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Prepared in cooperation with the Bureau of Reclamation, Yakama Nation Fisheries, McNary Fisheries Compensation Committee, Bonneville Power Administration, and the Pacific Northwest National Laboratory

Monitoring the Movements of Juvenile Pacific Lamprey (*Entosphenus tridentatus*) in the Yakima River, Washington, Using Acoustic Telemetry, 2019–20

Open-File Report 2022–1052

U.S. Department of the Interior
U.S. Geological Survey

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	1.094	yard (yd)
kilometer (km)	0.3107	mile (mi)
	Volume	
liter (L)	33.81402	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
	Mass	
milligram (mg)	0.00003527	ounce, avoirdupois (oz)
gram (g)	0.03527	ounce, avoirdupois (oz)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32.$$

Supplemental Information

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

Abbreviations

Chandler facility	Chandler Juvenile Fish Monitoring Facility
CI	confidence interval
ELAT	Eel-Lamprey Acoustic Transmitter
MSS-222	tricaine methanesulfonate
PNNL	Pacific Northwest National Laboratory
Reclamation	Bureau of Reclamation
rkm	river kilometer
salmon	juvenile Chinook, coho, sockeye, or chum salmon, and steelhead (*Oncorhynchus* spp.)
USGS	U.S. Geological Survey
Wapato	Wapato release site
YNF	Yakama Nation Fisheries

Monitoring the Movements of Juvenile Pacific Lamprey (*Entosphenus tridentatus*) in the Yakima River, Washington, Using Acoustic Telemetry, 2019–20

By Theresa L. Liedtke[1], Ralph T. Lampman[2], Patrick Monk[3], Amy C. Hansen[1], Tobias J. Kock[1], Tyler E. Beals[2], Daniel Z. Deng[4], and Michael S. Porter[2]

Abstract

Anthropogenic barriers to main-stem and tributary passage are one of the primary threats associated with declining populations of Pacific Lamprey (*Entosphenus tridentatus*) in the Columbia River Basin. Juvenile lamprey are of special interest because their downstream migration to the ocean may be affected by barriers such as dams or water diversions. Telemetry studies that describe the movement and passage of juvenile lamprey have not been possible until the recent development of a micro-transmitter specifically for use in juvenile lamprey and eels. Through a collaborative research approach, we used these prototype transmitters and acoustic monitoring arrays installed for a juvenile salmon (*Oncorhynchus* spp.) migration study to evaluate juvenile lamprey movements in the Yakima River (river kilometer 179 to the river mouth) in 2019 and 2020. We tagged and released 152 juvenile lamprey from April 30 to June 5, 2019, and on June 9, 2020. Lamprey were released 6.9 kilometers (km) upstream from Wapato Dam, 1.2 km upstream from Prosser Dam, and into the canal and tailrace at Prosser Dam. Most tagged lamprey did not initiate downstream movements within the 18 days of tag life, as evidenced by our detections of lamprey in the highest numbers at the first monitoring site downstream from their release site, with limited or no detections at sites farther downstream. There was no evidence of missed detections (lamprey detected at a downstream site without corresponding detections upstream). Overall detections of tagged lamprey were low: 27.0 percent in 2019 and 48.0 percent in 2020. River flows were less than the 10-year average during the monitoring period and water temperatures were variable. Lamprey arrived at detections sites predominantly during periods of darkness (85.3–96.6 percent) following daytime releases. Travel rates through the study area ranged from 0.2 to 45.3 kilometers per day, and lamprey generally remained at each detection station for less than about 20 minutes. Groups of lamprey released together generally had similar travel rates with a small number of fish that moved more quickly or slowly than the remainder of the group. In addition to monitoring the migration and behavior of juvenile lamprey, we also assessed some assumptions of survival models (determining downstream drift of purposely killed fish and empirically measuring transmitter operating life) to benefit future evaluations focused on migration survival of juvenile lamprey.

[1]U.S. Geological Survey

[2]Yakama Nation Fisheries

[3]Bureau of Reclamation

[4]Pacific Northwest National Laboratory

Introduction

Anthropogenic barriers to main-stem and tributary passage (upstream and downstream) are one of the primary threats associated with declining populations of Pacific Lamprey (*Entosphenus tridentatus)* in the Columbia River Basin (Columbia River Inter-Tribal Fish Commission, 2011). Telemetry has been used to describe dam-passage routes and survival of juvenile salmon and steelhead (*Oncorhynchus* spp., hereinafter "salmon") in the Columbia and Snake Rivers for decades, and more recently adult lamprey movements and passage have been monitored using these technologies (Moser and others, 2011; Keefer and others, 2013). Juvenile and larval lamprey, however, are much smaller than adults, and have not, until recently, been monitored with telemetry because available transmitters were too large. Juvenile lamprey are of special interest because little is known about their downstream migration patterns and how they may be affected by barriers such as dams or entrainment in water diversions. Resource managers, especially from Tribal entities, have been seeking information on juvenile Pacific Lamprey movements for several years, waiting for telemetry technology to advance to the point when a transmitter of appropriate size for this life stage became available. The Pacific Northwest National Laboratory (PNNL) and the U.S. Army Corps of Engineers developed a micro-transmitter specifically for use in juvenile lampreys and eels (Deng and others, 2018). The transmitter is still undergoing development and testing and is not yet commercially available, but field tests have produced promising results (Deng and others, 2018). Through a collaborative research approach, we used these prototype transmitters to do a pilot-level evaluation of juvenile lamprey movements in the Yakima and Columbia Rivers in 2018 (Liedtke and others, 2019). The current study was designed to be a continuation of the 2018 pilot study, including additional lamprey and a wider range of environmental conditions. As we did with the 2018 study, we partnered with an ongoing study by the U.S. Geological Survey (USGS), the Bureau of Reclamation (Reclamation), and Yakama Nation Fisheries (YNF) that used acoustic telemetry to monitor juvenile salmon (hereinafter the juvenile salmon study). The juvenile salmon study had a series of acoustic receivers in the lower 172 river kilometers (rkm) of the Yakima River that could detect the new lamprey transmitters. Working collaboratively, we describe the movements of juvenile Pacific Lamprey within the study area monitored by these acoustic receivers to supplement the 2018 study and assist with addressing critical information gaps for this life stage. Based on our observations in 2018, our study goals in 2019 and 2020 were to (1) release tagged lamprey high upstream in the study area to maximize our ability to detect them at several sites as they traveled downstream, (2) release lamprey under different hydrologic conditions than in 2018, and (3) begin preparing for future studies where lamprey survival could be estimated by evaluating some survival model assumptions.

Methods

Study Area

The study was conducted in the lower Yakima River, from about rkm 180 to the river mouth, and in the Columbia River, from the Yakima River mouth to the mouth of the Klickitat River. Personnel from the juvenile salmon study installed and maintained acoustic monitoring receivers at eight sites in the Yakima River (fig. 1), one site in the Columbia River near Kennewick and Pasco, Washington, and one site at the mouth of the Klickitat River. Receiver deployments were designed to detect fish as they approached and passed dams or entered irrigation canals.

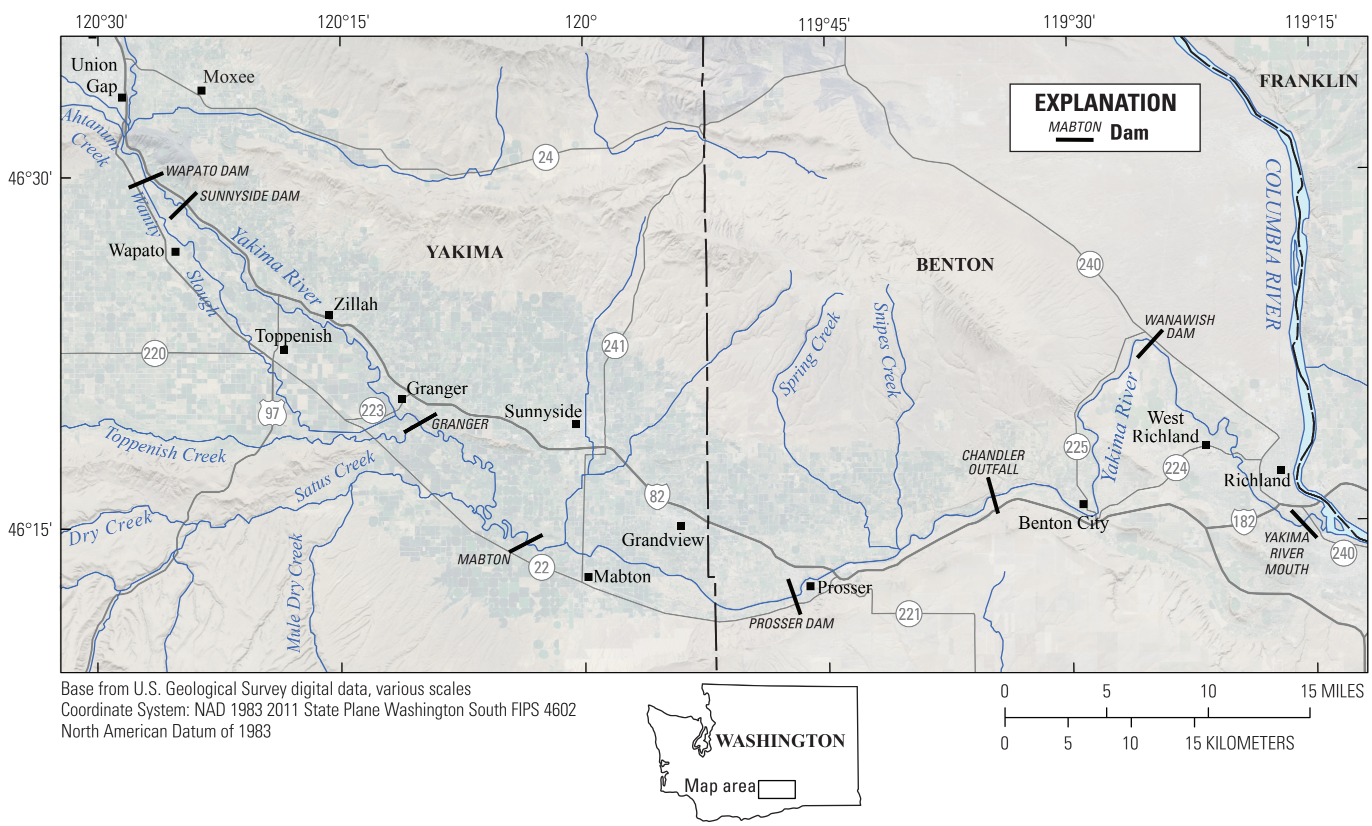

Figure 1. Eight acoustic telemetry monitoring sites (indicated by black lines, perpendicular to the river) for juvenile Pacific Lamprey in the Yakima River, Washington, 2019 and 2020.

