Technical Report 2020-1

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 - 2019

Study Code: LMP-P-17-1

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T.J. Blubaugh, G. Brink, M. Hanks, C.T. Boggs and C.C. Caudill

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For

U.S. Army Corps of Engineers
Portland District

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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 2019, our adult lamprey research and monitoring project evaluated two recent structural and operational modifications at lower Columbia River dams: (1) systematic reductions in nighttime fishway velocity at Bonneville Dam and experimental reductions in nighttime fishway velocity at The Dalles Dam; and (2) use of a Lamprey Passage Structure (LPS) inside the Washington (WA)-shore fishway downstream from the count station at Bonneville Dam. Here, we also report fishway and dam passage metrics for Bonneville, The Dalles, and John Day dams. Patterns of migration and passage at larger geographic scales are presented in a companion report (Keefer et al. 2020).

Sample summary

In 2019, sample sizes were limited by a lower-than-average lamprey abundance and conservation limits on tagging. With these limits, 449 adult Pacific Lampreys were collected and double-tagged with a radio transmitter and HD PIT tag and another 314 lampreys were tagged with only HD PIT tags at the Adult Fish Facility (AFF) at Bonneville Dam and released downstream. Movements of double-tagged lampreys were monitored using fixed-site receivers with aerial and underwater antennas in the tailraces and fishways 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 double-tagged lampreys. Lamprey behaviors and passage metrics from 2019 were compared to those from previous studies.

Fishway entrance velocity reductions at Bonneville and The Dalles dams

Water velocity was reduced each night at Bonneville Powerhouse 1 and Bradford Island (BI) spillway fishway openings (i.e., the fishway entrances) and was experimentally manipulated at night to reduce water velocity at the Dalles Dam east fishway openings. Entrance efficiency in 2019 was higher at Bonneville Dam during nightly reduced conditions compared to previous years. However, increased entrance efficiency was not associated with an increase in overall fishway passage efficiency, consistent with results from similar studies at Bonneville Dam Powerhouse 2. Double-tagged lampreys that approached fishways were significantly more likely to enter The Dalles Dam east fishway during the reduced velocity treatment than during the ‘normal’ treatment, which was consistent with the 2018 experimental results at the same location. Similar to results from Bonneville Dam, where the reduced velocity conditions increased both the proportion of lampreys that entered fishways and the rate at which they entered, the reduced velocity treatment did not measurably affect lamprey fishway passage success after they entered a fishway because many fish turned around within the fishway, regardless of velocity treatment experienced downstream.

Lamprey behavior near the UMTJ-LPS at Bonneville Dam

A dual-ramp LPS was recently installed in the WA-shore fishway at Bonneville Dam near the upstream migrant tunnel junction (UMTJ) and just upstream from the overflow-weir section of the fish ladder. A small percentage of tagged lampreys used the UMTJ-LPS in 2019, which was similar to rates observed in 2018. In 2019, of the total number of tagged lampreys (double and PIT) that reached the UMTJ study area (that subsequently passed or did not pass the dam), 8% of double-tagged and 4% of PIT-tagged lampreys passed the dam via the UMTJ-LPS. Among tagged lampreys that passed the dam (after reaching the UMTJ study area), telemetry records indicated most lampreys passed via the fishway serpentine weir route (double-tagged lamprey: 6.1% passed via UMTJ-LPS, 35.3 % via AWS-LPS, and 58.6% via serpentine weirs; PIT-tagged lamprey: 11.8% via UMTJ-LPS, 16.1 % via AWS-LPS, and 72.1% via serpentine weirs). Within the double-tagged group, fish arriving later in the season to the UMTJ junction area were more likely to use the ladder. Nearly all lampreys that used the UMTJ-LPS initially swam past the structure to the serpentine or AWS sections prior to ascension and all but one tagged lamprey ascended the south ramp.

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 2019, as in previous years. Movements of double-tagged lampreys near the count windows, serpentine weirs, and AWS channels of the WA-shore and BI fishways at Bonneville Dam indicated that 28-35% of fish that reached these areas did not pass the dam, which was consistent with findings from previous years. A large majority of lamprey that entered fishways but did not pass the dam reached the serpentine weir sections (87% WA-shore; 82% BI), highlighting the location as an ongoing passage bottleneck.

Lamprey behavior and passage in serpentine weirs in relation to slot orifices in WA-shore fishway at Bonneville Dam

Lamprey slot orifices were installed in the serpentine weir section of the WA-shore fishway to provide a direct passage route upstream through the fishway segment. Slot orifices were available to lampreys in 2018 at three weirs and eight slots were available in 2019. Direct monitoring was not possible. Rather, we indirectly evaluated slot use by comparing detection histories on radio and PIT antennas in the serpentine weir section for double-tagged lampreys. We tentatively conclude that the slot orifices were likely used in the serpentine section of the fishway and we found no evidence that the slots impeded lamprey passage in 2019.

Fishway approach and entry rates

Overall, lamprey passage metrics fell within the ranges observed in previous years. On average, lampreys approached Bonneville fishway openings 11.8 times per fish (n = 379), entered fishways 2.4 times per fish among entrants (n = 331), and of those that exited fishways into the tailrace (n = 252), lampreys exited 2.4 times per fish (1.9 times per fish among all 331 unique fishway entrants). At Bonneville Dam, the largest numbers of fishway approaches, entries, and exits were at Powerhouse 2 (PH2). Mean entrance metrics at The Dalles Dam were 2.4 approaches, 1.5 entries among entrants, and 1.7 exits per fish among fish that exited (0.8

exits per fish among unique fishway entrants). Most approaches and entries at The Dalles Dam occurred at the North fishway in 2019. At John Day Dam, lampreys approached 3.5 times, entered 2.1 times and exited 2.2 times per fish on average.

Fishway and dam passage efficiency and effectiveness estimates

Dam and fishway passage efficiencies in 2019 were similar at Bonneville Dam, slightly lower at the Dalles Dam, and higher at John Day than the median values from previous years. Dam passage efficiency (the number of tagged lampreys that passed the dam divided by the number that approached a fishway) at Bonneville Dam was 42-46% (n = 355-379 approached; the first estimate excludes 24 recaptured fish). Dam passage efficiency was ~66% (n = 116) at The Dalles Dam, 78% (n = 50) at John Day Dam, and 45% (n = 11) at McNary Dam. Fishway passage efficiencies (the number of tagged lampreys that passed a dam divided by the number that entered a fishway) were 49-52% at Bonneville Dam (n = 307-331 entered), ~70% (n = 109) at The Dalles Dam, 83% (n = 47) at John Day Dam and 50% (n = 10) 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 Powerhouse 1 South shore entrance (~81%, n = 59) and were lowest at PH2 south entrances (~46%, n = 166). Entrance efficiencies at The Dalles Dam were highest at the north entrance (99%, n = 70) and lowest at the west powerhouse entrance (69%, n = 13). Entrance efficiencies at John Day Dam ranged from 100% (n = 20) at the north entrance to 52% (n = 33) at the south-shore entrance. At McNary Dam, site-specific fishway entrance efficiencies ranged from 100% (n = 3) at the north-powerhouse entrance to 40% (n = 5) at the north entrance.

Fishway and dam passage times

Median dam passage times (i.e., the interval between first tailrace record and last detection at a ladder top at each dam) were 8.2 d at Bonneville, 3.3 d at The Dalles, 2.4 d at John Day, and 2.2 d at McNary dams. Median times from first fishway entrance to exit from the top of a ladder were 3.0 d at Bonneville, 1.1 d at The Dalles, 2.3 d at John Day, and 1.4 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 (the number of unique lampreys that fell back at a dam divided by the unique number that passed a dam) were ~3% at Bonneville Dam, 4% at The Dalles Dam, 13% at John Day Dam and 20% at McNary Dam (n = 1 of 5). No lampreys that fell back reascended at any dam with the exception of John Day Dam, where two of five fallback fish reascended.

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; Wills 2014). In the Columbia River basin, a multi-year series of radiotelemetry and PIT-tag studies have described adult 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, 2019; Clabough et al. 2015, 2019). These and other studies have identified many locations where lampreys 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; Moser et al. 2019), and reduction of fishway water velocities (Boggs et al. 2010; Johnson et al. 2010, 2012; Clabough et al. 2019).

In 2018 and 2019, 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 entrance velocity at Bonneville and The Dalles dams; and (2) construction of a new LPS (UMTJ-LPS) inside the WA-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 (UMTJ-LPS) to circumvent passage challenges in the serpentine weirs.

Reduced entrance velocities at night have been examined because 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 $m \bullet sec^{-1}$, which are considerably higher than the estimated critical adult lamprey swimming speed of 0.8 $m \bullet sec^{-1}$ (Mesa et al. 2003) and are higher than velocities found to impede lamprey passage in experimental studies (> 1.2 $m \bullet sec^{-1}$, Keefer et al. 2008). In response, entrance water velocity was experimentally reduced at night at Bonneville Dam Powerhouse 2 entrances in 2007, 2008, and 2009 in an effort to improve conditions at night, when lampreys are more active, while meeting fish passage criteria for salmonid fishes during daytime hours. 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 a zero velocity (standby) condition (5-9%). Subsequently, reduced nighttime fishway entrance head (i.e., velocity) was incorporated into the Fish Passage Plan for Powerhouse 2. Nighttime head reductions were implemented at Bonneville's Bradford Island (BI) fishways (Powerhouse 1 and BI spillway entrances) in 2019 after experimental reduction studies in 2018 provided evidence of improved entrance rates (Clabough et al. 2019). Experimental reductions in nighttime velocities were also conducted at The Dalles east fishway in 2018 (Clabough et al.

2019) and 2019 (reported herein).

Construction and installation of LPS systems to provide an alternative or bypass routes for adult lamprey has been a core component of fishway improvement efforts. 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 at these locations (e.g., Clabough et al. 2012). In the winter of 2016-2017, the 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 lampreys to bypass the adult count station and the serpentine weir section of the WA-shore fishway after ascending ramps in the main fishway channel below the count station or ramps at the head of the AWS channel. An additional minor modification was performed prior to the 2018 and 2019 lamprey migrations by cutting slot orifices at the fishway floor in three (2018) or eight (2019) weir walls in the WA-shore fishway serpentine weir section in an effort to provide more direct passage through the section (e.g., Gallion et al. 2017).

We used radiotelemetry and HD PIT telemetry to address several complimentary objectives in 2019. In this report, we present results on: (1) nightime velocity reductions at fishway entrances 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, (4) indirect evaluation of lamprey passage behavior in the WA-shore serpentine weirs in relation to the slot orifices, and (5) 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, 2019). System-wide summaries of lamprey behaviors, escapement, and distribution are reported separately (see Keefer et al. 2020). Results from experimental flume studies and an accelerometer tag evaluation conducted in 2019 are also provided in a separate report (see Hanchett and Caudill 2020).

1. Lamprey Collection, Tagging, and Monitoring

Tagging and monitoring

Adult lampreys used in this study were collected at Bonneville Dam (Columbia River kilometer [rkm] 235). Fish were collected in two traps located at the WA-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°. The LFS is located outside of the north downstream entrance of the WA-shore fishway and served as an entrance modification to provide a lamprey-specific entrance and passage route from the tailrace (Zorich et al. 2018). 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 2019, a total of 1,025 lamprey were tagged at Bonneville Dam for four study groups. The first group included 449 tagged with radio transmitters and half-duplex passive integrated transponder (HD PIT) tags. These double-tagged fish were all released downstream from Bonneville Dam near Hamilton Island (n = 217; rkm 232.5) or near Tanner Creek (n = 232; rkm 232.0), with the release site randomly assigned each day. The second group had 314 (n=159 Tanner Creek, n=155 Hamilton Island) that were tagged with only HD PIT tags and were released downstream from the dam for general migration evaluations. The third group had 218 lampreys that were PIT tagged for use in experimental flume studies, and 217 of these were released upstream from Bonneville Dam at the public boat launch in Stevenson, WA (rkm 242.7). One of the 218 lampreys died before it could be used in experimental flume trials and released (0.1% of the tagged samples) and it was censored from all analyses. The fourth group was an accelerometer tag evaluation that included 44 fish released into the Washington-shore fishway near the AFF. Results from the experiments and accelerometer study were reported separately (see Hanchett and Caudill 2020). The double- and PIT-tagged lampreys were randomly selected from collected lampreys. However, we note that it was unknown whether lampreys collected inside Bonneville fishways were representative of the run at large.

All lampreys 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 Fatmeter (Distell Inc., West Lothian, Scotland). While under anesthesia, lampreys 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 7.8 ml•L^{-1}). Lampreys 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 (BIO32.HDX.03V2, 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 dewatered (left) and in operation (right) in the Washington-shore fish ladder at Bonneville Dam.

In 2019, we tagged and released 449 double-tagged adult Pacific Lampreys and 314 HD PIT lampreys (May 19-Sep 9) (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 2019 was 70,876 (N. McClain, USACE, *personal communication*). Downstream-released PIT-tagged lampreys represented ~0.44% of the total corrected count and double-tagged lamprey represented ~0.63% of the count at the dam in 2019. Tagged totals were lower than achieved in 2018 because in-season tagging for all sample groups combined was limited to 2% of the cumulative daytime count.

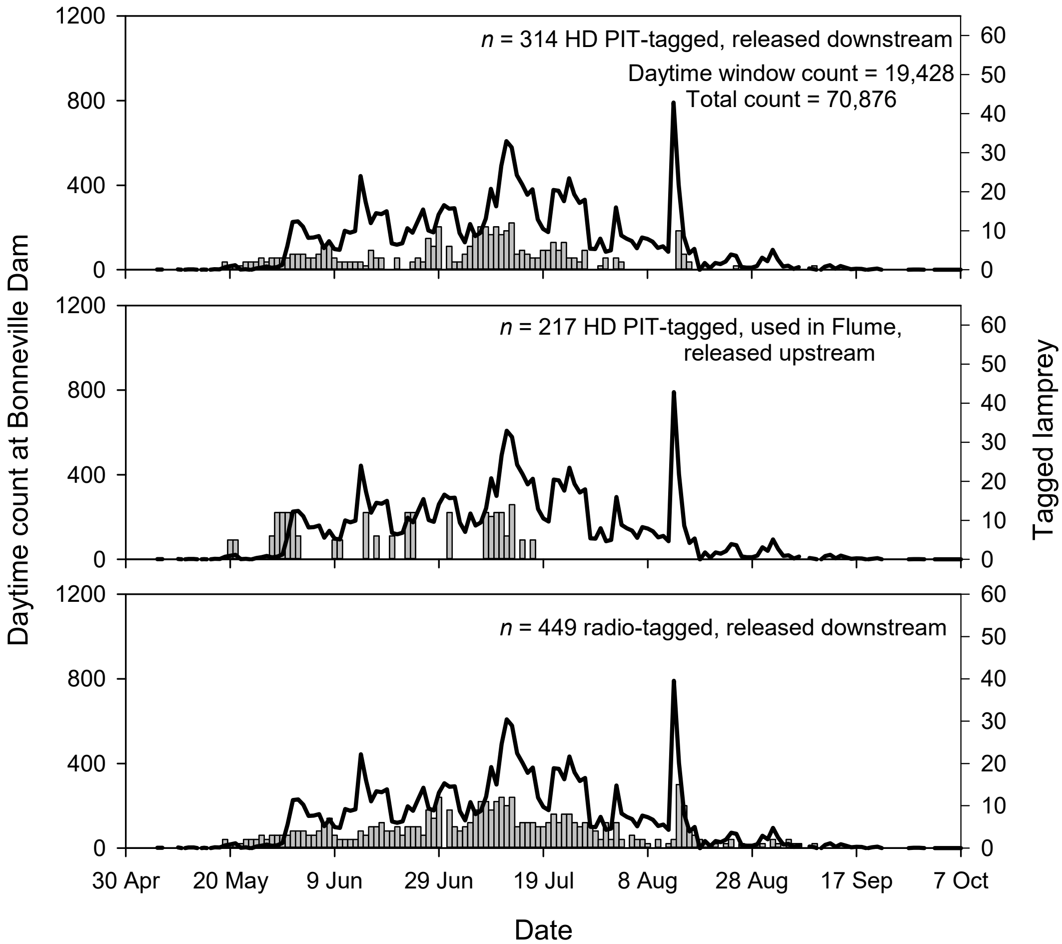

Figure 2. Number of adult Pacific Lampreys counted passing Bonneville Dam during the day (solid lines) and the numbers that were collected and tagged (bars) in 2019. 'Total count' is the corrected total from daytime counts at windows, night video at windows, and LPS passage estimates through 31 December. 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. Double-tagged fish used in the accelerometer tag 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 to receive transmissions on multiple frequencies simultaneously. Aerial antennas were used to monitor tailraces at each dam except McNary Dam. 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 2018-2019 (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 and 2019 only included fishway entrances and top-of-the-ladder-exits. In 2019, we installed two additional underwater antennas at Bonneville Dam in the WA-shore ladder serpentine weir section to augment radio coverage near the new lamprey slot orifices. See Appendix A for radio and HD PIT antennas locations with equipment at Lower Columbia dams.

HD PIT tag monitoring – We monitored lamprey movements at Bonneville, The Dalles, and John Day dams with half-duplex PIT antennas (Table 1). Additional PIT detection data were 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) operated by University of Idaho used to monitor lamprey passage at lower Columbia River dams in 2019. 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 (Pacific States Marine Fisheries Commission).

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

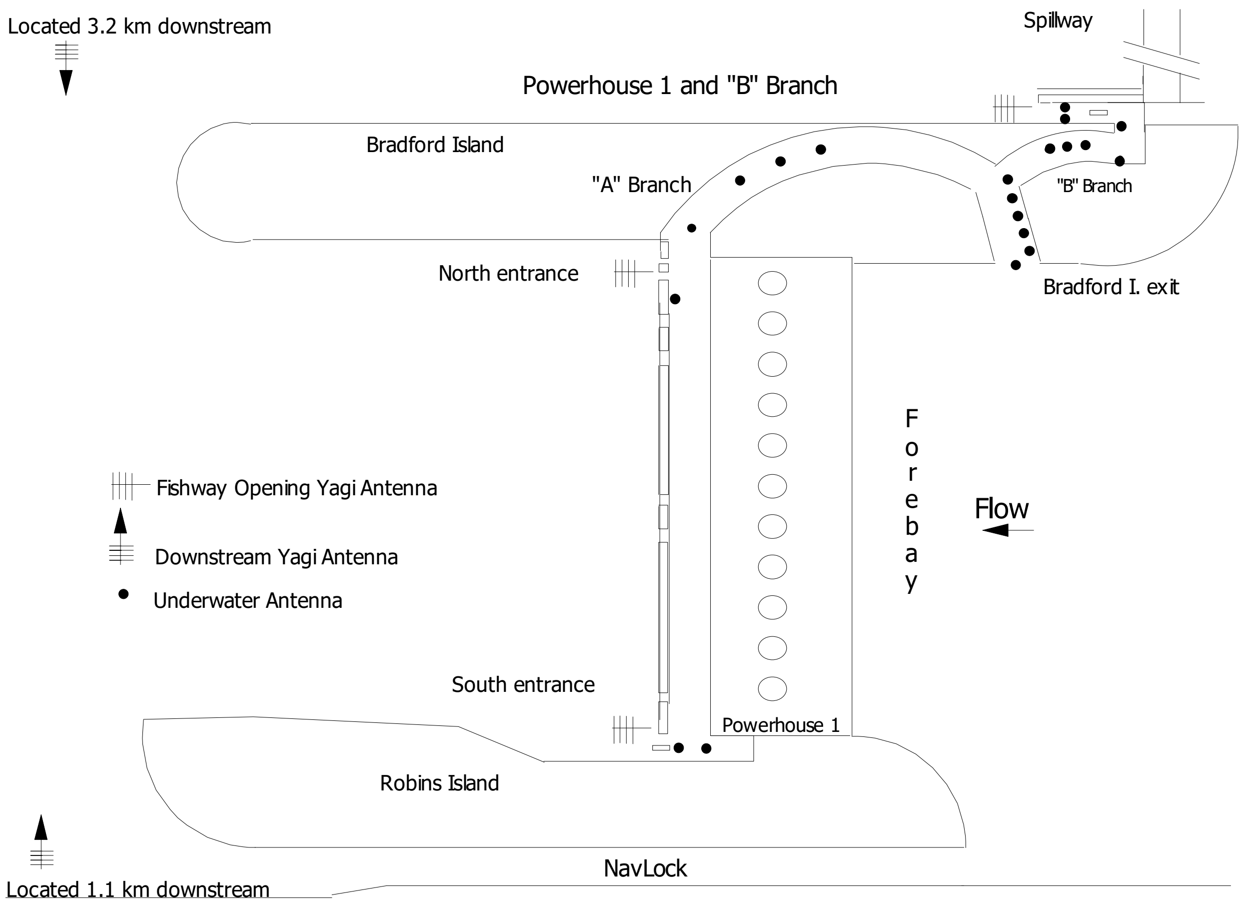

Figure 3. Diagram showing radio antenna deployments at Bonneville Dam Powerhouse 1 and B-Branch fishways in 2019 (not to scale).

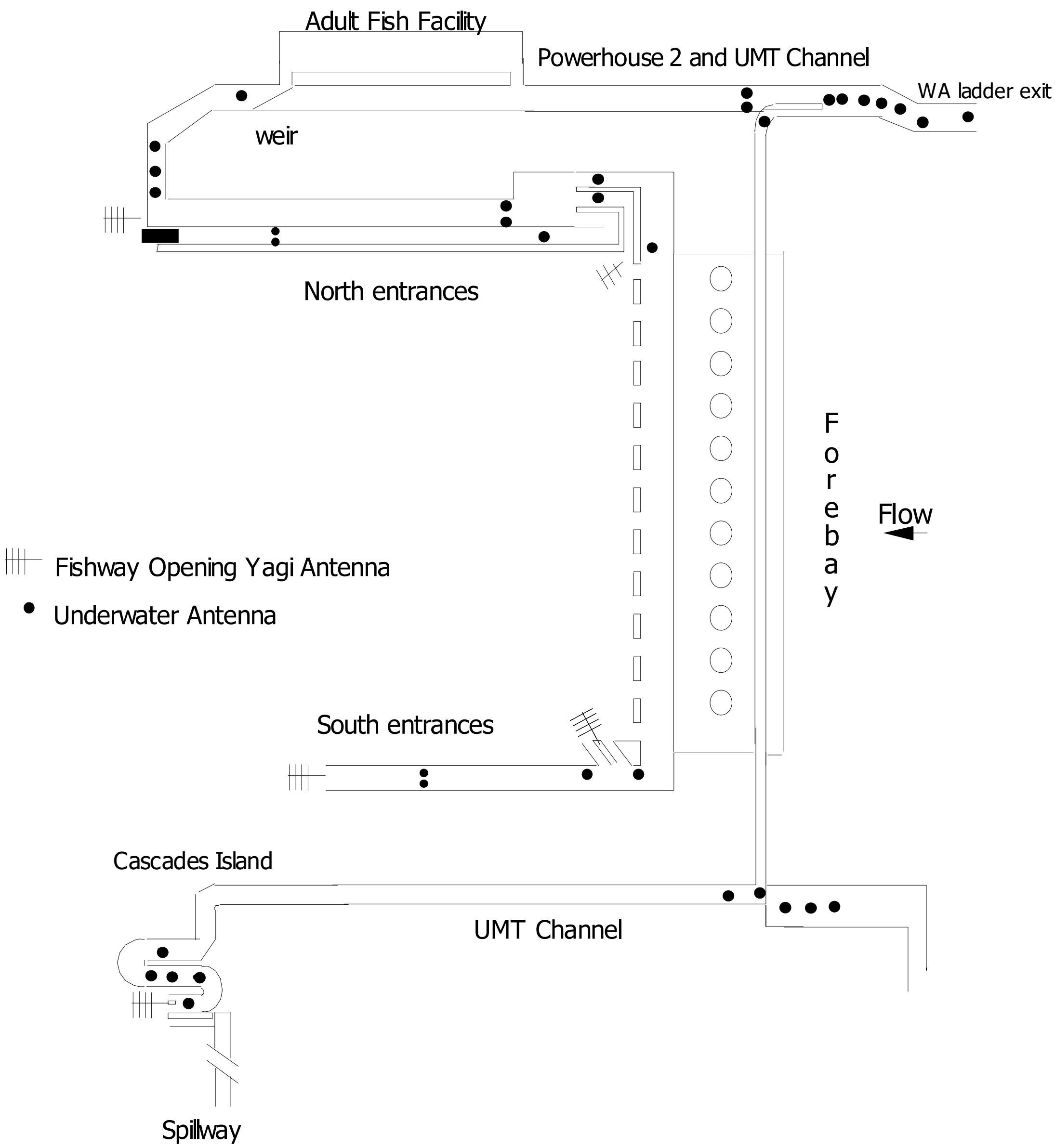

Figure 4. Diagram showing radio antenna deployments at Bonneville Dam Powerhouse 2 and Cascades Island fishways in 2019 (not to scale).

