Use of Adult Pacific Lamprey Passage Structures at Bonneville and John Day Dams
2018 Annual Report

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On the cover: The Bradford Island LPS adjustable exit slide and new camera box which contains an in-line paddle counter. The exit slide is twice as long as the previous PVC pipe and is lined with 1/8" grooved ultra-high molecular weight (UHMW) density plastic in an attempt to prevent lamprey attachment.

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Executive Summary

Low passage efficiencies of adult Pacific Lamprey (*Entosphenus tridentatus*) at Bonneville Dam have been implicated as one factor contributing to their basin wide decline. To improve passage, lamprey specific fishways were built to help lamprey over dead ends and around areas of difficult passage thus increasing passage efficiencies. Our objectives were to safely operate the lamprey passage systems (LPSs), improve passage estimates using video validation, and evaluate lamprey use during the 2018 migration season compared to previous years. LPSs continue to pass nearly half the lamprey over Bonneville Dam indicating how important these routes of passage are. Improved accuracy and dependability of LPS counting systems would reduce video review costs and integration of these counts into the current fish counting program would provide a complete estimate of lamprey passage at Bonneville Dam.

Lamprey Passage Structures performance was evaluated using total passage at each LPS, proportional passage, run timing, and relative use compared to total dam escapement including nearby window counts. A summary of annual LPS passage is presented as an indicator of relative use and proportional routes of LPS passage are used to compare among locations and between years.

There are six lamprey specific fishways, five at Bonneville Dam and one at John Day Dam. LPS passage at Bonneville Dam during the 2018 season (April – October) was 60,420 fish or 46% of estimated total lamprey escapement which was 131,268 by the end of 2018. Of the lamprey that used LPSs, they favored the Washington shore fish ladder's auxiliary water supply (WA-AWS) LPS (52% of LPS passage), Bradford Island fish ladder's auxiliary water supply (BI-AWS) LPS (47%), and then the Cascades Island fishway entrance (CI-ENT) LPS (1%), which is a single ramp at the fishway entrance. The University of Idaho report capturing 591 lamprey from Washington shore's Lamprey Flume Structure (May-August) and Columbia River Inter-Tribal Fish Commission (CRITFC) technicians report capturing 1,873 lamprey from the John Day north ladder LPS trap (June - August).

LPS mechanical counter accuracy was validated using video and was corrected for over-counting (negative percent difference) and under-counting (positive percent difference). Percent difference varied by location from (-3%) at Washington shore fish ladder's junction with the Upstream Migrant Tunnel (WA-UMTJ), +5% at WA-AWS, (-6%) at CI-ENT, to +33% at BI-AWS's new mechanical counter. The raw mechanical count for all LPSs combined was adjusted up by 16%, indicating we have not yet reach the (+/-) 5% standard followed by the visual (window) salmonid counting program.

Managers depend on timely, accurate counts at Bonneville Dam as an indication of the health of the Columbia Basin's lamprey population and to set tribal translocation goals. The mechanical counters used on the LPSs are lower cost than direct live counts and monitoring passage around the clock, but are imperfect. Performing video validation adds greatly to their operating cost. To help meet the USACE Pacific Lamprey Passage Improvements Implementation Plan's goal of developing techniques for lamprey counting, we suggest trials of innovative counters such as photoelectric counters placed in line with the current paddle counters to determine the best path forward. Finally, as LPSs continue to pass a large proportion of all lamprey passing Bonneville Dam, these counts need to be integrated with the current on-line day and night window counts to better reflect actual lamprey passage at the dam.

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Introduction

Background

In response to repeated calls from Columbia Basin tribes for help with Pacific Lamprey (*Entosphenus tridentatus*) monitoring and passage at U.S. Army Corps of Engineers dams, several structural and operational changes have been made – including the installation of lamprey-specific fishways. The Corps' fish counting program is the primary source for monitoring anadromous Pacific Lamprey populations in the Columbia River Basin. The program began in 1938 at Bonneville Dam and has been used as evidence of a population level decline, though recent runs have increased. Scientists have attributed the decline to several causes including spawning and rearing habitat loss from dam inundation, the difficulty adults have passing dams, irrigation diversions that strand juveniles, and poor ocean conditions leading to decreased prey (Close et al. 2002, Keefer et al. 2013 'bottle neck report', Murauskas et al. 2013).

As a result of this decline, there has been significant regional concern regarding the stability of lamprey populations in the Columbia Basin causing the State of Oregon to list Pacific Lamprey as State sensitive species in 1993. Regional Native American tribes were the first to voiced concern about the decline of lamprey, a culturally important species, and developed their own recovery plan (CRITFC 2011, see also Close et al. 2002). In January 2005, a "finding of insufficient information to evaluate status" was determined by the U.S. Fish and Wildlife Service (50 C.F.R. Part 17) resulting in no Endangered Species Act listing.

In May 2008, the Columbia Basin Fish Accords addressing actions to protect Pacific Lamprey was signed between the Federal Columbia River Power System Action Agencies and the Fish Accord signatory Tribes (consisting of the Confederated Tribes of the Umatilla Indian Reservation, the Confederated Tribes of the Warm Springs Reservation of Oregon, and the Confederated Tribes and Bands of the Yakama Nation), and the Columbia River Inter-Tribal Fish Commission (CRITFC) (BPA ROD 2008). Specific to the U.S Army Corps of Engineers (USACE), the Fish Accords required collaboration with the signatory Tribes and the U.S. Fish and Wildlife Service to develop and implement a 10-year lamprey passage improvement plan (USACE 2014). The goal of the Pacific Lamprey Passage Plan within the Northwestern Division of USACE is to improve lamprey passage at Corps dams along the lower Columbia and Snake rivers.

Bonneville Dam is the first dam on the mainstem Columbia River that Pacific Lamprey must ascend to reach upstream spawning habitat. In their review of several lamprey passage studies, Keefer et al. (2013) found the median fishway passage efficiency proportion (unique lamprey that passed / unique lamprey that entered) from 1997-2010 was 0.52 at Bonneville Dam and they contrast this to passage efficiency of adult salmonids which was 0.95 at Bonneville Dam. They also found that increasing passage at Bonneville Dam would result in increased passage at all upriver dams.

The swimming scope and anguilliform locomotion of Pacific Lamprey are very different from the subcarangiform locomotion of salmonids (*Oncorhynchus spp.*) for which the Bonneville Dam fishways were designed. Salmon are stronger swimmers, attracted by high water velocities as they find their way upriver, and are unaffected by 90° corners commonly found in fishways. In contrast, the velocities, turbulence, and sharp turns at Bonneville Dam fishways often exceed Pacific Lamprey swimming capacity (Clay 1994, Johnson et al. 2012), forcing them to attach with their oral sucker to hold, rest, and eventually burst forward to the next attachment point. Adult salmonid critical swimming (Ucrit) speeds can range from 101 to 165 cm/s (Geist et al. 2003), while adult Pacific Lamprey have a mean Ucrit of 86.2 cm/s at 15°C (Moser and Mesa 2009). However, they have been recorded in Bonneville Dam's fish ladders flow control section swimming through 240 cm/s velocities by Kirk et al. (2016) who suggests fatigue from multiple high velocity sections can lead to passage failure; a view also held by other researchers (see Haro et al. 2004).

Once inside fishways, adult salmon are guided and excluded from potential dead ends by diffuser grating and picketed leads (Clay 1994). Adult lamprey however, can pass through most diffuser gratings and picketed leads wider than 19 mm (¾ inch) and may get lost in areas fish were not intended to enter (e.g. auxiliary water supply channels and diffuser pits). Thus, the salmonid focused fish ladders create impediments to Pacific Lamprey passage in both structure design and water velocity. Recently, strides have been made to incorporate lamprey passage criteria into fishway design (Pacific Lamprey Technical Workgroup 2017) and in routing them around locations that are difficult to pass (Moser at al. 2010, Goodman and Reid 2017).

Several structural and operational changes have been made in the USACE salmonid fish ladders, including installation of Lamprey Passage Structures (LPSs) inside the ladders and the addition of major modification to fishway entrance to increase lamprey passage. There are four LPSs at Bonneville Dam and one at John Day Dam. The LPSs are alternative fishways designed specifically for lamprey. They have lower velocity and volume of water than salmonid fishways, entrance ramps designed for climbing out of the salmonid fishway using their oral disk, rest boxes at the top of ramps, and exits that typically slide downward to the forebay to ease lamprey passage. Entrance modifications include a keyhole shaped entrance bulkhead installed at Cascades Island entrance and the John Day North entrance (JDA-N ENT). Operationally, night time flows have been reduced at Bonneville's Powerhouse 2 fishway entrances for lamprey due to their nocturnal behavior passing dams and difficulty overcoming the water velocities at salmonid fishway entrances. Several other improvements are described in USACE Pacific Lamprey passage improvements implementation plan: 2008–2018 (2014 update). The goal of these improvements is to increase the numbers of lamprey that successfully pass through the dam and decrease turn around.

Accurate counting of Pacific Lamprey is necessary to determine changes abundance over time. Recently, there has been an effort to refine techniques for counting lamprey that pass USACE dams. Specifically, modifications to the LPSs count systems and methodologies in reviewing video have improved the accuracy of passage estimates. Passage is the primary metric that regional fisheries managers use to assess the health of the Pacific Lamprey population in the Columbia River Basin.

Life History of the Pacific Lamprey ***Entosphenus tridentatus***

The anadromous Pacific Lamprey is an integral part of the Columbia River ecosystem. Lamprey serve as an important food source for white sturgeon (*Acipenser transmontanus)*, an occasional food source for California (*Zalophus californianus*) Steller sea lions (*Eumetopias jubatus*) (Tidwell et al. 2019), terrestrial predators like raccoons, river otter, mink, and avian predators such as Great Blue

Herron, Bald Eagles, and Osprey. They act as a buffer to predation for threatened and endangered salmonid species, which have synchronous juvenile out migrations. Pacific Lamprey begin their lives in rivers and streams along the west coast of North America that drain into the Pacific Ocean. As eyeless larvae, or ammocoetes, they burrow into fine substrate and filter feed for four to six years retaining and cycling stream nutrients (Kan 1975). In the macropthalmia phase, lamprey undergo physical metamorphoses over several months, growing eyes and teeth to prepare for life in the ocean. Adults spend 20-40 months in the ocean feeding as external parasites on several species of fish and marine mammals (Kan 1975) then cease feeding and return to fresh water in the spring and summer. They may overwinter in the main stem Columbia River before moving into tributaries to spawn. Lamprey die shortly after spawning, returning valuable marine-derived nutrients to the riverine habitat (Beamish 1980, USFWS 2008, Wang and Schaller 2015). Further research is needed to understand the passage requirements of lamprey at dams, what is needed to help them reach spawning habitats, and in turn help conserve this species to ensure a more diverse and healthy ecosystem.

Objectives

To help increase lamprey passage and count accuracy, our objectives were to:

1) Operate the lamprey passage structures at Bonneville Dam with regular inspections to ensure functionality and safe passage.

2) Validate and correct for mechanical counters used to monitor these structures, thus improving passage estimates.

3) Evaluate use of the lamprey passage structures (number passed), between location and years, relative to total dam passage.

Methods

Study Area and Location of LPSs

Bonneville Dam, at 146 river miles from the Pacific Ocean, is the first mainstem dam that adult migrating lamprey encounter on the Columbia River. They can use multiple passage routes through the dam, including the fish ladders that were designed for salmonid passage and LPSs that were designed specifically for lamprey passage. During 2018, we monitored four LPSs at Bonneville Dam located at Bradford Island, Cascades Island, and two at the Washington shore. Two systems were monitored by other groups, the Lamprey Flume Structure located at Washington shore's north downstream fishway entrance (Figure 1), and the John Day Dam's north entrance LPS and terminal trap. The elevator used to access this trap was repaired allowing this LPS to be operated for the first time since 2015.