Environmental Conditions

We used data collected at existing streamgages in the Yakima River to describe water temperature and river-flow patterns during the study. Daily water temperature data from the Reclamation streamgage located at the Chandler fish screen weather station (about rkm 75) were downloaded on June 17, 2021, for the March 1–July 15 time period (Bureau of Reclamation, 2021a). Daily river-flow data from the Reclamation streamgage located near Parker, Washington (about rkm 168), were downloaded on June 17, 2021, for the March 1–July 15 time period (Bureau of Reclamation, 2021b). Diel periods were assigned using civil twilight at Prosser, Washington, downloaded on June 17, 2021 (Sunrise Sunset, 2021).

Fish Collection, Tagging, and Release

The primary collection effort for juvenile Pacific Lamprey was at the Chandler Juvenile Fish Monitoring Facility (hereinafter “the Chandler facility”) in Prosser, Washington. To supplement fish collected at the Chandler facility, we monitored juvenile lamprey collection efforts at rotary screw traps in Toppenish Creek and Ahtanum Creek (tributaries to the Yakima River) and at the McNary Dam and John Day Dam fish collection facilities on the Columbia River. When juvenile lamprey were collected at these sites within a few days of our tagging date, we transported them to the Chandler facility for tagging. Ideally, all study fish would have been collected from a single location; however, the low collection numbers and unpredictable nature of juvenile lamprey catches required a more flexible approach. We prioritized fish collected at the Chandler facility and the two tributary creeks and only tagged lamprey from the Columbia River dams when fish from these sources were limited.

Acoustic transmitters were surgically implanted in the body cavity of juvenile lamprey using techniques described in Mesa and others (2012) and Liedtke and others (2019). Fish-handling and aseptic techniques followed principles in Liedtke and others (2012). The prototype transmitter, called the ELAT model (for Eel-Lamprey Acoustic Transmitter), was 12 × 2 millimeters (mm), weighed 80 milligrams, and had an 18-day expected battery life with a pulse-rate interval of 3 seconds. The transmitter was developed to match the dimensions of a 12-mm Passive Integrated Transponder, which have been successfully implanted in juvenile lamprey (Mesa and others, 2012). To minimize variability, a single experienced tagger was used for all study fish. Fish holding times prior to tagging were variable to allow fish collected over a short period (3–4 days) to be combined into a larger group. Fish were anesthetized individually in a solution of tricaine methanesulfonate (MS-222, 100–150 milligrams per liter [mg/L]) buffered with an equal amount of sodium bicarbonate. When fish showed reduced responsiveness, they were removed from the anesthetic, weighed to the nearest 0.1 gram (g), and measured to the nearest 1 mm. Each fish was then placed into a groove cut into a moist closed-cell foam pad saturated with river water. We made a 2–3-mm-long incision 20–22 mm posterior to the last gill pores with a 3.0-mm microsurgical scalpel (15-degree blade; AngioTech, Vancouver, British Columbia, Canada), inserted the transmitter through the incision, and guided the transmitter anteriorly. No sutures were used to close the incision. The entire tagging procedure (including weighing and measuring) took about 60–90 seconds per fish. Photographs were taken of each tagged fish immediately following the insertion of the tag, and then the fish was placed in a recovery container with dissolved oxygen from 100 to 110 percent saturation to expedite recovery from anesthesia.

Following tagging, lamprey were held in perforated 19-L recovery containers in a tank supplied with flowing river water for a minimum of 18 hours prior to release. Lamprey were held in low densities (no more than five lamprey per 19-L container) without substrate to avoid the potential for injury when containers were moved. An acoustic receiver was deployed in the tank to monitor and confirm transmitter function. For transport to release sites, containers were transferred to an insulated tote in the bed of a truck and supplied with oxygen through a diffuser to maintain dissolved oxygen saturation from 90 to 110 percent. Water temperature in the transport tote was maintained within 2 degrees Celsius (°C) of the recovery tank and river temperature at the release site. Lamprey in recovery containers were observed prior to transport. Any lamprey that demonstrated irregular swimming, was dead, or was in poor condition was removed from the release group.

Tagged lamprey were released at four locations. The Wapato release site (hereinafter Wapato), selected to be consistent with the 2018 study (Liedtke and others, 2019), was located at the State Route 24 bridge, about 6.9 rkm upstream from Wapato Dam. Fish were released at three sites near Prosser Dam: the boat ramp (1.2 rkm upstream from Prosser Dam), in the canal (about 170 meters [m] downstream from the headgate), and in the tailrace (about 240 m downstream from Prosser Dam; fig. 2). We released tagged lamprey at the Prosser sites to mitigate the risk that lamprey released at the Wapato site might not reach the river mouth within the 18 days of predicted transmitter life. All releases were completed during daylight conditions. Release time was recorded for each group, and lamprey within a group were released within 1 minute of other lamprey in that same group.

To evaluate the ability of the monitoring array to detect the new lamprey ELAT transmitters, the juvenile salmon study implanted 41 ELAT transmitters into subyearling Chinook salmon *(Oncorhynchus tshawytscha)* in 2020 and monitored their movements. Salmon were collected at the Chandler facility, held 18–30 hours to evacuate their stomach and recover from handling, tagged following Liedtke and others (2012), held 18–36 hours to recover, and then released. Salmon implanted with the ELAT tag were released at several locations, but only subyearling Chinook salmon released 10.4 rkm upstream from Prosser Dam on June 11, 2020, were used to compare with the tagged lamprey owing to common release location and timing.

Figure 2. Release locations of acoustically tagged juvenile Pacific Lamprey near Prosser Dam in the Yakima River, Washington, 2019 and 2020. Image source: Google Earth™ 2021.

Releases of Purposely Killed Fish

To assist in planning for future telemetry studies that might assess survival of tagged juvenile lamprey, we released purposely killed lamprey to test survival model assumptions. Telemetry studies that estimate the survival of juvenile salmon at dams in the Columbia River Basin commonly release purposely killed fish (Skalski and others, 2010; Tomka and others, 2020). The ideal procedure for purposely killed fish would not distort fish tissues so fish would drift in the river as if they died naturally. Following the approach detailed in Tomka and others (2020) for juvenile salmon, we collected and tagged juvenile lamprey in preparation for a release event, and then randomly selected tagged fish to be euthanized. There were no established procedures for euthanizing juvenile lamprey, so we conducted some preliminary testing. Like the approach used for salmon (Tomka and others, 2020), we exposed lamprey to a high concentration of buffered MS-222 (300–500 mg/L) for 60 minutes. Although lamprey appeared to be dead following these exposures, we held fish overnight and found them alive the following morning. Other researchers have documented similar results with juvenile salmon, where fish revived after a high-dose MS-222 exposure (Tomka and others, 2020). We increased the MS-222 concentration (900 mg/L) and the exposure duration (2 hours) during our testing and found that fish again were able to revive. The procedure we selected for the study was 900-mg/L buffered MS-222 for a 10–12 hour period. No lamprey survived this procedure when we tested it in our laboratory. To enact this procedure in the field, we randomly selected tagged fish to be euthanized (after standard procedures for collection, tagging, and recovery), placed them in a container with buffered MS-222, and held them overnight. The purposely killed fish were held in a container (with no water exchange) adjacent to the tank that held tagged lamprey. Immediately prior to release, the euthanized fish were transferred to a holding container matching the live tagged lamprey and loaded into a transport tank with the study fish. All transport and release procedures were conducted as described for study fish.

Monitoring of Tagged Fish

The juvenile salmon study (USGS-Reclamation-YNF) had eight monitoring sites in the Yakima River (fig. 1), one site in the Columbia River near Kennewick and Pasco, Washington, and one site at the mouth of the Klickitat River. The two sites in the Columbia River were located at the Blue Bridge (Pioneer Memorial Bridge) that crosses the Columbia River as U.S. Route 395 (rkm 530), and at Memaloose Island near the mouth of the Klickitat River (rkm 287). The Blue Bridge site was used in both study years, whereas the Memaloose Island site was only used in 2019. Multiple acoustic receivers typically were used to monitor a site—for example, eight receivers at Wanawish Dam and two receivers at the Yakima River mouth. We were able to share acoustic receiver detections across multiple studies because all the study partners used the same juvenile salmon acoustic telemetry system (JSATS). All detections of tagged lamprey were gathered, and we compiled a dataset that was reviewed and proofed for analyses.