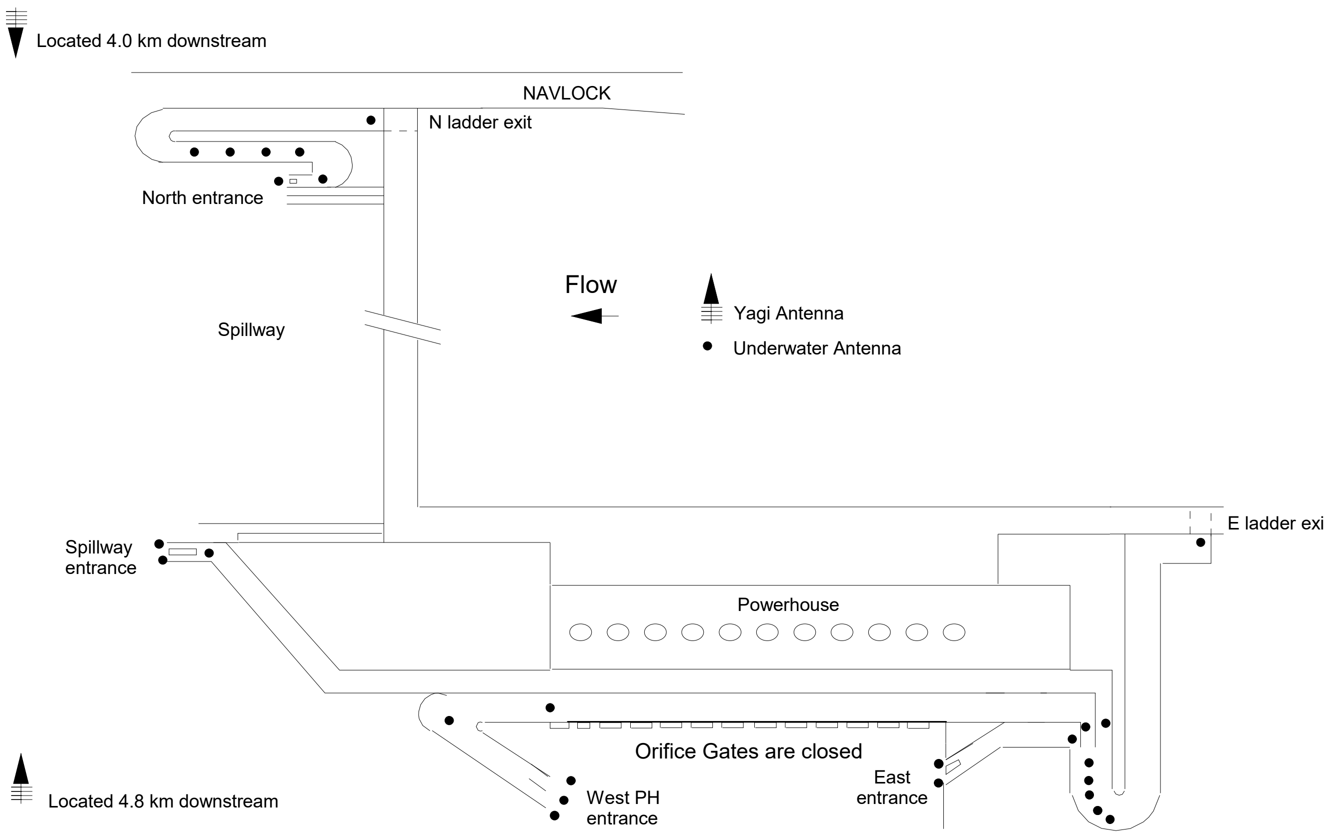

Figure 5. Diagram showing radio antenna deployments at The Dalles Dam in 2019 (not to scale).

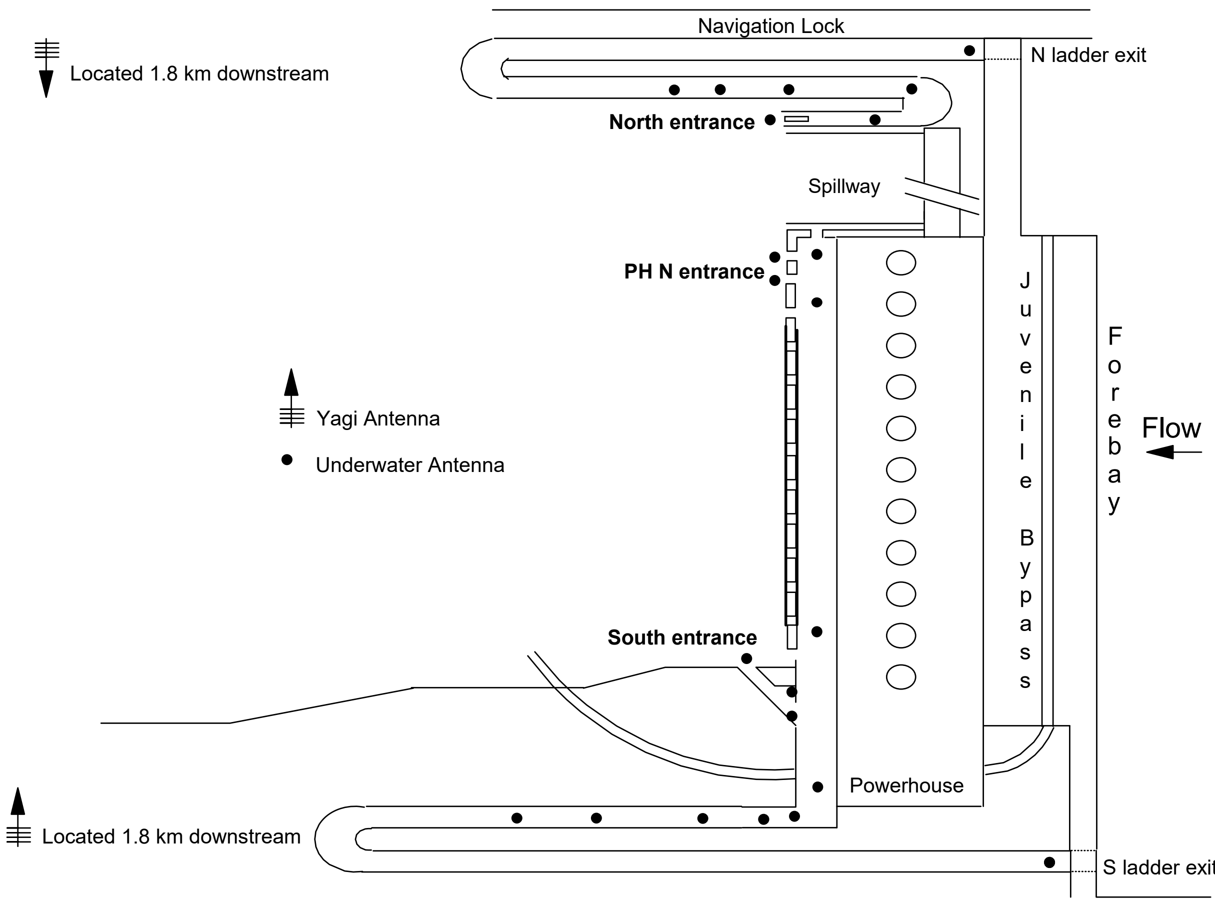

Figure 6. Diagram showing radio antenna deployments at John Day Dam in 2019 (not to scale).

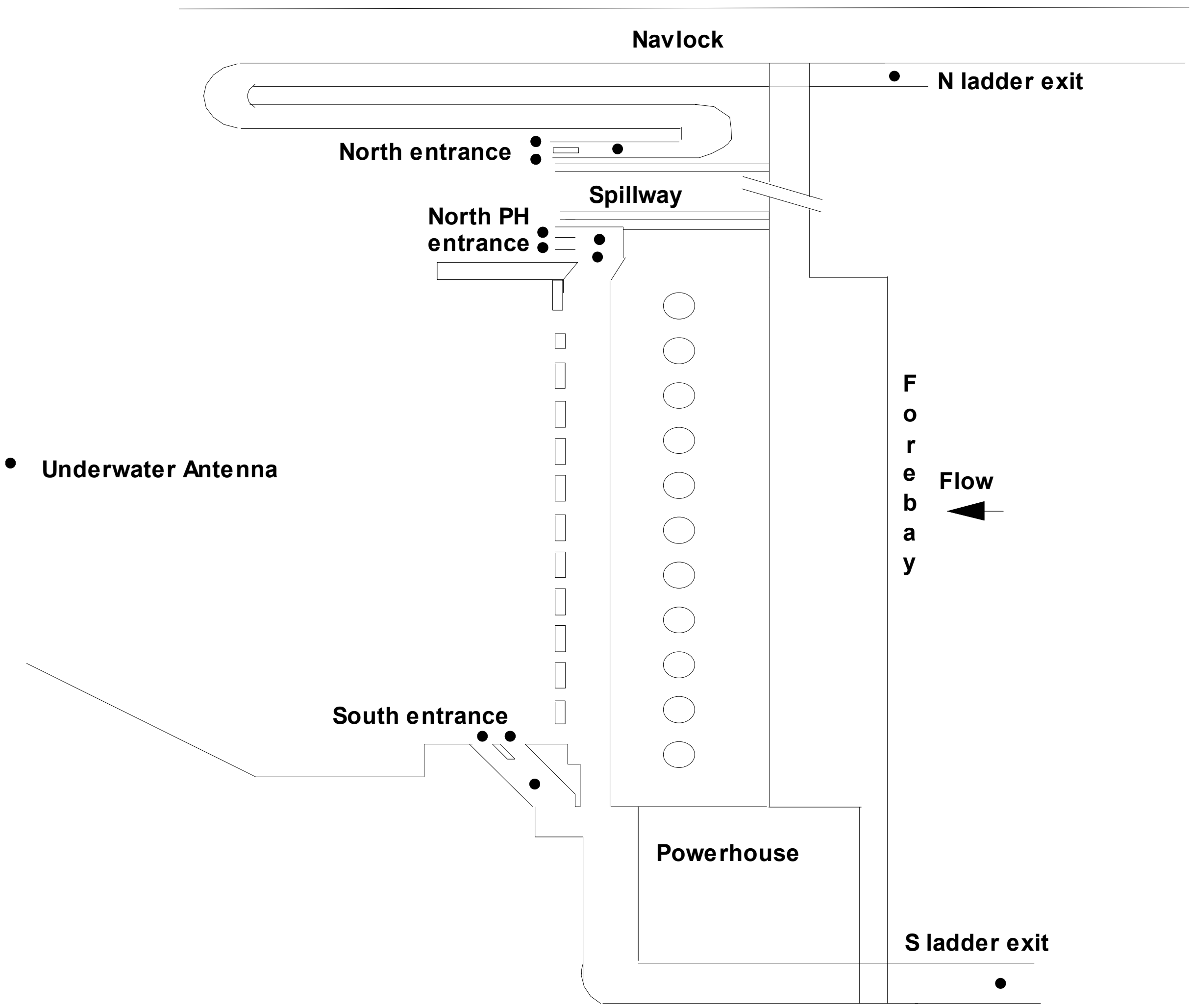

Figure 7. Diagram showing radio antenna deployments at McNary Dam in 2019 (not to scale).

Environmental conditions at Bonneville Dam

Environmental conditions at Bonneville Dam during the 2019 lamprey migration were characterized by below average flow and spill May through July 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 2019 were slightly warmer than the 10-year average during the passage season (May through September). A maximum water temperature of 22.3 °C occurred on 13 August and was 0.5 °C warmer than the 10-year average maximum.

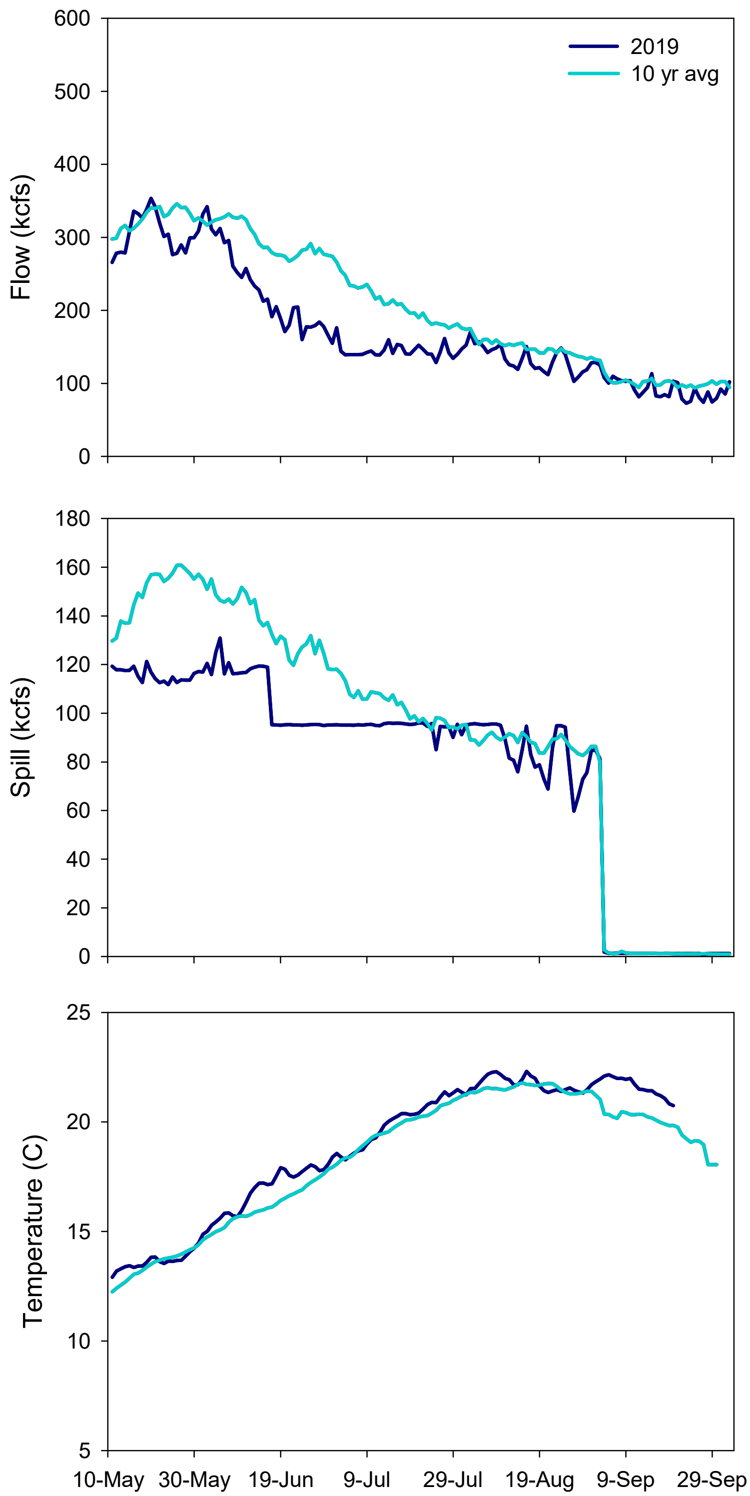

Figure 8. Mean daily Columbia River discharge (flow, kcfs), spill (kcfs), and water temperature (°C) at Bonneville Dam during the 2019 adult Pacific Lamprey migration and the ten-year average (source: http://www.cbr.washington.edu/dart/query /river_daily).

2. Nighttime fishway velocity reductions and experiments

Methods

Fishway operations

At Bonneville Dam, entrance velocities were reduced on all nights between 1 June and 31 August in the Bradford Island fishways in 2019 (Powerhouse 1 and B-Branch). The 2019 operational protocols differed from the 2018 experimental tests where nighttime entrance water velocities were altered between 'normal' and 'reduced' conditions in a randomized block design at Bradford Island (Clabough et al. 2019). At Bonneville Dam in 2019, water velocities through fishway entrances were manipulated by adjusting the difference in water elevation (head) between the inside of the fishway (e.g., the collection channel) and the tailrace (maintaining a ~0.15 m head difference). Changes in head at fishway entrances at Bonneville PH1 and B-branch (BI 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) 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, reduced discharge and head 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 Johnson et al. [2012] at Bonneville's PH2 experiment).

At The Dalles Dam, nighttime entrance water velocities were altered between 'normal' and 'reduced' conditions in a randomized block design from 1 June to 31 in the east fishway in 2019 (similar to 2018 operational protocols). At The Dalles east fishway, the two target head differences were 0.45 m for the control condition (normal) and 0.21 m for the treatment condition (reduced). 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 velocity occurred, the operation was for six hours from 22:00 h to 04:00 h. At The Dalles Dam, the east entrance weirs were adjusted to alter the entrance slot geometry and thereby head and velocity at the entrance during nighttime (i.e., there were no changes in discharge and the experimental effects were restricted to the entrance areas).

In addition to the records of fishway operations maintained by the Corps, we tracked the 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, two water level loggers (Hobo U20-001-04) were installed, one in the tailrace outside the east entrance and one downstream of the junction pool inside the east ladder. All level logger data were collected at a five-minute interval.

Data analyses

We used several methods to evaluate the effects of the fishway head (i.e., velocity) reduction on double-tagged lamprey behaviors. The principal objectives of the head reductions were to increase the proportion of lampreys that entered 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 (Figure 9).

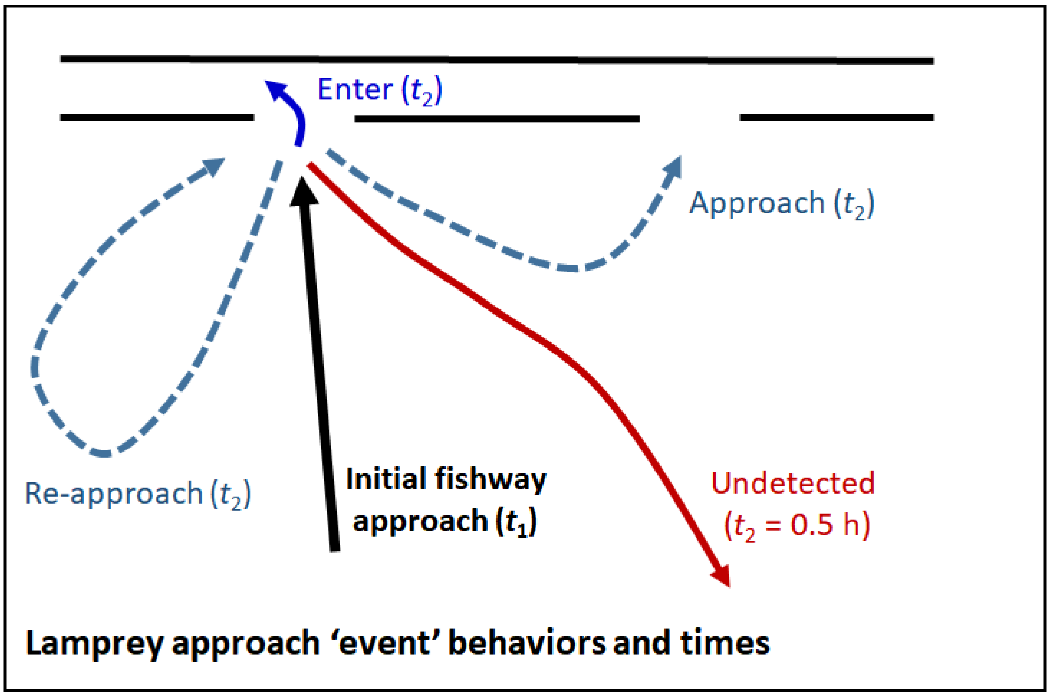

Figure 9. Schematic of a lamprey approaching a fishway opening and subsequent behaviors. Each approach event could be followed by one of four behaviors: 1) fishway entry; 2) fishway approach at another opening at the same fishway; 3) re-approach at the original opening; and 4) no further detection at the fishway within 30 minutes of the initial fishway approach.

To test for effects of the reduced treatment on entry proportions at The Dalles Dam, we calculated two metrics by treatment: 1) the number of unique lampreys that were detected entering a fishway divided by the number of unique fish detected approaching a fishway opening; and 2) the proportion of fishway entry events divided by the number of fishway approach events. The individual-based metric has been reported in many previous lamprey studies as site-specific fishway passage efficiency (e.g., Keefer et al. 2012), but was somewhat less appropriate for this experimental design. The event-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 in SAS v.9.2 (SAS Institute, Cary, North Carolina).

The fishway head manipulations affected water velocities only in the most downstream fishway segments at Bonneville and The Dalles dams. Therefore, we expected that any impacts on lamprey behaviors would be 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

Fishway entrance head was reduced nightly at Bonneville Dam and the experimental manipulation of fishway entrance head levels was successful at The Dalles east ladder (Figures 10 and 11). During the study period at Bonneville Dam, entrance velocities were reduced nightly (22:00 – 04:00, 1 June – 31 August), and the reduced velocity occurred 91% (Powerhouse 1) and 84% (B-Branch) of the nights (Table 2). When daytime hours were included, the reduced condition at Bonneville occurred 25-29% of the time. Randomized reduced treatments at The Dalles Dam occurred on 16% of nights during the experimental period and 5% of the total combined day and night hours.

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. Additionally, nighttime reduced velocities were not consistently achieved at the B-Branch entrance until ~18 June. 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).

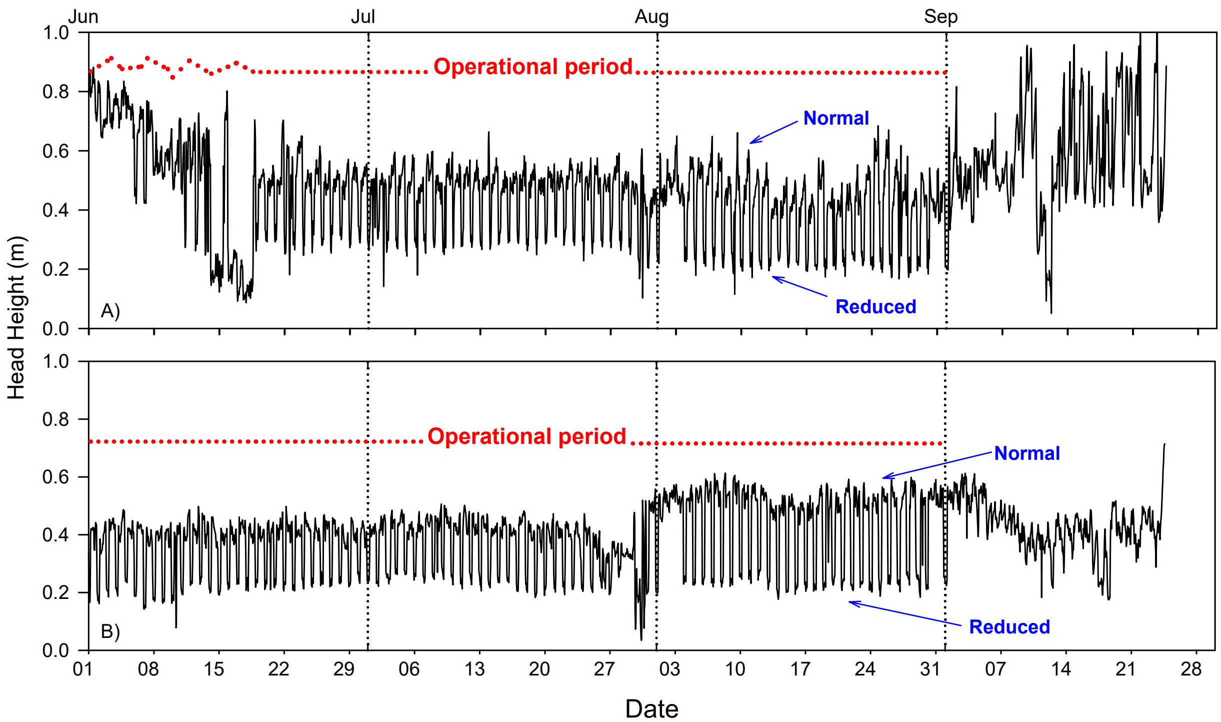

Figure 10. Head height (m) measured with water level loggers (mean hourly) inside and outside the A) Bradford Island B-Branch (spillway) and B) Bradford Island Powerhouse 1 entrances during normal and reduced velocity conditions throughout the study period (1 June to 31 August) at Bonneville Dam in 2019.

