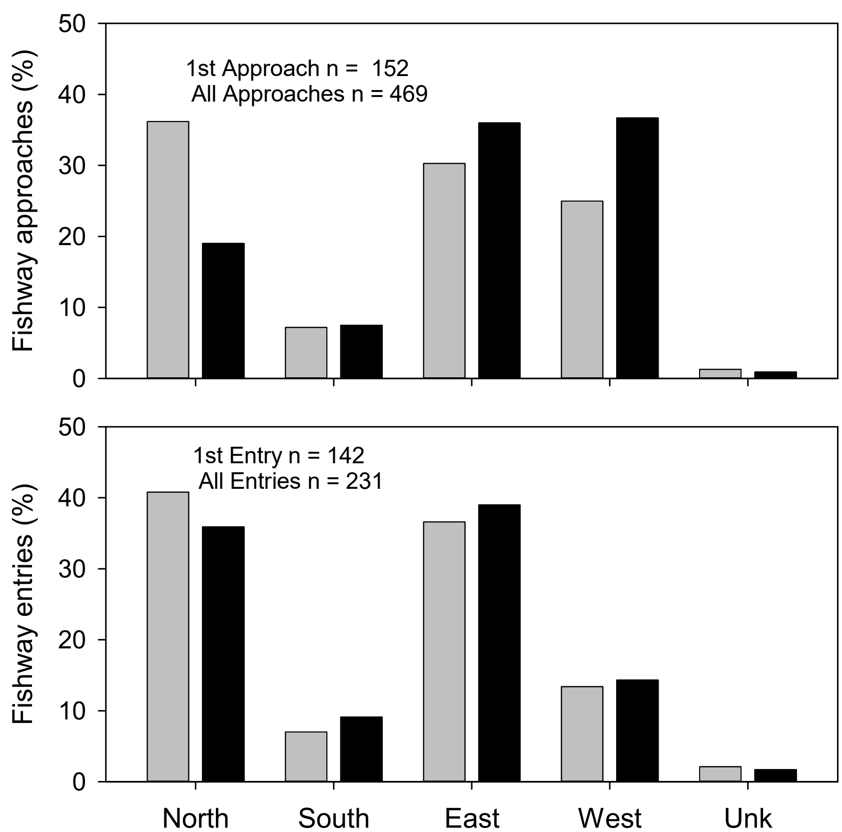

Figure 28. Distributions of first (gray bars) and total (black bars) fishway approach, and fishway entry sites by radio-tagged adult Pacific Lampreys at The Dalles Dam in 2018. The Unknown (Unk) category includes fish recorded in a fishway without a clear fishway approach or entry record.

The Dalles passage times

Fishway approach, entry, and dam passage – A total of 164 unique lampreys was detected at The Dalles Dam and/or tailrace in 2018 and 68 (41%) of these fish were recorded at the tailrace sites on their first apparent approach to the fishways. Twelve (18%) of the 68 lamprey recorded in the tailrace were not recorded approaching the dam. Median passage times from the first tailrace record to first fishway approach, first fishway entry, and to pass the dam were 12.7, 17.9, and 81.3 h, respectively (Table 12). On median, most lampreys entered a fishway quickly after their first recorded approach (0.2 h), from their first fishway entry into a transition pool (0.1 h), and for fish that passed the dam, through transition pools (0.9 h). The median time lamprey used to swim from their first fishway entrance to exit from a ladder top was slightly over a day (27.5 h, *mean* = 85.1 h). Fish used a median of 20.2 h (*mean* = 24.3 h) to swim from their final transition pool exit to a ladder top.

Table 12. Summary of passage times for radio-tagged adult Pacific Lamprey at The Dalles Dam in 2018. Q1 and Q3 are first and third quartiles, respectively.

Passage segment			Passage time (h)			
Start	Finish	*n*	Median	Mean	Q1	Q3
Tailrace	First approach	46	12.2	27.8	4.3	24.1
Tailrace	First entrance	40	17.4	33.7	6.9	40.6
Tailrace	Past dam	40	80.3	155.9	47.6	139.9
First approach	First entrance	98	0.2	14.5	0.1	2.9
First approach	Past dam	85	50.6	110.3	24.1	139.8
First entrance	Transition pool entry	96	0.1	7.5	0.1	0.4
First entrance	Past dam	80	27.5	85.1	20.4	74.0
Transition pool entry	Transition pool exit[a]	101	0.9	39.9	0.4	47.6
Transition pool exit	Past dam	102	20.2	24.3	6.8	24.6

[a] includes only fish that passed the dam

The Dalles passage efficiency

Of the 164 tagged lampreys detected at The Dalles Dam or tailrace in 2018, 93% approached a fishway, 87% entered a fishway, and 66% passed the dam (Table 13). The 2018 percentage of lampreys that approached was slightly lower than the median value from ten previous study years (93% vs. 94%). The percentages of lampreys that entered (87%) and passed (66%) The Dalles Dam in 2018 were slightly higher than median values from previous study years (81% and 63%, respectively). Of the lampreys that approached a fishway in 2018, 93% subsequently entered a fishway, which was higher than the median from previous study years (87%). Dam-wide dam passage efficiency was 72% and dam-wide fishway passage efficiency was 77% in 2018; both estimates were slightly higher than corresponding median values from previous years (67% and 74%, respectively).