Data Analysis

Acoustic telemetry data records were processed to remove false-positive detection events prior to analyzing fish movement data. False-positive records are defined as a transmitter detection that was recorded on a telemetry receiver when the transmitter was not actually present at the site. These false-positive records are common in most active telemetry systems (Beeman and Perry, 2012). We used an automated proofing program to remove false-positive records. This program removed records if (1) the detection record was from a transmitter that was not released during the study, (2) the record matched criteria that indicated the detection likely resulted from reflections of valid transmitter signals (multipath), (3) the detection record did not match a multiple of the transmitter pulse interval, or (4) the record was not followed by at least two valid records of that transmitter on each receiver (McMichael and others, 2010).

A final dataset was created by merging the processed acoustic telemetry detection records with biological data collected during tagging. These data are available online from the StreamNet—Fish Data for the Northwest web site (Pacific States Marine Fisheries Commission, 2022). The tagging and release data and processed telemetry data were then merged and sorted chronologically for each fish in the study. Detections that occurred before a fish's release date and time were removed and the final dataset was then queried to summarize fish detections at specific sites in the study area. These summaries were used to describe movement patterns of tagged fish, including travel time, travel rate, residence time, and hour of arrival. Travel time was calculated between detection or release locations as the difference from the last detection at one site to the first detection at another site. Travel rate used the travel time calculation and the distance between sites. Residence time was calculated as the difference in time from the first to the last detection of a tagged lamprey at a given site. Diel period using civil twilight and hour of arrival was assigned at the first detection at each telemetry site. The comparison between lamprey and subyearling Chinook salmon tagged with the ELAT tag was calculated as the percentage of fish detected at the downstream end of the reach divided by the number of fish detected at the upstream end of the reach.

Transmitter-Life and Fish-Condition Evaluations

The actual operating life of the ELAT transmitters was empirically determined in laboratory evaluations at the USGS Columbia River Research Laboratory in Cook, Washington, in 2019 and 2020. In 2019, transmitters were manufactured and delivered to the study team in three batches, spanning a 30-day period. We randomly selected transmitters from each batch, combined them into a test group, and initiated a tag-life test within 45 days of the earliest tag delivery date. In 2020, transmitter production was interrupted because of the Covid-19 pandemic, causing substantial delay (83 days) between the first and second production and delivery batches. The first batch of transmitters was used to tag juvenile lamprey for the single release group in 2020 and 10 tags were used in a tag-life test. The delayed delivery of the second batch of tags prevented us from collecting, tagging, and releasing a second study group of lamprey. Because the number of lamprey collected daily at the Chandler facility and other sites in the Yakima River was low and water temperatures were elevated, the entire second tag batch was allocated to tag-life testing. To improve our understanding of the useful life of the tags once they were delivered, we conducted four tag-life tests at various shelf-life durations from June to December 2020.

To initiate a tag-life test, transmitters were activated following the same procedures used in the field studies. Tags were placed in individual compartments of plastic boxes filled with water. The plastic boxes were floated in a 1.5-m circular fiberglass tank filled with temperature-controlled water to simulate Yakima River water temperatures during the study period. A single receiver in each of the two tanks monitored the transmitters until they all stopped functioning, at which point the test was terminated. The data were processed through the same filter as the fish detection data. We calculated tag life from the time of tag activation to the last detection of the tag during the laboratory test. We tabulated the number of tags that stopped functioning in less than 10 days, from 10 to 15 days, and after 15 days. Based on the anticipated tag life of 18 days, tags that stopped functioning in 15 days or less were categorized as having failed prematurely. For each test, we summarized median tag life, percentage of tags that failed prematurely, and time-to-event Kaplan-Meier survivorship analysis (Hosmer and Lemeshow, 1999).

In 2019 and 2020, we evaluated transmitter life and fish condition in small groups of tagged lamprey held at the Yakama Nation Prosser Hatchery in Prosser, Washington (adjacent to the Chandler facility). The goal of these tests was to supplement the information on tag life and to assess the risk of transmitter loss and negative outcomes from tagging. Fish were collected, tagged, and recovered as described for study fish. Tagged lamprey were held in perforated 19-L containers with small rocks for cover. Containers were held in a tank supplied with flowing river water and monitored by an acoustic telemetry receiver. Fish were checked every 1–3 days to document any moribund fish or mortalities. Following an approximately 30-day holding period, lamprey were euthanized, and internal and external exams were conducted to evaluate fish condition.

Results

River Environment

River flows were less than the 10-year average (2011–20) in 2019 and 2020 during the tagged juvenile lamprey monitoring periods, and water temperature was variable. The maximum river flow during our 2019 monitoring period (5,262 cubic feet per second [ft^3/s]) occurred on May 13, which was slightly earlier than the 10-year average (fig. 3). A secondary, smaller flow peak of 3,805 ft^3/s occurred on May 27, 2019, before flows decreased to about 500 ft^3/s in June. During the first fish release on April 30, 2019, flow was decreasing but then increased to the maximum flow at 5,262 ft^3/s in mid-May (fig. 4). Similarly, the May 14, 2019, release was on a decreasing flow until an increase that peaked on May 27, 2019 (fig. 4). Lamprey released on June 4 and 5, 2019, were exposed to steady flows of less than 800 ft^3/s (fig. 4). Water temperature increased from 11.5 to 24.9 °C in 2019 with peaks on May 7 at 18.3 °C, June 3 at 23.7 °C, and June 16 at 24.9 °C, and was above the 10-year average (2011–20) during most of the monitoring period (fig. 5). Water temperature increased during the periods when the lamprey tags were functioning following the April and May 2019 releases and remained above 20 °C for the June 4 and 5 releases (figs. 4 and 5). River flows in 2020 were less than the 10-year average but were similar to flows in 2018 and 2019 during the brief lamprey monitoring period in June. Lamprey released on June 9, 2020, had a nearly constant river flow of about 2,600 ft^3/s, which decreased to 364 ft^3/s, and then remained less than 1,400 ft^3/s for the remainder of the 2020 study period (figs. 3 and 4). Water temperature during the June 2020 monitoring period ranged from 14.1 to 21.2 °C (figs. 4 and 5).

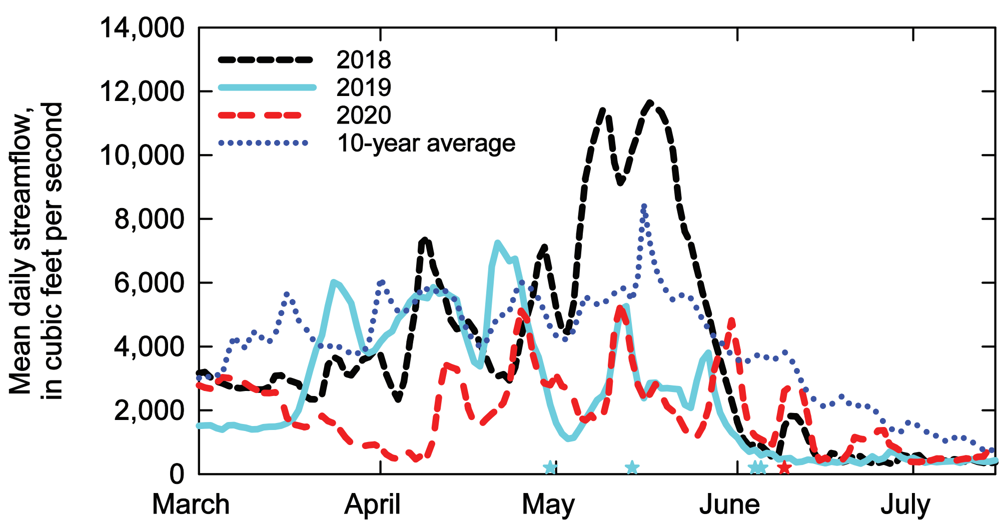

Figure 3. Mean daily streamflow in the Yakima River, Washington, in 2018, 2019, and 2020 and the 10-year average (2011–20; Bureau of Reclamation, 2021b). Colored stars indicate acoustically tagged Pacific Lamprey release dates by year.