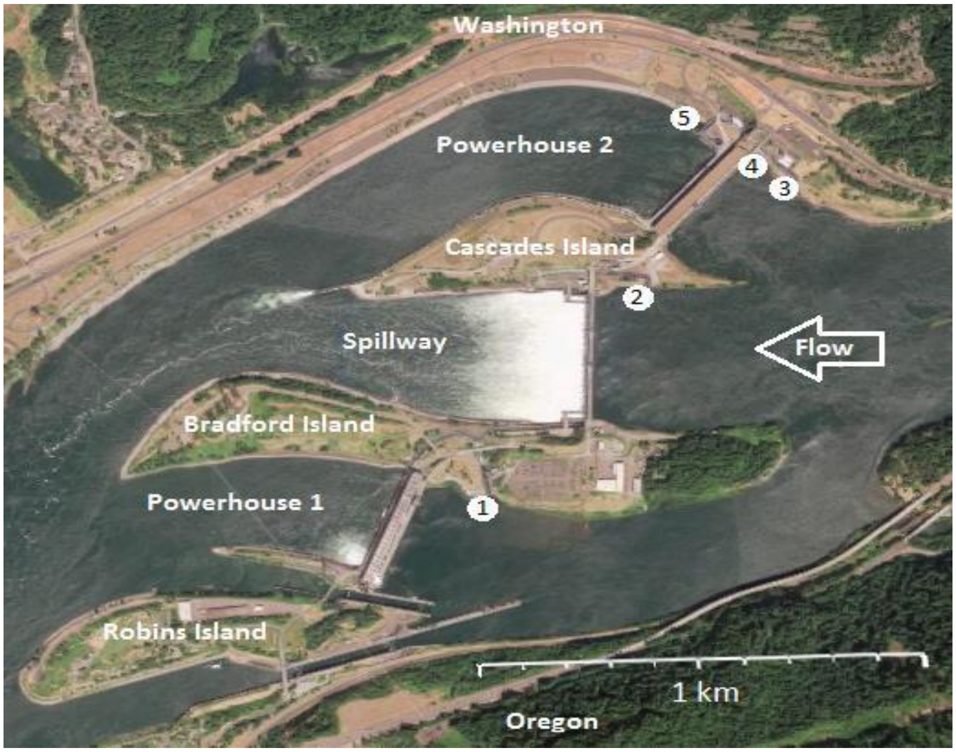

Figure 1. Lamprey specific fishway locations at Bonneville Dam and year first operated. (1) Bradford Island AWS LPS in 2003 (2) Cascades Island ENT LPS in 2009 (3) Washington shore AWS LPS in 2010 (4) Washington shore UMTJ LPS in 2017 (5) Washington shore Lamprey Flume structure in 2013.

The Bradford Island auxiliary water supply (BI-AWS) LPS was installed in 2003 as a trap and haul site and extended to the forebay in 2004 to provide a route of passage for lamprey that swim through or under the picket leads and into the auxiliary water supply channel dead-end. There are now two entrance ramps in this channel that parallel the Bradford Island flow control (serpentine weir) section. This LPS has a total length of 35.9 meters (118.1 feet) and height of 7.9 meters (25.9 feet) (Zobott et al. 2015, Table 1). The exit is located near the Bradford Island adult fish ladder exit in the forebay of Powerhouse 1. In 2018 a new exit slide lined with 1/8” grooved ultra-high molecular weight (UHMW) plastic replaced the PVC tube to release lamprey further out away from the rip rap and fish ladder exit. Also, a new camera box, in-line paddle, and new counter (Dwyer) and data logger (DATA DI-161) were installed to increase count accuracy and aid with video review.

The Cascades Island entrance (CI-ENT) LPS was installed in the winter of 2008-2009 and is unique because of its length and location. The entrance to the LPS is just inside the Cascades Island fishway entrance in the spillway tailrace and the exit was extended into the spillway forebay in 2013. It has a total length of 162.4 meters (532.8 feet) and height of 27.0 meters (88.6 feet), the longest and highest climb of all USACE LPSs (Zobott et al. 2015 Table 1). The entrance consists of one ramp creating a back eddy and competes with high flows to attract lamprey out of the fishway. In 2018 a new counter (Dwyer) and data logger (DATAQ DI-161) as well as a full duplex antenna were added near the exit pipe to monitor the movement of PIT (Passive Integrated Transponder) tagged lamprey. Alarms were added to the upstream upwelling boxes at the Cascades Island LPS to alert the control room when the water level dropped below the depth of the sensor.

The Washington shore adult fish ladder auxiliary water supply (WA-AWS) LPS was installed in 2007 and modeled after the BI-AWS with two entrance ramps. It provides a passage route from the auxiliary water supply channel to the top of the fishway, bypassing the flow control section (serpentine weirs). It has a total length of 20.8 meters (68.2 feet) and height of 9.2 meters (30.2 feet) (Zobott et al. 2015, Table 1). In the winter of 2016-2017 the PVC exit pipe was replaced with a bar-screen lined shoot and new count system designed by USACE engineers. In the process the angle of the exit was changed from 55° to 45° causing exiting lamprey to contact the far fishway wall. As an in-season fix, fish screen was added to form a cone at the end of the shoot to direct lamprey into the middle of the fishway. In 2017-2018 a plunge box was added to the end of the exit to dissipate energy and allow them to volitionally drop into the center of the fishway. Video was used to evaluate how lamprey would interact with the plunge box.

In the winter of 2016-2017 two additional LPS entrance ramps were installed near the junction of the upstream migrant tunnel with the Washington shore fishway (WA-UMTJ LPS). The ramps are connected to the existing WA-AWS via several meters of off the shelf aluminum irrigation pipe. After traversing the pipe, lamprey swim through an upwelling box and descend via a small bar screen ramp, where they trigger a paddle counter on their way to rest box 3 of the original WA-AWS LPS. From there, they continue to the WA-AWS LPS exit and are counted again. Thus the sums of both counters is not additive but does indicate which entrance ramps were used. For a more complete description of the BI-AWS and WA-AWS LPSs history see Moser et al. 2010.

The Lamprey Flume Structure (LFS) is located at the mouth of the Washington shore fish ladder's north downstream entrance and was installed in June of 2013. The flume structure has upper and lower entrances that span the entire fishway entrance. It was designed to guide approaching lamprey into a separate system to bypass the known passage bottlenecks in the Washington shore fish ladder. The LFS currently ends in a trap from which lamprey are collected and typically transported upstream. It has a total length of 57 meters (187 feet) and height of 8.5 meters (27.9 feet) (Zobott et al. 2015 Table 1). Two well pumps mounted to the North Downstream Entrance (NDE) monolith provides water to the trap box and upper (LPS-like) section of the flume while a large butterfly valve controls gravity fed attraction water that flows through the lower LFS.

The John Day North Entrance (JDA-N ENT) LPS was installed in 2013 along with major fishway entrance modifications to help Pacific Lamprey: a variable width entrance weir to provide faster salmon velocities high in the water column and slower, lamprey friendly velocities low in the water column as well as a flow disrupting bollard field attached to the floor. The LPS collects lamprey from the upstream end of the bollard field and allows them to climb to a rest box, then the collection box on the deck, 10.7 meters above the fishway floor (Budwig et al. 2014). They pass through the upwelling box and fall into the trap box where they are collected and typically transported upstream.

Operation and Inspection - Methods

Lamprey Passage Systems

The LPSs were operated to encompass the adult lamprey passage season at Bonneville Dam, typically April to October, and regularly inspected. Inspections were conducted to assure water was flowing properly, count systems were operational, nothing was blocking fish movement, and to remove lamprey mortalities. Any malfunctioning parts, such as occasional pump screen fouling of the LPS were addressed or reported to Bonneville project biologists, who coordinated repairs.

Accessible LPS rest boxes and holding tanks were inspected for build-up of sediment and flushed if needed. Rest boxes were not flushed if lamprey were present, as some drains are not screened and the lamprey could be flushed out. The first two rest boxes in the lower section of CI-ENT LPS are not accessible during regular inspections. These rest boxes require a crane and man-basket to access and are checked if passage problems arise. They can be flushed remotely using a pneumatic system, to remove silt and/or lamprey carcasses which could potentially lead to passage delays.

Lamprey mortalities were removed from the LPS rest boxes so passage was not delayed. Research on sea lamprey (*Petromyzon marinus*) suggests that during early phases of their migration they avoid pheromones produced by dead or dying conspecifics (Wagner et al. 2011). Lamprey that appeared moribund and did not respond to stimuli were removed with a dip net and further inspected to confirm mortality. The location, date, total length (cm), and inter-dorsal fin distance (cm) (used as a measure of maturity) of mortalities were recorded and are summarized in Appendix C. They were then scanned for PIT tags, photographed, and either placed in a freezer for histological examination by USFWS Fish Health Lab or returned to the river if decomposition had progressed too far for histological evaluation. Mortality information was submitted to Bonneville project biologists. They, in turn, included this information in a Memorandum for the Record for distribution to the Fish Passage Operations & Maintenance (FPOM) workgroup, a regional group of fish managers representing state, tribal, and federal fish and wildlife agencies.

Lamprey Systems Operated by Others

In 2018, the Lamprey Flume System (Figure 2) was operated by the University of Idaho, from April to August, and was inspected daily as a potential collection point for research. The attraction water butterfly valve was held constant at 60 percent open and the upper entrance knife gate was held at 36” open, as measured from the top of the screw to the top of the black gear casing. Results of this trapping effort were provided by the University of Idaho and summarized here to be consistent with previous reports.

To determine if decreased use of the LFS in 2017 was due to obstruction, an ROV was used to inspect the entrance. A summary of this inspection can be found in the results section.

Figure 2. Lamprey Flume Structure (LFS) meets with rest box one (yellow arrow) and attraction water grey pipe (blue arrow) feeds in from below. Washington shore's north upstream fishway entrance at right and north downstream entrance (white arrow).

In 2018, the John Day north ladder LPS was operated by CRITFC technicians as they collected lamprey daily from 21 June to 22 August in support of the translocation programs of the Nez Perce, Yakama, and Umatilla Tribes in an effort to re-populate up river tributaries. This season is the first time it has been operated since 2015 due to an out of service elevator, which is needed to access the LPS for safe, fast, fish transportation.

Passage Validation and Estimates - Methods

Lamprey Passage System

LPS mechanical counters associated with each volitional passage LPS are imperfect (Zorich et al. 2018) and require validation and correction of counts before they can be used. The mechanical counting systems at Bonneville Dam are very similar designs with the exception of the older paddle and limit still in use at CI-ENT LPS. The newer paddle and switch at the three other sites, designed by Portland District engineers, uses a proximity detector to monitor a ferrous tab attached to the paddle's axle as an indicator of passage (**Figure 3**). When lamprey pass down the exit, they move the paddle and the attached ferrous tab. This movement is detected by the proximity detector and it sends a voltage pulse. This voltage pulse is tallied by the counter (Dwyer brand) and recorded by the data logger (DATAQ DI-161), which totals the number of pulses at pre-set intervals (set to 60 seconds) and is then written to a computer three times a day. The CI-ENT LPS retains the use of its original perforated in-line paddle that is attached to the arm of a limit switch (Honeywell Heavy Duty Limit Switch model numbers: LSA1A) that sends a signal to the same Dwyer counter and DATAQ DI-161 logger used at other sites.

Figure 3. Bradford Island LPS mechanical counter components new for 2018. Left, proximity detector and ferrous tab (cover removed). Middle, inside of camera box showing black paddle, 1/8" grooved PVC, upwelling box fyking, and smooth face near the fyking where some lamprey attached. Not shown Dwyer counter display and DATAQ DI-161 data logger installed in the count station.

At CI-ENT LPS, the location of the paddle is in-line within the PVC exit pipe, eliminating paddle bounce induced count error. Also, the limit switch has enough tension to properly seat the paddle after a fish passes. New additions at the CI-ENT LPS exit area for 2018 are the Dwyer counter for the LPS and the full duplex transceiver and antenna with Ferriday cage (**Figure 4**).

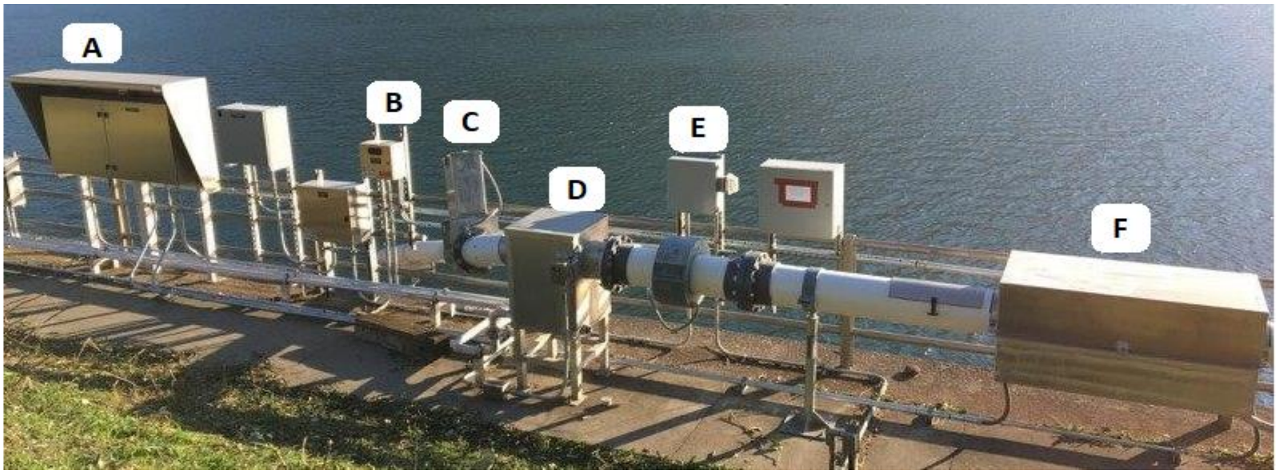

Figure 4. Cascades Island ENT LPS exit including A) PIT Transceivers, B) Dwyer counter, C) Camera box above count paddle, D) Upwelling Box #1, E) Half Duplex antenna, and F) Full Duplex PIT antenna. Fish move from right to left and exit in the spillway forebay.