The 109 tagged fish counted as passing the dam included one radio-tagged lamprey recaptured in the east fishway by CRITFC personnel on 9 August 2018. It was released into the forebay. Of the 108 non-recaptured lamprey that passed the dam, 48 (44%) passed via the north fishway and 60 (56%) passed via the east fishway.

Table 13. Dam-wide passage efficiency metrics for unique radio-tagged Pacific Lamprey at The Dalles Dam in 1997-2002, 2007-2010, 2014, and 2018. At Dam = recorded in tailrace or at a fishway; Approached = approached fishway opening; Entered = entered fishway; Passed = passed dam. Fish were tagged at Bonneville Dam. Sources for pre-2018 data: Keefer et al. (2012) and Clabough et al. (2015).

	1997	**1998**	**1999**	**2000**	**2001**	**2002**	**2007**	**2008**	**2009**	**2010**	**2014**	**2018**
At Dam (*n*)	66	43	49	91	94	73	38	95	112	104	163	164
Approached (*n*)	64	38	-	84	92	70	31	90	103	93	157	152
Entered (*n*)	48	33	-	82	77	61	29	77	95	84	111	142
Passed (*n*)	35	24	24	67	68	46	21	63	68	70	75	109
Approached:At Dam	0.97	0.88	-	0.93	0.98	0.96	0.82	0.95	0.92	0.89	0.96	0.93
Entered:At Dam	0.73	0.77	-	0.90	0.82	0.84	0.76	0.81	0.85	0.81	0.68	0.87
Passed:At Dam	0.53	0.56	0.49	0.74	0.72	0.63	0.55	0.66	0.61	0.67	0.66	0.66
Entered:Approached	0.75	0.87	-	0.96	0.84	0.87	0.94	0.86	0.92	0.90	0.71	0.93
Passed:Approached	0.55	0.63	-	0.79	0.74	0.66	0.68	0.70	0.66	0.75	0.48	0.72
Passed:Entered	0.73	0.73	-	0.82	0.88	0.75	0.72	0.82	0.72	0.83	0.68	0.77

At individual fishway openings, 98% of radio-tagged lampreys that first approached the north-shore fishway (*n* = 55) also made their first entry there. The percentages of unique lamprey first entering a fishway to unique fish first approaching it were 76% for the east opening (*n* = 46), 54% for the south spillway (*n* = 11), and 40% for the west powerhouse (*n* = 37) openings. The site-specific entrance efficiency estimate for the north fishway for the 70 unique lampreys that approached there at least once was 99% (i.e., 69 fish entered at least once). The site-specific estimate was also high for the east fishway (82% of 80 unique fish), while the south spillway and west powerhouse estimates were 65% (*n* = 23) and 45% (*n* = 66), respectively. The proportion of total approach events that resulted in entry events was also highest at the North opening (93%, *n* = 89), followed by the South spillway (60%, *n* = 35), East (53% *n* = 169), and West powerhouse opening (19%, *n* = 172).

The Dalles - most upstream point reached by fish that did not pass

Over half (52%, *n* = 231) of all fishway entry events did not result in dam passage (Table 14). Identifying turnaround locations was more difficult at The Dalles Dam (relative to at Bonneville Dam) because there were fewer fishway monitoring sites. Among failed dam passage attempts in the north-shore fishway, 91% of the 35 turnarounds were apparently in the transition pool and the remainder were inferred to be upstream from the transition area in the ladder, but downstream from the ladder top. Similarly, 90% of the 52 east opening entry events that did not result in dam passage had turnarounds in the east fishway transition pool and 10% of turnarounds occurred upstream in the ladder. Among 15 failed entry events that originated at the south spillway opening, two-thirds had turnarounds within the south fishway collection channel.

The 19 failed entry events at the west powerhouse opening had turnarounds in the west fishway collection channel (47%) and the east transition pool (53%).

Table 14. Numbers of fishway entry events recorded for radio-tagged adult Pacific Lampreys that did not result in dam passage, and estimated turnaround locations inside fishways in 2018. Turnaround locations were inferred from underwater antenna sites inside fishways.