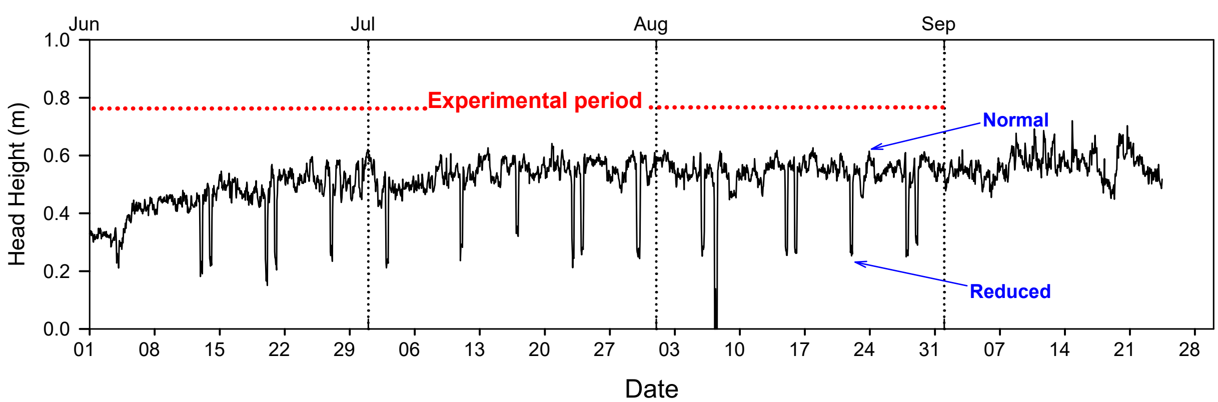

Figure 11. Head height (m) measured with water level loggers (mean hourly) inside and outside the Dalles east fishway entrance during normal and reduced velocity conditions throughout the experimental period (1 June to 31 August) at The Dalles Dam in 2019.

Table 2. Total number of days that normal, reduced, transition and unclassified conditions occurred at Bonneville and The Dalles dams during reduced entrance velocities at night (22:00-04:00 h) and 24 h period (day and night) from 18 June (Bonneville B-Branch) and 1 June through 31 August (Bonneville Powerhouse 1 and The Dalles East entrance).

Time period	Location	Normal (d)	Reduced (d)	Transition[1] (d)	Unclassified[2] (d)
Night	Bonneville Dam				
	Powerhouse 1	2.3 (9%)	24.5 (91%)	-	-
	B-Branch	3.2 (15%)	17.8 (84%)	-	0.3 (1%)
Day and night	Bonneville Dam				
	Powerhouse 1	64.5 (70%)	27.2 (29%)	-	0.3 (1%)
	B-Branch	52.9 (73%)	18.5 (25%)	-	1.6 (2%)
Night	The Dalles Dam				
	East entrance	22.2 (83%)	4.4 (16%)	0.7 (1%)	-
Day and night	The Dalles Dam				
	East entrance	86.7 (94%)	4.6 (5%)	0.3 (<1%)	0.3 (<1%)

[1] transition conditions occurred during treatment switching.
[2] unclassified conditions occurred when values did not meet the criteria of normal or reduced conditions.

Lamprey approach and entry behaviors

Among the 379 double-tagged lampreys that approached Bonneville Dam in 2019, 17% (*n* = 64) made at least one approach at Powerhouse 1 and 48% (*n* = 179) made one at the B-Branch entrance (Figure 12). Among previous study years, 2019 had the lowest percentage of fishway-approaching lamprey make an approach at PH1 and the highest percentage make an approach at the B-Branch opening.

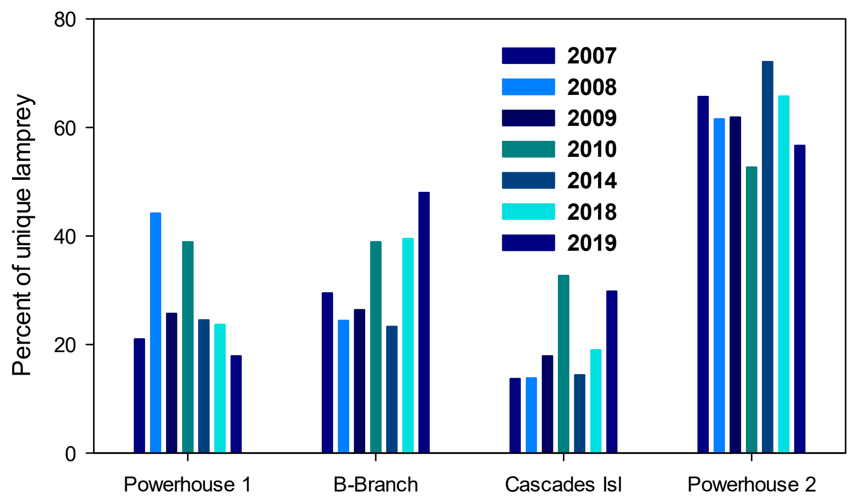

Figure 12. Percentage of unique lamprey (unique lamprey approaches at each site/all first approaches) at Bonneville Dam fishway entrances in 2007-2010, 2014, and 2018-2019.

Lampreys approached and entered fishways throughout the nighttime velocity reduction period, although activity tapered off in August at Bonneville Powerhouse 1 and at The Dalles Powerhouse (Figure 13). Most of the lamprey activity near the fishway entrances occurred at night (Figure 14).

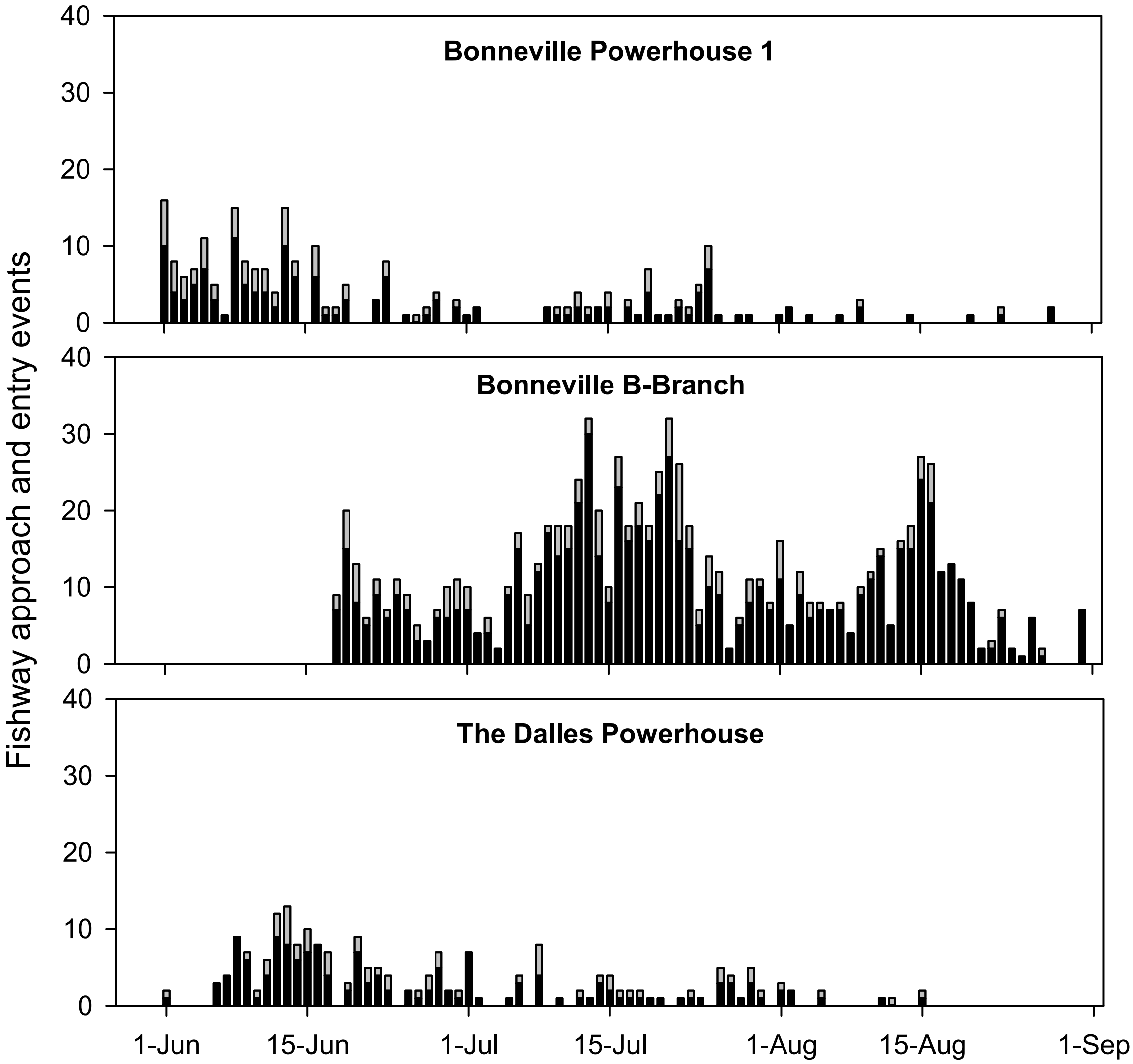

Figure 13. Numbers of fishway approach (black shaded area of bars) and fishway entry (gray shaded area of bars) events by double-tagged adult Pacific Lampreys during the nighttime fishway velocity reductions at Bonneville Dam and velocity experiments at The Dalles Dam in 2019.

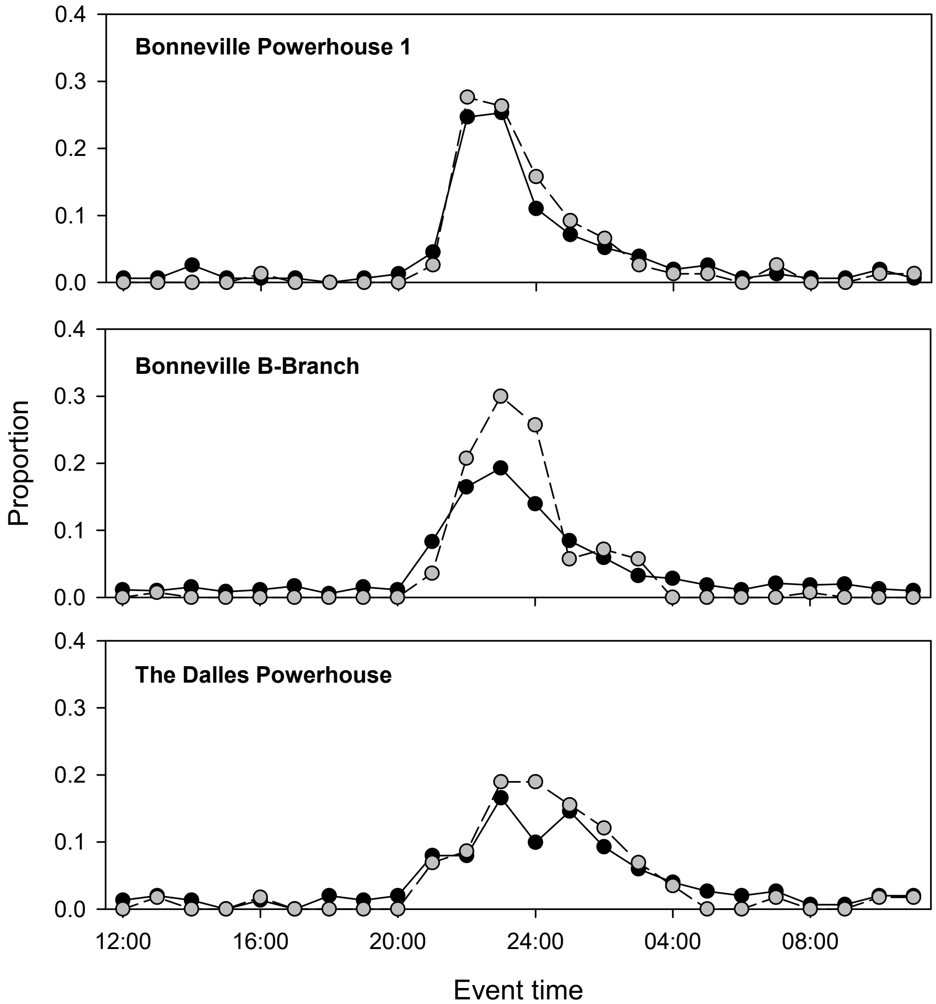

Figure 14. Distributions of the times that double-tagged adult Pacific Lampreys approached (black circles) and entered (gray circles) fishways during nighttime fishway velocity reductions at Bonneville Dam and experimental velocity reductions at The Dalles Dam in 2019.

Lamprey passage outcomes

We compared entrance and fishway passage efficiencies in 2019 at Bonneville Powerhouse 1 and B-branch to values from comparable years to gauge the effectiveness of reduced velocities. Powerhouse 1 entrance efficiency in 2019 (0.83) was higher than the median (0.66) of previous years (with no nighttime reduced velocity) and slightly higher than in 2018 (0.77) when there were experimental reduced nighttime operations (Figure 15). However, after fishway entrance, unique fishway passage efficiency at Powerhouse 1 in 2019 (0.40) was slightly lower than the value from 2018 (0.49, Figure 16) and it was below the median of previous years (0.53). Unique entrance efficiency at Bonneville B-branch in 2019 (0.64, Figure 17) was much lower than at Powerhouse 1 (0.83) but was slightly higher than the B-Branch median (0.54) from previous years (with no nighttime reduced velocity) and higher than the 2018 experimental results (0.55). Although there was a slight improvement in entry efficiency at the B-Branch, unique fishway passage efficiency (i.e., the number that passed the dam the dam/ the number that entered the fishway) was lower in 2019 (0.35) than in 2018 (0.45) and was comparable to the median from previous years (0.39, Figure 18).

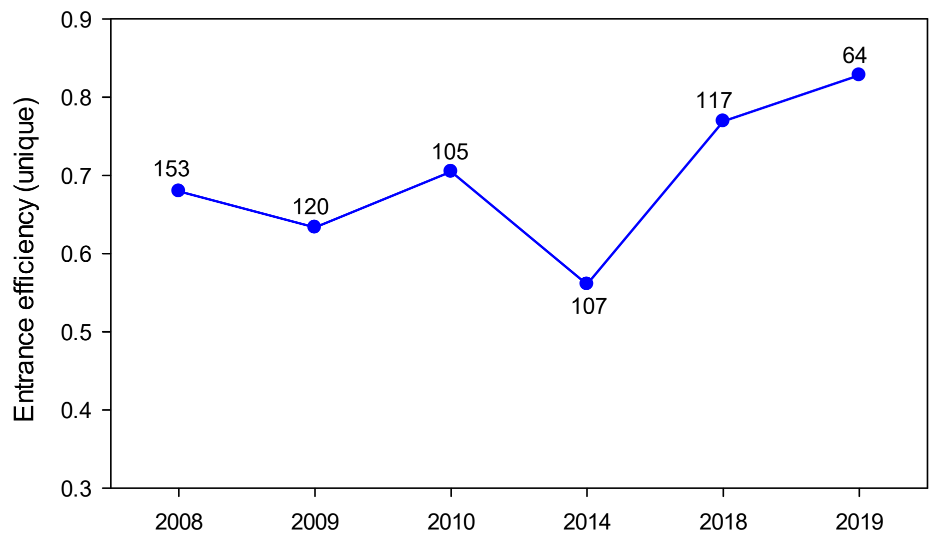

Figure 15. Entrance efficiency (number that entered the fishway/ number that approached the fishway) of unique double-tagged adult Pacific Lampreys at Bonneville Powerhouse 1 fishway entrances in 2008-2010, 2014 and 2018-2019. Samples sizes are above or below each data point.

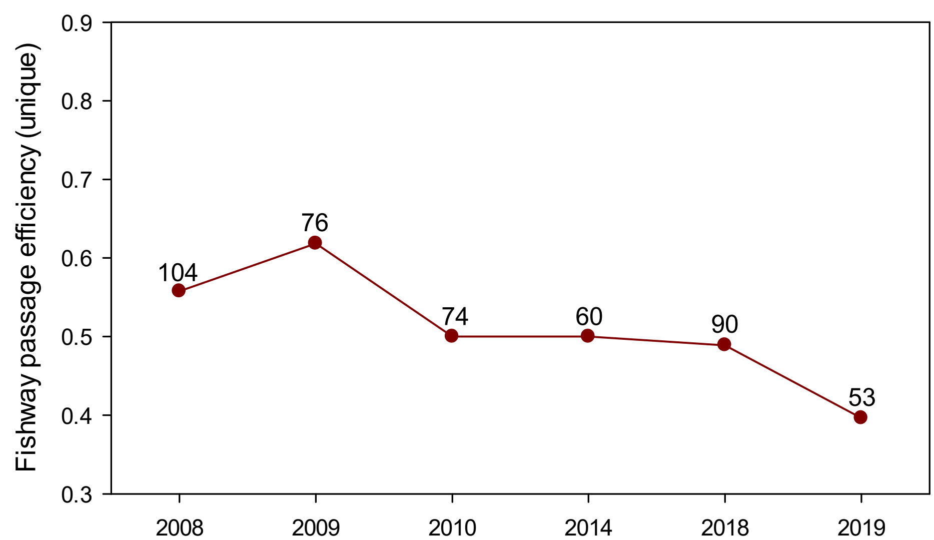

Figure 16. Fishway passage efficiency (number that passed the dam/ number that entered the fishway) of unique double-tagged adult Pacific Lampreys at Bonneville Powerhouse 1 in 2008-2010, 2014 and 2018-2019. Samples sizes are listed above each data point.

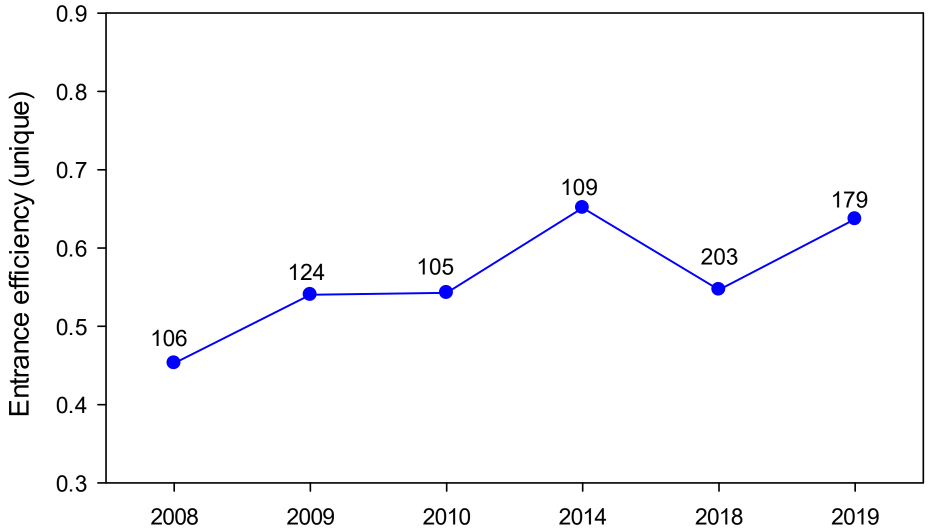

Figure 17. Entrance efficiency (number that entered the fishway/ number that approached the fishway) of unique double-tagged adult Pacific Lampreys at Bonneville B-branch in 2008-2010, 2014 and 2018-2019. Samples sizes are above each data point.

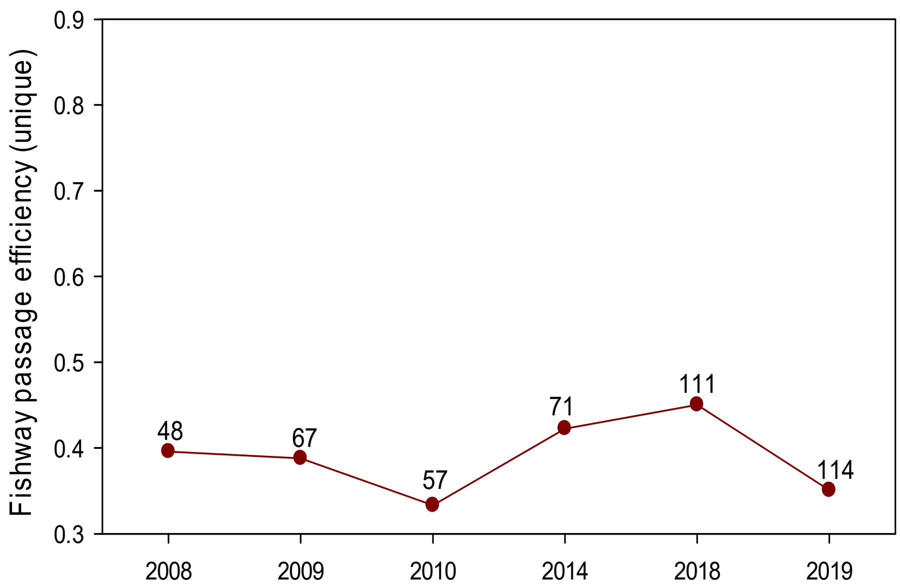

Figure 18. Fishway passage efficiency (number that passed the dam/ number that entered the fishway) of unique double-tagged adult Pacific Lampreys at Bonneville B-branch in 2008-2010, 2014 and 2018-2019. Samples sizes are above each data point.

Overall, reduced nighttime velocities appeared to increase fishway entry rates in 2019 but did not improve dam passage. Using event-based fishway passage efficiencies, the 2019 Powerhouse 1 efficiency (0.28) ranked the lowest among previous years (*range* = 0.32-0.55) (Figure 19). This was also the case at Bonneville B-Branch where event-based fishway passage efficiency in 2019 was 0.24, the same as in 2014 but lower than estimates in 2018 (0.34) and all other previous years (0.26-0.33) (Figure 20).

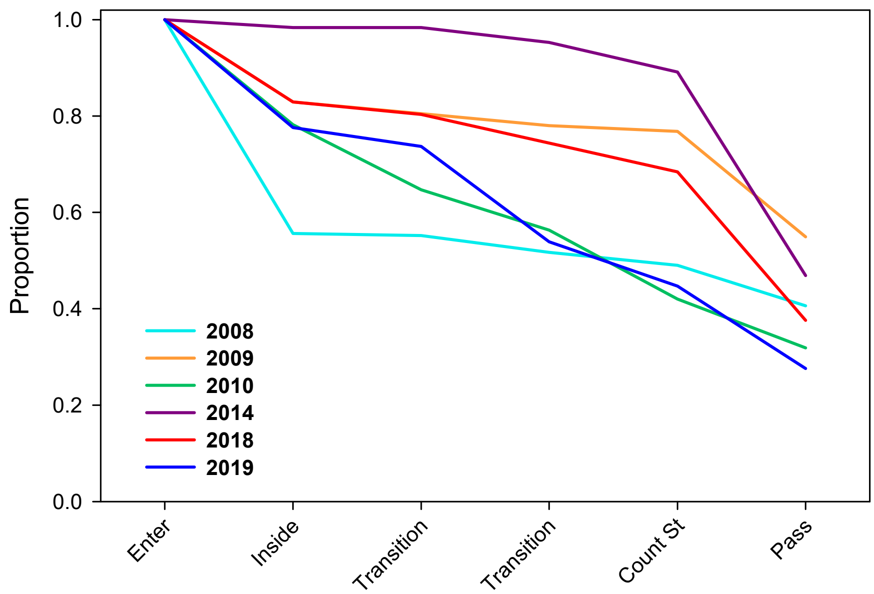

Figure 19. Proportions of double-tagged lampreys after entry at Powerhouse 1 that were recorded inside the lower fishway, in the transition pool area, at the count station, and that passed the dam in 2008-2010, 2014, and 2018-2019.

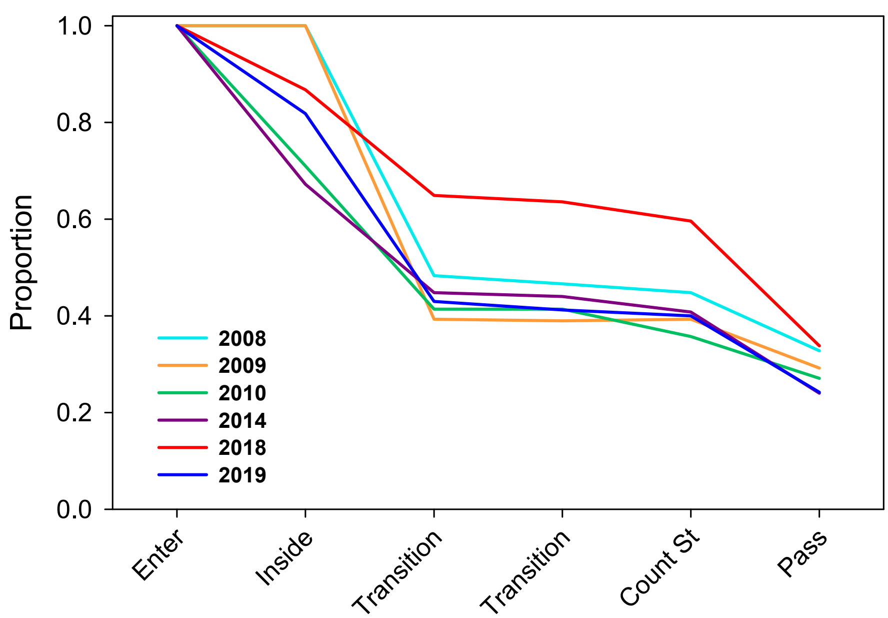

Figure 20. Proportions of double-tagged lampreys after entry at B-Branch, that were recorded inside the lower fishway, in the transition pool area, at the count station, and that passed the dam in 2008-2010, 2014, and 2018-2019.