Figure 5 shows a close up view of the CI-ENT LPS mechanical counting system. It is included here due to the small correction factor typically associated with this simple system. It has fewer moving parts than the newer design, the paddle has not needed adjustment, and the limit switch is more easily available compared to a proximity detector.

Figure 5. CI-ENT LPS exit camera box (left) and in-line paddle and limit switch (right).

To collect video at the LPSs we used an IP camera with infrared lights (Pelco Sarix IMP319-1ERS globe) mounted above the paddle counters (Figure 6 and Figure 7) attached to a DVR or NVR (Pelco DX4708HD (DVR) or a HIK Vision DS-7204HQI-K1 Network Video Recorder at BI-AWS and CI-ENT LPSs and a Pelco Digital Sentry DS SRV2 Series DVR at WA-AWS and WA-UMTJ).

Figure 6. WA-AWS LPS exit showing (left to right) PIT antenna, upwelling box with black latch, camera box (covering the paddle), and Dwyer counter display with red warning tags. Right panel shows camera box with lid removed, globe camera, and proximity detector with blue tape pointed at curved ferrous tab indicating position of paddle (open/closed).

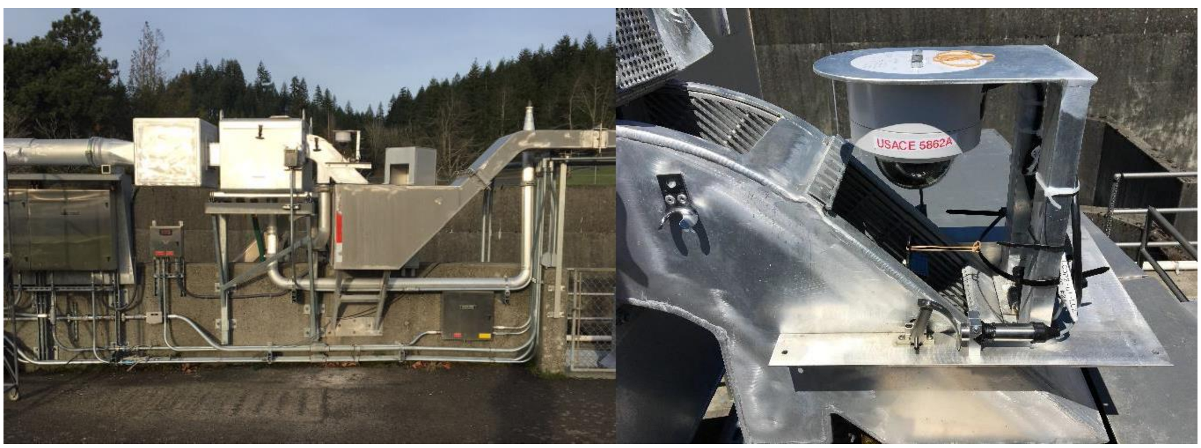

Figure 7. The WA-UMTJ LPS (shiny) as it enters the older WA-AWS LPS rest box three (dull). Left image: from left to right, traversing sections (aluminum irrigation pipe), PIT antenna, upwelling box (with black latch), camera and counting paddle (box removed). Right image: close up of globe camera pointing down on counter paddle, binder clip and rubber band to help seat paddle, curved metal indicator tab attached to axle, and proximity detector that sends count pulse when tab is not detected.

During LPS inspections, tests were conducted to ensure the counting systems were functioning properly, logging systems were checked, and data were downloaded. The paddle was actuated ten times by hand and the counts on the data logger digital display were verified. The date, time, and number of these test pulses were recorded so they could be removed from the data set before analysis. If there were any issues noted, the mechanical counters were adjusted to improve the accuracy. Passage data from the new DATAQ data logger were automatically written to a laptop three times a day as text files and downloaded and transferred to the office network on Mondays, Wednesdays, and Fridays. Occasionally, power outages and other glitches led to gaps in the lamprey counts. The count for these days were either taken directly from the counter displays, when available, or interpolated from data records on either side of the gap.

Video recordings were used to validate the data reported by the mechanical counting systems and calculate correction factors. Recordings were done every other week for two nights, from 20:00 to 06:00 - typical peak hours for lamprey passage. Binder clips and rubber bands were attached to the top of the paddles at WA-AWS and the WA-UMTJ and replaced as needed to help reduce under-counts. The rubber bands helped to ensure the paddle would return to the proper position after lamprey passage and not stick in the “up” position or leave a gap that lamprey could slide under (**Figure 7** right).

A correction factor was calculated and applied to the raw mechanical counts to increase the accuracy of the LPS passage and estimate the difference between the mechanical and corrected counts was quantified using percent difference. To calculate the correction factor, we divided the number of lamprey that were observed passing in each video review period by the number of lamprey that were logged by the mechanical counter (Equation 1).

Equation 1. $$Correction\ Factor = \frac{Video\ Count}{Mechanical\ Count}$$

Daily counts were multiplied by correction factors from the nearest biweekly review. To be compatible with early reports we followed the methods of Gallion et al. (2017) to calculate percent difference.

Equation 2. $$Difference\ (\%) = \left(\frac{Corrected\ Estimate - Mechanical\ Count}{Mechancial\ Count}\right) * 100$$

LPS run timing is represented using box and whisker plots (seasonal) and histograms (hourly). To determine seasonal run timing, the corrected daily passage estimates for each LPS was used to identify the first and last passage event, and calculate 10%, 50%, and 90% passage completion dates. For historical context, these values are also presented for previous years. Finally, we updated a linear regression model that uses daytime window count at The Dalles Dam to estimate total lamprey escapement at Bonneville Dam, (regression model) and compared it to the total dam passage estimate presented in this report (sum method). The model and supporting data is presented in Appendix B.

For data analysis an R script (R version 3.5.1 R Core Team 2018) was used to stitch together raw count files, remove paddle tests, sum daily passage, and generate the linear regression model with 95% confidence intervals. Microsoft Excel 2013 was used to apply correction factors, report counts to the region, and generate graphics.

Evaluation of Performance - Methods

Lamprey Passage System

Lamprey Passage System performance was evaluated using the number passed at each LPS relative to other LPSs and relative total dam passage. Two short-term projects used video to monitor lamprey behavior at the new WA AWS LPS plunge box and new BI AWS LPS exit slide. A summary of annual LPS passage is presented as a long term record of use in Appendix A and a bar graph is used to show proportional routes of LPS passage among locations and between years. Relative use was used to compare between LPS locations and the years 2015-2018. It was calculated by dividing passage at each LPS by the estimate of total dam passage (total dam passage = day time counts + night time counts+ LPS passage+ trap and haul take).

Similar to previous authors, we used "relative use" to further evaluate LPS performance among LPSs and between years. However we estimated total passage at Bonneville Dam as the sum of all known passage routes for 2017 and 2018, or using a linear regression model for 2015 and 2016 (Gallion et al. 2017) rather than multiplying the daytime index (window counts) by three (Corbett et al. 2014 Table 1 and earlier NOAA reports).

The Washington shore exit plunge box was monitored for safe passage. While reviewing video in 2017, it was determined that some lamprey were contacting the bridge wall as they fell from the LPS exit. As an in-season fix, a piece of submersible traveling screen was fashioned into a cone directing lamprey to the center of the fishway (**Figure 8** left). That cone was replaced with a plunge box, installed in the winter of 2017-18 (**Figure 8** right). Using an Arm Bullet Color Camera mounted to a hand rail and GANZ DVR, we recorded and confirmed this modification was successful at protecting lamprey from grazing the bridge or fishway wall. We also monitored it for delay to be sure fish were not holding there.

Figure 8. At the WA-AWS exit a cone of fish screen material was used to prevent lamprey from grazing the bridge wall or the opposing fishway wall (left image 2017). In 2018 this was replaced with a plunge box with a rolled lip that reduced the energy of the falling lamprey and allowed them to volitionally exit (right image).

During a night time inspection we learned that lamprey were attaching and holding to the BI-AWS exit slide's grooved plastic. To quantify the number and attachment time, we used an Arm Bullet Color Camera mounted to a rail and a GANZ DVR to record lamprey behavior. Video was reviewed from 1800 to 2100 and 0500 to 0800 hours, as this allowed for ambient lighting to be used, voiding concerns that artificial light might cause them to release. Three video review sessions were recorded: baseline (July 25-26), double flow rate (August 6-7), and after the exit slide was power washed (August 29-30). Descriptive statistics of attachment behavior are provided in the Results section.

Results

Operation and Inspection - Results

The Bonneville LPSs operated between 189 and 237 days in 2018, while the LFS was operated for 157 days and the JDA-N ENT LPS was operated for 63 days (Table 1). Bonneville LPSs were inspected between three and five times a week depending on run strength, while the LFS and JDA-N LPS traps were checked daily. The pumps for the BI-AWS were started on 8 March to allow for the newly built exit section to season and the system was dewatered on 31 October. The Cascades Island and Washington shore LPSs were watered 25 April and also dewatered 31 October. By the middle of September the University of Idaho requested to dewater the LFS because it was collecting so few fish and the JDA-N LPS was taken out of service in August after Tribal translocation collection needs were met.

Table 1. Operation dates of Lamprey Passage Systems and Lamprey Flume Structure at Bonneville Dam, and the John Day north ladder entrance LPS.

Location	Start Date	End Date	Days of Operation
Bradford Island AWS	3/8/2018	10/31/2018	237
Cascades Island Entrance	4/25/2018	10/31/2018	186*
Washington shore AWS	4/25/2018	10/31/2018	189
Washington shore UMTJ	4/25/2018	10/31/2018	189
Washington shore NDE LFS[¥]	4/10/2018	9/14/2018	157
John Day North Entrance[†]	6/21/2018	8/22/2018	63

*Two of four Cascades Island Entrance pumps failed and were out of service from 4-6 June 2018.
[¥]Operated under contract by the University of Idaho. [†]Operated for translocation by CRITFC technicians.

Lamprey Passage System

LPSs were inspected five days a week during peak passage (June-August) and three days a week outside that range. Water supply volume to the LPSs at BI-AWS, WA-AWS, and WA-UMTJ was sufficient for the entire passage season. However, sometime between the Sunday fishway inspection by a project biologist on 3 June and the morning of 4 June, one of the sump pumps at the CI-ENT pond failed, tripping the GFCI outlet causing the second pump to stop. This stranded lamprey in lower rest boxes without incoming fresh water. The CI-ENT LPS was dewatered and Bonneville electricians installed industrial pumps and low water alarms and it was back in service by 7 June.

Like salmon, some lamprey die due to the rigors of freshwater migration. In total, 81 lamprey mortalities were found in Bonneville LPSs in 2018. Two mortalities were found in the BI-AWS

(0.01% of passage), 63 in the CI-ENT (7.1% of passage), 10 in the WA-AWS (0.03% of passage), and 6 in the WA-UMTJ (0.10% of passage). The pump failure at CI-ENT stopped water flow during a time of high lamprey passage, ultimately causing all 63 mortalities in the LPS. The pumps did not have low water alarms when initially installed, however, after this failure, more durable pumps have been installed and the upwelling box that supplies the climbing section is equipped with low water alarms that alerts the control room.

Additional lamprey mortalities were found in the fish ladders when inspected by Bonneville Dam project biologists. Those mortalities are not covered in this report, but can be found on the FPOM website (http://www.nwd-wc.usace.army.mil/tmt/documents/FPOM/2010/). Not all lamprey that die during migration are detected, some may simply wash down the fishway back into the river.

Passage was not affected by sediment loading in the LPSs this season, however, to aid visibility in the rest boxes during inspections, sediment was occasionally flushed. The WA-UMTJ rest boxes 1 and 2 had the most sediment buildup towards the end of the 2018 season. The screen at CI-ENT pond (a transition between the climbing section and traversing section) was occasionally scrubbed with a stiff brush to clean off algal growth.