		Turnaround locations			
Entry site	Entry n	N. Tran. pool	N. ladder		
North	35	32	3		
		S. Coll. Ch.	W. Coll. Ch.	E. Tran. pool	E. ladder
East	52			47	5
South	15	10		2	3
West	19		9	10	
Total	121	42	12	59	8

The Dalles fallbacks

Five unique radio-tagged lampreys that passed the The Dalles Dam in 2018 fell back. Four did not reascend a fishway and were last detected in The Dalles tailrace. One tagged lamprey fell back and reascended a fishway three times. It was recaptured at Sherar's Falls in the Deschutes River on 27 July 2018.

John Day fishway use

Fishway approach, entry, and dam passage – At John Day Dam, 67 lampreys approached fishway entrances in 2018, 61 (91%) entered a fishway and 43 subsequently exited to the tailrace one or more times. The highest percentage of the tagged fish was first recorded approaching the south-shore entrance (n = 27, 40% of 67), followed by the north-shore entrance (n = 23, 34%), and the north powerhouse entrance (n = 7, 10%). Fifteen percent (n = 10) of first approaches were by fish with unknown approach locations near the south fishway (likely at the unmonitored collection channel orifices). First entries were highest at the north-shore entrance (n = 20, 33% of 61) followed by the south-shore entrance (n = 16, 26%), and the north powerhouse entrance (n = 5, 8%); 33% had unknown entrance locations at the south fishway (n =20).

Distributions of total fishway approaches and entries were generally consistent with first approach and entry locations, with the highest percentage of total approaches (67%) occurring at the south-shore entrance while and total entries (25%) occurring at both the north- and south-shore entrances. Lampreys approached fishways a median of 1 time (*mean* = 1.6 times) per fish. Lampreys entered fishways a median of 1 time (*mean* = 1.8 times) per fish. The subset that exited back to the tailrace did so a median of 2.0 times (*mean* = 2.1 times). The north-shore entrance was exited most frequently (n = 10 times), followed by the south-shore entrance (n = 5 times).

John Day passage times

Fishway approach, entry, and dam passage – A total of 72 lampreys were detected at John Day Dam. Detection efficiency at the tailrace antennas was low, with only 28% (20 of 72) of the tagged fish recorded at the tailrace sites; 3 of the 20 (15%) recorded in the tailrace were not detected at the dam (Table 15). Median passage times from the first tailrace record to first fishway approach, first fishway entry, and to pass the dam were 5.8, 7.6, and 47.9 h, respectively (Table 15). Most lampreys moved quickly into a fishway after their first recorded approach (*median* = 0.3 h, *n* = 28), from first fishway entry into a transition pool (*median* = 0.1 h, *n* = 39), and through transition pools (*median* = 0.2 h, *n* = 24). In contrast, passage time variability was much higher for the segment from first fishway entry to exit from the ladder top (*median* = 24.1 h, *n* = 28). This was partially due to the time spent exiting and re-entering the fishways and transition pools. Lampreys took a median of 20.8 h (*n* = 24) to pass from transition pool exit to exit from the top of a ladder.

Table 15. Summary of passage times for radio-tagged adult Pacific Lampreys at John Day Dam in 2018. Q1 and Q3 are first and third quartiles, respectively.

Passage segment			Passage time (h)			
Start	Finish	*n*	Median	Mean	Q1	Q3
Tailrace	First approach	20	5.8	15.2	2.3	19.4
Tailrace	First entrance	15	7.6	19.6	3.7	18.4
Tailrace	Past dam	14	47.9	75.9	21.5	57.3
First approach	First entrance	28	0.3	10.7	0.1	0.4
First approach	Past dam	35	28.7	111.6	19.2	63.7
First entrance	Transition pool entry	39	0.1	2.8	0.1	0.4
First entrance	Past dam	28	24.1	96.2	14.1	47.0
Transition pool entry	Transition pool exit	24	0.2	25.2	0.1	1.4
Transition pool exit	Past dam	24	20.8	22.0	7.6	25.8

John Day passage efficiency

A total of 68 lampreys were recorded approaching fishways at John Day Dam and 47 passed the dam (including 4 that were recaptured in traps near the count stations) for a dam-wide dam passage efficiency estimate of 69% (Tables 16-17). Sixty-two fish entered a fishway for a dam-wide fishway passage efficiency of 76% (47/62). Of the 62 fish that entered, fishway passage efficiency was highest for fish that first entered the north entrance (80%, *n* = 20/25), followed by those that entered the south entrance (69%, *n* = 9/16), and the north powerhouse entrance (40%, *n* = 2/5). Fish with unknown entry times and sites (*n* = 20) were excluded from site-specific estimates. The dam-wide dam passage efficiency (69%) and fishway passage efficiency (76%) in 2018 at John Day Dam were considerably higher than corresponding median estimates from previous years (52% and 54%, respectively) (Table 17). Site-specific fishway entrance efficiency at individual openings was highest at the north entrance (78%, 25 entered of 32 unique fish that approached) followed by 60% (9/15) at the north powerhouse entrance and 50% (17/34) at the south-shore entrance (Table 18).