Entry rates at The Dalles in 2019 were higher at the east powerhouse entrance during reduced velocity periods than during normal conditions. Unique fish entrance efficiency was higher at the east entrance during reduced velocity (100%) than during normal conditions (66%) (χ^2 = 5.1, P = 0.02, n = 46). However, unique fish entrance efficiency did not differ significantly between reduced and normal velocity conditions at the south spillway (χ^2 = 0.1, P = 0.70, n = 12) or west powerhouse (χ^2 = 0.1, P = 0.74, n = 36) entrances in 2019 (Figure 21). We observed similar results in event-based entrance efficiency estimates, with a nearly three-fold higher rate at the east entrance during reduced velocity conditions (87%) than during normal velocity conditions (30%) (χ^2 = 15.3, P < 0.001, n = 103; Figure 21). No differences were observed in event-based entrance efficiency between water velocity conditions at the south spillway (χ^2 = 0.1, P = 0.92, n = 14) or the west powerhouse (χ^2 = 0.0, P = 1.00, n = 49) entrances (Figure 21).

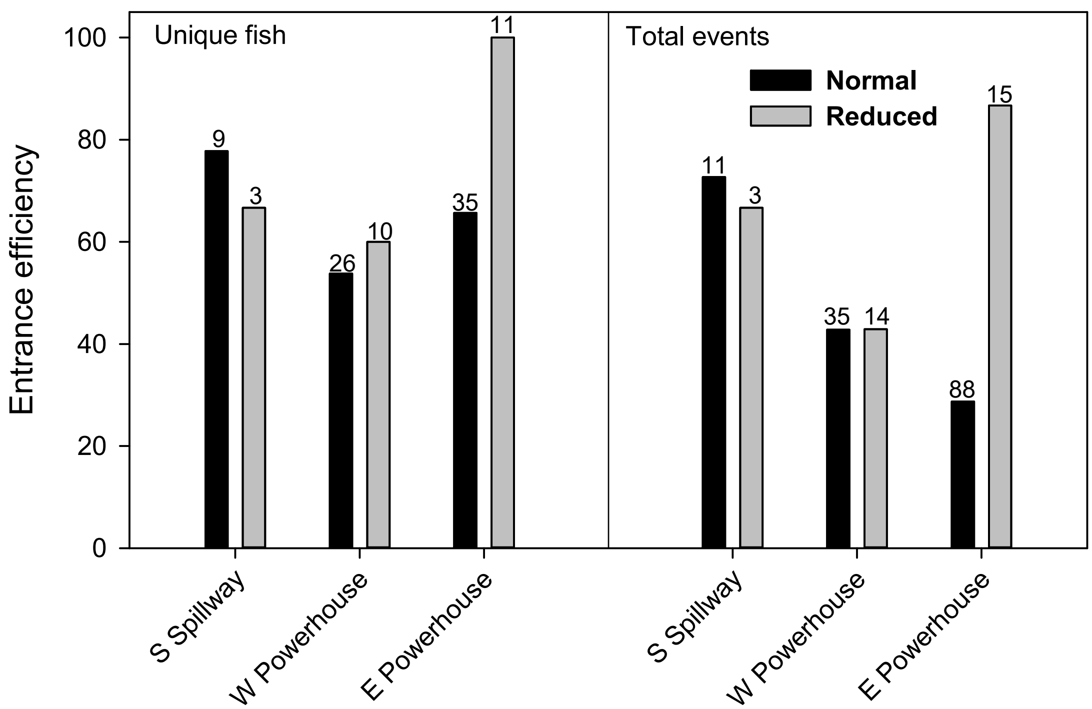

Figure 21. Entrance efficiency (number that entered the fishway/ number that approached the fishway) of unique fish (left panel) and total events (right panel) at The Dalles south spillway, west and east powerhouse entrances during normal and reduced nighttime velocities in 2019. Samples sizes are above each bar.

Discussion

The fishway head manipulations were designed to reduce velocity at the fishway openings and thereby increase the proportion of lampreys that entered fishways. These objectives were achieved at all three study sites in 2019. Event-based fishway entry metrics accounted for velocity conditions and indicated clear statistical improvements in lamprey entry success during the reduced head treatments. The experimental results in 2018-2019 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 reducing velocities on lamprey behaviors was also spatially constrained, and we found little evidence that lamprey behaviors were affected upstream from the head control points at Bonneville Dam. 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 effects of reduced velocity upstream from control points was expected, similar to 2018 experimental results (Clabough et al. 2019), and consistent with observations in the Johnson et al. (2012) experiment.

There was relatively more uncertainty in the reduced velocity 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 at The Dalles (raising and lowering weirs). Second, there were fewer double-tagged lampreys at The Dalles Dam, and third, there was limited lamprey use of the spillway and west powerhouse entrances at The Dalles Dam in 2019. Nonetheless, the reduced treatment effects on lamprey behaviors at The Dalles Dam were very qualitatively consistent with the nightly reduced velocity results at Bonneville Dam.

The generally consistent increase in lamprey entrance efficiency at fishway openings at Bonneville and The Dalles dams implies operations that meet adult salmonid velocity criteria impede lamprey passage behaviors (e.g., Johnson et al. 2012). However, reduced velocities have not measurably increased dam passage success for lamprey, likely because of passage bottlenecks upstream from the fishway entrance areas. Whether nighttime reductions in entrance velocity should be implemented in the absence of a clear full-dam benefit is an open question, but in the absence of strong operational constraints, we recommend reduced nighttime entrance velocity operations continue because available data indicate increased fishway entrance efficiency and fishway use.

3. Lamprey behaviors near the new UMTJ-LPS

Methods

Monitoring sites

Movements of double-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 22-23). 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 by 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.

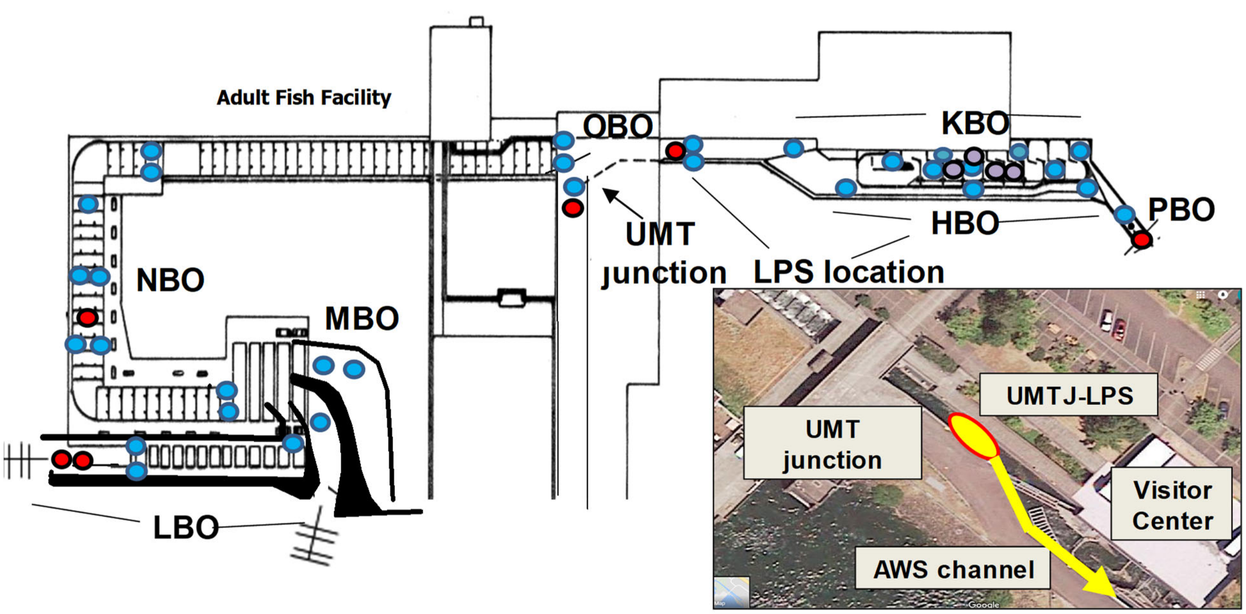

Figure 22. Map of aerial and underwater radio antennas (●, *BO = receiver labels), University of Idaho (UI) HD PIT antennas (●), and PTAGIS dual PIT antennas (●) in the Washington shore fish ladder and AWS channel used to monitor fish behavior. Sites upstream from the UMT Junction were used to evaluate movements near the UMTJ-LPS in 2019.

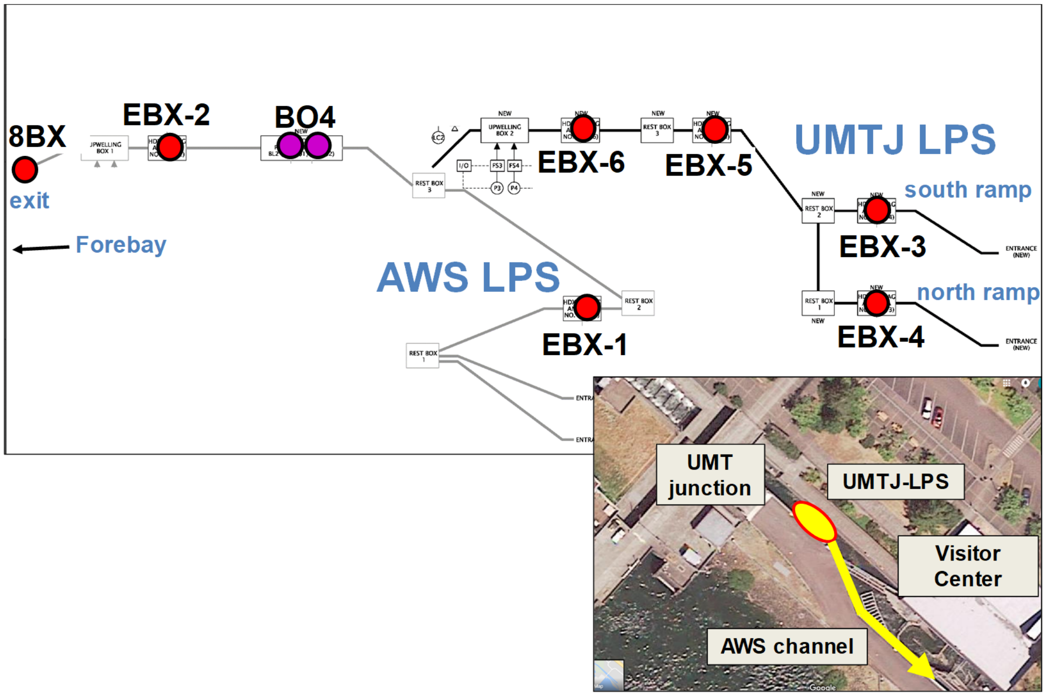

Figure 23. Map of UI (●, *BX-# labels), and PTAGIS HD PIT antennas (●, BO4) in the Washington-shore LPSs (UMTJ-LPS and AWS-LPS) in 2019.

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) lampreys – In total, 137 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 137, 6 (4%) passed through the UMTJ-LPS, 35 (26%) passed via the AWS-LPS, 58 (42%) passed via the ladder, 5 (4%) were recaptured at the AFF, and 33 (24%) did not pass the dam via the WA-shore ladder. Of the 33 that did not pass the dam via the WA-shore, 4 (12%) eventually passed via the BI ladder.

Of the 6 lampreys that passed through the UMTJ-LPS, 100% entered the south ramp of the LPS. All lampreys 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 24). Passage times from UMTJ-LPS detection until dam passage were 0.9 h (n = 6), on median. Median times to pass from the UMT junction (below the UMTJ-LPS) to the top of the ladder were 0.2 d (n = 3) for fish that used the UMTJ-LPS, 0.8 d for fish that used the AWS-LPS (n =20), and 1.1 d for fish that used the ladder (n = 15). For the other three fish that used the UMTJ-LPS but were initially detected in the vertical slot weirs (i.e. missed detection at UMT junction; Figure 24) median total passage time was 7.9 d (n = 3).

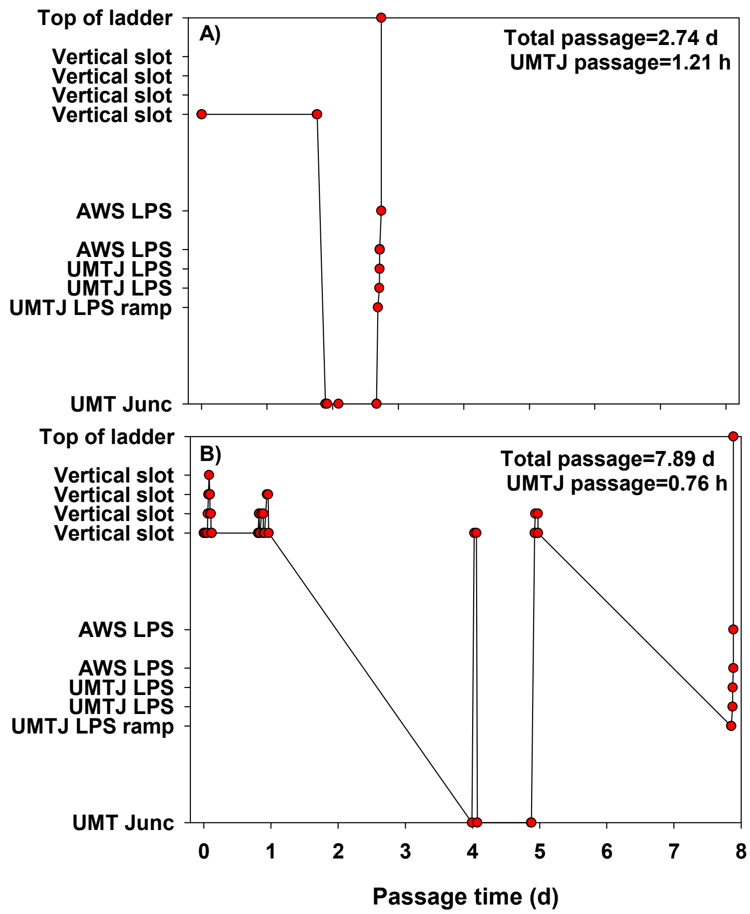

Figure 24. Examples of PIT-tagged lamprey movements and passage times inside the WA-shore fishway before they passed via the UMTJ-LPS. Passage dates were A) 31-July and B) 19-June in 2019. Y-axis labels correspond to locations of individual PIT antennas, ordered from downstream to upstream and 'vertical slot' = serpentine weir.

Double-tagged lampreys – Similar to PIT-tagged lampreys, a near majority of double-tagged lampreys reaching the UMTJ passed via the ladder, with smaller portions passing one of the LPS routes. A total of 139 unique double-tagged lampreys were recorded at one or more antennas near the WA-shore UMTJ-LPS (from the UMT channel junction upstream). Of the 139 lampreys, 11 (8%) passed via the UMTJ-LPS, 15 (11%) passed via the AWS-LPS, 67 (48%) passed via the ladder, 7 (5%) were recaptured at the AFF, and 39 (28%) did not pass the dam via the WA-shore fishway. One lamprey that passed the dam via the UMTJ-LPS backed down the WA-shore fishway and exited to the tailrace. Two (5%) of the 39 lampreys that exited the WA-shore fishway to the tailrace eventually passed the dam via the BI fishway.

Of the 11 double-tagged lampreys that passed via the UMTJ-LPS, 1 (9%) entered the north ramp and 10 (91%) entered the south ramp. Eight initially moved upstream past the UMTJ-LPS 1-4 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 2.7 d for fish using the UMTJ-LPS (n = 7), 1.1 d for fish using the AWS-LPS (n = 9), and 0.9 d for fish using the ladder (n = 46). For fish that were initially detected in the vertical slot weirs (i.e., missed detection at UMT junction OBO2 antenna) median total passage time was 0.8 d (n = 4) for fish that used the UMTJ-LPS. We note total passage times for PIT and double-tagged samples are not directly comparable because of differences in antenna locations for PIT and radio monitoring sites in the main WA-shore fishway channel (Figure 22).

PIT and double-tagged lampreys – Similar proportions of PIT- and double-tagged lampreys passed the dam ($\chi^2 = 0.69$, $P = 0.407$). PIT- and double-tagged lampreys were more likely to pass the dam via the ladder than via LPS routes ($n = 192$, $\chi^2 = 9.94$, $P = 0.001$). Among lampreys that passed the dam, route use for PIT-tagged lampreys was 6.1% UMTJ-LPS, 35.3 % AWS-LPS, and 58.6% ladder and was 11.8%, 16.1 %, and 72.1%, respectively, for double-tagged lampreys. There were no differences in lamprey size metrics among routes (UMTJ-LPS, AWS-LPS, ladder) for PIT or double-tagged lampreys (ANOVA, all $P > 0.05$). However, migration date (first detection at UMT junction) differed among routes for double-tagged lampreys (df =2, $F = 4.53$, $P = 0.013$), where the average date of ladder use was later in the season (Figure 25).

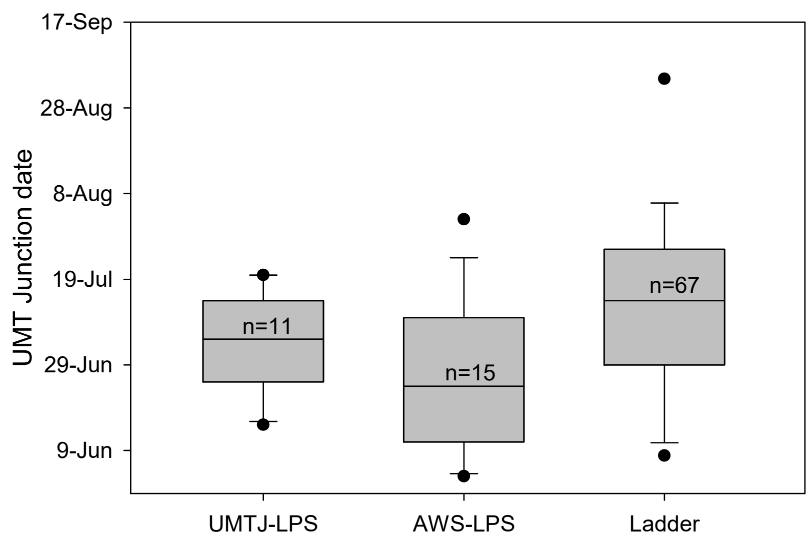

Figure 25. Box plots of first UMT junction date for double-tagged lampreys that passed Bonneville Dam via three routes at the WA-shore fishway. Distributions show 5th, 10th, 25th, 50th, 75th, 90^{th,} and 95th percentiles.

Lamprey behavior after exiting the LPSs at Bonneville Dam

Washington-shore fishway – Overall, 64 (96%) of radio and PIT tagged lampreys that exited LPS structures continued migrating upstream while 3 (4%) had records indicating downstream movements. Forty-six double-tagged fish had detections on AWS radio antennas and 26 likely passed through the WA-shore LPSs (11 UMTJ-LPS + 15 AWS-LPS) based on PIT detections.

One of the eleven lampreys 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. One lamprey passed through the UMTJ-LPS and then swam down the WA-shore fishway and exited to the tailrace. One lamprey passed the WA-shore fishway through the AWS-LPS, swam upstream to The Dalles Dam and later (13 days) fell back past Bonneville Dam and was last recorded in the tailrace. Forty-one PIT-tagged (only) lampreys passed via the WA-shore LPSs (6 UMTJ-LPS + 35 AWS-LPS) and had no detections indicating downstream movements.

Cascades Island fishway – Two PIT-tagged (only) lamprey were detected in and passed via the CI LPS.

Bradford Island fishway – Twenty-eight double-tagged fish were detected in the AWS (on radio antennas) and 15 likely passed the fishway through the LPS based on PIT detections. Two of the 15 lampreys (13%) that passed via the BI AWS-LPS fell back, but here were no records that indicated these fish moved down the BI ladder. Both fish were recorded in the tailrace via an unknown route, 1 and 11 days after exiting into the forebay.

Another 20 PIT-tagged (only) lamprey passed via the BI AWS-LPS and one (5%) fell back. There were no records that indicated this fish moved down the ladder. The lamprey reascended the dam via the BI fishway, fell back a second time and was eventually recaptured at the AFF (WA-shore), released at Stevenson, WA and was last detected at Lyle Falls in the Klickitat River.

Discussion

Overall, a small percentage (4-8%) of tagged lampreys that reached the area of the UMTJ-LPS used it to pass the dam at the WA-shore fishway in 2019. The 2019 use rates were similar to those observed in 2018 (first year of operation), which were 4-6% (Clabough et al. 2019). Telemetry records indicated that the low percentage was likely due to lampreys failing to initially locate the UMTJ-LPS ramps or other environmental cues compelled them to swim past the structure upon initial encounter. Specifically, we observed high percentages of tagged lampreys (81% in 2019 and 92% in 2018; Clabough et al. 2019) that used the UMTJ-LPS initially swam upstream past the UMTJ-LPS multiple times before returning downstream to enter it 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 to the entrance of the LPS ramps (Keefer et al. 2011; Zobott et al. 2015). We note, however, that in our UMTJ-LPS observations using DIDSON in 2017, adult salmonids were not attracted to the UMTJ-LPS ramps (Clabough et al. 2018).

Lamprey passage times through the UMTJ-LPS to pass the dam were similar between radio- (1.1 h) and PIT-tagged (0.9 h) lampreys in 2019 and were also similar to times we observed in 2018 (0.8 -1.1 h; Clabough et al. 2019). However, overall passage times through the UMTJ-LPS from the UMT junction or vertical slot weir area to pass the dam varied and were related to how many times a fish ascended and descended the fishway. For PIT-tagged lampreys, times ranged from 0.1 to 14.0 d and from 0.1 to 10.0 d for double-tagged lampreys. In statistical analyses, we found similar proportions of PIT and double-tagged lampreys passed the dam in 2019. We also found PIT and double-tagged fish were more likely to pass via the ladder. However, in 2018 we found PIT-tagged fish were more likely to pass via the LPSs and double-tagged lampreys were more likely to pass via the ladder (Clabough et al. 2019). This between-year difference may have been attributed to more PIT-tagged lamprey using the slot orifices installed in the WA-shore fishway and/or may have been due to the smaller tagged sample in 2019. We also found that double-tagged lampreys were more likely to pass through the ladder later in the year, which could have been due to increased use of the lamprey slot orifices later in the year and/or effects of changing environmental conditions (e.g. water temperature or hydraulic head in the upper fishway segments).

A small percentage (5-13%) of lampreys that used the LPSs at Bonneville Dam swam down the ladder or fell back over the dam and approximately a third of those fish reascended a fishway. Backing down the ladder after exiting an LPS is possible at the WA-shore fishway because the LPS exits into the main fishway above the serpentine weirs rather than into the dam forebay. At the BI fishway, the exit from the LPS is into the forebay and is close (~6 m; 20 ft) to the main fish ladder exit. Extending the WA-shore LPS exit into the forebay could alleviate the downstream movement problem.

Overall, there are structural similarities between the AWS and UMTJ-LPSs, but the relatively high use of the AWS LPS suggests factors beyond design specifications of LPS structures affect lamprey use. The AWS LPS location near the head of a 'dead end' channel and initial bypass of the UMTJ-LPS by UMTJ-LPS users suggest a combination of guidance cues and individual motivation affect the induction of orientation to and climbing of LPS ramps. Specifically, climbing may not be induced in locations where free-swimming past the structure is readily achieved (i.e., the channel between the UMT and AWS pickets and the LPS entrance at the Cascades Island fishway) and/or strong structural or hydraulic guidance is necessary to induce climbing. Notably, the UMTJ-LPS rates of use did not measurably increase between 2018 and 2019 as has been observed in other locations after structures "season" for one or more years. Future siting of LPS structures should carefully consider the broader structural and hydraulic context of ramp placement. Selection of locations with structural and hydraulic conditions analogous to the AWS LPSs, i.e., at locations with structural and hydraulic barriers likely to mirror natural conditions inducing climbing such as at waterfalls or rapids may prove to produce higher LPS use rates.