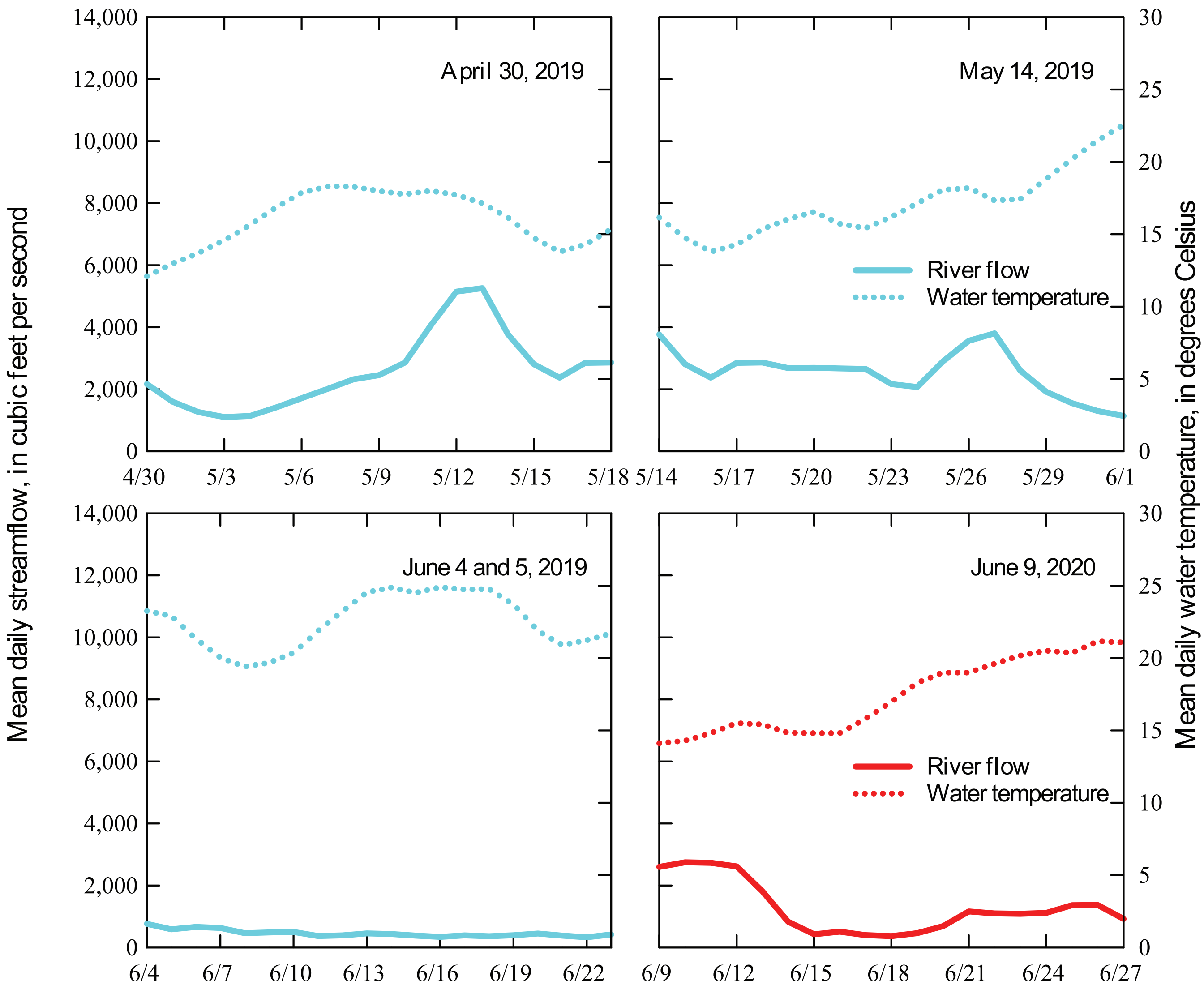

Figure 4. Mean daily streamflow and mean daily water temperature in the Yakima River, Washington, in 2019 and 2020 (Bureau of Reclamation, 2021a, 2021b). Each graph describes conditions for one lamprey release, indicated by the date in the upper right-hand corner. Blue lines represent 2019 conditions and red lines represent 2020 conditions.

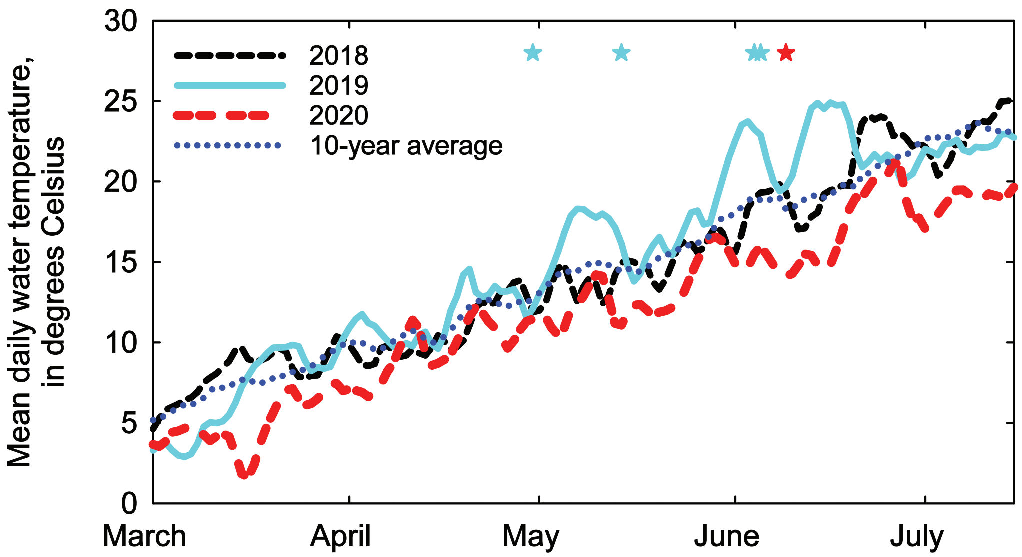

Figure 5. Mean daily water temperature in the Yakima River, Washington, in 2018, 2019, and 2020, and the 10-year average (2011–20; Bureau of Reclamation, 2021a). Colored stars indicate acoustically tagged Pacific Lamprey release dates by year.

Fish Collection, Tagging, and Release

Juvenile Lamprey

We tagged 154 juvenile lamprey during April 30–June 5, 2019, and on June 9, 2020 (table 1). Two lamprey were removed from the planned release groups because of concerns about fish condition (one lamprey on April 30, 2019) or tag performance (one lamprey on May 14, 2019), resulting in a total of 152 lamprey that were released. No mortalities were observed prior to release. The overall mean total length for the 152 lamprey released (study years pooled) was 150.1 mm and ranged from 135 to 181 mm (table 2). The overall mean mass for tagged lamprey was 4.5 g and ranged from 3.1 to 7.8 g (table 2). The mean transmitter burden (transmitter weight relative to body weight) was 1.8 percent and ranged from 1.0 to 2.6 percent. The length and weight distributions of tagged fish represent the selection criteria we applied to tagged lamprey (minimum tagging size of 140 mm total length), not the natural range of values that would be observed for lamprey from our collection sites.

Three tagged fish in 2019 and one tagged fish in 2020 were removed from the dataset during data review because their tags were not detected in the holding tank prior to release or at any monitoring station downstream. All analyses were conducted with the 148 tags confirmed to be functioning (table 1).

Table 1. Number of juvenile Pacific Lamprey acoustically tagged and released in the Yakima River, Washington, in 2019 and 2020.

[Wapato site is 6.9 river kilometers (rkm) upstream from Wapato Dam, Prosser boat ramp is 1.2 rkm upstream from Prosser Dam, Prosser canal site is about 170 meters (m) downstream from the headgate, and Prosser tailrace site is 240 m downstream from Prosser Dam. **Release date:** mm-dd-yyyy, month, day, year. **Release time:** hhmm, hours, minutes]

Release date (mm-dd-yyyy)	Release time (hhmm)	Release site	Number released		Number of active tags	
			Live	Euthanized	Live	Euthanized
04-30-2019	1605	Wapato	31	0	31	0
05-14-2019	1554	Wapato	24	2	22	2
06-04-2019	1111	Prosser tailrace	10	0	10	0
06-05-2019	0911	Prosser canal	5	0	5	0
06-05-2019	0924	Prosser boat ramp	23	0	22	0
06-05-2019	1055	Wapato	25	6	25	6
		Total 2019	118	8	115	8
06-09-2020	1632	Prosser boat ramp	26	0	25	0
		Total 2019–20	144	8	140	8

Table 2. Total length and mass of groups of acoustically tagged juvenile Pacific Lamprey released in the Yakima River, Washington, in 2019 and 2020.

[Wapato site is 6.9 river kilometers (rkm) upstream from Wapato Dam, Prosser boat ramp is 1.2 rkm upstream from Prosser Dam, Prosser canal site is about 170 meters (m) downstream from the headgate, and Prosser tailrace site is 239 m downstream from Prosser Dam. **Release date:** mm-dd-yyyy, month, day, year]

Release date (mm-dd-yyyy)	Release site	Length (millimeters)		Mass (grams)	
		Mean	Range	Mean	Range
04-30-2019	Wapato	150.0	140–169	4.3	3.4–6.0
05-14-2019	Wapato	148.6	138–165	4.2	3.1–5.7
06-04-2019	Prosser tailrace	153.3	144–165	4.8	4.0–6.0
06-05-2019	Prosser canal	148.6	140–159	4.3	3.4–5.5
06-05-2019	Prosser boat ramp	153.9	145–167	5.0	3.9–6.5
06-05-2019	Wapato	149.9	135–181	4.6	3.3–7.8
	Total 2019	150.5	135–181	4.5	3.1–7.8
06-09-2020	Prosser boat ramp	148.4	135–161	4.5	3.3–6.4
	Total 2019–20	150.1	135–181	4.5	3.1–7.8

Tagged lamprey were collected from three sites, and each tagging date included fish from 1–2 sites (table 3). The amount of time collected fish were held prior to tagging was variable to allow small groups of fish, collected across several days, to be combined in a single tag-release group. In 2019, the mean holding time (from date of collection to date of tagging) was 1.6 days and ranged from 0 to 4 days. In 2020, fish collection was challenging because of facility closures and staffing limitations associated with the Covid-19 pandemic. Most lamprey released in 2020 were held for 0–4 days, but four fish had longer holding times, ranging from 18 to 26 days (mean = 6.4 days; table 3). Overall, 59.5 percent of the study fish were collected at the Chandler facility, 25.0 percent came from John Day Dam, and 15.5 percent came from McNary Dam (table 3).

Table 3. Release sites and dates, collection sites and dates, and number of days fish were held prior to tagging for groups of acoustically tagged juvenile Pacific Lamprey released at four sites on the Yakima River, Washington, 2019 and 2020.