Table 16. Numbers of radio-tagged lamprey detected at John Day Dam in 2018, with the number detected approaching and entering fishways, and passing the dam, with dam and fishway passage efficiency estimates (Eff, %) calculated with the inclusion and exclusion of 4 recaptured lamprey (Rcps).

	Numbers				Percentages	
	At Dam	Approached	Entered	Passed	Dam Eff.	Fishway Eff.
Includes Rcps	72	68	62	47	69.1	75.8
Excludes Rcps		65	58	43	66.1	74.1

Table 17. Dam-wide passage efficiency metrics for unique radio-tagged Pacific Lamprey at John Day Dam in 1997-2002 and 2007-2010, 2014, and 2018. At Dam = recorded in tailrace or at a fishway; Approached = approached fishway opening; Entered = entered fishway; Passed = passed dam. Fish were tagged at Bonneville Dam.

	1997	**1998**	**1999**	**2000**	**2001**	**2002**	**2007**	**2008**	**2009**	**2010**	**2014**	**2018**
At Dam (*n*)	1	10	13	74	51	34	11	42	44	39	51	72
Approached (*n*)	1	10	-	70	47	34	-	-	42	-	48	68
Entered (*n*)	1	7	-	60	46	34	-	-	39	-	46	62
Passed (*n*)	0	3	3	28	25	17	9	27	22	34	40	47[1]
Approached:At Dam	1.00	1.00	-	0.95	0.92	0.92	-	-	0.95	-	0.94	0.94
Entered:At Dam	1.00	0.70	-	0.81	0.90	0.90	-	-	0.89	-	0.90	0.86
Passed:At Dam	0.00	0.30	0.23	0.38	0.49	0.49	0.82	0.64	0.50	0.87	0.78	0.65
Entered:Approached	1.00	0.70	-	0.86	0.98	0.98	-	-	0.93	-	0.96	0.91
Passed:Approached	0.00	0.30	-	0.40	0.53	0.53	-	-	0.52	-	0.83	0.69
Passed:Entered	0.00	0.43	-	0.47	0.54	0.54	-	-	0.56	-	0.87	0.76

[1] *n* = 43; when trap recaptures were treated as NOT PASSING the dam

John Day - most upstream point reached by fish that did not pass

Of the 72 radio-tagged fish recorded at John Day Dam, 25 (35%) did not pass the dam. Their most upstream locations included: 7 (28%) outside the south shore entrance, 5 (20%) at the base of the north ladder entrance, 3 (12%) in the tailrace site (north side), 2 (8%) inside the north powerhouse entrance, 2 (8%) in the south shore collection channel entrance, 2 (8%) in the south shore entrance, and 1 (5%) each inside the south shore entrance, outside the north powerhouse entrance, outside the north ladder entrance and the tailrace site (south).

John Day fallbacks

Fallback rates for radio-tagged lampreys were much higher at John Day Dam than at Bonneville (~2%) or The Dalles (5%) dams. Of the 47 unique, radio-tagged lampreys that passed John Day Dam, 6 (13%) had records that suggested they fell back at the dam at least once. No fish fell back more than one time. Of those that fell back, 4 (67%) did so after passing the dam via the north fishway and 2 (33%) after passing via the south fishway. Three of the six fallback fish reascended via the south fishway and one reascended via the north fishway; two fish were last detected downstream from the dam.

Table 18. Site-specific fishway entrance efficiency metrics for radio-tagged Pacific Lampreys at John Day Dam fishway openings in 1997-1998, 2000-2002, 2014, and 2018. Total approaches = total number of fishway approach events; Total entries = total number of fishway entry events; Unique approaches = number of unique fish that approached opening; Unique entries = number of unique fish that entered opening. Fish were tagged at Bonneville Dam.