4. Lamprey behaviors near Bonneville count stations and serpentine weirs

Methods

Movements of double-tagged lampreys were extensively monitored to evaluate passage success and identify passage bottlenecks. Underwater antennas were located near the UMT junction channel (WA-shore), near the count windows, serpentine weir sections and AWS channels of both the WA-shore and BI fishways in 2019 (Figure 26). Individual lamprey 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 first detection date above the UMT (WA-shore) or above the BI transition pool on passage outcomes using methods described in the UMTJ-LPS section. We used logistic regression in SAS v.9.2 (SAS Institute, Cary, North Carolina) for the model: dam passage (y/n) = date + weight + length + girth + dorsal distance.

Results

Washington-shore fishway – As described in the UMTJ-LPS section, 139 unique double-tagged lampreys were recorded with one or more antennas at or upstream from the UMT channel junction. Of the 139, 93 (67%) passed the dam, 39 (28%) did not pass the dam via the WA-shore fishway, and seven (5%) were recaptured in the WA-shore AFF. The seven 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 WA-shore fishway ($0.01 < \chi^2 < 1.76$, $P > 0.05$).

Lampreys moved extensively within the upper fishway. Of the 93 fish that passed the dam via the WA-shore, 88% (*n* =82) were recorded on the antenna below the count window (KBO5) and 92% (*n* = 86) were recorded on the antenna above the count window (KBO4; Figure 26). About a quarter (*n* = 22, 24%) of the 93 fish that passed the dam were recorded on antennas in both the serpentine weirs and inside the AWS channel. The majority of fish (72%) that passed the dam did so via the serpentine weirs, 16% passed through the AWS-LPS, and 12% passed through the combined UMTJ-LPS and AWS-LPS.

Of the fish that did not pass the dam via the WA-shore (*n* = 39), 90% were recorded on the antenna below the count window (KBO5) and 90% were recorded on the antenna above the count window (KBO4). The furthest upstream record (turnaround point) for a large majority (87%, *n* = 39) of fish that did not pass was in the serpentine weir section (Figure 27). Most (*n* = 30, 88% of 34) of the serpentine turnarounds were estimated to have occurred at the uppermost antennas (KBO6 = 17%; HBO5=6%, KBO2 = 65%). The next largest group of non-passers, (*n* = 3, 8% of 39) had their most upstream record near the UMT junction channel and the last two (5% of 39) had their most upstream records in the AWS channel at the most upstream antenna (HBO3; Figure 27). Neither of these 2 fish were detected in the WA-shore LPSs.

Of the 39 lampreys that did not pass, 87% (n = 34) were last recorded in the Bonneville tailrace, 5% (n = 2) were last detected in the WA-shore ladder, 5% (n = 2) passed the dam via the BI fishway, and 3% (n = 1) was last detected in the CI fishway. Equal numbers of lampreys that were last were recorded in the tailrace had exited WA-shore fishway through the UMT channel via the CI fishway (n = 17, 50% of 34) or exited the WA-shore fishway directly to the tailrace (n = 17, 50% of 34). Two of the 39 fish last recorded in the tailrace had exited to the tailrace after making multiple attempts to ascend the WA-shore fishway.

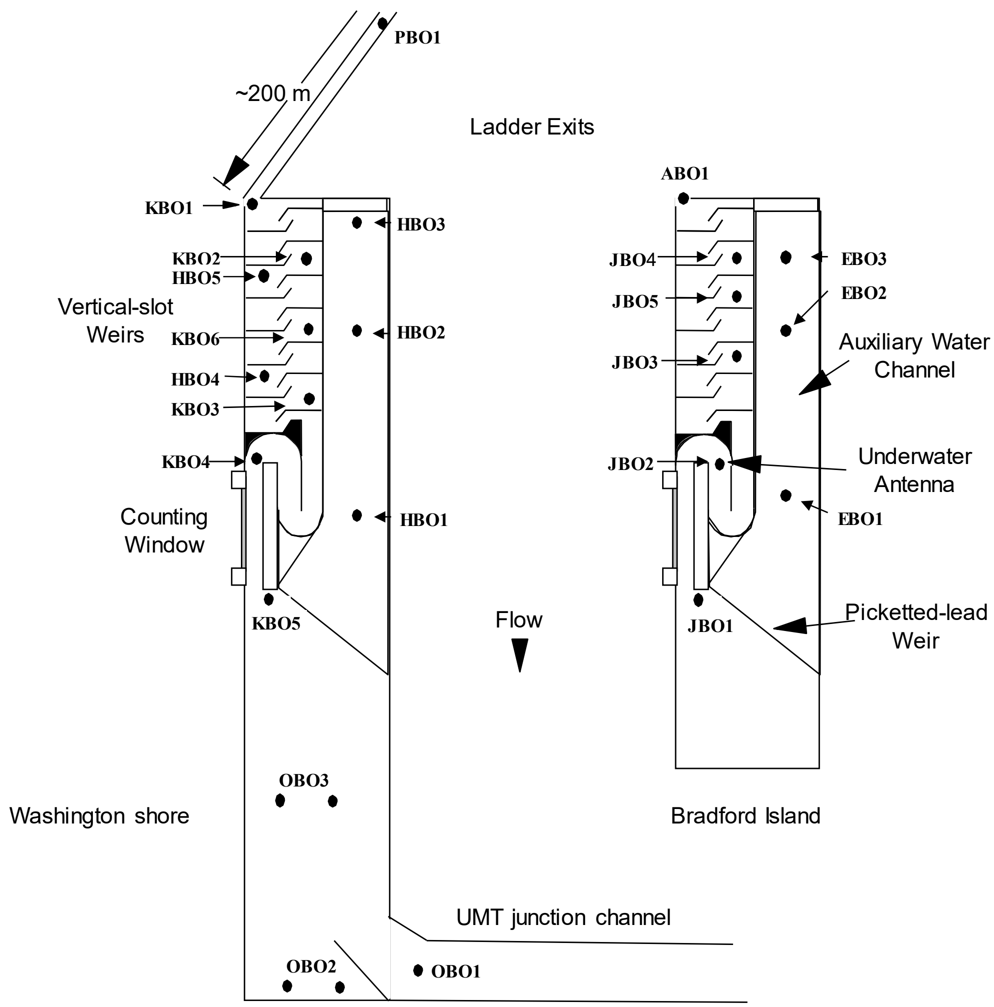

Figure 26. Overhead diagram of radio antenna deployments at upper sections of the Bonneville Dam fishways in 2019, including the UMT junction channel (WA-shore only), count stations, serpentine weirs, and auxiliary water supply (AWS) channels. Note drawings are not to scale and HBO4 and HBO5 were new antennas deployed in the WA-shore fishway in 2019.

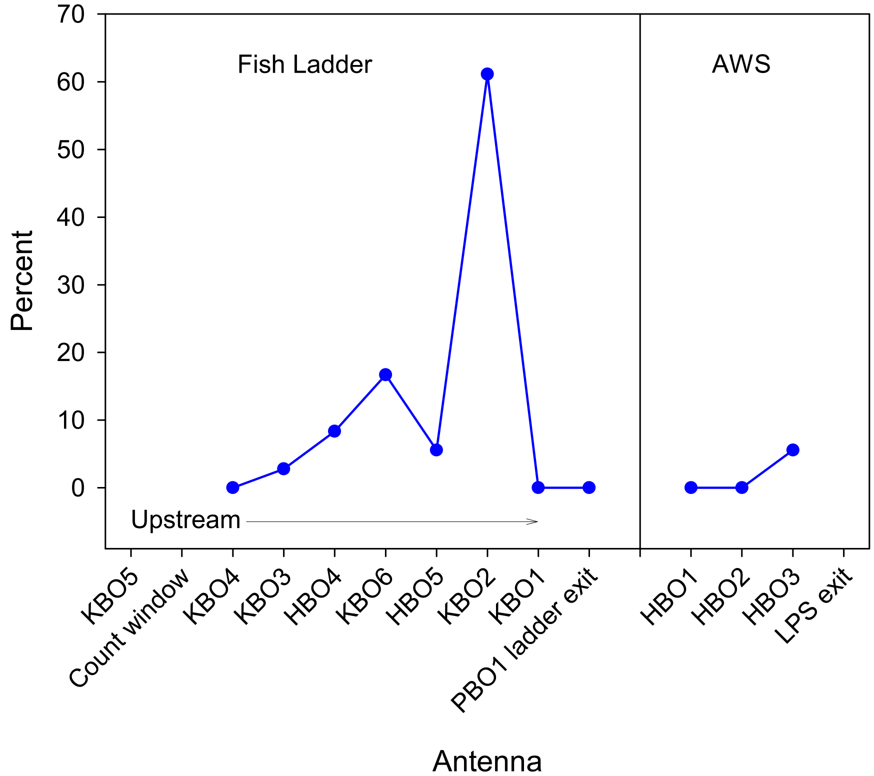

Figure 27. Distribution of furthest upstream detections, by antenna, for 39 double-tagged lampreys that did not pass Bonneville Dam after reaching upper sections of the WA-shore fishway ('Fish ladder') or LPSs. AWS = auxiliary water supply channel.

Bradford Island fishway – In total, 95 unique double-tagged lampreys were recorded at one or more antennas upstream from the BI junction pool. Of the 95 lampreys, 57 (60%) passed the dam via the BI fishway or LPS, 33 (35%) did not pass the dam, and five (5%) were recaptured in the BI AWS and released upstream at Stevenson, WA. The five recaptured fish were excluded from the behavior summary below. We found no differences in size or date among lampreys that did and did not pass the dam via the BI fishway ($1.07 < \chi^2 < 3.04$, $P > 0.05$).

Of the 57 fish that passed the dam, 98% (*n* = 56) were recorded on the antenna below the count window (JBO1) and 96% (*n* = 55) were recorded on the antenna above the count window (JBO2; Figure 26). More than a quarter (*n* = 16, 28%) of the fish that passed were recorded on antennas in both the serpentine weir section of the ladder and the AWS channel. The majority (74%) passed the dam through the ladder and 26% passed through the AWS-LPS.

Of the 33 fish that did not pass the dam via the BI fishway, 94% were recorded on the antenna below (JBO1) and above (JBO2) the count window. The furthest upstream record (turnaround point) for the majority (82%, *n* = 27) of fish that did not pass the dam was in the serpentine weirs. Of the 27 fish that ultimately turned around in the serpentine weir section, 20 (74%) were detected at the uppermost antennas (JBO5 = 48%; JBO4 = 26%; Figure 28). Two fish (6%) were detected at the top-of-ladder exit antenna (ABO1) before turning around and moving downstream. The other 12% (*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 33 fish that did not pass the dam via BI included 97% (*n* = 32) in the Bonneville tailrace and 3% (*n* = 1) that was last detected inside the BI fishway. Of the 32 fish last recorded in the tailrace, 59% (*n* = 19) moved downstream via the B-branch and 41% (*n* = 13) via the A-branch. Two of the 32 fish last recorded in the tailrace attempted to ascend the BI fishway multiple times from the tailrace.

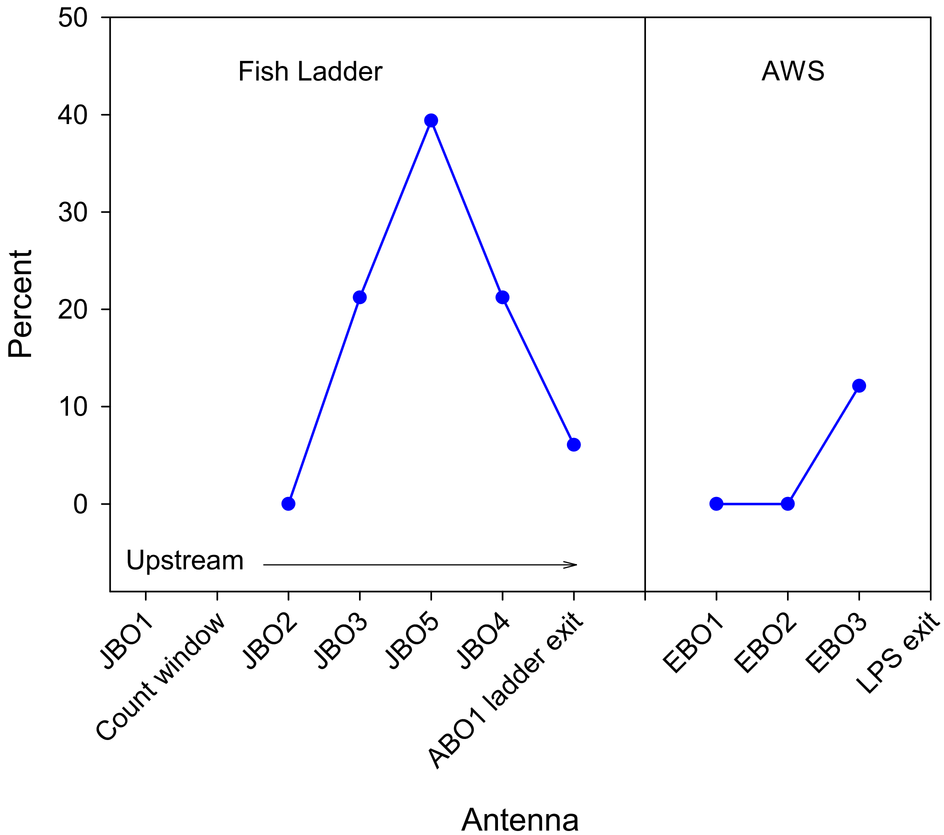

Figure 28. Distribution of furthest upstream detections, by antenna, for 33 double-tagged lampreys that did not pass Bonneville Dam via the BI fishway ('Fish Ladder') or LPS after reaching upper sections of the BI fishway ('Fish ladder'). AWS = auxiliary water supply channel.

Discussion

The proportions of lampreys reaching the serpentine weirs but failing to pass has been broadly similar between ladders and across years. We observed lower turnaround rates in the serpentine weir section of the WA-shore ladder in 2019 (28%) than in 2018 (34%). The 2019 turnaround percentage was the second lowest 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). In 2019, 35% of lampreys detected near the BI count station, or in the BI AWS, did not pass the dam. The 2019 estimate was in the middle of the range of values from previous study years: 16% (2008), 27% (2009), 26% (2010), 38% (2018), 43% (2014) (Johnson et al. 2009; Clabough et al. 2010b, 2011, 2015).

The majority of the non-passing fish still turned around in the serpentine weirs in both fish ladders. These areas have been previously identified as difficult areas of passage for lamprey due to high water velocity and turbulence (Clabough et al. 2012; Keefer et al. 2013b; Kirk et al. 2017). In 2019, 87% of non-passers turned around in the WA-shore serpentine weirs compared to 64% in 2018 and 71% in 2014 (Clabough et al. 2015; Clabough et al. 2019). At the BI fish ladder in 2019, 82% of non-passers turned around in the serpentine weirs compared to 80% in 2018 and 92% in 2014 (Clabough et al. 2015; Clabough et al. 2019). In 2019, we observed fewer non-passers turning around after reaching the antenna at the BI ladder top (6%) compared to 2018 (13%). In the WA-shore ladder, a smaller percentage of fish were detected on the antenna above the count window (KBO4; Figure 26) in 2018 (77%) than in 2014 (92%), which may have been due in part to fish using the lamprey slot orifice at Weir 1 (see Figure 29) and not being detected on KBO4 in 2018. Concomitant experiments demonstrating an effect of prior exercise on passage success suggest exercise physiology and prior condition influence passage decisions to a greater degree than morphological traits (Hanchett and Caudill 2020). The lack of relationship observed between size or date and passage outcome through the serpentine weirs was consistent with past studies testing for body size effects on passage through individual fishway segments which have generally failed to detect increases in passage probability among larger lampreys. The lack of effect contrasts strongly with increased passage by larger lampreys at the dam and at multi-dam reach scales (Keefer et al. 2012; Keefer et al. 2020).

5. Lamprey behaviors and passage in the Washington Shore fishway in relation to lamprey slot orifices

Methods

Slot orifices (horizontal openings 16” wide x 1.5” tall) were cut into the bases of the first three WA-shore serpentine weirs at Bonneville Dam in 2017 to provide lamprey a direct route upstream and facilitate dam passage (Gallion et al. 2017). The first three slots were available to lamprey during the 2017 and 2018 migrations (Figure 29). Before the 2019 migration, an additional six slot orifices were installed and the downstream-most slot (at Weir 1) was closed, making a total of eight slots available in 2019. Two additional underwater radio antennas (HBO4 [H4] and HBO5 [H5]; Figure 29) were installed on the north side of the serpentine weir section in 2019 to augment radio coverage of double-tagged lampreys near the slot orifices.

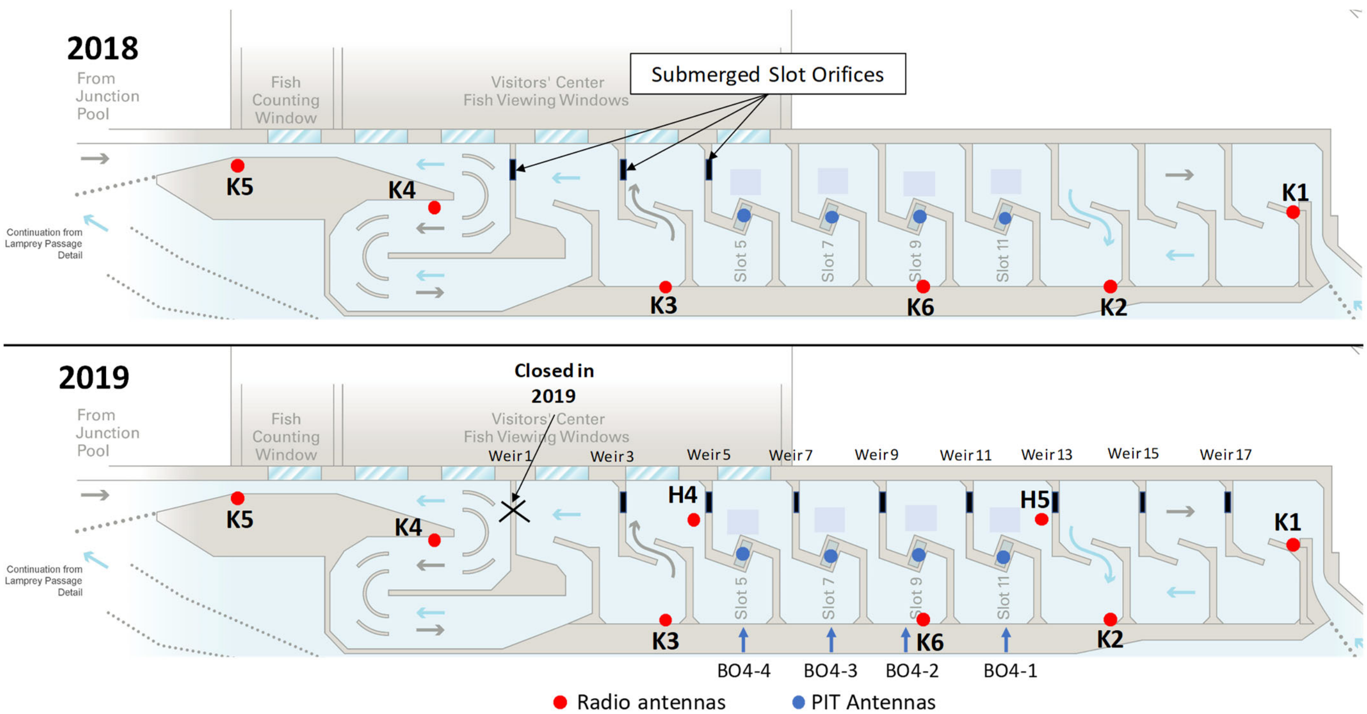

Figure 29. Overhead diagram of lamprey slot orifices, radio antenna, and PIT antenna deployments at the WA-Shore count station and serpentine weirs in 2018 and 2019. Note drawings are not to scale and HBO4 (H4) and HBO5 (H5) were new radio antennas deployed in the WA-shore fishway in 2019. Weir 1 lamprey orifice slot was closed in 2019.

Video monitoring or PIT technologies were not available in 2018 or 2019 to directly monitor lamprey movements through the lamprey slot orifices. We therefore evaluated HD PIT and radio data collected from double-tagged adult lampreys in both years to make indirect inferences about their use of the slot orifices between years. We assumed that if lamprey passing the dam used the lamprey slot orifices in 2019, those individuals would not be detected at the four slot PIT antennas or radio antennas on the south side of the fishway (Figure 29).

We identified unique, double-tagged lamprey that passed Bonneville Dam via the WA-shore serpentine weirs in each year and estimated the percentage of successful migrants (based on upstream records) that had no detections on the south-side radio antennas (i.e., KBO3 [K3] and KBO6 [K6]) none at the four BO4 PIT antennas monitoring the vertical-slots. We then compared percentages of passed lampreys that missed individual antennas between years.

Conversely, we compared the percentages of double-tagged lamprey detected on each radio and PIT antenna in the vertical-slot weirs in 2018 and 2019 and evaluated the proportions that passed the dam via the serpentine weirs in both years. For purposes of this evaluation, we interpolated detection values for antennas HBO4 and HBO5 in 2018 based on means of adjacent antennas (because HBO4 and HBO5 were not deployed in 2018). A decrease in passage probability at upper antennas in 2019 would indicate potential that the slots impeded passage by, for example, inducing downstream movements.

Results

Lampreys that passed via the serpentine weirs had higher percentages of ‘missed’ antenna-specific detections in 2019 compared to 2018 (Figure 30). Because proportionately more lamprey missed south-side radio and PIT antennas in 2019 compared to 2018, when fewer orifice slots were available, we tentatively conclude that alternate routes were likely used in this section of the fishway in 2019.

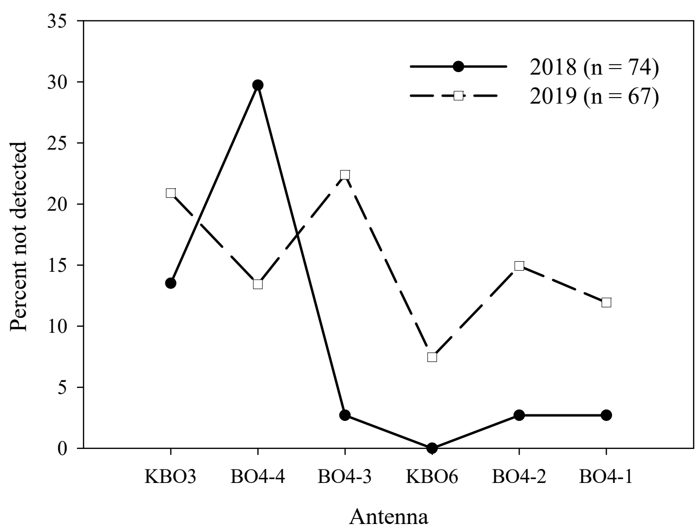

Figure 30. Percent of ‘missed’ detections on south-side radio antennas and on the vertical-slot BO4 PIT antennas by double-tagged Pacific Lampreys that successfully passed Bonneville Dam via the WA-shore serpentine weirs in 2018 and 2019. PIT antennas: BO4-1 - BO4-4; radio antennas KBO3 and KBO6 were on the south side of the fishway. Antennas are ordered from downstream to upstream. Lower detections among passing lamprey during 2019 than 2018, particularly on upstream antennas, is consistent with use of the lamprey slot orifices.

Higher percentages of double-tagged lamprey detected in the vertical-slot weirs passed via this section of the fishway in 2019 (51%) compared to 2018 (39%), suggesting at a minimum, that the increased number of slot orifices in 2019 compared to 2018 (8 vs. 3) did not impede lamprey passage (Figure 31).