Lamprey Systems Operated by Others

The LFS at Bonneville's second power house was operated from April to September by the University of Idaho for a total of 157 days. They reported no issues with intake pumps clogging or other aspects of LFS operations.

Due to lower than anticipated collection numbers in 2017 and previous years, there was concern the entrances of the LFS might be blocked. On 7 August 2018, the LFS entrance, outside of the fishway, was inspected by Bonneville project biologists using an underwater ROV. The video showed no signs of structural damage or blockage by sediment, woody debris, or aquatic vegetation. The entrances looked fine, however, the upper entrance was difficult to see as it sits upstream of the sea lion exclusion device stand. The lower entrance pickets are still very difficult to raise and lower via the manual wheel near the LPS trap. This may be due to a rusted cog on the south side of the lower entrance that moves the pickets (shows well in the ROV video).

The John Day north entrance LPS was operated by CRITFC from 21 June to 22 August, 63 days in 2018. They reported no problems with intake pumps clogging, however, they did report a short elevator outage during which they used fish bags to hoist lamprey from the tailrace deck up to the main roadway- a 96 foot elevation gain.

Passage Validation and Estimates - Results

Lamprey Passage System

Count validation was performed by comparing 700 hours of video and 4,734 passage events to the associated mechanical counts and correction factors were determined. They were calculated from 20 hours of video (two nights) reviewed at each site about every two weeks and ranged from 0.91 to 1.22 at the WA-UMTJ, 0.91 to 1.23 at WA-AWS, 0.81 to 1.00 at CI-ENT, and 0.89 to 1.89 at BI-

AWS. Video validation could not be performed some weeks due to equipment failures such as power outages or malfunctioning video recording, resulting in time gaps of up to five seconds (e.g. HikVision NVRs).

Table 2. Correction factors (CF) for Bonneville Dam LPS mechanical counters from video collected from 16 May to 20 September, 2018. The mechanical column is the value reported by counter. The video column is the observed count during the same time period. Validations that could not be performed due to equipment failures are represented by ‘na’.

Observation Period	Bradford Island AWS			Cascades Island Entrance			Washington AWS			Washington UMTJ		
	Mechanical	Video	CF	Mechanical	Video	CF	Mechanical	Video	CF	Mechanical	Video	CF
1	na	na	na	na	na	na	75	68	0.91	9	11	1.22
2	na	na	na	na	na	na	50	47	0.94	4	4	1.00
3	338	301	0.89	13	13	1.00	1060	1005	0.95	73	67	0.91
4	217	411	1.89	43	35	0.81	361	416	1.15	221	217	0.98
5	208	200	0.96	1	1	1.00	291	292	1.00	84	84	1.00
6	274	251	0.92	na	na	na	204	207	1.01	13	14	1.08
7	203	201	0.99	9	9	1.00	254	312	1.23	64	64	1.00
8	145	131	0.90	1	1	1.00	119	111	0.93	18	18	1.00
9	31	29	0.92	1	1	1.00	74	71	0.96	1	1	1.00
10	9	8	0.89	1	1	1.00	131	127	0.97	6	6	1.00

The majority of LPS mechanical counter error was due to under-counting at the new Bradford Island AWS count system. Video review during the fourth observation period showed the paddle was not re-seating and smaller lamprey were able to pass through a small gap uncounted. Extending the shock absorber helped the paddle to seat completely and alleviated the issue. The majority of over-counts at BI-AWS were due to lamprey turning and attaching to the smooth plate on either side of the upwelling box exit, activating the limit switch multiple times before passing (Table 3).

At the CI-ENT LPS, seven of ten observation periods yielded useful data, but passage numbers were low. Due to several factors, data loss and DVR malfunctions occurring in observation periods one, two, and six, and the pump failure during observation period five at CI-ENT LPS, few lamprey were recorded during the other video review periods (Table 2). However, this paddle has been reliable since its installation in 2013 and the most common over-count error is due to lamprey attaching above the paddle, hitting it with their tail, causing it to over-count as was the case in observation period four (**Table 2**).

At the WA-AWS LPS six of the ten observation periods resulted in over-counts due to paddle bounce and two resulted in under-counts. After adjustments to the ferrous tab, to increase or decrease how much of the arch covered the proximity detector, the correction factors remained low (**Table 2**).

Overall, the Bonneville LPS passage estimate during 2018 increased by 16% from 52,133 to 60,420 when corrected for mechanical counting error. Percent difference was used to compare count accuracy at each location and at all sites over the season (**Table 3**). Here we see the most accurate counting location, requiring the least corrections, was the WA-UMTJ, followed by the WA-AWS, then CI-ENT, and the newly designed BI-AWS count system required the most correction.

Table 3. Corrected estimates for lamprey passage at LPSs during 2018. Difference (%) = ((Corrected Estimate – Mechanical Count) / Mechanical Count) * 100 rounded to the nearest whole value.

LPS Location	Mechanical Count	Corrected Estimate	Difference (%)
Bradford Island AWS	21,153	28,105.6	+33
Cascades Island ENT	940	882.1	-6
Washington AWS	30,040	31,432.5	+5
Washington UMTJ	6,247	6,084.3	-3
Total*	52,133	60,420.2	+16

*Total does not include Washington UMTJ to prevent double counting. These fish swim into the Washington AWS LPS and are counted when exiting there.

Under-counts occurred when lamprey passage was seen in the video but not tallied by the mechanical counter, the most prominent was at the BI-AWS LPS due to a small gap between the paddle and the bottom of the exit chute. The WA-AWS LPS also had higher occurrences of under- and over-counting due to the ferrous tab used to indicate paddle position that was not lining up with the proximity sensor. It would slip on the axle and need to be repositioned.

Corrected daily lamprey passage fluctuated greatly at each of the LPSs with most fish passing in June and July (**Figure 9, Figure 10, and Figure 11**). The WA-AWS, CI-ENT, and BI-AWS LPSs accounted for 52.0%, 1.5%, and 46.5% of total passage, respectively. At most LPSs, the highest daily passage occurred during the end of June and early July and often exceeded the 24 hour count of the associated fish count window.

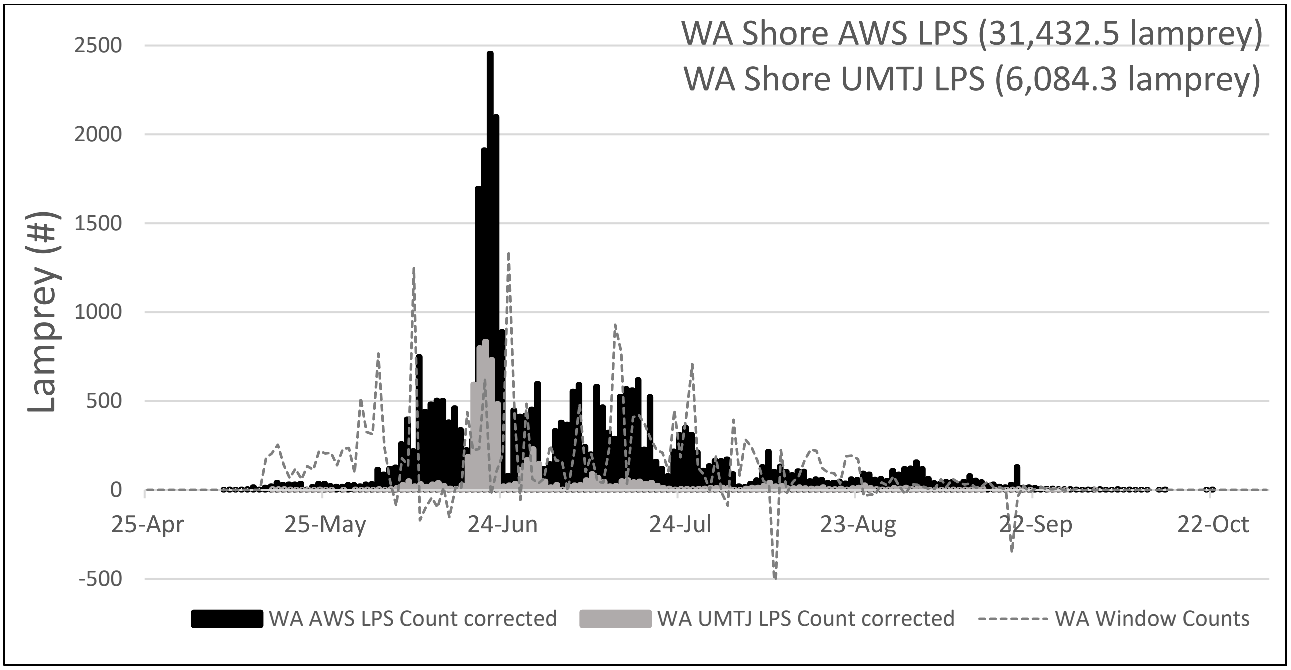

Figure 9. Washington Shore UMT Junction LPS (grey bars) which feeds into the Washington shore auxiliary water supply (WA-AWS, black bars) daily lamprey passage estimate (corrected). The WA-UMTJ lamprey do not add to the passage total. The dashed line represents cumulative 24 hour window counts at the Washington shore fish count window nearby.

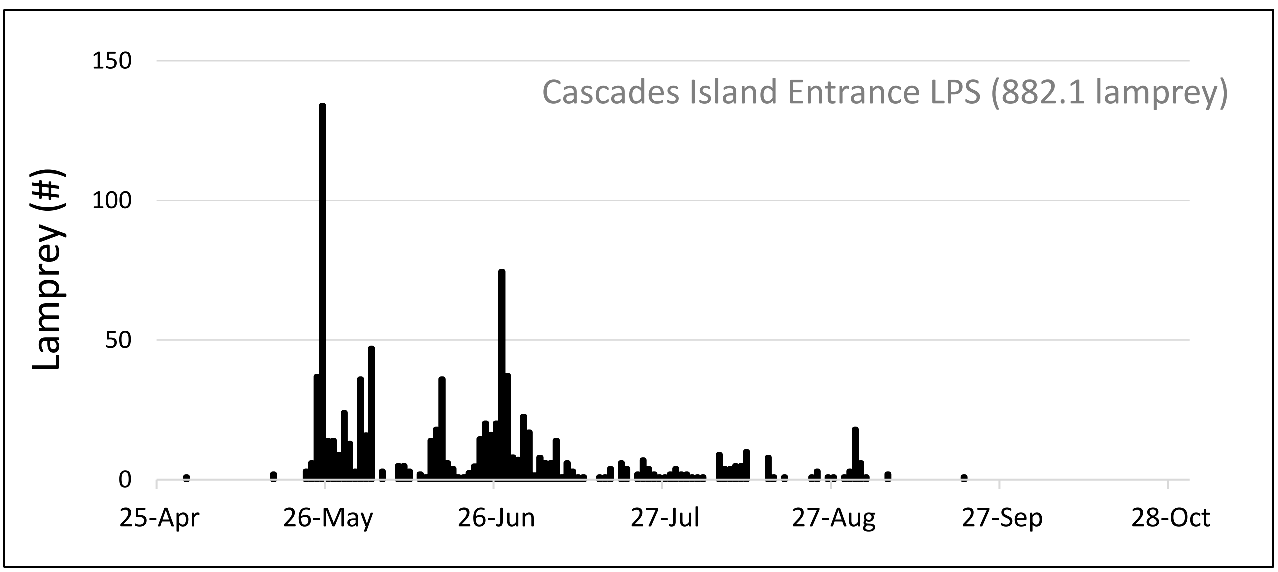

Figure 10. Cascades Island entrance LPS (CI-ENT LPS) daily lamprey passage estimates (corrected). There is no nearby window count for this time period. Instead fish are directed to the upstream migrant tunnel, across Powerhouse 2 to Washington shore fishway.

While lamprey passage at CI-ENT LPS began earlier than the other sites, it decreased dramatically after the pumps failed between 3-4 June and never seemed to recover (Figure 10). While the pumps were replaced and the LPS was up and running by 7 June there were only a few more days when passage exceeded 20 lamprey passing per day.