	1997	1998	1999	2000	2001	2002	2007	2008	2009	2010	2014	2018
South												
Total approaches (*n*)	7	17	-	107	163	80	-	-	-	-	13	112
Total entries (*n*)	5	10	-	27	92	29	-	-	-	-	5	27
Total efficiency	0.71	0.59	-	0.25	0.56	0.36	-	-	-	-	0.38	0.24
Unique approaches (*n*)	1	9	-	51	42	28	-	-	-	-	11	34
Unique entries (*n*)	1	5	-	23	38	17	-	-	-	-	5	17
Unique efficiency	1.00	0.56	-	0.45	0.90	0.61	-	-	-	-	0.45	0.50
South powerhouse												
Total approaches (*n*)	10	8	-	58	78	34	-	-	-	-	9	19
Total entries (*n*)	4	0	-	14	23	11	-	-	-	-	7	9
Total efficiency	0.40	0.00	-	0.24	0.29	0.32	-	-	-	-	0.78	0.56
Unique approaches (*n*)	1	4	-	29	26	14	-	-	-	-	7	15
Unique entries (*n*)	1	0	-	10	16	7	-	-	-	-	5	9
Unique efficiency	1.00	0.00	-	0.34	0.62	0.50	-	-	-	-	0.71	0.60
North												
Total approaches (*n*)	6	6	-	38	35	57	-	-	-	-	30	39
Total entries (*n*)	4	3	-	20	29	34	-	-	-	-	25	29
Total efficiency	0.67	0.50	-	0.53	0.83	0.60	-	-	-	-	0.83	0.74
Unique approaches (*n*)	1	4	-	27	11	18	-	-	-	-	26	32
Unique entries (*n*)	1	3	-	18	8	17	-	-	-	-	24	25
Unique efficiency	1.00	0.75	-	0.67	0.73	0.94	-	-	-	-	0.92	0.78
South unknown												
Total approaches (*n*)	1	-	-	30	49	21	-	-	-	-	21	43
Total entries (*n*)	0	-	-	29	49	20	-	-	-	-	21	43
Total efficiency	0.00	-	-	0.97	1.00	0.95	-	-	-	-	1.00	1.00
Unique approaches (*n*)	1	-	-	27	28	14	-	-	-	-	20	26
Unique entries (*n*)	0	-	-	26	28	13	-	-	-	-	20	26
Unique efficiency	0.00	-	-	0.96	1.00	0.93	-	-	-	-	1.00	1.00

John Day north (JDN) entrance

Radio-tagged lamprey – In 2018, lamprey entrance efficiency at the JDN entrance was 78% (Table 18). Of the 29 entry events (by 25 fish), 8 exit events were recorded to the tailrace for an exit ratio of (8/29 = 28%). The median time from fishway approach to entry was 2 min and ranged from < 1 to 65 min. After radio-tagged lampreys entered the north fishway, the median time to reach the base of the ladder was 3.3 min (*range* = 1-111 min). Only one (5%) adult lamprey at the John Day north entrance had an approach-to-entry time of > 1 h whereas no lamprey that entered had >1 h passage times from entrance to the first ladder antenna. Of the 25 unique fish that entered the JDN entrance, 20 (including three recaptures) successfully passed the dam for a fishway passage efficiency estimate of 80%. Of the five fish that did not pass via JDN three turned around (apparently between weirs 13 and 14) above the transition pool, one fish turned around in the lower transition pool while the other exited JDN and passed via the south-shore fishway. Of the six fish that fell back at John Day Dam, three (50%) fell back at the top of the north ladder. One fish reascended the south ladder while the other two did not reascend.

PIT tag detection histories – A total of 66 lampreys was detected on one or more of the PIT antennas near the JDN fishway entrance (two antennas outside the variable-width weir and two inside the entrance upstream from the variable-width weir, Figure 29). The 66 lampreys included 14 double-tagged fish (21%), 32 PIT-tagged fish released below Bonneville Dam (48%), and 20 PIT-tagged fish released upstream from Bonneville near Stevenson (30%).

Of the 66 PIT lampreys detected, 58 (88%) were recorded on the outside antenna array (Note: six of these fish were recorded on their second dam passage). The majority of outside antenna detections occurred on the south side (86%) and 9% of unique approaches were recorded on both outside antennas. Only 41% (n = 27) of lampreys that entered were detected on the inside PIT antenna array, suggesting fish were free swimming in the water column or were near fishway walls but not near the floor. In total, 12 of the 27 fish (44%) were detected on both inside antennas, 10 (37%) were on the south inside antenna, and 5 (19%) were on the north inside antenna.

Of the 66 lampreys detected at the PIT antennas, 38 (58%) eventually passed the dam via the JDN ladder, 9 (14%) passed via the south-shore fishway, 5 (8%) were recaptured in the LPS trap box, 2 (3%) passed the dam via an unknown route, and 12 (18%) did not pass the dam. Twelve of the fish detected at the PIT antennas were recorded falling back past John Day Dam one or more times. Eight fish fell back after passing the north ladder, three after passing the south ladder, and one fish fell back after recapture (north LPS) and subsequent release into the John Day forebay. All but one fallback fish reascended a fishway at the dam.