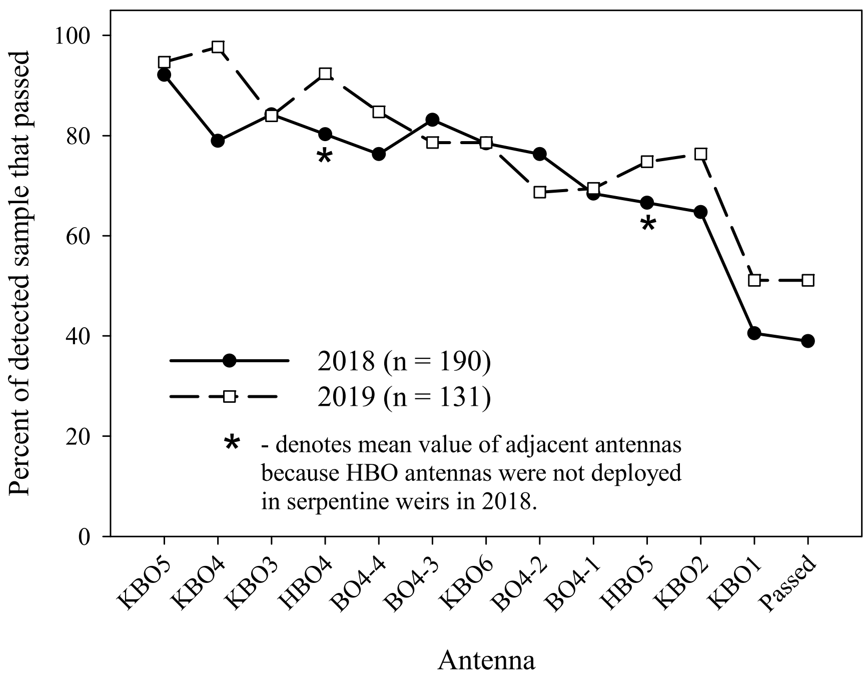

Figure 31. Percent of double-tagged adult Pacific Lampreys detected on south-side radio antennas and on the vertical-slot BO4 PIT antennas that successfully passed Bonneville Dam via the WA-shore serpentine weirs in 2018 and 2019.

Discussion

We emphasize that no direct observations of lampreys using the slot orifices were made for this evaluation in either year by our research group. No outages were observed on radio receivers KBO or HBO in 2018 (when HBO monitored the AWS only) or 2019 so we have reasonable confidence in our radio detection/non-detection estimates. Similarly, detection efficiencies for the vertical-slot PIT detectors are ~99% (N. Tancreto, PSMFC, *personal communication*). We conclude patterns of movement between years are consistent with use of the lamprey slot orifices, though other mechanisms are possible and we recommend direct observation in future years to confirm use of this route by migrating lampreys. Nevertheless, the conclusion is consistent with the findings of Gallion et al. (2017), who used video monitoring of lamprey behavior near the slot orifices and found net upstream movements of lampreys who interacted with the orifices at weir 3 (upstream/ downstream ratio of 2:1) and weir 5 (upstream/downstream movement ratio of 3:2). There were net downstream movements at weir 1 in 2017, where slower water velocities were present, which was the basis for the authors recommending the slot orifice at weir 1 be closed before the 2018 migration.

6. General fishway and dam passage metrics

Methods

General fishway and dam passage metrics were only evaluated for double-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 double-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 one or more transition pool), 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 lampreys 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 a dam

At each dam, we reviewed the detection histories for each unique double-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 449 double-tagged lampreys released downstream from Bonneville Dam, 379 (84%) approached a Bonneville Dam fishway. The highest percentage first approached at Powerhouse 2 (PH2) fishway openings (44%), followed by the BI spillway opening (28%), Powerhouse 1 (PH1, 14%) and the CI spillway opening (10%; Figure 32). Seventeen first approach events were at unknown PH2 locations (< 4%). The highest percentage of all approach events was at PH2 (69%), followed by the spillway (24%), and PH1 (4%). On average, lamprey approached fishways 11.8 times per fish (*median* = 6; *range* = 1-218), though we note active approaches could not be distinguished from "swim-by" events.

Fishway entries – A total of 331 lampreys were recorded inside Bonneville Dam fishways (74% of 449 released and 87% of 379 that approached a fishway). Many lampreys first entered at PH2 (14% at south entrances and 22% at north entrances) and the fewest first entered the PH1 north entrance (3%; Figure 32). Among the 52 first entry events where both time and location were unknown, all occurred at PH2. This was due in part to unmonitored routes along the face of the powerhouse. These 52 first unknown entry events represented ~16% of all 331 first entry events. The distribution of total fishway entries was generally similar to the distribution of first entries (Figure 32). Lampreys that entered a fishway did so 2.4 times per fish, on average (*median* = 2; *range* = 1-13).

Fishway exits – A total of 252 lampreys exited a Bonneville fishway to the tailrace, 76% of the 331 that entered. Most of the fishway exits (43% of first and 43% of total) were from PH2 openings, most frequently from the north-shore entrances (Figure 32). Approximately 30% of first exits and 31% of all exits were from the two fishways adjacent to the spillway combined. Thirteen percent of first exits and 11% of all exits were from PH1 openings. Exits from unknown sites comprised 14% of first exits and 16% of all exits, with nearly all (95 of 96) unknown fishway exits occurring at PH2. 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* = 1-12).

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 0.3 d (6.7 h), 1.2 d (28.9 h), and 8.2 d (197.2 h), respectively (Table 3). 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 0.3 d (6.6 h), 1.2 d (28.7 h), and 8.2 d (197.3 h), respectively. Lamprey release sites were near the aerial tailrace antennas at Bonneville Dam in 2019.

Lampreys entered a fishway after their first recorded approach in a median of 0.7 h. Passage times were also relatively rapid from first fishway entry to first transition pool entry (*median* = 0.016 h) but were slower through transition pools for lamprey that passed the dam (*median* = 1.8

h). Passage times were much longer and more variable from the transition pool exit to the top-of-ladder exit (*median* = 27.7 h).

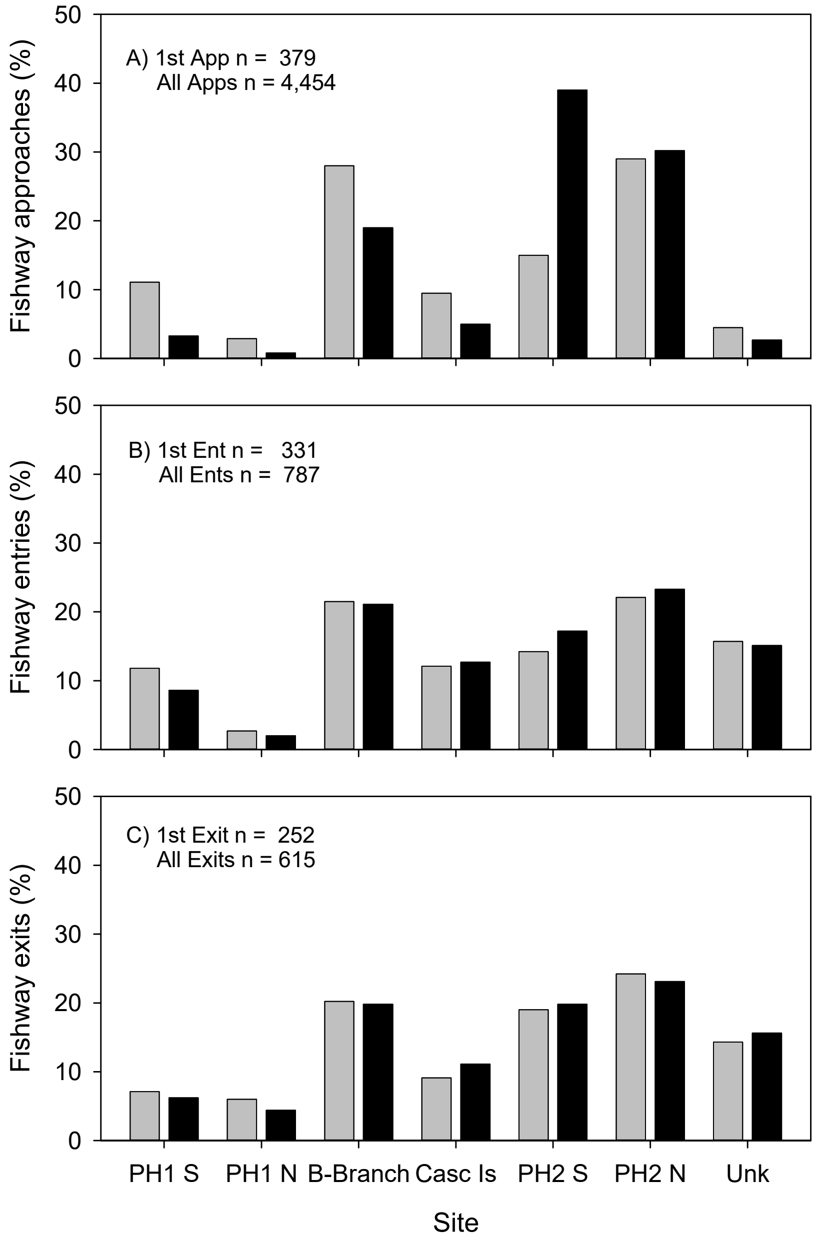

Figure 32. Distributions of first (gray bars) and total (black bars) fishway approaches, fishway entries, and fishway exits among sites by adult, double-tagged Pacific Lamprey at Bonneville Dam in 2019. The Unknown (Unk) category includes fish recorded inside a fishway without a clear fishway approach, entry, or exit site.

Table 3. Passage times for adult, double-tagged Pacific Lamprey at Bonneville Dam in 2019. Q1 and Q3 are first and third quartiles, respectively. This summary includes data for fish that were recaptured in the AFF or in the BI auxiliary water supply for passage segments where estimates could be calculated.

Passage segment			Passage time (h)			
Start	Finish	*n*	Median	Mean	Q1	Q3
Release	First approach	354	6.7	57.6	4.2	59.2
Release	First entrance	267	28.9	75.3	5.3	100.6
Release	Past dam	172	197.2	239.9	79.2	338.0
Tailrace	First approach	334	6.6	56.1	4.1	53.6
Tailrace	First entrance	253	28.7	75.1	5.3	100.5
Tailrace	Past dam	165	197.3	243.0	79.3	340.1
First approach	First entrance	267	0.7	33.9	0.2	24.3
First entrance	Transition pool entry	258	0.16	5.3	<0.01	0.3
First entrance	Past dam	134	73.0	124.2	26.0	172.1
Transition pool entry	Transition pool exit[a]	141	1.8	83.2	0.7	121.6
Transition pool exit	Past dam	141	27.7	63.6	23.6	71.9

[a] includes only fish that passed the dam.

Bonneville passage efficiency

Dam-wide passage efficiency – Of the 449 lampreys released downstream from Bonneville Dam, 379 (84%) were recorded approaching a Bonneville Dam fishway, 331 (74%) entered a fishway, and 173 (38%) passed the dam (Table 4). These three estimates were equal to or varied by 2-4% compared to pre-2019 median values from twelve previous study years (88%, 74%, and 40%, respectively). Eighty-seven percent of tagged lamprey that approached a fishway in 2019 subsequently entered a fishway. The 2019 estimate was roughly equal to the 2018 value (86%) and the median 86% value estimated from previous study years. Dam-wide dam passage efficiency (passed dam / approached fishway) was 46% and dam-wide fishway passage efficiency (passed dam / entered fishway) was 52% in both 2018 and 2019; both values were roughly equal to the corresponding median values from previous years.

Passage metrics varied slightly when including or censoring recaptured lamprey in calculations (Table 5). Twenty-four (5%) of the 449 fish were recaptured at the dam after being released downstream. Dam-wide dam passage efficiencies ranged from ~42-46% and dam-wide fishway passage efficiencies ranged from ~48-52%, depending on the inclusion or exclusion of recaptured fish.

Route-specific fishway entrance efficiency –Estimates of route-specific fishway passage efficiency ranged from 7 to 43% among sites, with the highest percentage of dam-passing lamprey observed among unique CI fishway entrants (Table 6). In contrast, few (7%) of the 76 unique lampreys that entered the PH2 South openings passed the dam. Passage efficiency estimates based on total entry events ranged from 4 to 33% among sites. Rankings among sites were similar for estimates based on the number of unique fish or total events at respective sites.

Table 4. Dam-wide passage efficiency metrics for unique, double-tagged Pacific Lamprey at Bonneville Dam in 1997-2002, 2007-2010, 2014, and 2018-2019. Released (Rels.) = released; Approached (App.) = approached fishway opening; Entered (Ent.) = entered fishway; Passed = passed dam. Fish were collected and tagged at Bonneville Dam. Sources for pre-2019 data: Keefer et al. (2012), and Clabough et al. (2015, 2019).

Year	Rels. *(n)*	App. *(n)*	Ent. *(n)*	Passed *(n)*	App./ Rels.	Ent./ Rels.	Passed/ Rels.	Ent./ App.	Passed/ App.	Passed/ Ent.
1997	147	129	102	49	0.88	0.69	0.33	0.79	0.38	0.48
1998	205	182	154	73	0.89	0.75	0.36	0.85	0.40	0.47
1999	199	183	162	82	0.92	0.81	0.41	0.89	0.45	0.51
2000	299	260	213	123	0.87	0.71	0.41	0.82	0.47	0.58
2001	298	277	240	129	0.93	0.81	0.43	0.87	0.47	0.54
2002	201	193	169	92	0.96	0.84	0.46	0.88	0.48	0.54
2007	398	271	201	83	0.68	0.51	0.21	0.74	0.31	0.41
2008	595	443	317	[1]156	0.74	0.53	0.26	0.72	0.35	0.49
2009	596	470	384	[2]198	0.79	0.64	0.33	0.82	0.42	0.52
2010	312	276	237	[3]128	0.88	0.76	0.41	0.86	0.46	0.54
2014	600	473	437	[4]240	0.79	0.73	0.40	0.92	0.51	0.55
2018	595	532	457	[5]237	0.89	0.77	0.40	0.86	0.45	0.52
Pre-2019 Median	-	-	-	-	**0.88**	**0.74**	**0.40**	**0.86**	**0.45**	**0.52**
2019	449	379	331	[6]173	0.84	0.74	0.38	0.87	0.46	0.52

[1] *n* = 146; [2] *n* = 177; [3] *n* = 126; [4] *n* = 220; [5] *n* = 222, [6] *n* = 149 when trap recaptures were treated as not passing the dam.

Table 5. Number of double-tagged lampreys released downstream from Bonneville Dam in 2019, 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 24 recaptured lamprey (Rcps.).

	Frequencies				Percentages	
	Released	Approached	Entered	Passed	Dam Eff.	Fishway Eff.
Includes Rcps.	449	379	331	173	45.6	52.3
Excludes Rcps.	-	355	307	149	42.0	48.5

Table 6. Route-specific fishway passage efficiencies (%) based on unique lampreys that entered, and total entries at each site, calculated as the ratio of unique double-tagged lampreys that passed Bonneville Dam to unique fish that first entered each fishway opening, or the total number of entry events at each fishway opening. The number of recapture events are listed in parentheses and are a subset of the number reported as passed.

				Passage efficiency (%)[1]	
Site[1]	No. unique lamprey that entered	No. total entries	No. passed dam (Rcps.)	Uniq. Lamprey	Total Events
PH 1 South	48	68	18 (0)	37.5 (3)	26.5 (2)
PH 1 North	15	16	3 (0)	20.0 (5)	18.8 (5)
B-Branch	114	166	41 (5)	36.0 (4)	24.7 (4)
Cascades Island	77	100	33 (3)	42.9 (1)	33.0 (1)
PH 2 South	76	135	5 (2)	6.6 (6)	3.7 (6)
PH 2 North	123	183	48 (8)	39.0 (2)	26.2 (3)

[1] recaptured fish treated as passing the dam.

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 PH1 South (81%) and CI (69%) openings. The percentage of total approach events that resulted in entry events was also highest at the PH1 South opening (47%), followed by CI (45%), PH1 North (43%), the PH2 openings (21%), and the B-Branch opening (20%) (Figure 33).

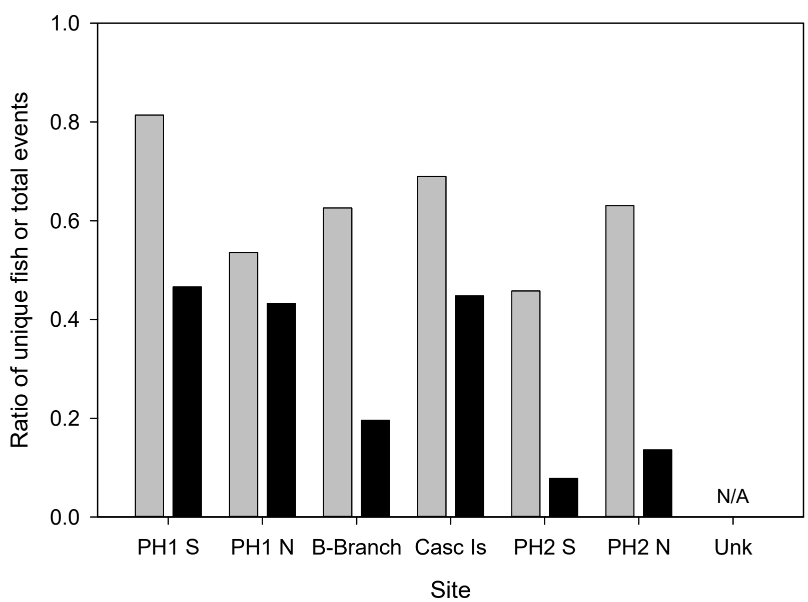

Figure 33. Ratio of unique, double-tagged lampreys at Bonneville Dam in 2019 that entered fishway openings they approached at any time (gray bars) and the ratio of total approach events that resulted in a fishway entry (black bars).

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

A total of 276 double-tagged lampreys did not pass Bonneville Dam in 2019, 61.5% of the 449 released and 59.3% of 425 released when the 24 recaptured fish were excluded. The most upstream site recorded for the 276 non-passing fish included 4 (1%) fish at the release site, 66 (24%) in the tailrace, 48 (17%) outside a fishway opening, and 158 (57%) inside a fishway (Table 7).

The 48 lamprey that were recorded approaching but not entering a fishway were first recorded outside all of the primary fishway openings. These included PH1 south (2% of 48), PH1 North (2%), B-Branch (56%), CI (15%), PH2 south (10%), and PH2 north (15%).

The most upstream locations for the 158 lamprey that entered a fishway, but did not pass the dam, were distributed throughout the fishways, with over half (57%) inside the WA-shore fishway (Table 7). Less than half (67/158 = 42%) of the fish had their most upstream detection in the upper reaches of the Washington-shore or BI fishways, specifically in the serpentine weir sections, near the BI ladder top, or in the auxiliary water supply (AWS) channels. Approximately 10% of the 67 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 sites with similar configuration, 47% (75 of 158) lampreys had their most upstream detection in one of the four transition pools at the dam.

Bonneville - turnaround locations for each fishway entry event that did not result in dam passage

There were 188 entry events at the BI fishway that did not result in dam passage. Approximately 20% (38/188) of the turnarounds were in the serpentine weirs or in the AWS channel (section 6 in Figure 34) and 61% (115/189) were in one of the two transition pools (sections 4 & 7 in Figure 34; Table 8).

There were 426 unsuccessful entry events at the WA-shore fishway. About 39% (165/426) were near the PH2 South fishway openings or the unmonitored sluice gates (sections 12, 13, or 14) of the PH2 collection channel. Another 40% (171/426) of Washington-shore fishway turnaround events occurred in one of the two transition pools (sections 9, 16, 17, & 18 in Figure 35; Table 8). Eleven percent (45/426) were in the vertical slot weirs or AWS.

Table 7. The most upstream detection locations recorded for 276 double-tagged lampreys that did not pass Bonneville Dam in 2019, including locations for the 158 lamprey that entered a fishway and did not pass the dam (Note: 24 fish that were recaptured and released upstream were excluded).

	n	Percent of 276	Percent of 158
Did not pass dam	**276**		
Release sites	4	1.4	
Tailrace only	66	23.9	
Approach fishway	48	17.4	
Entered fishway	158	57.2	
Did not pass dam, but entered fishway	**158**		
Bradford Island fishway			
PH1 collection channel	3	1.1	1.9
A-Branch transition pool	10	3.6	6.3
B-Branch transition pool	22	8.0	13.9
Ladder between transition pool & window	0	0.0	0.0
Serpentine weirs	28	10.1	17.7
Serpentine weirs / auxiliary water supply channel	4	1.4	2.5
Top of ladder exit area	1	0.4	0.6
Washington-shore fishway			
PH2 collection channel	8	2.9	5.1
Cascades Island transition pool	12	4.3	7.6
Cascades Island / UMT	2	0.7	1.3
PH2 transition pool	31	11.2	19.6
Ladder between transition pool & window	3	1.1	1.9
Serpentine weirs	28	10.1	17.7
Serpentine weirs / auxiliary water supply channel[1]	3	1.1	1.9
Auxiliary water supply channel	3	1.1	1.9

[1] some direct movement between the WA-shore serpentine weirs and the auxiliary water supply (AWS) channel was possible in 2019.

Table 8. Numbers of fishway entry events recorded for double-tagged adult lampreys and estimated turnaround locations inside fishways for events that did not result in Bonneville Dam passage in 2019. 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	50	17	2	2	21		8		
PH1-N	13		2	1	5		5		
SP-S	125						25	89	11
Total	**188**	**17**	**4**	**3**	**26**		**38**	**89**	**11**

		Turnaround location in Washington-shore fishway											
		9	10	11	12	13[b]	14[b]	15	16	17	18	19	20
SP-N	67	8	34	2	1							1	21
PH2-S-D	63				3	58				1		1	
PH2-S-U	67					64				2	1		
PH2-N-D	60							6	30	20			4
PH2-N-U	75									58	7		10
PH2-UNK	94				2	37			4	31	9	1	10
Total	**426**	**8**	**34**	**2**	**6**	**159**	**-**	**6**	**34**	**112**	**17**	**3**	**45**

[a] Powerhouse 1 sluice gates were closed in 2019.
[b] some segment 13 events likely occurred in unmonitored segment 14 in 2019.

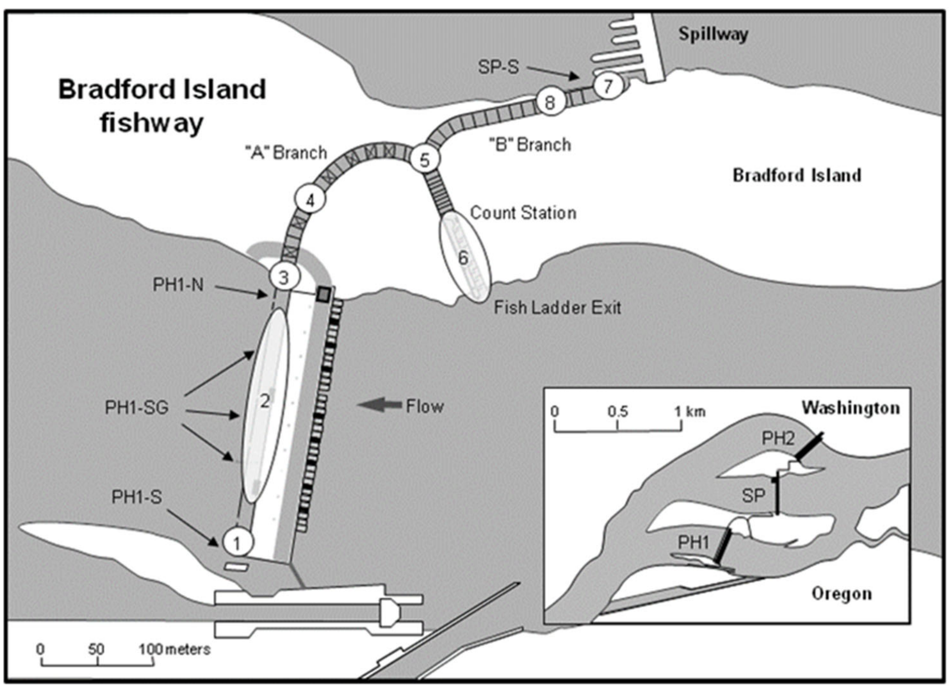

Figure 34. Map of Powerhouse 1 and the Bradford Island fishway at Bonneville Dam. Circles and ellipses show locations inside the fishway where double-tagged lamprey turnaround events were assigned. Inset shows the configuration of Bonneville Dam, including the two powerhouses and the spillway. PH1 = Powerhouse 1; PH2 = Powerhouse 2; SP = spillway; SG = sluice gate. Note: Powerhouse 1 SGs were closed in 2019.