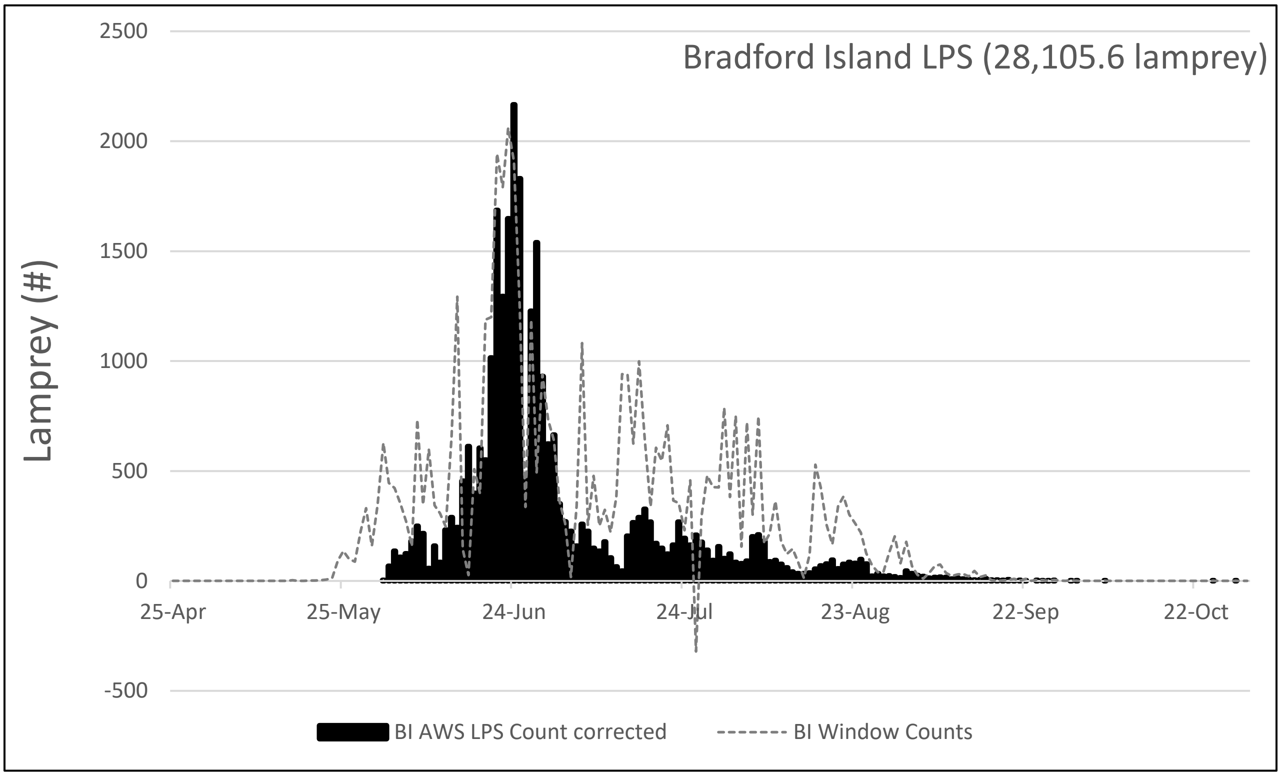

Figure 11. Bradford Island auxiliary water supply (BI-AWS LPS) daily lamprey passage estimates (corrected). The dashed grey line represents cumulative 24 hour window counts from the Bradford Island window.

Bradford Island AWS LPS passage started about one week after Pacific Lamprey were seen in the nearby counting window. In late June, passage was similar in magnitude to the window counts, however LPS passage then decreased.

Lamprey run timing through the LPSs was slightly earlier than previous years at BI-AWS and CI-ENT LPSs and similar at WA-AWS as determined by the 50th percentile (**Figure 12**). The first lamprey of the season passed through the CI-ENT LPS on 30 April and the last lamprey passed on 29 October at BI-AWS, two days prior to the LPSs being dewatered and shut down for the season. No lamprey were collected from the LPSs during dewatering. However, there were still a few moving up and down past the Bradford Island count window into December and it appears they overwintered there.

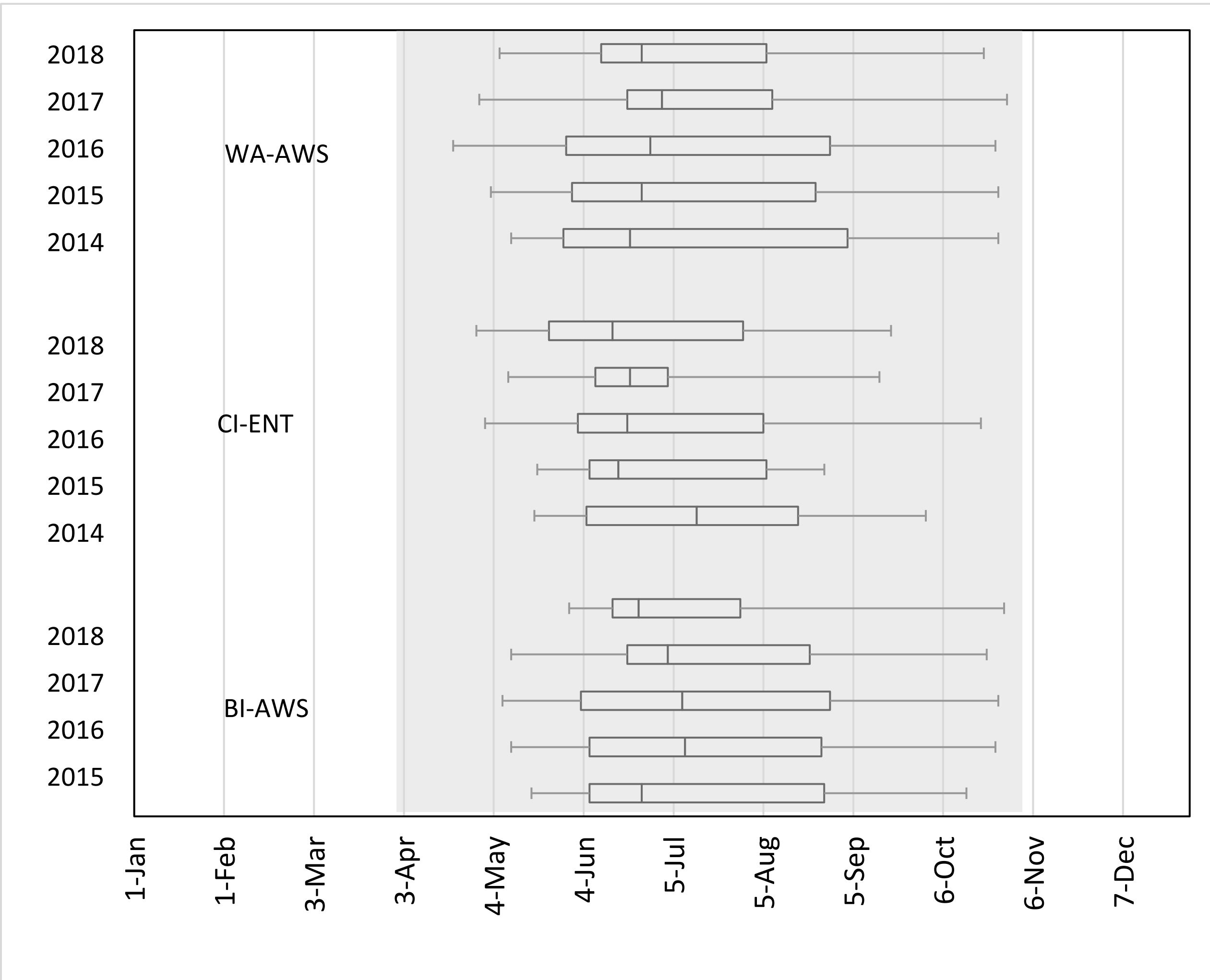

Figure 12. Run timing of Pacific Lamprey using Lamprey Passage Structures. Whiskers are dates of the first and last fish passage, boxes show 10%, 50% and 90% run completion dates. Grey box indicates typical dates of LPS operation (1 April to 31 October).

Diurnal passage through the LPSs is very similar for WA-UMTJ, WA-AWS, and BI-AWS with most passage occurring in the dark of night and decreasing at dawn (**Figure 13**). However, as in previous years, passage at CI-ENT was more protracted, showing a more gradual increase at sunset and gradual decrease after dawn.

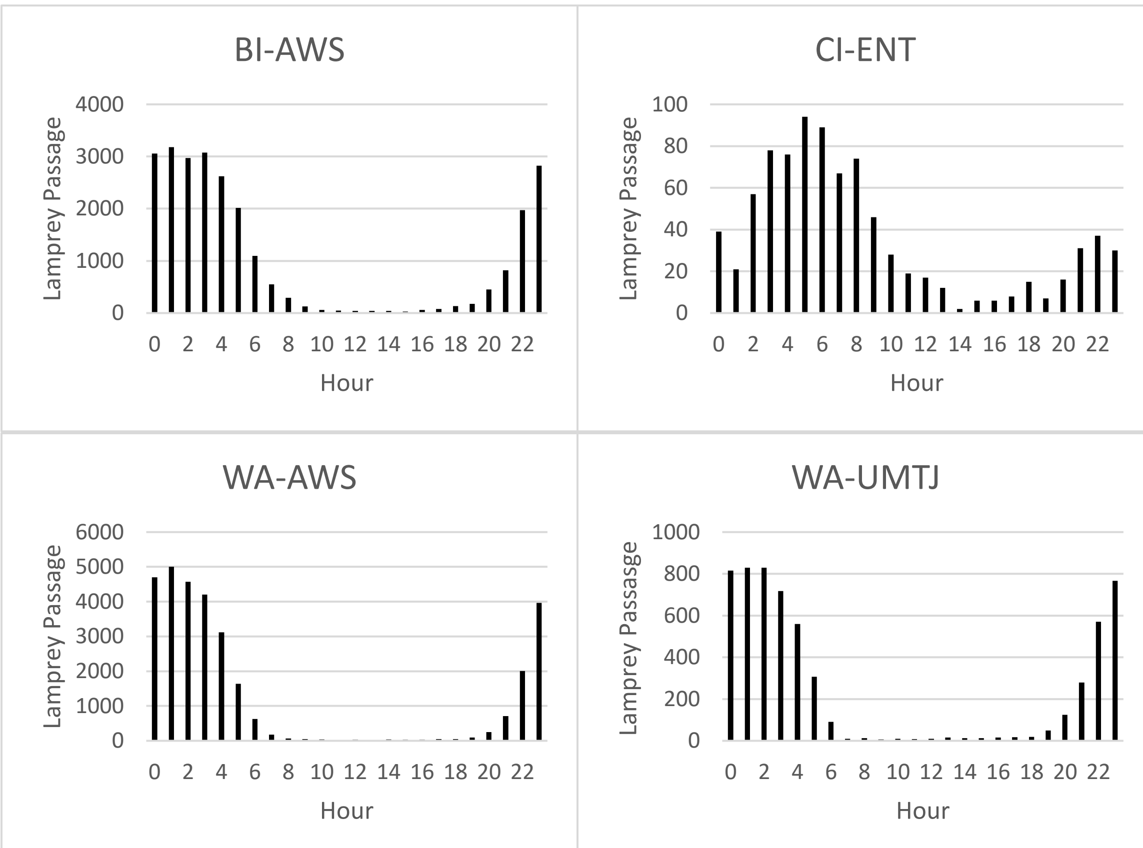

Figure 13. Diurnal distribution of lamprey passage by hour through LPSs at Bonneville Dam 2018. The LFS and JDA N-ENT traps do not have a mechanical counter, or time stamp, so are not presented here. Note changing y-axis.

Current count systems operate on a complicated network requiring communication between the switch (activated by the paddle), counter, data logger, and laptop. Through close inspection of the date-time stamps, breaks in that communication have been identified. Of the 237 days of operation at the BI-AWS LPS there were 24 breaks in the data records due to software glitches and power outages, for a total time of 21.6 days or 9% of the operational time. Half of the breaks were ten hours or less with the largest break of 3.9 days due to a power outage from 25 to 29 May when there was very little count window passage. The CI-ENT had 26 breaks in the data records, totaling 8.1 days or 4% of the operational time. The Washington shore data had the fewest data gaps, 18 data breaks totaling 1 day or 0.5% of the operational time. As most lamprey moved at night, data gaps of more than one night were filled using data written on inspection sheets or using linear interpolation from data on both sides of the break.

We collected one night of video to determine if lamprey would pass safely using the Washington shore plunge box without delaying passage. The plunge box replaced a 2017 in-season fix (a collar built of fish screen material) to help fish drop into the center of the fishway. Video of fish behavior showed that most lamprey quickly passed out of the plunge box with a mean residence time of five minutes. However, later in the year during a nighttime tour on 11 June, several lamprey were seen attaching to the outside of the plunge box, and two were able to actually climb back into the box. The qualitative observations of back climbing took place over about 15 minutes indicating the behavior may be frequent.