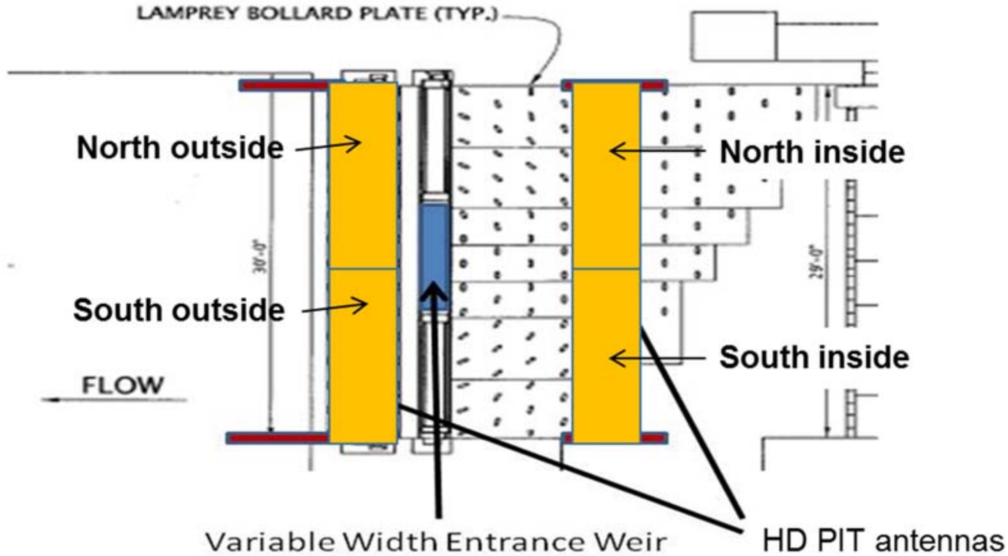

Figure 29. Overhead diagram of HD-PIT antenna array (orange rectangles) near the John Day north fishway entrance in 2018.

McNary summary

A total of 23 radio-tagged lampreys were recorded at McNary Dam in 2018. Of these, 13 (57%) first approached the south-shore fishway, 5 (22%) first approached the north fishway, 3 (13%) first approached the north powerhouse opening, and 2 (9%) first approached at unknown north powerhouse sites. All of the fish that approached also entered a fishway with 13 (57%) entering the south-shore opening, six (26%) entering the north fishway and two (9%) entering the north powerhouse site. Two fish (9%) entered at unknown south-shore sites. At McNary Dam site-specific fishway entrance efficiencies (number of unique lamprey that entered/ the number of unique lamprey that approached the same site) ranged from 100% at the north and south-shore entrances to 67% at the north powerhouse entrance.

Overall, 20 of the 23 lampreys passed McNary Dam for a dam-wide dam passage efficiency of 87% (Table 19). The dam-wide dam passage efficiency (87%) for McNary Dam in 2018 was higher than the median estimates from previous years (81%) while dam-wide fishway passage efficiency (87%) was similar to the corresponding median estimates from previous years (89%; Table 19). Of the fish that passed in 2018, 12 (60%) passed via the south-shore fishway, 6 (30%) passed via the north fishway, and 2 (10%) passed via an unknown route. While telemetry coverage was limited, we were able to calculate passage times for several segments at McNary Dam. Median passage times from first fishway approach to first fishway entry and to pass the dam were 0.1 (n = 21) and 21.9 h (n = 17), respectively (Table 20). Although the sample size was low (n = 6) lampreys appeared to move quickly from first fishway entry into a transition pool (*median* = 0.1 h). Median passage time was longer for the segment from first fishway entry to exit from the ladder top (*median* = 10.3 h, *n* = 17). No lampreys were recorded falling back at McNary Dam.

Table 19. Dam-wide passage efficiency metrics for unique radio-tagged Pacific Lamprey at McNary Dam in 2000-2002 and 2008-2010, 2014 and 2018. At Dam = recorded in tailrace or at a fishway; Approached = approached fishway opening; Entered = entered fishway; Passed = passed dam. Fish were tagged at Bonneville Dam.

	1997	1998	1999	2000	2001	2002	2007	2008	2009	2010	2014	2018
At Dam (*n*)	-	-	-	13	9	5	-	8	10	11	7	23
Approached (*n*)	-	-	-	13	9	2	-	8	10	11	7	23
Entered (*n*)	-	-	-	12	9	2	-	7	10	7	7	23
Passed (*n*)	-	-	-	11	6	2	-	7	8	6	7	20
Approached:At Dam	-	-	-	1.00	1.00	0.40	-	1.00	1.00	1.00	1.00	1.00
Entered:At Dam	-	-	-	0.92	1.00	0.40	-	0.88	1.00	0.64	1.00	1.00
Passed:At Dam	-	-	-	0.85	0.67	0.40	-	0.88	0.80	0.55	1.00	0.87
Entered:Approached	-	-	-	0.92	1.00	1.00	-	0.88	1.00	0.64	1.00	1.00
Passed:Approached	-	-	-	0.82	0.67	1.00	-	0.88	0.80	0.55	1.00	0.87
Passed:Entered	-	-	-	0.92	0.67	1.00	-	1.00	0.80	0.86	1.00	0.87

Table 20. Summary of passage times for radio-tagged adult Pacific Lamprey at McNary Dam in 2018. Q1 and Q3 are first and third quartiles, respectively.