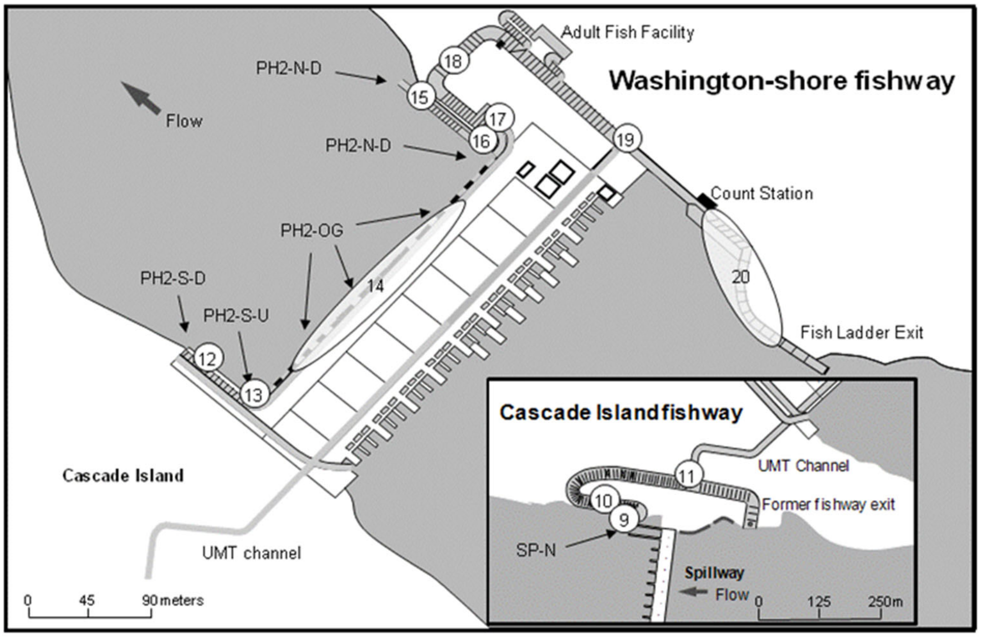

Figure 35. Map of Powerhouse 2 and the Washington-shore fishway at Bonneville Dam. Circles and ellipses show locations inside the fishway where Pacific Lamprey turnaround events were assigned. Inset shows the Cascade Island fishway, which has one entrance (SP-N) and joins the Washington-shore fishway at the terminus of the UMT channel. PH2 = Powerhouse 2; SP = spillway; OG = orifice gate. Note: Powerhouse 2 OGs were open and unmonitored in 2019.

Bonneville - lampreys in Cascades Island AWS

Three double-tagged lampreys were recorded in the CI AWS channel in 2019. One lamprey swam directly into the CI AWS via the CI spillway entrance and two entered it after swimming down the UMT from the WA-shore fishway. Based on radiotelemetry detections, only 2 of the 3 lampreys eventually passed the dam; both via the WA-shore vertical slot weirs. The third fish exited the CI fishway to the tailrace.

Bonneville fallbacks

We recorded five unique double-tagged lampreys (~3% of the total that passed the dam) falling back past the dam. Three fish fell back after passing the BI fishway. One of the three fish passed via the BI fishway and then swam down the same fishway approximately two days after exiting into the forebay. Among the two fallback fish that passed via the WA-shore, one swam down the WA-shore fishway ~8 d after its passage event and the other was detected at The Dalles Dam before falling back at Bonneville Dam. None of the 5 double-tagged lampreys that fell back reascended Bonneville Dam.

The Dalles fishway use

Fishway approach, entry, and dam passage – Of the 116 double-tagged lampreys detected approaching a fishway in 2019, 109 entered, and 51 subsequently exited back into the tailrace one or more times. The highest percentage of tagged fish made their first approach at the north-shore fishway (55%), followed by the east (25%), west powerhouse (14%), and south spillway (6%) openings (Figure 36). Slightly less than 60% of all first entries occurred at the north-shore opening, followed by the east (24%), west powerhouse (11%), and south spillway (6%) openings. 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 among the other sites. Lampreys approached fishways a median of one time (*mean* = 2.4 times) per fish and entered fishways a median of one time (*mean* = 1.5 times) per fish. The 51 tagged lampreys that exited a fishway back to the tailrace did so a median of one time (*mean* = 1.7 times). The highest percentage of all fishway exits was at the north (59%), followed by the east (20%), west powerhouse (10%), and south spillway (8%) fishway openings.

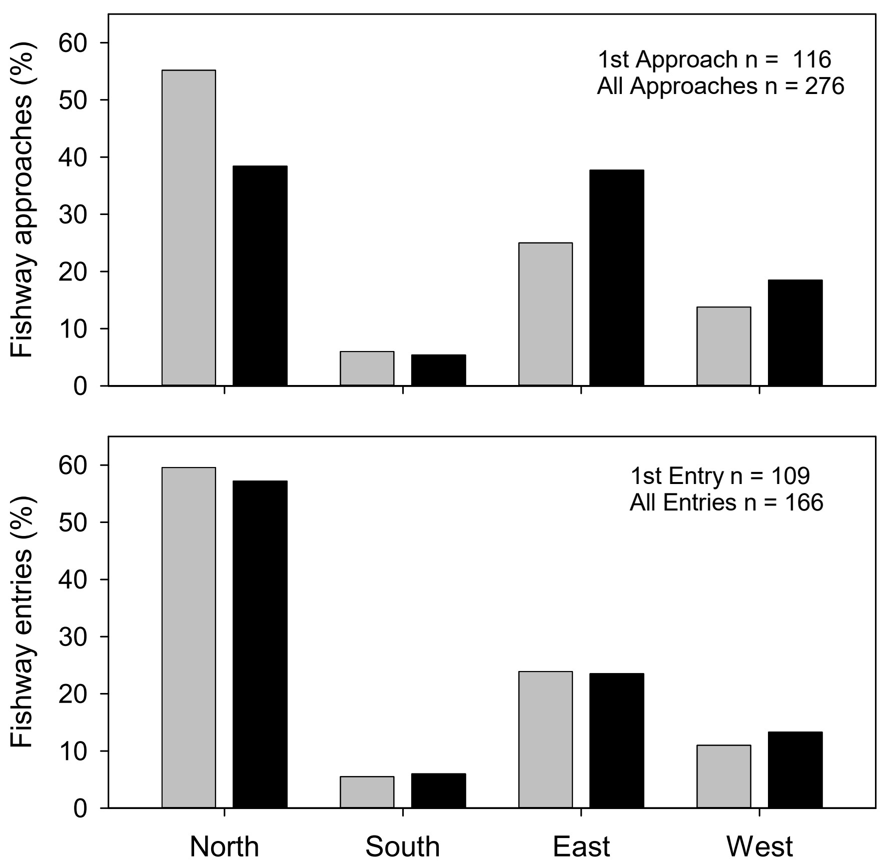

Figure 36. Distributions of first (gray bars) and total (black bars) fishway approaches, and fishway entries by double-tagged adult Pacific Lamprey at fishway openings at The Dalles Dam in 2019.

The Dalles passage times

Fishway approach, entry, and dam passage – A total of 122 unique lampreys was detected at The Dalles Dam and/or tailrace in 2019 and 20 (16%) of these fish were recorded at the tailrace sites on their first apparent approach to the fishways. Six (30%) of the 20 lampreys 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 21.1, 21.2, and 78.4 h, respectively (Table 9). 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 (0.6 h). The median time lampreys used to swim from their first fishway entrance to exit from a ladder top was slightly over a day (26.4 h, *mean* = 68.6 h). Fish used a median of 21.5 h (*mean* = 36.5 h) to swim from their final transition pool exit to a ladder top.

Table 9. Summary of passage times for double-tagged adult Pacific Lampreys at The Dalles Dam in 2019. Q1 and Q3 are first and third quartiles, respectively.

Passage segment			Passage time (h)			
Start	Finish	*n*	Median	Mean	Q1	Q3
Tailrace	First approach	14	21.1	36.5	4.2	23.0
Tailrace	First entrance	14	21.2	55.3	4.2	23.4
Tailrace	Past dam	10	78.4	123.5	71.4	132.4
First approach	First entrance	90	0.2	20.0	0.1	1.8
First approach	Past dam	65	44.8	81.0	21.6	97.2
First entrance	Transition pool entry	89	<0.1	3.0	<0.1	0.1
First entrance	Past dam	56	26.4	68.6	21.2	68.5
Transition pool entry	Transition pool exit[a]	53	0.6	28.1	0.4	12.3
Transition pool exit	Past dam	53	21.5	36.5	6.0	25.5

[a] includes only fish that passed the dam

The Dalles Dam passage efficiency

Of the 122 tagged lampreys detected at The Dalles Dam or tailrace in 2019, 95% approached a fishway, 89% entered a fishway, and 63% passed the dam (Table 10). The 2019 percentage of lampreys that approached (95%) was similar to the median value from eleven previous study years (93%). The percentage of lampreys that entered The Dalles Dam in 2019 (89%) was slightly higher than the median value from previous study years (81%), potentially related to experimental reductions in entrance velocity in 2019 or to recent lamprey-specific modifications at the north fishway, whereas the percentage that passed was similar (63% in 2019 vs. a median of 65% in previous years). Of the lampreys that approached a fishway in 2019, 94% subsequently entered a fishway, which was higher than the median from previous study years (87%). Dam-wide dam passage efficiency was 66% and dam-wide fishway passage efficiency was 71% in 2019; both point estimates were slightly lower than corresponding median values from previous years (68% and 75%, respectively).

The 77 tagged fish counted as passing the dam included three double-tagged lampreys recaptured in the east fishway by Columbia River Inter-Tribal Fisheries Commission (CRITFC) personnel. All recaptured lampreys were released into the forebay. Of the 74 non-recaptured lampreys that passed the dam, 42 (57%) passed via the north fishway and 32 (43%) passed via the east fishway.

Table 10. Dam-wide passage efficiency metrics for unique double-tagged Pacific Lamprey at The Dalles Dam in 1997-2002, 2007-2010, 2014, 2018 and 2019. At Dam = recorded in tailrace or at a fishway; Approached (App.) = approached fishway opening; Entered (Ent.) = entered fishway; Passed = passed dam. Fish were tagged at Bonneville Dam. Sources for pre-2019 data: Keefer et al. (2012) and Clabough et al. (2015, 2019).

Year	At Dam (*n*)	App. (*n*)	Ent. (*n*)	Passed (*n*)	App./ At Dam	Ent./ At Dam	Passed/ At Dam	Ent./ App.	Passed/ App.	Passed/ Ent.
1997	66	64	48	35	0.97	0.73	0.53	0.75	0.55	0.73
1998	43	38	33	24	0.88	0.77	0.56	0.87	0.63	073
1999	49	-	-	24	-	-	0.49	-	-	-
2000	91	84	82	67	0.93	0.90	0.74	0.96	0.79	0.82
2001	94	92	77	68	0.98	0.82	0.72	0.84	0.74	0.88
2002	73	70	61	46	0.96	0.84	0.63	0.87	0.66	0.75
2007	38	31	29	21	0.82	0.76	0.55	0.94	0.68	0.72
2008	95	90	77	63	0.95	0.81	0.66	0.86	0.70	0.82
2009	112	103	95	68	0.92	0.85	0.61	0.92	0.66	0.72
2010	104	93	84	70	0.89	0.81	0.67	0.90	0.75	0.83
2014	163	157	111	75	0.96	0.68	0.66	0.71	0.48	0.68
2018	164	152	142	109	0.93	0.87	0.66	0.93	0.72	0.77
Pre-2019 Median	-	-	-	-	**0.93**	**0.81**	**0.65**	**0.87**	**0.68**	**0.75**
2019	122	116	109	77	0.95	0.89	0.63	0.94	0.66	0.71

At individual fishway openings, 99% of double-tagged lampreys that first approached the north-shore fishway (*n* = 64) also made their first entry there. The percentages of unique lamprey that first entered a fishway to unique fish that first approached it were 83% for the east opening (*n* = 29), 71% for the south spillway (*n* =7), and 50% for the west powerhouse (*n* = 16) openings.

Route-specific fishway passage efficiency – The route-specific fishway passage efficiency estimates based on unique fish was highest at the east (69%) and north (61%) fishway openings, whereas the south and west openings were 44% and 45%, respectively (Table 11). The route-specific efficiency based on total entry events varied less among sites (*range* = 40–53%). Rankings among sites were the same for estimates based on the number of unique fish and total events.

Table 11. Route-specific fishway passage efficiencies (%) based on unique lampreys entering, and total entries at each site, calculated as the ratio of unique double-tagged lampreys that passed The Dalles Dam to unique fish that first entered each fishway opening, or the total number of entry events at each fishway opening. The number of recapture events (Rcps.) are listed in parentheses and are a subset of the number reported as passed.

				Passage efficiency (%)[1]	
Site[1]	No. unique lamprey that entered	No. total entries	No. passed dam (Rcps.)	Unique Lamprey	Total Events
North	69	95	42 (0)	60.9	44.2
South Spillway	9	10	4 (0)	44.4	40.0
East	32	39	22 (3)	68.8	52.8
West powerhouse	20	22	9 (0)	45.0	40.9

[1] recaptured fish treated as passing the dam.

Site-specific fishway entrance efficiency – Most lampreys entered at locations they approached. Among the four main fishway openings at The Dalles Dam, the percentage of unique lampreys that approached and entered the same site was highest at the north-shore (99%; 69 entrants among 70 unique fish that approached) and east (82% of 39 unique fish that approached) openings, whereas the south spillway and west powerhouse estimates were 69% (n = 13) and 61% (n = 33), respectively, indicating higher rates of movement between entrances prior to entry. The proportion of total approach events that resulted in entry events was also highest at the north opening (90%, n = 106 total approaches), followed by lower rates at the south spillway (67%, n = 15), west (43%, n = 51), and east powerhouse openings (38%, n = 104).

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

Over half (54%, n = 166) of all fishway entry events did not result in dam passage (Table 12). 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, 92% of the 53 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, 82% of the 17 east opening entry events that did not result in dam passage had turnarounds in the east fishway transition pool and 18% of turnarounds occurred upstream in the ladder. Among six failed entry events that originated at the south spillway opening, five had turnarounds within the south fishway collection channel. The 13 failed entry events at the west powerhouse opening had turnarounds in the west fishway collection channel (54%), the east transition pool (38%), and the east ladder (8%).

Table 12. Numbers of fishway entry events recorded for double-tagged adult Pacific Lampreys that did not result in dam passage, and estimated turnaround locations inside fishways in 2019. Turnaround locations were inferred from detection records at underwater antenna sites inside fishways.

		Turnaround locations			
Entry site	Entry n	N. Tran. pool	N. ladder		
North	53	49	4		
		S. Coll. Ch.	W. Coll. Ch.	E. Tran. pool	E. ladder
East	17			14	3
South	6	5		1	
West	13		7	5	1
Total	89	54	11	20	4

The Dalles fallbacks

Three double-tagged lampreys that passed the The Dalles Dam in 2019 fell back. No lampreys reascended the dam, two were last detected in The Dalles tailrace, and one re-entered the north fishway once before exiting to the tailrace.

John Day fishway use

Fishway approach, entry, and dam passage – At John Day Dam, 50 lampreys approached fishway entrances in 2019, 47 (94%) entered a fishway and 28 (56%) 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* = 26, 52% of 50), followed by the north-shore entrance (*n* = 14, 28%), and the north powerhouse entrance (*n* = 4, 18%). Twelve percent (*n* = 6) of first approaches were by fish with unknown approach locations near the south fishway (likely at the unmonitored, open collection channel floating orifice gates). First entries were highest at the north-shore entrance (*n* = 15, 32% of 47) followed by the south-shore entrance (*n* = 11, 23%), and the north powerhouse entrance (*n* = 8, 17%); 28% (*n* = 13) had unknown entrance locations at the south fishway.

Distributions of total fishway approaches and entries were generally consistent with first approach and entry locations, with the highest percentage of total approaches (55%, *n* = 96) occurring at the south-shore entrance, 21% (*n* = 36) occurring at the north-shore entry and 11% (*n* = 20) at the north powerhouse entrance. Thirteen percent (*n* = 23) of total approaches were by fish with unknown approach locations near the south fishway. Lampreys approached fishways a median of 3 times (*mean* = 3.5 times) per fish. Lampreys entered fishways a median of 2.0 times (*mean* = 2.1 times) per fish. The subset that exited back to the tailrace did so a median of 2.0 times (*mean* = 2.2 times). The north-shore entrance was exited most frequently (*n* = 15 times), followed by the south-shore entrance (*n* = 10 times).

John Day passage times

Fishway approach, entry, and dam passage – A total of 56 lampreys were detected at John Day Dam. Detection efficiency at the tailrace antennas was low, with only 39% (22 of 56) of the tagged fish recorded at the tailrace sites. Median passage times from the first tailrace record to first fishway approach, first fishway entry, and to pass the dam were 1.9, 6.6, and 119 h, respectively (Table 13). Most lampreys moved slowly into a fishway after their first recorded approach (*median* = 0.7 h, *n* = 23), but more quickly from first fishway entry into a transition pool (*median* = 0.2 h, *n* = 20), and through transition pools (*median* = 0.2 h, *n* = 23). In contrast, passage time duration and variability were much higher for the segment from first fishway entry to exit from the ladder top (*median* = 56.6 h, *n* = 21) and was related to the time fish spent exiting and re-entering the fishways and transition pools. Lampreys took a median of 10.2 h (*n* = 24) to pass from transition pool exit to exit from the top of a ladder.

Table 13. Summary of passage times for double-tagged adult Pacific Lampreys at John Day Dam in 2019. Q1 and Q3 are first and third quartiles, respectively.

Passage segment			Passage time (h)			
Start	Finish	*n*	Median	Mean	Q1	Q3
Tailrace	First approach	14	1.9	5.4	1.3	8.0
Tailrace	First entrance	12	6.6	26.1	2.0	17.7
Tailrace	Past dam	15	119.0	121.6	47.3	176.9
First approach	First entrance	23	0.7	12.9	0.2	6.6
First approach	Past dam	28	57.4	98.3	18.1	132.2
First entrance	Transition pool entry	20	0.2	14.5	0.1	0.6
First entrance	Past dam	21	56.6	98.7	17.4	126
Transition pool entry	Transition pool exit	23	0.2	10.2	0.1	2.4
Transition pool exit	Past dam	24	10.2	24.0	7.4	31.7

John Day passage efficiency

A total of 50 lampreys was recorded approaching fishways at John Day Dam and 39 passed the dam (one fish passed the dam undetected and was excluded from the calculations) for a dam-wide dam passage efficiency estimate of 78% (Table 14). Forty-seven fish entered a fishway for a dam-wide fishway passage efficiency estimate of 83% (39/47). The dam-wide dam passage efficiency (78%) and fishway passage efficiency (83%) in 2019 at John Day Dam were considerably higher than corresponding median estimates from previous years (53% and 54%, respectively) (Table 15).

Of the 47 fish that entered a fishway, 37 passed the dam by a known route. The route-specific passage efficiency was highest for fish that first entered the north entrance (87%, *n* = 13/15), followed by those that entered the south entrance (73%, *n* = 8/11), and the north powerhouse entrance (63%, *n* = 5/6; Table 15). Fish with unknown entry times and sites (*n* =

13) were excluded from route-specific estimates. Two fish with no entry records also passed the dam.

Site-specific fishway entrance efficiency at individual openings was highest at the north entrance (100% of the 21 unique fish that approached) followed by 69% (11/16) at the north powerhouse entrance and 52% (17/33) at the south-shore entrance (Table 16).

Table 14. Dam-wide passage efficiency metrics for unique double-tagged Pacific Lampreys at John Day Dam in 1997-2002 and 2007-2010, 2014, and 2018-2019. At Dam = recorded in tailrace or at a fishway; Approached (App.) = approached fishway opening; Entered (Ent.) = entered fishway; Passed = passed dam. Fish were tagged at Bonneville Dam. Sources for pre-2019 data: Keefer et al. (2012) and Clabough et al. (2015, 2019).

Year	At Dam *(n)*	App. *(n)*	Ent. *(n)*	Passed *(n)*	App./ At Dam	Ent./ At Dam	Passed/ At Dam	Ent./ App.	Passed/ App.	Passed/ Ent.
1997	1	1	1	0	1.00	1.00	0.00	1.00	0.00	0.00
1998	10	10	7	3	1.00	0.70	0.30	0.70	0.30	0.43
1999	13	-	-	3	-	-	0.23	-	-	-
2000	74	70	60	28	0.95	0.81	0.38	0.86	0.40	0.47
2001	51	47	46	25	0.92	0.90	0.49	0.98	0.53	0.54
2002	34	34	34	17	0.92	0.90	0.49	0.98	0.53	0.54
2007	11	-	-	9	-	-	0.82	-	-	-
2008	42	-	-	27	-	-	0.64	-	-	-
2009	44	42	39	22	0.95	0.89	0.50	0.93	0.52	0.56
2010	39	-	-	34	-	-	0.87	-	-	-
2014	51	48	46	40	0.94	0.90	0.78	0.96	0.83	0.87
2018	72	68	62	47	0.94	0.86	0.65	0.91	0.69	0.76
Pre-2019 Median	-	-	-	-	**0.95**	**0.90**	**0.50**	**0.95**	**0.53**	**0.54**
2019	56	50	47	39	0.89	0.84	0.70	0.94	0.78	0.83

Table 15. Route-specific fishway passage efficiencies based on unique lampreys entering and total entries at each site at John Day Dam, 2019. Metrics were calculated as the ratio of unique, double-tagged lampreys that passed John Day Dam to unique fish that first entered each fishway opening, or the total number of entry events at each fishway opening.

Site	No. unique lamprey that entered	No. total entries	No. passed dam	Passage efficiency (%) Unique Lamprey	Total Events
South ladder	15	31	13	86.7	41.9
North PH	8	13	5	62.5	38.5
North ladder	11	30	8	72.7	26.7
South unknown	13	24	11	84.6	45.8

Table 16. Site-specific fishway entrance efficiency metrics for double-tagged Pacific Lampreys at John Day Dam fishway openings in 1997-1998, 2000-2002, 2014, 2018-2019. 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. Note metrics were not available for 2007-2010. Sources for pre-2019 data: Keefer et al. (2012) and Clabough et al. (2015, 2019).

	1997	1998	2000	2001	2002	2014	2018	2019
South								
Total approaches (*n*)	7	17	107	163	80	13	112	96
Total entries (*n*)	5	10	27	92	29	5	27	30
Total efficiency	0.71	0.59	0.25	0.56	0.36	0.38	0.24	0.31
Unique approaches (*n*)	1	9	51	42	28	11	34	33
Unique entries (*n*)	1	5	23	38	17	5	17	17
Unique efficiency	1.00	0.56	0.45	0.90	0.61	0.45	0.50	0.52
North powerhouse								
Total approaches (*n*)	10	8	58	78	34	9	19	20
Total entries (*n*)	4	0	14	23	11	7	9	13
Total efficiency	0.40	0.00	0.24	0.29	0.32	0.78	0.56	0.65
Unique approaches (*n*)	1	4	29	26	14	7	15	16
Unique entries (*n*)	1	0	10	16	7	5	9	11
Unique efficiency	1.00	0.00	0.34	0.62	0.50	0.71	0.60	0.69
North ladder								
Total approaches (*n*)	6	6	38	35	57	30	39	29
Total entries (*n*)	4	3	20	29	34	25	29	24
Total efficiency	0.67	0.50	0.53	0.83	0.60	0.83	0.74	0.86
Unique approaches (*n*)	1	4	27	11	18	26	32	21
Unique entries (*n*)	1	3	18	8	17	24	25	21
Unique efficiency	1.00	0.75	0.67	0.73	0.94	0.92	0.78	1.00
South unknown								
Total approaches (*n*)	1	-	30	49	21	21	43	22
Total entries (*n*)	0	-	29	49	20	21	43	22
Total efficiency	0.00	-	0.97	1.00	0.95	1.00	1.00	1.00
Unique approaches (*n*)	1	-	27	28	14	20	26	20
Unique entries (*n*)	0	-	26	28	13	20	26	20
Unique efficiency	0.00	-	0.96	1.00	0.93	1.00	1.00	1.00

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

Of the 56 double-tagged fish recorded at John Day Dam, 17 (30%) did not pass the dam. The most upstream locations in the small sample included: 5 (29%) tailrace site south, 4 (24%) bottom of the north-ladder entrance, 2 (12%) outside the north-powerhouse entrance, 2 (12%) outside the south -entrance and 1 each (6%) inside the north-powerhouse entrance, south shore-ladder transition pool, inside the south-shore entrance, and the tailrace site north.

John Day fallbacks

Fallback percentages for double-tagged lampreys were much higher at John Day Dam than at Bonneville (~2%) or The Dalles (5%) dams. Of the 39 unique double-tagged lampreys that passed John Day Dam, 5 (13%) had records that suggested they fell back at the dam at least once. No fish fell back more than one time. All of the fish that fell back did so after passing the dam via the north fishway (see below).

John Day north (JDN) entrance

Double-tagged lampreys – We evaluated movements within the JDN entrance in detail because the fishway entrance underwent extensive modifications to improve conditions for Pacific lamprey and salmonids during winters 2011-2013 (Clabough et al. 2015). In 2019, total site-specific entrance efficiency at the JDN entrance was 86% (24 of 29 lampreys that approached entered the fishway; Table 16). Of the 24 entry events (by 21 unique fish), 15 exit events were recorded to the tailrace for an exit ratio of (15/24 = 63%). The median time from fishway approach to entry was 2 min and ranged from < 1 to 65 min. After double-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 JDN had an approach-to-entry time of > 1 h whereas no lampreys that entered had >1 h passage times from entrance to the first ladder antenna. Of the 18 unique fish that entered the JDN entrance, 11 successfully passed the dam for a fishway passage efficiency estimate of 61%. Of the seven fish that did not pass via JDN, three turned around above the transition pool (apparently between weirs 13 and 14), one fish turned around inside the north entrance, and the other three exited JDN and passed via the south-shore fishway. Of the five fish that fell back at John Day Dam, all (100%) fell back after passing the north ladder. Two fish reascended the south ladder while the other three did not reascend.