[**Abbreviation:** mm-dd-yyyy, month, day, year]

Release site	Release date (mm-dd-yyyy)	Tag date (mm-dd-yyyy)	Collection site	Number released	Collection date (mm-dd-yyyy)	Number of days held
Wapato	04-30-2019	04-29-2019	Chandler facility	16	04-29-2019	0
	04-30-2019	04-29-2019	McNary Dam	15	04-29-2019	0
	05-14-2019	05-13-2019	John Day Dam	7	05-09-2019	4
	05-14-2019	05-13-2019	McNary Dam	5	05-09-2019	4
	05-14-2019	05-13-2019	John Day Dam	9	05-11-2019	2
	05-14-2019	05-13-2019	McNary Dam	3	05-11-2019	2
Prosser tailrace	06-04-2019	06-03-2019	Chandler facility	10	06-02-2019	1
Prosser canal	06-05-2019	06-04-2019	Chandler facility	5	06-02-2019	2
Prosser boat ramp	06-05-2019	06-04-2019	Chandler facility	22	06-02-2019	2
Wapato	06-05-2019	06-04-2019	Chandler facility	31	06-02-2019	2
Prosser boat ramp	06-09-2020	06-08-2020	Chandler facility	1	05-13-2020	26
	06-09-2020	06-08-2020	Chandler facility	1	05-14-2020	25
	06-09-2020	06-08-2020	Chandler facility	1	05-17-2020	22
	06-09-2020	06-08-2020	Chandler facility	1	05-21-2020	18
	06-09-2020	06-08-2020	John Day Dam	16	06-04-2020	4
	06-09-2020	06-08-2020	John Day Dam	2	06-06-2020	2
	06-09-2020	06-08-2020	John Day Dam	3	06-08-2020	0

Subyearling Chinook Salmon

We tagged 41 subyearling Chinook salmon with ELAT transmitters and released them in the Yakima River in 2020. Of the 41 salmon, those released 10.4 rkm upstream from Prosser Dam (n = 7) on June 11, 2020, were used to compare with the lamprey tagged with the same transmitters. The remaining salmon were released at locations and under conditions that did not align well with our releases of tagged lamprey. The salmon implanted with ELAT tags averaged 110.1 mm in fork length (range 101–113 mm), and 15.1 g in weight (range 11.4–17.3 g), with a tag burden of 0.5 percent (range 0.4–0.7 percent). All fish were confirmed to have active tags prior to release.

Detection Summary

A total of 123 lamprey with active tags were released in 2019, including 115 live fish and 8 euthanized fish (table 1). None of the eight euthanized lamprey were detected in the study area. Of the 115 fish released alive, 31 (27.0 percent) were detected in the study area (fig. 6). The maximum number of days lamprey were detected in the study area in 2019 was 16.0 days (table 4), and the mean time was 6.0 days. Release groups collected at the Chandler facility and held 1–2 days prior to tagging had the highest percentage of fish detected in the study area (26 of 62, 41.9 percent; fig. 6; table 4). A total of 13.3 percent of fish collected at John Day Dam and 4.5 percent of fish collected at McNary Dam were detected in the study area (fig. 6; table 4).

In 2020, 12 of the 25 fish (48.0 percent) released were detected in the study area. Lamprey spent an average of 2.6 days in the study area (range 0.2–12.4 days; table 4). Most of the fish detected (52.4 percent) were collected from John Day Dam and held for 4 days or less (fig. 6; table 4). One of the four fish collected at Chandler facility was detected in the study area after being held 26 days prior to tagging (fig. 6; table 4).

After release in 2019, lamprey were detected at Wapato, Sunnyside, and Prosser Dams (fig. 7, table 5). Of the 78 fish released upstream from Wapato Dam, 8 fish were detected at Wapato Dam with some individuals at multiple locations (3 fish in the canal, 6 fish in the west forebay, and 2 fish in the

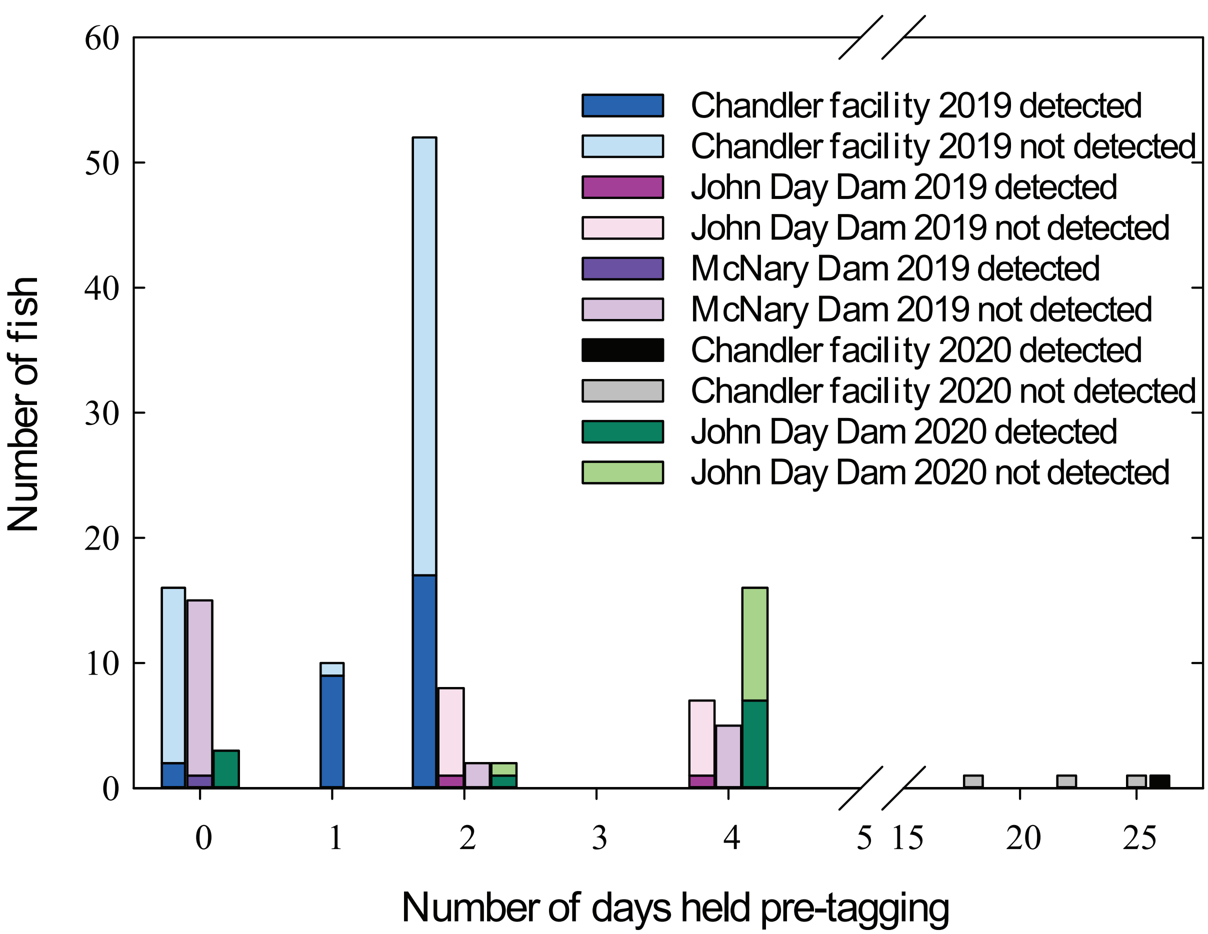

Figure 6. Acoustically tagged juvenile Pacific Lamprey in the study area, detected and not detected, by collection site and number of days held prior to tagging and release into the Yakima River, Washington, 2019 and 2020. Euthanized fish were omitted from this graph.

Table 4. Release sites and dates, collection sites and dates, number of days fish were held prior to tagging, percentage of fish detected in the study area, and days detected in the study area for groups of acoustically tagged Pacific Lamprey released at four sites on the Yakima River, Washington, 2019 and 2020.

[Mean number of days in the study area are of detected fish. Euthanized fish were omitted from this table. **Abbreviations:** mm-dd-yyyy, month, day, year; NA, not applicable]