Passage segment			Passage time (h)			
Start	Finish	*n*	Median	Mean	Q1	Q3
First approach	First entrance	21	0.1	20.7	0.1	0.2
First approach	Past dam	17	21.9	177.4	6.5	50.1
First entrance	Transition pool entry	6	0.1	0.2	0.1	0.2
First entrance	Past dam	17	10.3	151.8	5.3	23.1

Discussion

The primary objectives for Section 5 of this report were to summarize radio-tagged adult lamprey use of fishways (including LPSs), and to calculate lamprey passage times, passage efficiencies, and fallback percentages at the four lower Columbia River dams. We also used the radiotelemetry data to look at lamprey behaviors at specific locations with known passage problems (e.g., the count stations, AWS channels, and serpentine weir sections at Bonneville Dam) and sites with recent modifications to improve lamprey passage (e.g., the UMTJ-LPS at Bonneville Dam and the reconfigured John Day north fishway entrance area).

Bonneville Dam

The percentage of radio-tagged lampreys that were detected at Bonneville Dam after release in 2018 (89%) was slightly higher than the 11-year average (i.e., 1997-2002, 2007-2010, & 2014) of 85% (Keefer et al. 2012; Clabough et al. 2015). The 2018 value was also consistent with values from 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 fishways (i.e., orifice/sluice gates were open and monitored at both Powerhouses). Lampreys not detected at Bonneville Dam in 2018 could have shed transmitters, may have abandoned upstream migration, may have died from tagging effects (i.e., 3 of 599 [0.5%]) double-tagged lampreys died before release in 2018) or predation (pinnipeds and white sturgeon *Acipenser transmontanus*), 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) and comparison of detection histories of double-tagged lamprey in radio- and PIT arrays in 2018. There was one case of a transmitter not working or being shed in 2018 based on PIT detections of a double-tagged lamprey in the Bradford Island vertical slot weirs, which had no corresponding radio detections inside the fishway.

Dam passage efficiency (fishway approach to top of ladder) at Bonneville Dam in 2018 (43% with recaptured fish excluded and 45% with recaptured fish treated as passing the dam) was slightly above average compared to most recent lamprey radio-telemetry studies (*mean* = 41%, *median* = 42%, *n*= 5 years, *range* =31-51%, 2007-2010 and 2014; Keefer et al. 2012; Clabough et al. 2015). The 2007-2010 and 2014 studies used similar methods to those used in 2018 and lamprey body sizes were representative of the runs at large (in contrast to radiotelemetry studies in 1997-2002, when only larger-bodied fish were tagged). The 2018 result discontinued an apparent increasing trend in Bonneville passage success discerned in the five-year time series of radiotelemetry and HD-PIT studies starting in 2007 (Keefer et al. 2015). Operational and structural factors (e.g., 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/or incremental effects of recent fishway modifications at Bonneville Dam (Keefer et al. 2010; Clabough et al. 2010a) were cited as potential explanations for the trend of increasing lamprey passage success from 2007 to 2014 (Clabough et al. 2015).

We had hypothesized that lamprey passage success at Bonneville Dam in 2018 would be at the high end of the reported range given the reduced nighttime velocity experiment at the Bradford Island fishway and the new UMTJ-LPS (among other incremental improvements since 2014). However, the potential benefits of passage improvements may have been partially offset by an outbreak of furunculosis (a disease associated with infection by *Aeromonas salmonicida*) in the 2018 lamprey run. Furunculosis was identified in mid-migration, and thereafter symptomatic lampreys had about 8% lower passage success at Bonneville Dam than non-symptomatic lampreys (details in Keefer et al. 2019). In Atlantic salmon (*Salmo salar*) infected with furunculosis, critical swim speed was greatly reduced and fish exhaustion occurred sooner compared to controls (Yi et al. 2016). Symptoms of furunculosis have been present in other adult Pacific lamprey run-years (Ralph Lampman, *personal communication*) but the incidence of the disease and its potential effects on behavior and dam passage success have not been previously evaluated. Consequently, we are uncertain whether the apparent increased prevalence of the disease in 2018 affected study results.

The distribution of turnaround sites for failed Bonneville Dam passage attempts in 2018 were largely consistent with previous evaluations, which found turnarounds likely to occur in the first or second fishway segment encountered after fishway entry (Keefer et al. 2012, 2013b). Over half of all WA-shore fishway turnarounds in 2018 were near the PH2 South fishway openings or the unmonitored sluice gates of the PH2 collection channel and approximately one third (32-36%) of both WA-shore and Bradford Island failed passage attempts occurred in one of their transition pools. Smaller percentages of all 2018 turnaround events (12%) were in the WA-shore vertical slot weirs or AWS channels but 27% of individual non-passing fish that entered a fishway had their most-upstream detection at those sites. In comparison, 40% of all entry events to the Bradford Island fishway resulted in turnarounds in the serpentine weirs or in the AWS channel whereas 22% of individual, non-passing fish had their most-upstream detection there. The serpentine weir sections in the upper WA-shore and Bradford Island fishways continue to be among the most difficult fishway sections for adult lamprey that do not pass Bonneville Dam.