PIT tag detection histories – A total of 67 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 37). The 67 lampreys included 20 double-tagged fish (30%), 24 PIT-tagged fish released below Bonneville Dam (36%), and 23 PIT-tagged fish released upstream from Bonneville near Stevenson (34%).

Of the 67 PIT-tagged lampreys detected, 59 (88%) were recorded on the outside antenna array (Note: One of these fish was recorded only during its second dam passage event). The majority of outside antenna detections occurred on the south side (81%) and 25% of unique approaches were recorded on both outside antennas. Only 32% (n = 21) of lampreys that entered were detected on the inside PIT antenna array, suggesting that fish were free swimming in the water column or were near fishway walls but not near the floor once they passed the fishway entrance weir. In total, 8 of the 21 fish (38%) were detected on both inside antennas, 6 (29%) were on the south inside antenna, and 7 (33%) were on the north inside antenna.

Of the 67 lampreys detected at the PIT antennas, 51 (76%) eventually passed the dam via the JDN ladder, 8 (12%) passed via the south-shore fishway, and 8 (12%) did not pass the dam. Sixteen of the 21 (76%) detected on the inside fishway antenna passed the dam. Fourteen of the fish detected at the PIT antennas were recorded falling back past John Day Dam one or more times. Twelve fish fell back after passing the north ladder and three after passing the south ladder. Sixty percent (9 of 15) of fish that fell back reascended a fishway at the dam.

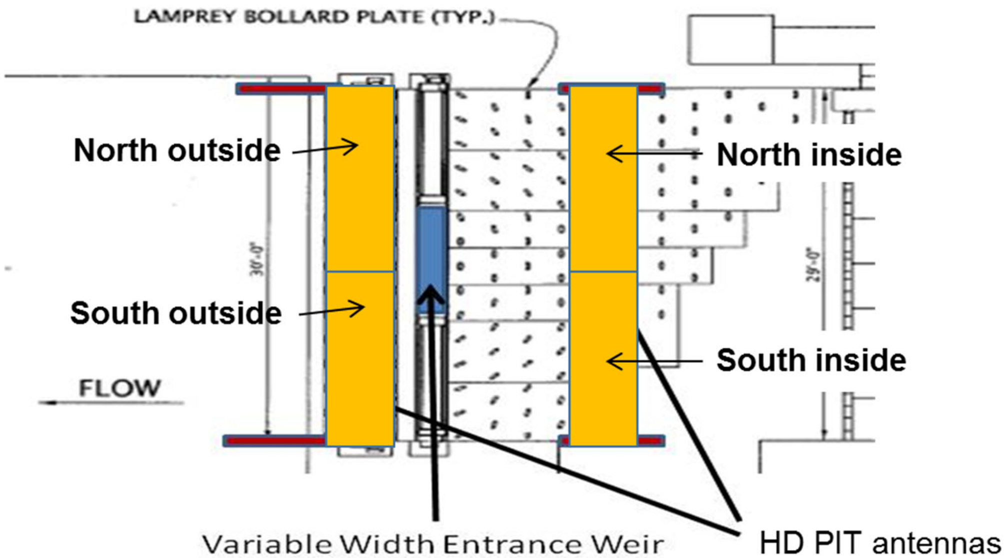

Figure 37. Overhead diagram of HD PIT antenna array (orange rectangles) near the John Day north fishway entrance in 2019.

McNary summary

A total of 11 double-tagged lampreys were recorded at McNary Dam in 2019. Of these, 6 (54%) first approached the south-shore fishway, 4 (36%) first approached the north fishway, and 1 (9%) first approached the north-powerhouse opening. Ten of eleven (91%) fish that approached also entered a fishway with 8 (80%) entering the south-shore opening and 1 each (10%) entering the north fishway and the north-powerhouse site. At McNary Dam, site-specific fishway entrance efficiencies (number of unique lampreys that entered / the number of unique lampreys that approached the same site) ranged from 100% (3/3) at the north powerhouse and north ladder entrances to 40% (2/5) at the north entrance. Entrance efficiency at the south-shore entrance was 73%, with 8 of the 11 unique lampreys entering the fishway.

Overall, 5 of the 11 lampreys detected at McNary Dam passed, for a dam-wide dam passage efficiency of 45% (Table 17). The dam-wide dam passage efficiency (45%) for McNary Dam in 2019 was lower than all previous study years except for 2002, whereas the dam-wide fishway passage efficiency (also 45%) was the lowest among eight previous years (Table 17). We note that sample sizes were generally low in all years. Of the 5 fish that passed in 2019, all (100%) passed via the south-shore fishway. While telemetry coverage was limited and sample size was small, 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 0.2 h (n = 9) and 52.1 h (n = 6), respectively (Table 18). Although the sample size was low (n = 3), tagged lampreys moved slowly from first fishway entry to exit from the ladder top (*median* = 33.3 h, *range* 9.9-50 h). Of the 5 lampreys that passed McNary Dam, 1 (20%) fell back and it did not reascend the dam.

Table 17. Dam-wide passage efficiency metrics for unique double-tagged Pacific Lampreys at McNary Dam in 2000-2002 and 2008-2010, 2014 and 2018-2019. At Dam = recorded in tailrace or at a fishway; Approached (App.) = approached fishway opening; Entered (Ent.) = entered fishway; Passed = passed dam. Fish were tagged at Bonneville Dam. Sources for pre-2019 data: Keefer et al. (2012) and Clabough et al. (2015, 2019).

Year	At Dam *(n)*	App. *(n)*	Ent. *(n)*	Passed *(n)*	App./ At Dam	Ent./ At Dam	Passed/ At Dam	Ent./ App.	Passed/ App.	Passed/ Ent.
2000	13	13	12	11	1.00	0.92	0.85	0.92	0.82	0.92
2001	9	9	9	6	1.00	1.00	0.67	1.00	0.67	0.67
2002	5	2	2	2	0.40	0.40	0.40	1.00	1.00	1.00
2008	8	8	7	7	1.00	0.88	0.88	0.88	0.88	1.00
2009	10	10	10	8	1.00	1.00	0.80	1.00	0.80	0.80
2010	11	11	7	6	1.00	0.64	0.55	0.64	0.55	0.86
2014	7	7	7	7	1.00	1.00	1.00	1.00	1.00	1.00
2018	23	23	23	20	1.00	1.00	0.87	1.00	0.87	0.87
Pre-2019 Median	-	-	-	-	**1.00**	**0.96**	**0.83**	**1.00**	**0.85**	**0.90**
2019	11	11	10	5	1.00	0.91	0.45	0.91	0.45	0.50

Table 18. Summary of passage times for double-tagged adult Pacific Lampreys at McNary Dam in 2019. 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	9	0.2	56.8	0.2	1.7
First approach	Past dam	6	52.1	68.8	45.9	71.8
First entrance	Past dam	5	33.3	32.7	9.9	50.0

Discussion

The primary objectives for this Section were to summarize double-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 analyzed lamprey passage metrics and behavior 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 double-tagged lampreys detected at Bonneville Dam after release in 2019 (84%) was similar to the 12-year average (i.e., 1997-2002, 2007-2010, & 2014 and 2018) of 85% (Keefer et al. 2012; Clabough et al. 2015 and 2019). The 2019 value was slightly lower than values from the 1997-2002 studies (87-96%), when double-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 2019 could have shed transmitters, may have abandoned upstream migration, may have died from tagging effects (although none of the 449 double-tagged lampreys died before release in 2019) 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 transmitters) and comparison of detection histories of double-tagged lampreys in radio- and PIT arrays in 2019. There were three cases of transmitters that stopped working or were shed in 2019 based on PIT detections of double-tagged lampreys in radio-monitored fishways where there were no radio detections (i.e., not attributable to receiver outages).

Dam passage efficiency (fishway approach to top of ladder) at Bonneville Dam in 2019 (42% with recaptured fish excluded and 46% with recaptured fish treated as passing the dam) was on par or slightly above average compared to most recent lamprey radio-telemetry studies (*mean* = 42%, *median* = 44%, n= 6 years, *range* =31-51%, 2007-2010 and 2014 and 2018; Keefer et al. 2012; Clabough et al. 2015 and 2019). The 2007-2010 and 2014 and 2018 studies used similar methods to those used in 2019 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 radio tagged). The 2019 results were similar to the 2018 efficiency estimates, which 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).

Environmental factors may have affected lamprey passage in 2019 compared to 2018 and other years. We had hypothesized that lamprey passage success at Bonneville Dam in 2018 and 2019 would be at the high end of the reported range given the reduced nighttime velocity conditions at the BI fishway in both years and the new UMTJ-LPS (among other incremental improvements since 2014). However, the potential benefits of passage improvements may have been partially offset by the presence of furunculosis (a disease associated with infection by *Aeromonas salmonicida*) in the 2018 and 2019 lamprey runs. Furunculosis was identified in mid-migration in 2018, and thereafter symptomatic lampreys had about 8% lower passage success at Bonneville Dam than asymptomatic lampreys (details in Keefer et al. 2019). Symptoms of furunculosis were evaluated in all double-tagged lampreys in 2019, when only 10 (16%) of 62 symptomatic lampreys passed Bonneville Dam compared to 42% (162/387) of asymptomatic fish. 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 in the Columbia River (Ralph Lampman, *personal communication*) but the incidence of the disease and its potential effects on behavior and dam passage success were not systematically monitored or evaluated. Consequently, we are uncertain to what degree the presence of the disease in 2018 and 2019 may have affected study results in comparison to previous telemetry study years (additional details of associations between lamprey passage and furunculosis in the 2019 samples are presented in Keefer et al. [2020]).

The distribution of turnaround sites for failed Bonneville Dam passage attempts in 2019 were largely consistent with previous results, which found turnarounds likely to occur in the first or second fishway segment encountered after fishway entry (Keefer et al. 2012, 2013b). Slightly less than 40% of all WA-shore fishway turnarounds in 2019 were near the PH2 South fishway openings or the unmonitored sluice gates of the PH2 collection channel. Transition pools were also sites with high percentages of turnarounds in 2019 (i.e., 40% of turnarounds in the WA-shore fishway and 61% of turnarounds in the BI fishway). Smaller percentages of all 2019 turnaround events were in the serpentine weirs or in the AWS channels whereas approximately 40% of all individual, non-passing fish had their most-upstream detection in the upper sections of one of the fishways. The transition pools and serpentine weir sections in the upper WA-shore and BI fishways continue to be among the most difficult fishway sections for adult lampreys 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 lampreys 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 & 2019 nighttime reduced velocity experiments) to benefit lamprey *per se* have been implemented.

Overall, passage metrics at The Dalles Dam fluctuated around values observed in past years and the 2019 overall passage efficiency estimates at The Dalles Dam were 2-4% lower than the median values from eleven previous radiotelemetry study years at the dam. Site-specific entrance efficiencies for unique fish at the west and south fishway openings in 2019 were 61% and 69%, respectively. The 2019 value at the west powerhouse opening represented an improvement in efficiency compared to the median value from eleven years (i.e., 1997-1998, 2000-2002, & 2007-2010, 2014 and 2018) of previous studies (45%, Keefer et al. 2012, Clabough et al. 2015, 2019). The site-specific entrance efficiency at the south spillway opening in 2019 (69%) was only slightly higher than the 11-year median value (65%). Among failed dam passage attempts by lampreys that entered the north-shore and east fishway openings, 90% of all turnarounds occurred in one of the transition pools.

Despite the difficulty some lampreys had passing the Dalles Dam in 2019, the percentages of lampreys that passed the dam after approaching (66%) or entering (71%) 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), more motivated or lamprey of higher condition (Hanchett and Caudill 2020) or to fewer passage obstacles (e.g., vertical slot weirs vs. serpentine weirs) at The Dalles fishways compared to at Bonneville Dam.

John Day Dam

Overall, dam passage (passed/approached) efficiency for lampreys at John Day Dam (78%) was higher than that at The Dalles Dam (66%) and substantially higher than at Bonneville Dam (46%) in 2019. The 2019 dam passage efficiency estimate was considerably higher than the corresponding median estimate from previous study years (53%) at John Day Dam. Patterns were similar for the fishway passage (passed/entered) estimates, with relatively high efficiency (83%) in 2019. Among previous study years, 2018 was the most comparable at John Day Dam in terms of radiotelemetry monitoring effort; dam and fishway passage efficiency estimates were 69% and 76%, respectively, in 2018. In 2019, site-specific fishway passage efficiencies were highest at the John Day north fishway (100%) followed by the north powerhouse (69%) and the south fishway (52%). The pattern was similar in 2018, when efficiency was also highest at the north fishway (78%), followed by the north powerhouse (60%) and south fishway (50%). While passage success was relatively high at John Day Dam, the fallback rate was also elevated compared to at downstream dams. The lamprey fallback percentage at John Day Dam was 13% in both 2019 and 2018 and was considerably higher than at Bonneville Dam (3%) and The Dalles Dam (4%) in 2019.

At John Day Dam, several structural modifications were made to the north fishway entrance in the winters of 2012 and 2013 in order to improve passage of adult salmonids and Pacific Lamprey. These modifications included the removal of lower fishway weirs; closure of one of two entrance slots; and installations of a variable-width entrance weir, a bollard field, and a lamprey passage system (LPS). Median site-specific entrance efficiency of unique double-tagged lampreys at John Day north entrance was higher (0.90) post modification (2014, 2018-2019; Clabough et al. 2019) than in pre-modification (0.78) years (2000-2002; Keefer et al. 2012). This pattern was also observed in site-specific entrance efficiency of total events with a median of 0.81 post-modification and 0.65 in pre-modification years. Increases in median entrance efficiency (unique and total) of double-tagged lampreys at the John Day north entrance are likely a result of prior passage modifications.

McNary Dam

Overall, lamprey passage at McNary Dam has been consistently higher compared to Bonneville, The Dalles and John Day Dams (Keefer et al. 2012, 2013a). In 2019, 100% (n = 11) of the fish at the dam approached a fishway, and 91% (n = 10) of the fish that approached subsequently entered a fishway. Overall, the dam-wide dam passage efficiency (5 out of 11, 45%) at McNary Dam in 2019 was lower than the estimate from 2018 (87%) and median estimates from previous years (82%), though we caution sample sizes were low. The dam-wide fishway passage efficiency (50%) was also lower than the corresponding 2018 estimate (85%) and the median (90%) from previous years (2000-2002, 2008-2010, and 2014).

While only 5 double-tagged fish passed McNary Dam in 2019, all passed via the south-shore fishway. This pattern was largely consistent with the small sample that passed the dam in 2018 when 60%, (n =12) passed via the south shore fishway, 6 (30%) passed via the north fishway and 2 (10%) passed via an unknown route. Similarly, all seven lampreys recorded passing the dam in 2014 passed via the south shore fishway.

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Appendix A. Table 1. List of radio antennas, HD PIT antennas, and other equipment that remained at the Washington Shore or in the WA-Shore Fishway at Bonneville Dam in 2019.

Location	Type	Site	Description
Washington Shore Fishway			
PH2 Entrance South	RT	DBO	1 pair conduit approx. 1/3 way from west entrance to tunnel entrance, cable crosses fishway. A2, A3
			1 conduit just downstream of east entrance towards west entrance, A5
			1 conduit just inside east entrance towards PH, A6
PH2 Entrance North	RT	LBO	1 pair conduit approx. 1/3 way from west entrance to tunnel entrance, cable crosses fish way, A2, A3
			1 pair conduit just downstream of tunnel entrance, A6
PH2 Junction Pool	RT	MBO	1 pair conduit inside north tunnel with run out to deck, some cable crosses fishway, A1
			1 pair conduit inside center tunnel with runout on wall to deck, A2
			single conduit antenna on north wall of junction pool, A6
			1 pair conduit just upstream of junction pool, A3, 4
North Ladder	RT	NBO	1 pair conduit at first weir above 90-degree turn, cable cross fishway, A1
			1 pair conduit between 6th and 7th weirs, some cable crosses fishway A2
			1 pair conduit on the 15th weir, some cable crosses fishway, A3
			1 pair conduit just downstream of AFF picket lead, cable crosses fishway (?) A4
	HD PIT	7BX	4 antennas mid ladder between first and second 90 degree turns. Flex runout drapes across fishway.
LFS	HD PIT	LBX/RBX	4 antennas hard wired through metal conduit to 5 SS equipment boxes. Readers and tuners removed.
WA Shore Serpentine Weirs	RT	KBO	single conduit antenna just downstream of count window, A5
			single conduit antenna just upstream of count window, old
			single conduit antenna at first turn upstream of count window, A4
			single conduit antenna on south wall between weirs 1 and 2, A3
			single conduit antenna on south wall between weirs 6 and 7, A6
			single conduit antenna on south wall between weirs 14 and 15, A2
			single conduit antenna in final serpentine pool, A1
WA Shore AWS	RT	HBO	single conduit between crowder and tainter gate, A1
			single conduit approx. 50 ft. upstream of tainter gate, A2
			single conduit antenna near the LPS, A3

Appendix A. Table 1 (continued). List of radio antennas, HD PIT antennas, and other equipment that remained at the Washington Shore or in the WA-Shore Fishway at Bonneville Dam in 2019.

Location	Type	Site	Description
Washington Shore Fishway			
UMT Junction	RT	OBO	1 pair conduit upstream end of UMT, some cable crosses fishway, A1
			1 pair conduit on last weir from lower ladder, some cable crosses fishway, A2
			1 pair conduit under LPS platform, some cable crosses fishway, A3
	HD PIT	DBX	antenna in upstream end of UMT with flex conduit runout along wall to railing
WA Top of Ladder Exit	HD PIT	8BX	Exit antenna in bulkhead slot
Adult Fish Facility (AFF)			
West entrance – under walkway	-	-	Wooden cabinet labeled with C. Caudill contact info, empty. Trashcan lamprey tank dolly.
Tagging area	-	-	Tanks still plumbed, flooring still over grating, bucket of misc. non-Univ. of Idaho materials.
Flume	HD PIT	-	Wooden slot weirs and PIT antennas still installed.
FERL	-	-	Prototype ramp-still assembled. Large rolling live well (question on owner-no label).
Tailrace- north shore	RT	2BO	Wooden post - cemented into ground

Appendix A. Table 2. List of radio antennas, HD PIT antennas and other equipment that remained in the Cascades Island Fishway at Bonneville Dam in 2019.

Location	Type	Site	Description
Cascades Island			
Entrance	RT	CBO	Old conduit under LPS, behind ladder, and maybe elsewhere in turn pool
	HD PIT	0BX	4 antennas at entrance with conduit runout straight up to pier nose deck.
Lower Ladder	RT	XBO	single conduit antenna on 1st center support, A1
			single conduit antenna on 8th center support, cable crosses half fishway, A2
			single conduit antenna on 17th center support, cable crosses half fishway, A3
LPS	HD PIT	4BX	NOAA sites. Hard wired. All equipment remains.
UMT Entrance/AWS	RT	FBO	single conduit antenna on north wall at UMT entrance, A1
			single conduit antenna on south wall of AWS just upstream of picket lead and behind count building, A2
			single conduit antenna on south wall of AWS just upstream of tainter gate, A3
			single conduit antenna on south wall of AWS 50 ft. upstream of tainter gate, A4
Serpentine/old fishway exit	RT	-	Several old conduit antennas
	HD PIT	3BX	NOAA site. Metal cabinet with solar panel. PVC antenna at UMT picket leads. All equipment remains.

Appendix A. Table 3. List of radio antennas, HD PIT antennas and other equipment that remained in the Bradford Island Fishway at Bonneville Dam in 2019.

Location	Type	Site	Description
Bradford Island			
South Spillway Entrance	RT	BBO	1 pair conduit inside entrance before turn, A2, A3
			old conduit behind ladder
			1 pair just upstream of turn, A4, A5
B-Branch Ladder	RT	WBO	single conduit antenna on 1st center support of fishway, A1
			single conduit antenna on 11th center support of fishway, cable crosses half fishway, A2
			single conduit antenna on 25th center support of fishway, cable crosses half fishway, A3
South PH1 Entrance	RT	4BO	single conduit between two entrance gates
North PH1 Entrance	RT	8BO	single conduit antenna on west wall at 3rd crossbeam of fishway
			old conduit by ladder gauge
PH1 Collection channel	RT	-	several (~4-5) old conduit distributed between N and S end of PH
A-Branch Ladder	RT	VBO	1 pair conduit where the fishway widens, one on center support and one on west wall, A1
			single conduit antenna on 11th center support, cable crosses half fishway, A2
			single conduit antenna on center support about 50 ft. upstream of the road overpass, cable crosses half fishway, A3
Bradford Island Serpentine Weir	RT	JBO	single conduit antenna downstream of count window, A1
			single conduit antenna upstream of count window inside of first turn, A2
			single conduit antenna between weirs 2 and 3, A3
			single conduit antenna between weirs 6 and 7, A5
			single conduit antenna between weirs 12 and 13, A4
Bradford Island AWS	RT	EBO	single conduit antenna upstream of tainter gate, A1
			single conduit antenna at LPS entrance, A2
			single conduit antenna at top of LPS, A3
BI Top of Ladder Exit	RT	ABO	two conduit antennas at last serpentine weir, A1
	HD PIT	9BX	Exit antenna with flex runout to half wall above exit
LPS	HD PIT	1B1-4	NOAA sites. 4 antennas hard wired to equipment boxes. All equipment remains.

Appendix A. Table 4. List of radio antennas, HD PIT antennas and other equipment that remained at The Dalles Dam in 2019.

Location	Type	Site	Description
Tailrace			
South	RT	1TD	Wooden post cemented into ground
North	RT	2TD	Poured concrete slab
North Ladder			
Top of Ladder Exit	RT	5TD	single conduit antenna downstream of walking bridge below the exit pool
	HD PIT	CTX	slot and orifice antennas in last weir with flex runout to railing. Exit antenna with flex conduit runout to wall under overhang.
East Ladder			
South Spillway Entrance	RT	ATD	1 pair conduit at upstream end of entrance pool, A3
West Powerhouse Entrance	RT	JTD	1 pair conduit at 180-degree bend, just downstream of collection channel, A4
East Powerhouse Entrance	RT	HTD	1 pair conduit at 90-degree bend of entrance pool, A3
			1 pair conduit and a wall mounted 4-element yagi at exit of collection channel, A4
			1 pair conduit and a wall mounted 4-element yagi at exit of transport tunnel, A5
	Level logger		PVC stilling well on wall PH side of entrance pool
East Ladder	RT	GTD	1 pair conduit before weir 1, A1
			1 pair conduit on weir 20, A5
Below Count Window	HD PIT	ATX	4 antennas in one location between 180 degree turn and upper ladder turn. Flex runout drapes across fishway to railing.

Appendix A. Table 5. List of radio antennas, HD PIT antennas and other equipment that remained at John Day Dam in 2019.

Location	Type	Site	Description
Tailrace			
South	RT	1JD	poured concrete slab, wooden post cemented in ground
North	RT	2JD	poured concrete slab, wooden post cemented in ground
North Ladder			
Powerhouse Entrance	RT	BJD	conduit antenna under road deck grating upstream of entrance, A4
	HD PIT	WJX	4 antennas at entrance with flex conduit runout to rails
Top of Ladder Exit	HD PIT	DJX	2 antennas with flex conduit runout to railing
South Ladder			
South Entrance	RT	LJD	2 conduit antennas in entrance pool, A2, A3
South Ladder	RT	MJD	1 pair conduit at ladder turn upstream of junction pool, A2
			single antenna between weirs 8 and 9, A5
			single antenna between weirs 12 and 13, A6
			old conduit on weir (~18) between A6 and count window
South Ladder Count Station	HD PIT	JDX	NOAA site - all equipment left in place and running.
Top of Ladder Exit	HD PIT	EJX	Exit antenna with flex conduit runout to wall under stairs.

Appendix A. Table 6. List of HD PIT antennas that remained at McNary in 2019.

Location	Type	Site	Description
North Ladder			
Top of Ladder Exit	HD PIT	JMX	Antennas with flex conduit runout to rail
South Ladder			
South Entrance	HD PIT	FMX	Antennas with flex conduit runout to rail
Top of Ladder Exit	HD PIT	GMX	Antennas with flex conduit runout to rail