Release site	Release date (mm-dd-yyyy)	Collection site	Number released	Collection date (mm-dd-yyyy)	Number of days held	Percentage detected	Mean number of days in study area (minimum–maximum)
Wapato	04-30-2019	Chandler facility	16	04-29-2019	0	12.5	12.3 (12.3–12.3)
	04-30-2019	McNary Dam	15	04-29-2019	0	6.7	13.3
	04-30-2019	John Day Dam	7	05-09-2019	4	14.3	0.3
	05-14-2019	McNary Dam	5	05-09-2019	4	0.0	NA
	05-14-2019	John Day Dam	8	05-11-2019	2	12.5	0.3
	05-14-2019	McNary Dam	2	05-11-2019	2	0.0	NA
Prosser tailrace	05-14-2019	Chandler facility	10	06-02-2019	1	90.0	3.1 (0.4–11.5)
Prosser canal	06-04-2019	Chandler facility	5	06-02-2019	2	80.0	9.8 (4.6–16.0)
Prosser boat ramp	06-05-2019	Chandler facility	22	06-02-2019	2	45.5	7.6 (0.7–13.6)
Wapato	06-05-2019	Chandler facility	25	06-02-2019	2	12.0	1.9 (0.5–4.6)
Prosser boat ramp	06-05-2019	Chandler facility	1	05-13-2020	26	100.0	1.3
	06-09-2020	Chandler facility	1	05-14-2020	25	0.0	NA
	06-09-2020	Chandler facility	1	05-17-2020	22	0.0	NA
	06-09-2020	Chandler facility	1	05-21-2020	18	0.0	NA
	06-09-2020	John Day Dam	106	06-04-2020	4	43.8	3.1 (0.2–12.4)
	06-09-2020	John Day Dam	2	06-06-2020	2	50.0	4.3
	06-09-2020	John Day Dam	3	06-08-2020	0	100.0	1.0 (0.3–2.4)

east forebay), and 5 fish were detected at Sunnyside Dam forebay (fig. 8). Two of the three fish detected in the Wapato Dam canal were not later detected at any other monitoring site. The remaining fish detected in the canal was subsequently detected at Sunnyside Dam. No lamprey were detected in the canal at Sunnyside Dam (table 5). None of the lamprey released at Wapato were detected at monitoring sites farther downstream than Sunnyside Dam (fig. 8). Similarly, lamprey released at several locations near Prosser Dam were detected near the dam, but not at monitoring sites farther downstream. The 22 fish released at the boat ramp upstream from Prosser Dam were detected in the forebay (eight fish), in the canal (two fish) and in the tailrace (5 fish; fig. 8). The five lamprey released in the canal were detected in the canal (four fish) and the tailrace (one fish; fig. 8). The 10 fish released in the tailrace were detected in the tailrace (nine fish) and in the forebay (one fish). The lamprey detected in the forebay presumably was detected owing to a predation event (fig. 8).

In 2020, a single release of 25 lamprey occurred at the boat ramp upstream from Prosser Dam. This group of fish was detected in the Prosser Dam forebay (12 fish), in the Prosser Dam canal (2 fish), in the Prosser Dam tailrace (7 fish), and at the monitoring site near the Chandler Power Plant outfall (3 fish; fig. 7; table 5). Additionally, one lamprey was detected at the Wanawish Dam forebay and tailrace and the Yakima River mouth (fig. 7) as it moved downstream.

No tagged lamprey were detected at several sites in the Yakima and Columbia Rivers (table 5). In 2019, lamprey were not detected in the canal downstream from the screens at Wapato, Sunnyside, or Prosser Dams, so there was no evidence of entrainment through the screens. In 2020, fish were not detected at Prosser Dam canal downstream from the screens or in the canals at Wanawish Dam. No fish in either year were detected at the Blue Bridge in the Columbia River or at the Memaloose Island site in 2019 (not used in 2020).

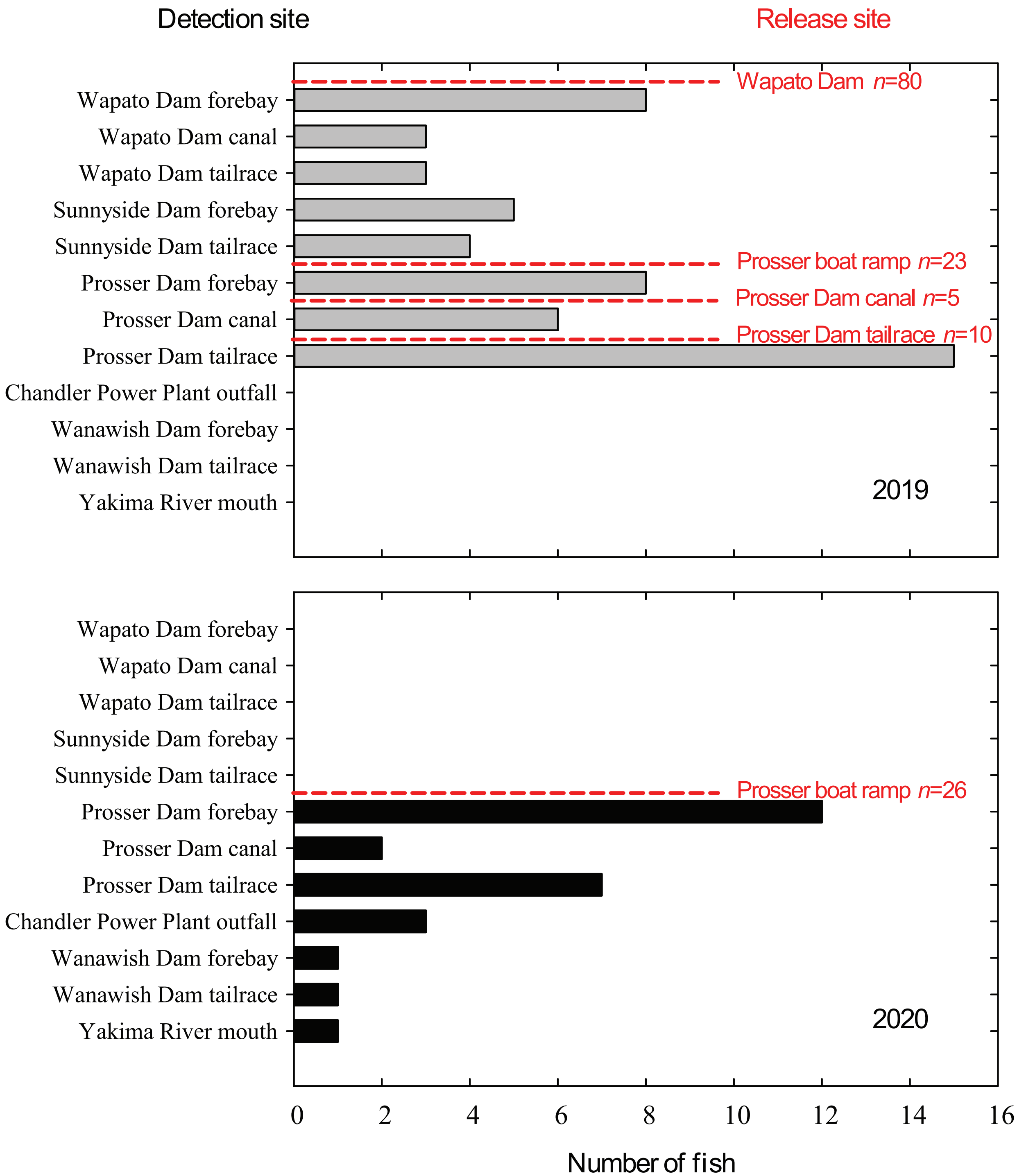

Figure 7. Number of fish and sites where acoustically tagged juvenile Pacific Lamprey were detected following release in the Yakima River, Washington, 2019 and 2020. *n*, number of tagged lamprey released.

Table 5. Monitoring sites where acoustically tagged juvenile Pacific Lamprey were detected, not detected, or not available for detection in the Yakima and Columbia Rivers, Washington, 2019 and 2020.

[Sites upstream from the release or otherwise not available are marked as NA. **Abbreviations:** NA, not applicable; x, detected; 0, not detected]

Acoustic detection location	2019	2020
Wapato Dam forebay west	x	NA
Wapato Dam forebay east	x	NA
Wapato Dam canal	x	NA
Wapato canal downstream from screens	0	NA
Wapato Dam tailrace west	x	NA
Wapato Dam tailrace east	0	NA
Sunnyside Dam forebay	x	NA
Sunnyside Dam canal	0	NA
Sunnyside Dam canal downstream from screens	0	NA
Sunnyside Dam tailrace	x	NA
Granger	0	NA
Mabton	0	NA
Prosser Dam forebay	x	x
Prosser Dam canal	x	x
Prosser Dam canal below screens	0	0
Prosser Dam tailrace	x	x
Chandler Power Plant outfall	0	x
Wanawish Dam forebay	0	x
Wanawish Dam west canal	0	0
Wanawish Dam west canal downstream from screens	0	0
Wanawish Dam east canal	0	0
Wanawish Dam tailrace	0	x
Yakima River mouth	0	x
Blue Bridge	0	0
Memaloose Island	0	NA