The Dalles Dam

Poor entrance efficiency at the west powerhouse and south spillway openings, difficulty passing the transition pools in both east and north fishways, and the entrance channel at the north fishway were identified by Keefer et al. (2012) as sites where lamprey passage at The Dalles Dam might be improved. Elevating picket leads to allow lamprey to have alternative passage routes near count stations has occurred at The Dalles Dam, but generally few large-scale structural modifications (e.g., bollard fields, LPSs) or operational changes (apart from the 2018 nighttime head reduction experiment) to benefit lamprey *per se* have been implemented.

Overall, site-specific passage metrics at The Dalles Dam fluctuated around values observed in past years and the 2018 overall passage efficiency estimates at The Dalles Dam were 3-5% higher than the median values from ten previous radiotelemetry study years at the dam. Site-specific entrance efficiency for unique fish at the west and south fishway openings in 2018 were 45% and 65%, respectively. The 2018 value at the west powerhouse opening represented a minor change from the median value from nine years (i.e., 1997-1998, 2000-2002, & 2007-2010) of previous studies (47%, Keefer et al. 2012) but was higher than the 2014 value (33%, Clabough et al. 2015). The site-specific entrance efficiency at the south spillway opening in 2018 approximated the 10-year median value (64%) but was lower than the 2014 value (81%). Among failed dam passage attempts by lamprey that entered the north-shore and east fishway, more than 90% of turnarounds occurred in one of the transition pools.

Despite the difficulty some lamprey had passing the Dalles Dam in 2018, the percentages of lamprey that passed the dam after approaching (72%) or entering (77%) a fishway were considerably higher than at Bonneville Dam. This may have been due in part to the selection that has been observed favoring larger-bodied lampreys (Keefer et al. 2013a) or to fewer passage obstacles (e.g., vertical slot weirs) at The Dalles fishways compared to at Bonneville Dam.

John Day Dam

Overall, dam passage efficiency for lampreys at John Day Dam (69%) was similar to at The Dalles Dam (72%) and substantially higher than at Bonneville Dam (43-45%) in 2018. The 2018 dam passage efficiency estimate was considerably higher than the corresponding median estimate from previous study years (52%) at The Dalles Dam. Patterns were similar for the fishway passage estimates, with relatively high efficiency (76%) in 2018. Among previous study years, 2014 was the most comparable at John Day Dam in terms of radiotelemetry monitoring effort; dam and fishway passage efficiency estimates were 83% and 87%, respectively, in 2014. In 2018, site-specific fishway passage efficiencies were highest at the John Day north fishway (78%) followed by the south powerhouse (60%) and the south fishway (50%). The pattern was similar in 2014, when efficiency was also highest at the north fishway (92%), followed by the south powerhouse (71%) and south fishway (45%). Lamprey passage times in 2018 were broadly similar to those in 2014. While the fallback rate at John Day in 2018 (13%) was higher than the other three dams (range 0-5%) it was substantially lower than observed in 2014 (35%).

McNary Dam

Overall, lamprey passage at McNary Dam has been consistently higher compared to Bonneville, The Dalles and McNary Dams (Keefer et al. 2012, 2013a). In 2018, 100% of the fish at the dam approached a fishway and 100% of the fish that approached entered a fishway. Overall, the dam-wide dam passage efficiency (87%) at McNary Dam in 2018 was higher than the median estimates from previous years (82%) while dam-wide fishway passage efficiency (87%) was slightly lower to the corresponding median estimate (92%) from previous years (2000-2002, 2008-2010, & 2014). Moreover, these 2018 passage efficiencies estimates were also higher than median values for fish released in the McNary Dam tailrace from 2005-2010; 65% and 80% for dam passage and fishway passage efficiency, respectively (Keefer et al. 2013b).

Lamprey passed McNary Dam quickly in 2018, with median passage times of 10.3 h from first fishway entry to top-of-ladder and 21.9 h from first approach to top-of-ladder. While the approach to top-of-ladder time was similar to 2014 (19.4 h) the entry to top-of-ladder passage time at McNary in 2018 (10.3 h) was nearly twice as fast as observed as in in 2014 (19.4 h). The entry to passage time at McNary Dam in 2018 was also more than twice as fast as John Day Dam in 2018 (24.1 h). Of the 20 lampreys that passed McNary Dam, 12 (60%) passed via the south-shore fishway, 6 (30%) passed via the north fishway and 2 (10%) passed via an unknown route. In contrast, all seven lamprey recorded passing the dam in 2014 passed via the south-shore fishway.

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