Lamprey Systems Operated by Others

The lamprey flume structure was operated under contract by the University of Idaho as part of a larger lamprey passage study using both PIT and radio-tagged fish. This system ends in a terminal trap box where fish are hand counted and typically moved to holding tanks at the Adult Fish Facility. These counts do not require video validation. In 2018, the LFS was operated for 157 days and had the highest number of lamprey collected to date, 591 lamprey (**Table 4**).

Table 4. Annual lamprey collection at Bonneville Dam's Washington shore Lamprey Flume Structure.

Year	Dates Operated	Days (#)	Lamprey collected (#)
2013*	4 June – 20 August	45	29
2014*	20 May – 10 September	113	545
2015	5 May - 31 August	107	69
2017	22 June - 24 August	64	51
2018	10 April – 14 September	157	591

*Values from Kirk et al. 2015. In 2013 the LFS was shut down for 16 days due to in-season repairs, thus the date range is greater than 45 days. In 2016 the LFS was not operated due to a missing hatch which left an opening in the upstream flume section.

The University of Idaho is writing a report that will cover daily collection from the LFS as well as results of their passage study using PIT and radio-tagged lamprey (Keefer et al. in prep).

The John Day north ladder LPS was operated by CRITFC this season. They provided the data for Figure 14 which shows the timing and magnitude of their trapping effort as compared with the 24 hour window counts from John Day's north ladder. In total, the JDA N-ENT was operated for 63 days in 2018 and collected a record high 1,873 lamprey (**Table 5**).

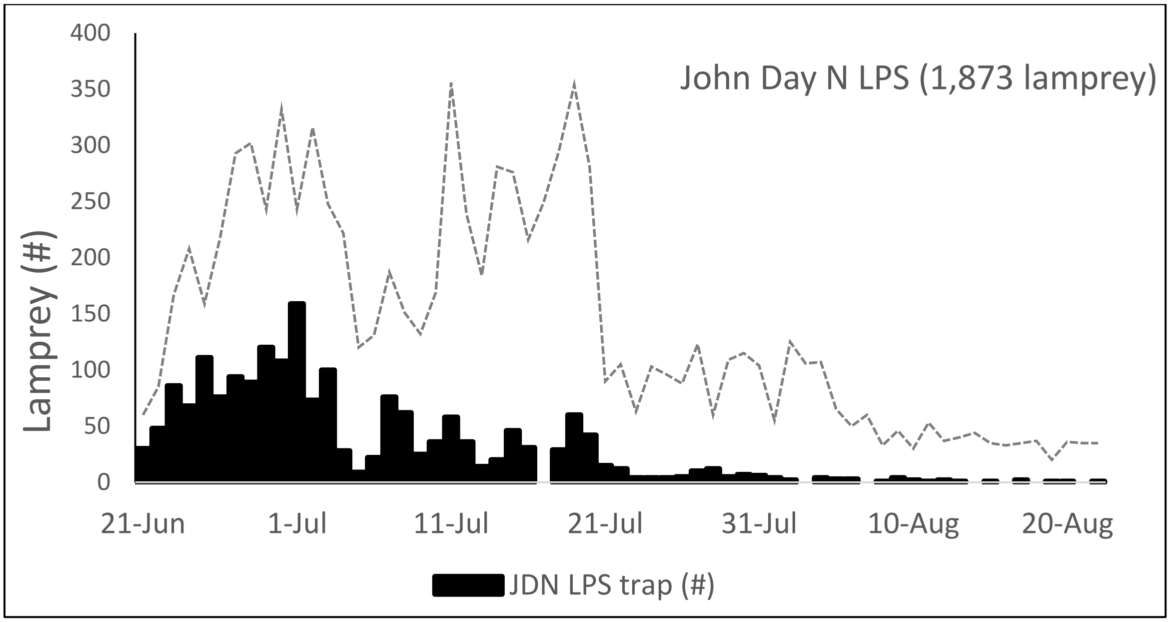

Figure 14. John Day north ladder entrance LPS number of lamprey trapped each day (bars) and cumulative 24 hour window counts from the John Day north counting window higher in the ladder (dashed line). Data courtesy of CRITFC lamprey translocation crew.

Table 5. Annual lamprey collection at the John Day Dam north fishway entrance LPS which ends in a terminal trap box. It was not operated in 2016 or 2017 due to a broken elevator.

Year	Dates Operated	Days (#)	Lamprey Collected
2014	25 June - 30 September	97	1,228
2015	5 May - 17 September	70	419
2018	21 June - 22 August	63	1,873

Evaluation of Performance – Results

Lamprey Passage Systems

Use of Bonneville LPSs has generally increased at both BI-AWS and WA-AWS since 2010, however WA-AWS showed a decrease this year (**Figure 15**). The proportional use of LPS routes was more evenly distributed between BI-AWS and WA-AWS this year, similar to 2013 and 2014. Total LPS passage was 60,420 with WA-AWS LPS accounting for 31,432 lamprey (52%) and BI-AWS passing 28,105 lamprey (46.5%), while CI-ENT passed 882 lamprey (1.5%) in 2018. The WA-UMTJ LPS collected 6,084 lamprey, or 19% used this entrance in its second season. Lamprey passage at BI-AWS decreased slightly between 2017 and 2018 from 28,843 to 28,105 (-2.6%), respectively. Passage also decreased at CI-ENT by 29% from 3,027 in 2017 to 882 in 2018.

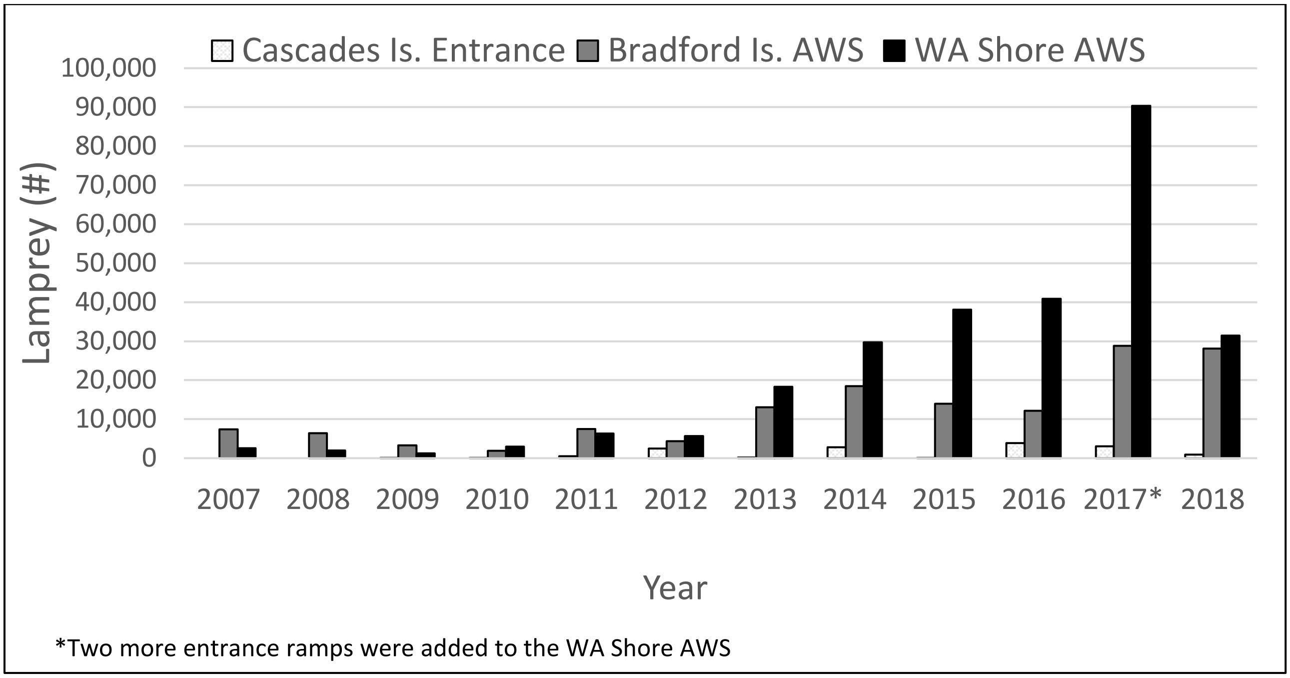

Figure 15. Annual lamprey passage estimates for Washington shore AWS (black), Bradford Island AWS (grey), and Cascades Island entrance (white) LPSs during 2007-2018.

As various modifications to improve LPS passage have taken place, year to year changes in lamprey abundance confounds performance evaluations. To control for run size we looked at proportional routes of passage, percent of lamprey using each LPS, to see if they are changing over time or if they are affected by improvements such as additional entrance ramps. As Figure 16 shows, since 2013 there has been an increasing proportion of lamprey choosing the WA-AWS LPS. However, in 2018 lamprey chose the WA-AWS and BI-AWS LPSs nearly equally. The proportion using the CI-ENT LPS is small with some variation between years.

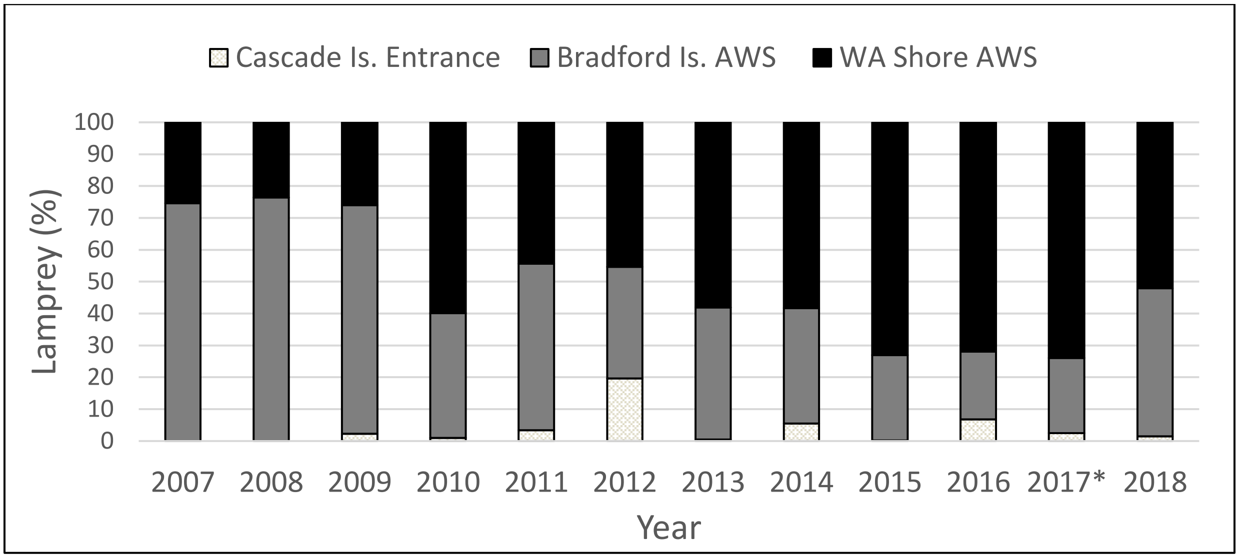

Figure 16. Proportional routes for LPS passed fish 2007-18. CI-ENT was first installed in 2009 as was the lamprey friendly keyhole entrance slot (variable width weir) and bollards that were part of the same entrance modification. *Two new entrance ramps to the WA-UMTJ LPS installed in winter of 2016/17.

As lamprey migrate up the Columbia River to spawn reach Bonneville Dam, they must choose between three tailraces with varying flows dependent on powerhouse priority (powerhouse 1, spillway, or powerhouse 2) Thus that initial choice can impact which LPS entrances are available to them. Table 6 provides a broad look at LPS proportional passage (the number of fish passing an LPS as a percent of total dam passage) in recent years. It also highlights the proportional increase in passage at the BI AWS LPS in 2018 and a reduction at the two other sites.

Table 6. Use of LPSs relative to estimated lamprey passage at Bonneville Dam. Units are passage number (with percent of estimated dam passage).

Year	Bonneville Dam Estimated Passage	WA-AWS LPS	CI-ENT LPS	BI-AWS LPS	Total LPS
2018	131,765	31,432 (24)	882 (0.6)	28,105 (21)	60,420 (46)
2017	292,411	90,377 (31)	3,027 (1)	28,843 (10)	122,247(42)
2016*	121,850	40,880 (34)	3,851 (3)	12,115 (10)	56,864 (47)
2015*	130,332	38,069 (29)	72 (0.1)	13,986 (11)	52,127 (41)

* LPS passage numbers for 2015-16 from Gallion et al. 2017 tables 5-7.