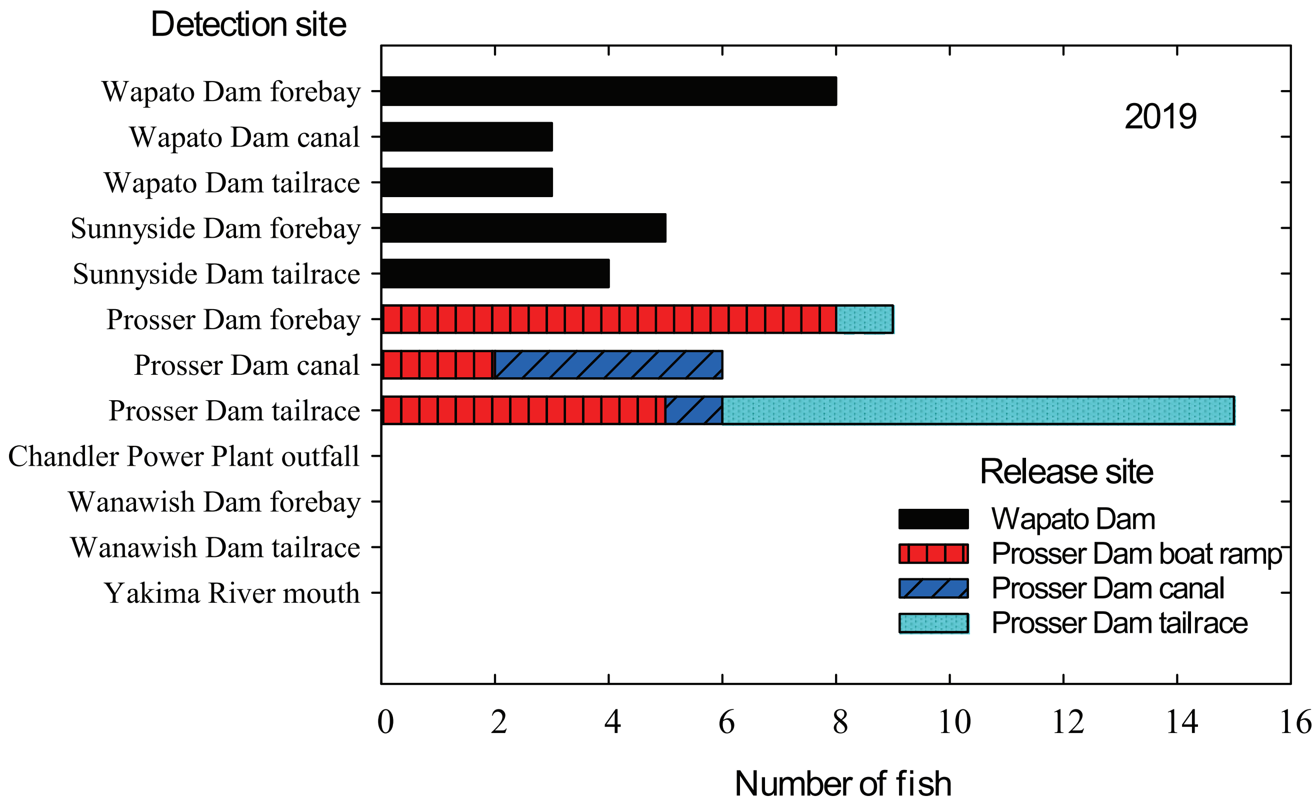

Figure 8. Number of fish and sites where acoustically tagged juvenile Pacific Lamprey were detected following release, by release location, in the Yakima River, Washington, 2019. All 2020 study fish were released at a single location and are not shown.

Light Condition at Time of Arrival at Detection Sites

Lamprey arrived at detection sites primarily at night in 2019 (85.3 percent; 52 of 61 detections) and 2020 (96.6 percent; 28 of 29 detections; figs. 9 and 10). In 2019, four detection sites had at least one lamprey arrive during daylight conditions (fig. 9). The Prosser Dam tailrace site had the most daylight arrivals, with five fish, and the Prosser Dam canal had two lamprey arrive during the day. The most common hour for nighttime arrival in 2019 was 2200 hours (36.5 percent), followed by 2300 hours (26.9 percent) and 0000 hours (13.5 percent). No lamprey arrived in the pre-dawn darkness hours of 0300 or 0400 h (fig. 9). In 2020, the only daylight arrival was detected at the Prosser Dam tailrace site (fig. 10). Like 2019, the most common hour for nighttime arrival was 2200 hours (46.4 percent), followed by 2300 hours (28.6 percent). In contrast to 2019, no arrivals occurred in the 0000 hours and 10.7 percent of the nighttime arrivals occurred in the 0300 hours (fig. 10).

Travel Times, Travel Rates, and Residence Times

Travel times and rates were variable across release sites and study years. In 2019, the median travel time, from the release site upstream from Wapato Dam to the forebay of Wapato Dam, was 2.3 days (table 6). Some lamprey moved quickly from the release site to the dam and others were substantially slower, as evidenced by the range of travel times from 0.3 to 12.3 days (table 6). Each release group generally had similar travel times with a single fish or a few fish that moved more quickly or slowly than the remainder of the group. The median travel time from the release site to Sunnyside Dam was 4.5 days, and the range of travel times was large. Lamprey released at the Prosser boat ramp in 2019 had a median travel time of 6.7 days to reach the forebay of Prosser Dam and 1.6 days to reach the tailrace. Like the travel times from the Wapato release site, the range of travel times from the Prosser boat ramp to the dam was wide (from less than 1 day to more than 11 days; table 6). Considering the short distance from the release site to the detection sites (less than 2 km), the variability in travel times suggests that some lamprey initiated movement quickly and others delayed. Median travel rates were highest from the Wapato release site to Wapato Dam (3.0 kilometers per day [km/d]) and Sunnyside Dam (2.3 km/d) and lowest from the Prosser boat ramp to Prosser Dam (0.2–1.2 km/d; table 6). The highest travel rates we observed in 2019 were greater than 25 km/d.

In 2020, lamprey were only released at the Prosser Dam boat ramp, and median travel times from the release site to the dam forebay and tailrace were both 0.3 days (table 6). Lamprey detected at the Chandler Power Plant outfall had a

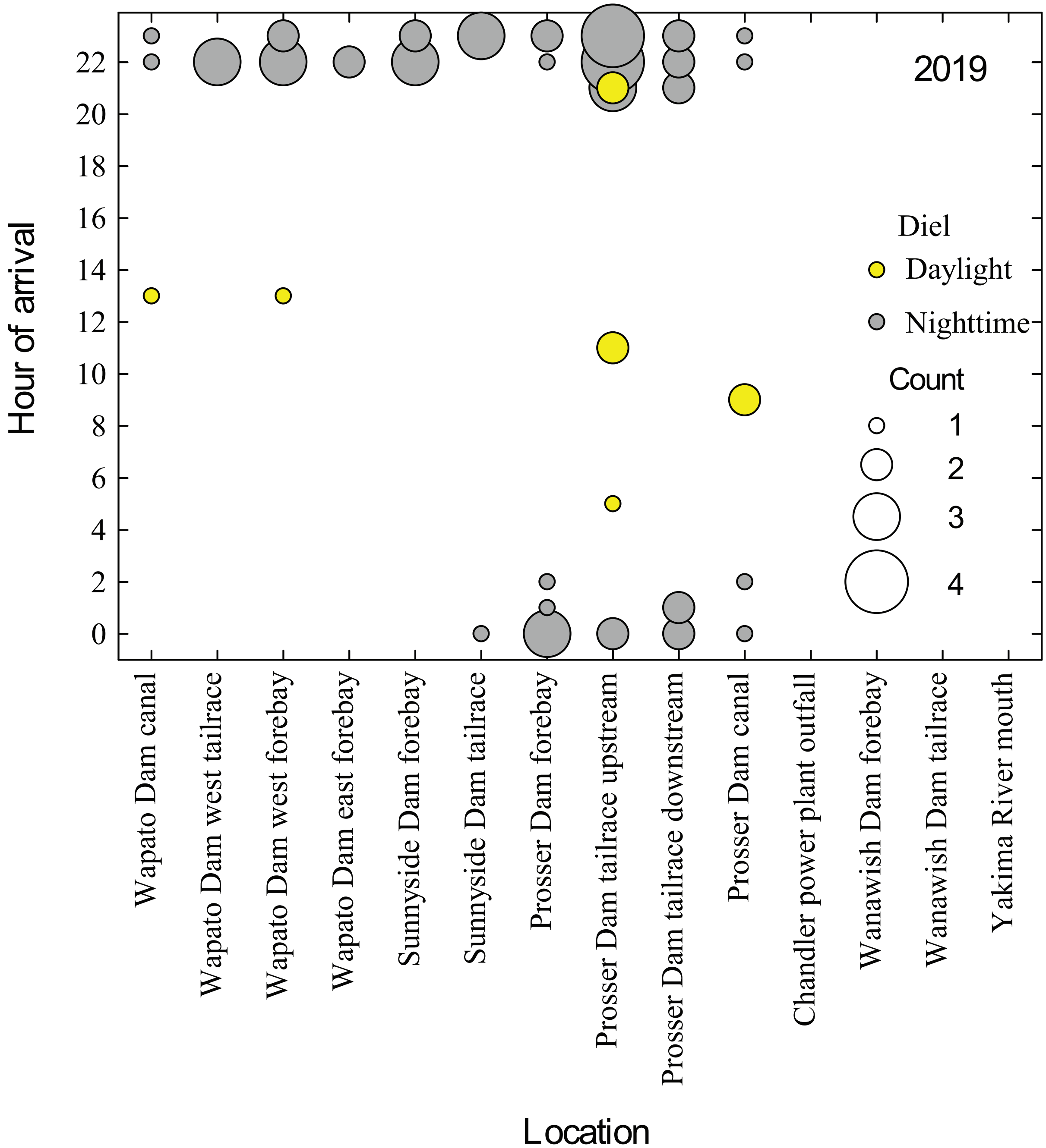

Figure 9. Hour of acoustically tagged juvenile Pacific Lamprey arrival at each acoustic telemetry site in the Yakima River, Washington, 2019. Diel period is defined by civil twilight and the size of circles is proportional to the number of fish represented in each value.

median travel time of 0.4 days. Compared to lamprey released at the same location in 2019, the 2020 median travel times were faster, although the range of travel times was similar in both years. Median travel rates in 2020 were higher than those observed in 2019: 4.6 km/d to the Prosser Dam forebay and 6.7 km/d to the tailrace (table 6). The small group of fish (three lamprey) detected at the Chandler Power Plant outfall had the fastest median travel rate we observed in the study, at 45.3 km/d.