To develop a realistic passage estimate for Bonneville Dam when counts are net negative, we developed a linear regression model with an $r^2 = 0.98$ using lamprey counts at Bonneville Dam and The Dalles Dam (see Appendix B for details). We used this model's result to bookend our summation estimate. Using the 2018 daytime window counts at The Dalles Dam (30,696) in the regression model results in a Bonneville Dam passage estimate of 107,423 (94,327 – 120,519 upper and lower 95% CI), lower than our summation estimate.

We investigated lamprey attachment behavior at the BI-AWS grooved exit slide and tested a few improvements in an attempt to decrease lamprey attachment time on the exit slide. During the initial session, 10 of 29 lamprey attached (34%) to the exit slide for an average of 16 minutes and 24 seconds. The minimum attachment time was one minute and the maximum was 47 minutes. The average temperature during review times retrieved from a Hobo logger was 22.2° C. The most common reason for fish to release was being bumped by another passing lamprey. Flow rate at the exit ramp was increased in an attempt to prevent lamprey attachment. Of the 35 lamprey observed passing through the exit in that time period, 14 (40%) were observed attaching to the exit slide. The average temperature during this session was 22.4°C. The average attachment time was 20 minutes and 39 seconds with a range of 1 to 75 minutes. Finally, the exit slide was power washed to remove algae build up and ensure a clean surface to prevent attachment. Water flow rate at the exit slide remained double the initial session and the average temperature was 21.1°C. After power washing, eleven lamprey were observed passing during video review and none were able to attach to the exit ramp.

Lamprey Systems Operated by Others - Results

Both the Bonneville LFS and the JDA-N ENT LPS were successful in collecting lamprey this season with both collecting more than in previous years (**Table 4** and **Table 5**). While an evaluation of their performance is beyond the scope of this report, we included some graphic evaluation of the JDA-N LPS above to be consistent with previous years and have the information on lamprey passage available in one report. For more information about the Bonneville LFS performance, please see the report from the University of Idaho (Keefer et al. in prep.).

Conclusions

Operation and Inspection - Conclusions

The time frame for LPS operation, frequency of inspection, and newly covered climbing ramps were adequate to provide safe passage for most of the 2018 lamprey run. However a pump outage caused a mortality event. Window counts show that 5% of the run passed Bonneville Dam by 8 May and the run was 95% complete by 20 August. These dates were captured by LPS operations and we recommend continuing to operate LPSs during this time frame to provide additional routes of passage for early and later migrants. Providing an exit slide at the BI-AWS LPS that lamprey cannot attach to will reduce passage time, energy use, and prevent fish collisions on the slide. The timing of the pump outage at the CI-ENT LPS, a time of high use, led to a high number of mortalities and preventative steps are being taken.

An important operation issue during the 2018 passage season was a double pump outage at the Cascades Island LPS. It was caused when one pump failed and tripped a GFCI outlet (not standard at USACE projects) that both pumps were plugged into. This led to the death of most of the lamprey in the climbing section at the time. To mitigate for the mortalities caused by a pump failure at "the pond", a low water alarm was installed in the upwelling box and inspections were increased. Bonneville project biologists plan to switch to a lead/lag system which would start the second pump when the first pump fails rather than running both pumps all the time. However, the GFCI would also be problematic with a lead/lag system and so we suggest replacing it with a non GFCI outlet, or having the pumps on two separate electrical circuits if possible.

Operations at Bradford Island and Washington Shore LPSs went well this season and covering the climbing sections is believed to have prevented lamprey from becoming stranded on the grating below. At both locations, grated platforms have been installed above the auxiliary water supply to provide access to climbing ramps, rest boxes, and PIT antennas. Initially the climbing sections were open on top to allow for visual inspection, however each season some dead lamprey were collected from the grating near these sections (Zorich et al. 2018 Table 12). It was suspected that lamprey accidentally jumped out of the uncovered climbing sections, landed on the grating, and were unable to get back to the water. Hinged aluminum lids were added to the BI-AWS LPS in winter 2017/18 and the WA-AWS LPS has been covered with netting of different types over time. Unlike previous seasons, no lamprey mortalities were collected on grating near climbing ramps, suggesting that the installation of additional covers helped reduce mortality. No PIT tags were detected in any of the lamprey mortalities (see Appendix C).

Based on recommendations from the previous year's report, the LFS was started earlier this year, resulting in the greatest number of lamprey captured to date. However, the number of lamprey trapped dropped quickly, indicating a limited time frame for a strong capture efficiency. Lamprey captured here is likely bound by specific environmental conditions such as tailrace elevation (see Evaluation of Performance below).

Passage Validation and Estimates - Conclusions

We successfully used video to validate the mechanical counters, then calculated and applied correction factors to the mechanical counts, providing more accurate estimates of lamprey passage. Correction factors varied by site and through the season, supporting the need for frequent video validation to capture changing circumstances that influence them. Improved correction factors at the BI-AWS LPS are credited to moving the paddle from the end of the exit pipe to in-line. Through re-design and several small improvements, the percent difference from mechanical to corrected passage estimates is decreasing, but does not meet the standard of the visual fish counting program, ± 5% of the true (video) count (**Table 7**).

Table 7. Difference (%) between mechanical and corrected lamprey passage by LSP site from 2015-18.

LPS Location	2015	2016	2017	2018
BI AWS	(-33)	(-48)	(-65)	33
CI ENT	4	(-5)	(-26)	(-6)
WA AWS	(-32)	(-24)	92	5
WA UMTJ	Not installed	Not installed	(-19)	(-3)
All	(-32)	(-30)	(-9)	16

The BI-AWS's end of pipe paddle, used from 2015-17, resulted in false counts from paddle bounce and water pulses. It was corrected down by 33% in 2015, 48% in 2016 and 65% in 2017 (Gallion et al. 2017, Zorich et al. 2018) and corrected up by 33% this season. Initially the new counter at Bradford Island was over-counting during observation period three (correction factor of 0.89) due to paddle bounce. Next, during observation period four (correction factor of 1.89) the paddle was not completely closing – resulting in the bulk of the under-counting. Increasing the length of the shock absorber moved it closer to the axle's cam and helped it to seat properly, increasing accuracy in the remaining observation periods (correction factors of 0.89 to 0.99). Still, correction factors not equal to one indicate the system can be further improved.

The CI-ENT LPS limit switch counter was difficult to evaluate this season as the bulk of the passage happened early, and glitchy video from the site with gaps of up to five seconds, prevented adequate video validation during that time (observation periods one and two**,** Table 2). While there was very little passage during the later observation periods (from one to nine lamprey passing) the mechanical and video counts agreed (correction factors =1). However, with a seasonal percent difference of (-6%) this site fails to meet the Fish Passage Plan standard.

The WA-AWS and WA-UMTJ LPS counting systems were the most accurate with a total corrected difference of +5% and -3% respectively (Table 7Table 3). The WA-AWS count system tended to slightly over-count, however in observation periods four and seven it under-counted with CF's of 1.15 and 1.23 respectively. The WA-UMTJ LPS initially showed a slight under-count in observation period 1 (Mechanical = 9, video = 11) resulting in its largest CF of 1.22 but with low passage early in the run the impact was lessened. The CF's then leveled out with most at or near one, although later sample sizes are small, one lamprey and six lamprey in observation periods nine and ten respectively. While time consuming to collect and review, the use of video validation of LPS mechanical counters is an integral part of providing a realistic estimate of LPS use. We suggest that video validation is necessary until more accurate counting systems can be deployed.

The 24 hour window counts at Washington shore and Bradford Island are negative at times. This is an ongoing issue with lamprey window counts and is often credited to recycling of lamprey, specifically moving upstream behind the count station fish crowder mechanism unseen, then downstream through the count slot. Like the fishways, the count stations were designed for salmon, not the smaller Pacific Lamprey. However, the negative counts in late September were likely caused by a river otter that was hunting fish and lamprey in the ladder during this time (pers comm. Washington shore fish counters 9/23/19).

The highly variable nature of lamprey passage during the season, and the many moving parts of the current mechanical counter design, continues to make it difficult to achieve our goal of ± 5% of the true (video) count. If the count system or video system has issues during a passage boom, it will impact accuracy at that site for the entire season. This was the case for the BI-AWS location- during observation period four the paddle was not seating properly. While this was noticed and corrected during routine inspections, a large number of fish had already passed. We recommend installing several counters (mechanical, optical, electromagnetic, direct proximity detection etc.) at one site so they can all be compared to video collected at that site and with each other.

Evaluation of Performance - Conclusions

LPS passage at Bonneville Dam during the 2018 monitoring season (April – October) was 60,420 fish or 46% of estimated total lamprey escapement which was 131,268 by the end of 2018. This is similar to previous years when LPSs passed between 41-47% of the run (Table 6). Of the lamprey that used LPSs, they favored the WA-AWS LPS (52% of LPS passage), BI-AWS LPS (47%), and then the CI-ENT LPS (1%), which is a single ramp at the fishway entrance. The LPSs at Bonneville Dam continue to prove themselves important for lamprey passage, moving nearly half of all lamprey that pass the dam.

This is the first year we found disagreement between our summation estimate and our linear regression estimate. Our estimate calculated by summing all routes of passage fell outside the 95% CI of our linear regression model results: 107,423 (94,327 – 120,519 upper and lower 95% CI) and was 19% higher when comparing point estimates (summation = 131,268). This result is a little surprising as typically the model and summation estimates has strong agreement (Zorich et al. 2018) and we are uncertain of the cause. Some potential reasons include bad counts at Bonneville (recycling of lamprey past the fish count window), bad counts at The Dalles, or more lamprey than typical holding over in the Bonneville pool.

Performance at BI-AWS LPS increased compared to previous years. In terms of proportion of Bonneville Dam lamprey escapement (2015-17=10 or 11%, 2018=21%). This stems from the fact that the number passed by the BI-AWS LPS in 2018 was similar to 2017 even with total dam escapement dropping by about half (**Table 6**). The Bradford Island ladder window counted more lamprey passage (58%) than the Washington shore ladder (42%) from 1 April to 31 October (Columbia River DART accessed 2/7/19) suggesting dam operation, likely changes in water flow increased test spill or reduced exit flow night time operations at Powerhouse 1 and the B-branch to increase lamprey entrance efficiency may be playing a role.

At CI-ENT LPS, performance was quite variable and this season the low was likely influenced by the pump outage and subsequent mortality event there. Passage in 2018 was 822 lamprey placing it 5th out of the 10 years it has been operated (Appendix A 2009-2018). During this time the minimum use was 48 lamprey in 2010, the maximum was 3,851 lamprey in 2016, and the mean (excluding 2018) is 1,450 lamprey. The mortality event may have hindered overall passage due to pheromones from stressed or dying lamprey deterring others from the LPS entrance as Wagner et al. (2011) found in sea lamprey (*Petromyzon marinus*). It is yet to be determined if Pacific Lamprey have the same response. It should be noted that the CI-ENT LPS is uniquely located at a fishway entrance, thus has the potential to pass smaller lamprey, as measured by total length, which might not make it to other LPSs higher in the fish ladder (Kirk et al. 2015). Several years of radio telemetry studies, show that larger fish make it further up fishways and further up the river system (Keefer et al. 2013). So, while the number of fish pass by this LPS is modest, it has the potential to pass more of the smaller body sized lamprey that make it to Bonneville Dam.

As in previous years, the most used LPS was Washington Shore's AWS LPS. However proportional passage was reduced from 2017. We are uncertain why WA-AWS LPS use was reduced, but we see a similar pattern when we look at daytime window counts (see BI-AWS above for potential reasons proportional passage may have been reduced).

Interestingly, the concurrent lamprey passage study conducted by the University of Idaho using radio tagged lamprey found that the UMTJ entrances were initially passed by tagged lamprey and only used after they made several attempts to pass the serpentine weir (flow control) section or the auxiliary water supply section upstream (Keefer et al. *in prep.*). This is important because some of these fish may have never passed Bonneville Dam, falling back to the tailrace instead. We recommend increasing the attraction water flowing down the UMTJ entrance ramps to make it easier for lamprey to locate the entrances.

The Lamprey Flume structure collected more lamprey than any previous year, mostly early in the season when tailwater was highest. The current working hypothesis is that the reverse circulation, or vertical eddy, caused by the jet of attraction water exiting the fishway, swamps the LFS attraction flows once the tailwater drops to a yet to be determined level. This reverse circulation has been investigated when a variable width weir (keyhole weir) was proposed for Washington shore's north downstream entrance using a computer fluid dynamic modeled (AECOM 2010) and was recently measured using an acoustic Doppler current profiler or ACDP (Kirk et al. 2015). Our recommendation is to operate the LFS early in the season, the beginning of May or earlier, while recording tailrace water level (feet above mean sea level) to determine if or when the reverse circulation impacts lamprey collection at the LFS.

In 2018 the JDA-N LPS collected 1,873 lamprey, the most lamprey of the three years it has been operated. CRITFC technicians trapped during the peak of the run starting 21 June and then dewatered it when translocation goals were achieved on 22 August. Thus it was only operated for 63 days, but still collected more fish than previous years. Given a limited amount of data, the most efficient operating practices are yet to be determined. However, the elevator used to access the trap and move lamprey to the Smolt Monitoring Facility broke down during the passage season forcing staff to pull the lamprey up the side of the dam using fish bags. We recommend developing a strategy that would be faster, thus safer for lamprey, such as extending this LPS to allow access to the forebay or rebuilding the elevator so it is safe for moving lamprey and humans.

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Appendix A. Annual lamprey passage tables for Bonneville Dam LPSs

Table 8. Annual lamprey passage estimates at Washington auxiliary water supply Lamprey Passage Structure during 2007-2014 (Corbett et al. 2015), 2015-2016 (Gallion et al. 2016), and 2017-2018.

Year	Dates Operated	# Days	Estimated Passage
2007	25 June – 22 October	119	2,517
2008	13 May - 28 October	168	1,985
2009	26 May – 2 November	160	1,199
2010	8 June – 25 October	139	2,961
2011	26 May – 9 November	167	6,345
2012	2 June – 11 November	162	5,686
2013	16 May – 16 October	153	18,329
2014	8 May – 29 October	174	29,756[1]
2015	30 March – 28 October	212	38,069[1]
2016	5 April – 27 October	202	40,880[1]
2017	1 May – 31 October	184	90,377[1]
2018	25 April– 31 October	189	31,432[1]

1: Corrected for mechanical count error

Table 9. Annual lamprey passage estimates at Bradford Island auxiliary water supply lamprey passage structure during 2007-2015 (Corbett et al. 2015), 2015-2016 (Gallion et al. 2016), and 2017-2018.

Year	Dates Operated	# Days	Estimated Passage
2004	Unknown	NA	7,490
2005	Unknown	NA	9,242
2006	Unknown	NA	14,975
2007	8 May – 22 October	167	7,387
2008	13 May – 28 October	168	6,441
2009	26 May – 2 November	160	3,302
2010	4 June – 25 October	143	1,933
2011	26 May – 9 November[1]	154	7,476
2012	2 June – 9 November[2]	144	4,392
2013	16 May – 16 October[3]	141	13,066
2014	8 May – 20 October	165	17,587[5]
2015	30 March – 28 October	212	13,986[5]
2016	5 April – 27 October[4]	205	12,115[5]
2017	5 April– 31 October	210	28,843[5]
2018	8 March – 31 October	237	28,105[5]

1: 13 days of data gaps; 2: 16 days of data gaps; 3: 12 days of data gaps; 4: 2 days of data gaps; 5: Corrected for mechanical count error. In 2006 a second collection ramp was added to the east side of the AWS.

Table 10. Annual lamprey passage estimates at Cascades Island entrance lamprey passage structure during 2007-2014 (Corbett et al. 2015), 2015-2016 (Gallion et al. 2016), and 2017-2018.

Year	Dates Operated	# Days	Estimated Passage
2009	26 May – 3 September[1]	73	106
2010	31 May – 10 September[2]	75	48
2011	6 June – 15 September[3]	94	485
2012	23 May – 20 September[3]	113	2,472
2013	24 June – 4 October[3,4]	95	155
2014	14 May - 30 October[5]	167	2,832
2015	6 April – 30 September	177	72[6]
2016	8 April – 27 October	202	3,851[6]
2017	5 April– 31 October	210	3,027[6]
2018	25 April – 31 October	186	882[6]

1: Experimental flow testing was conducted; system was operated weekdays only; 5 days of data gaps; 2: LPS was operated weekdays only; 3: 7 days of data gaps; 4: CI LPS was extended to the forebay using mostly PVC pipe prior to 2013 operation; 5: two days of data gaps; 6: corrected for mechanical count error.

Appendix B. Bonneville Dam lamprey passage estimate using a linear regression model

Adult Pacific Lamprey can pass Bonneville Dam by several routes. Through the traditional salmonid fish ladder, they are visually counted through a window when passing count slots (Washington shore, Bradford Island, and occasionally Cascades Island). When passing through Lamprey Passage Structures (LPS) they are counted mechanically as described in this report and could be captured in traps and released upstream of the dam for research or for the tribal translocation program.

Visual lamprey counting, especially from night time video, is extremely difficult to perform accurately. Additionally, lamprey are seen passing underneath the fish crowder brushes and squeezing through the fish crowder picket leads suggesting they may still use this route to avoid the count slot after the picket lead spacing was reduced to ¾ inches. The serpentine weirs, or flow control section, upstream of the count slots at Bonneville Dam are a known turn around point for lamprey. They will repeatedly move back and forth through the count slot, attach to the window for long periods of time, and generally move in a less directed way than salmonids do. These varied behaviors result in dynamic movements of lamprey that make them difficult to track in the window. An additional complication is they may be able to move upstream behind the count slot, behind the crowder for example, and are only counted when they float downstream through the slot in the mid-water column, leading to further inaccuracies.

At Washington shore, the night time window counts can be highly negative (downstream movement) resulting in an unrealistic overall negative lamprey passage index for 2015 (daytime index 20,252 and night time index of (-122,914) with slightly positive index in 2016 (daytime index 28,091 and night time index (-26,123). These results are similar to the negative results from nighttime video in 2008 by previous researchers (Clabough et al. 2012) and the difficulties of video review experienced in the 1990's by Aaron Jackson CTUIR (pers. comm 2016). Possible reasons for this are recycling of lamprey within the adult ladders at the count station. Lamprey may move downstream past the count slot after exiting the LPS upstream, or take other unknown paths. Similarly, Bradford Island counts were negative during night time hourly counts, however overall the passage index was positive at this location in both 2015 and 2016 leading to questions of count accuracy.

To develop a realistic passage estimate for Bonneville Dam when counts are net negative, we looked for other lamprey counting locations that are highly correlated to Bonneville Dam in previous years. We used linear regression to model total passage at Bonneville during 2015 and 2016. We compared Bonneville Dam total passage index to The Dalles Dam day passage index from 2009 to 2014 and 2017. Only day time counts from The Dalles Dam were used because only two years of night counts were available (2013 and 2014). Night counts at Bonneville Dam were not reported prior to 2009. Annual passage at Bonneville Dam from 2009-2014 ranged from 17,299-114,746 and averaged 64,120 (Table 1). Lamprey passage in 2017 (292,303) was the highest since counting resumed.

Table 11. Pacific lamprey passage at Bonneville Dam consisting of daytime window indexs + night time video counts + LPS passed fish + fish trapped and released above the dam for research or tribal translocations. The Dalles Dam (daytime window indexs).

Year	Bonneville Dam	The Dalles Dam
2017	292,441	30,696
2014	120,100	11,662
2013	84,347	8,737
2012	93,456	6,241
2011	51,20	5,003
2010	24,564	1,726
2009	18,822	2,318

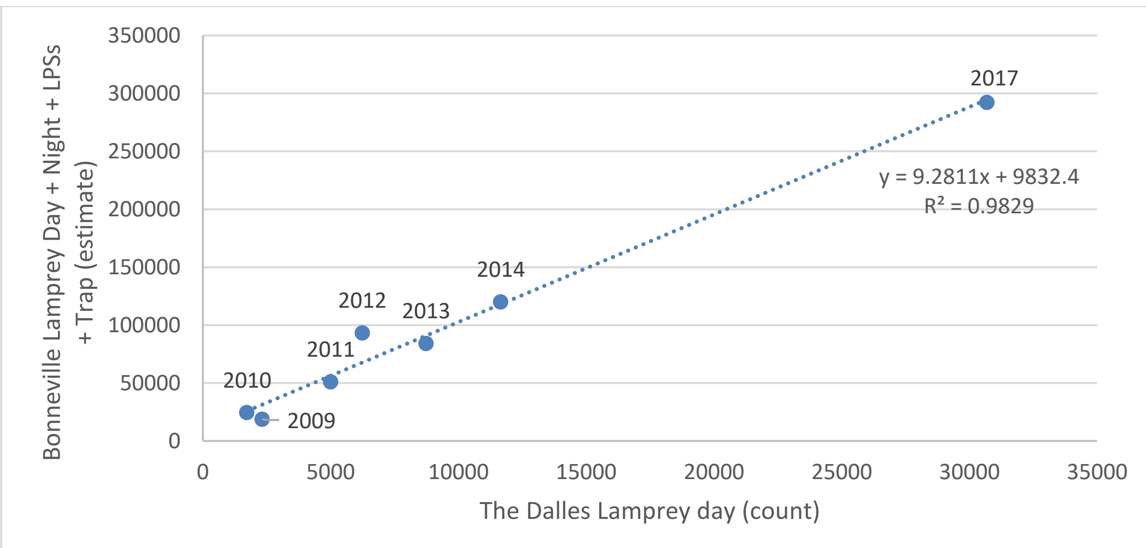

Figure 17. Regression model and passage data with fitted line. The x-axis is The Dalles daytime window index. The y-axis includes the Bonneville daytime window index + night time video counts + LPS counts + fish trapped and released above the dam for research or tribal translocations.

The line fitted to these data had an $r^2 = 0.98$ with a p-value = 0.0004. To estimate 2018, total lamprey passage we used these formula;

1) Bonneville Dam lamprey passage in 2018 = 9832.4 + 9.2811 * 10,515

Where 10,515 was the daytime index at The Dalles Dam during 2018. As a result, using this model estimate 107,423 (94,327 – 120,519 upper and lower 95% CI) lamprey passed Bonneville Dam during 2018 which is lower than the 131,765 estimated by summing all routes of passage in this report.

By including the counts from 2017, the regression equation was even more supported (R^2= 0.9829) than what was reported last year (R^2= 0.8964). Previous passage estimates fell near the regression line (Figure 17).

Appendix C. Morphometric summary of lamprey mortalities removed from LPSs at Bonneville Dam in 2018.

In Table 12 we report the number of lamprey mortalities removed by location. We also report measures of total length and the distance between the two dorsal fins. The inter-dorsal length is an indication of reproductive maturity. As Pacific Lamprey get closer to spawning the dorsal fins grow closer together.

On the night of 3 June, a double pump outage occurred at the CI-ENT LPS that led to the death of lamprey. Out of the 63 Pacific Lamprey mortalities found at CI-ENT, most were found on 4 June and a few residual mortalities were found the following days, presumably perishing from the same cause. A low water alarm was installed in the upwelling box #2 (near the pond) to alert Bonneville project dam operators if the water drops below a safe level. New, more industrial pumps were deployed, and the current plan is to install a lead-lag system. If the first pump fails, the second pump will start up.

Table 12. Summary statistics of Pacific Lamprey measurements from mortalities removed from Lamprey Passage Systems (LPS) at Bonneville Dam. RB = rest box numbered from down stream to up. UW = upwelling box, numbered from upstream to down.

		Number	Total Length (cm)			Inter-dorsal Length (cm)		
Location			Mean	Minimum	Maximum	Mean	Minimum	Maximum
Bradford Island AWS	RB1	2	57.5	57.0	58.0	4.0	2.7	3.5
	Total	**2**	**57.5**	**57.0**	**58.0**	**4.0**	**2.7**	**3.5**
Cascades Island Entrance	RB1	10			Not taken			
	RB3	7	60.7	50.0	66.1	3.6	2.5	4.4
	RB4	8	61.5	52.8	73.7	4.2	1.0	4.3
	RB6	38	63.3	56.5	74.5	4.0	2.5	5.5
	Total	**63**	**62.7**	**50.0**	**74.5**	**4.0**	**1.0**	**5.5**
Washington Shore AWS	RB1	4	69.1	63.0	73.5	4.7	3.6	5.7
	RB2	2	63	57.5	68.5	4.0	3.5	4.5
	UW1 & Plunge Box	4			Not taken			
	Total	**10**	**67.0**	**57.5**	**73.5**	**4.5**	**3.5**	**5.7**
Washington Shore UMTJ	RB1	1	67.0	67.0	67.0		Too decayed	
	RB2	5	63.7	60.7	68.2	5.1	2.5	9.0
	Total	**6**	**64.3**	**60.7**	**68.2**	**5.1**	**2.5**	**9.0**
Grand Total		81	63.1	50.0	74.5	4.0	1.0	9.0

*"Not taken" and "Too decayed" removed from averages.