Lamprey residence times at detection sites were generally brief (fig. 11). The maximum residence time for lamprey detected in the Wapato Dam forebay, canal, or tailrace in 2019 was about 20 minutes. At the Sunnyside Dam forebay and tailrace in 2019, the median residence times were 3.4 and 0.8 minutes and the maximum residence time was 9.0 minutes (fig. 11). Only two lamprey arrived during daytime conditions at Sunnyside Dam, and their residence times were comparable to lamprey that arrived under nighttime conditions. Lamprey

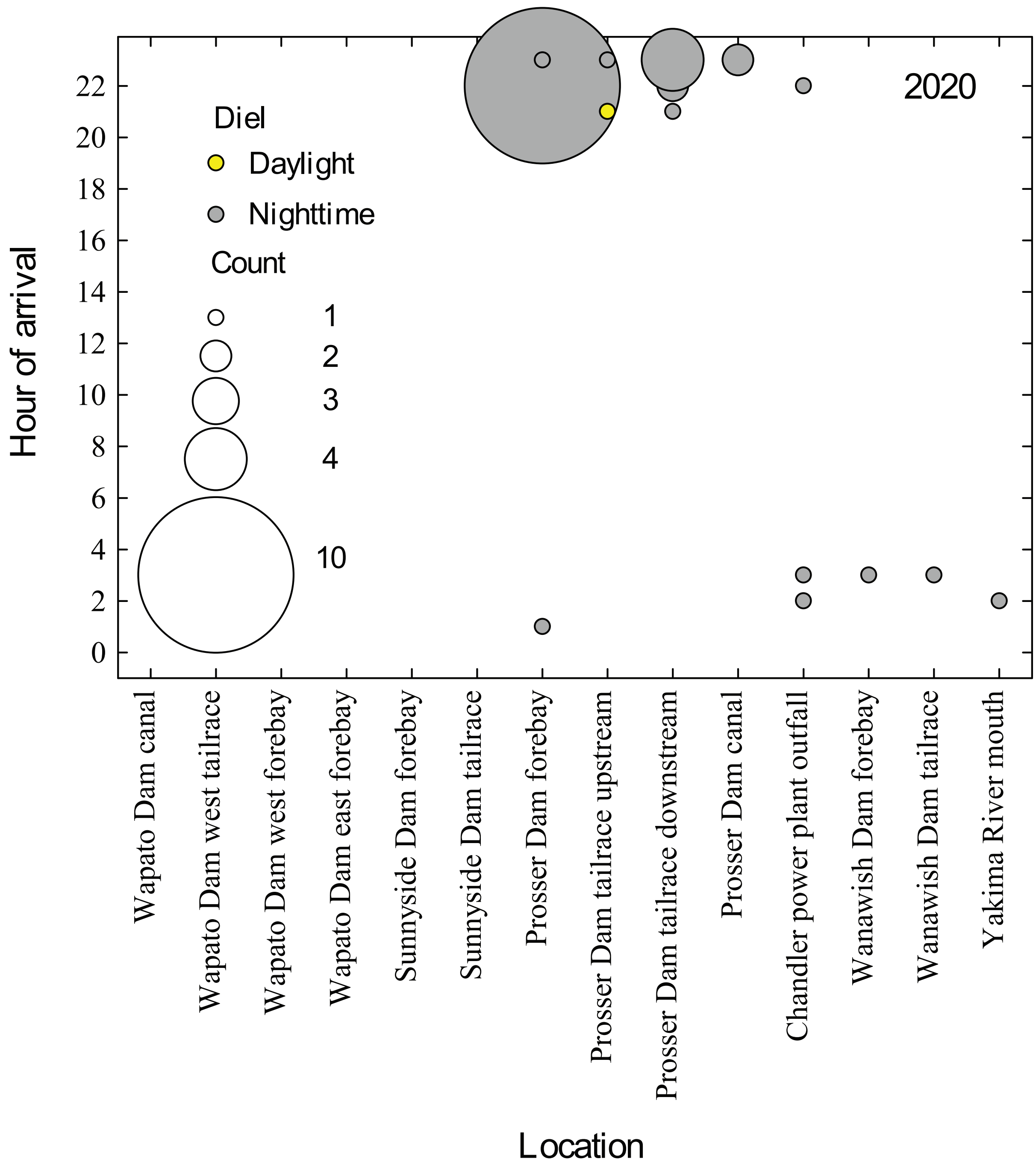

Figure 10. Hour of acoustically tagged juvenile Pacific Lamprey arrival at each acoustic telemetry site in the Yakima River, Washington, 2020. Diel period is defined by civil twilight and the size of circles is proportional to the number of fish represented in each value.

released at the Prosser Dam boat ramp in 2019 generally had lower residence times in the dam forebay (median 3.7 minutes) compared to the canal (median 29.0 minutes) and tailrace (median 2.3 hours; fig. 11). The small groups of lamprey released in the Prosser Dam canal and tailrace in 2019 had the highest residence times (about 11–12 days). Most fish released near Prosser Dam in 2019 arrived during nighttime conditions, and the few fish that arrived during the day had among the highest residence times in each release group (fig. 11). In 2020, all tagged lamprey were released at the Prosser Dam boat ramp and most fish were detected at Prosser Dam and the Chandler Power Plant outfall. The maximum residence time observed in 2020 was about 45 minutes and most fish had residence times of about 10 minutes (fig. 11).

Table 6. Travel time and travel rate for groups of acoustically tagged juvenile Pacific Lamprey in the Yakima River, Washington, 2019 and 2020.

[Travel time was calculated from the time of release to the time of first detection at the site indicated. Travel rate was calculated using the travel time and the distance from the release site. **Abbreviations:** km, kilometers; km/d, kilometers per day]

Year	Release site	Detection site	Distance from release site (km)	Number of fish	Travel time (days)		Travel rate (km/d)	
					Median	Range	Median	Range
2019	Wapato	Wapato Dam	6.9	8	2.3	0.3–12.3	3.0	0.6–26.7
		Sunnyside Dam	10.5	5	4.5	0.3–12.3	2.3	0.9–36.9
	Prosser boat ramp	Prosser Dam forebay	1.2	8	6.7	0.5–11.6	0.2	0.1–2.2
		Prosser Dam tailrace	1.9	5	1.6	0.6–12.5	1.2	0.2–3.4
2020	Prosser boat ramp	Prosser Dam forebay	1.2	12	0.3	0.2–12.4	4.6	0.1–5.1
		Prosser Dam tailrace	1.9	7	0.3	0.3–4.3	6.7	0.4–7.5
		Chandler Power Plant outfall	20.0	3	0.4	0.4–4.2	45.3	4.7–48.4

Comparison of ELAT Transmitter Detections in Pacific Lamprey and Subyearling Chinook Salmon

Detections of tagged lamprey were lower than detections of subyearling Chinook salmon implanted with the ELAT transmitter at three detection sites (fig. 12). We compared a group of 25 lamprey released at the Prosser Dam boat ramp on June 9, 2020, to a group of 7 salmon released upstream from Prosser Dam on June 11, 2020. The lowest detection rate for salmon and the highest detection rate for lamprey both occurred in the Prosser Dam forebay to tailrace reach: 83.3 percent (minimum) for salmon and 58.3 percent (maximum) for lamprey (fig. 12). The largest difference between lamprey and salmon detections occurred at the Prosser Dam tailrace to Chandler Power Plant outfall: salmon had 100 percent detection (5 of 5 salmon) and lamprey had 42.9 percent detection (3 of 7 lamprey).

Transmitter-Life and Fish-Condition Evaluations

The median transmitter life in 2019, as determined in our laboratory tests, was 18.2 days, which matched the anticipated tag life (table 7). One tag failed in less than 10 days (fig. 13) and 8.7 percent (2 of 23) of the tags met our definition of premature failure because they did not function beyond 15 days (table 7). In 2020, four tag-life tests were conducted, showing 20, 62, 103, and 185 days of shelf-life from tag delivery to the start of the test (table 7, fig. 14). The Covid-19 pandemic caused delays in tag production and testing in 2020, which led to a substantial delay between the completion of tag production and tag delivery for the second batch of transmitters. Tag production was completed near the end of March, but the final testing of tag performance conducted prior to delivery of the tags was not completed until early June. Because this delay is not standard for tag production, we have presented our shelf-life tests based on the number of days from delivery (typical approach) but also have summarized the number of days since the end of production (table 7). The date that tag production was completed for the 2019 deliveries and for the first delivery in 2020 could not be determined, and the shelf-life based on days since the end of production is reported as unknown (table 7).

In 2020, the tag-life test showed that extended shelf-life reduced tag performance. The 20-day shelf-life test (78 days post-production) was most comparable to the 2019 test and a comparison of the Kaplan-Meier survivorship plots (fig. 13) showed no significant difference (Wilcoxon, Z score [Z]=1.3778; probability [P]=0.2405). The 103-day shelf-life test included only 10 tags because our original intention was to combine these tags (delivered with the first batch of tags) with additional tags from the second batch to make a robust sample for the tag-life test. The delay in tag production because of the pandemic, however, caused the second batch to be delivered 83 days after the first batch, and we decided to present tag life separately for the two batches. The median tag life for the 20-day shelf-life group was 17.7 days and longer shelf-life periods resulted in reduced tag life (table 7; fig. 14). Pairwise comparisons of the four tag-life plots (fig. 14) showed that the 20-day shelf-life group was significantly different from the 62-day group (Wilcoxon, Z=12.2226, P=0.0005) and the 185-day group (Wilcoxon, Z=7.6178, P=0.0058) and marginally different from the 103-day group (Wilcoxon, Z=3.7006, P=0.0544). Another indication that extended shelf-life resulted in reduced tag performance was the increase in the percentage of tags that failed prematurely. The 20-day shelf-life test had 5.0 percent of tags fail prematurely, but the failure rate increased to 37.0–40.0 percent for the three tests with longer shelf-life (table 7). Although the 103-day test had a reduced sample size, the percentage of premature failures in the 62-, 103-, and 185-day shelf-life tests were comparable (table 7).

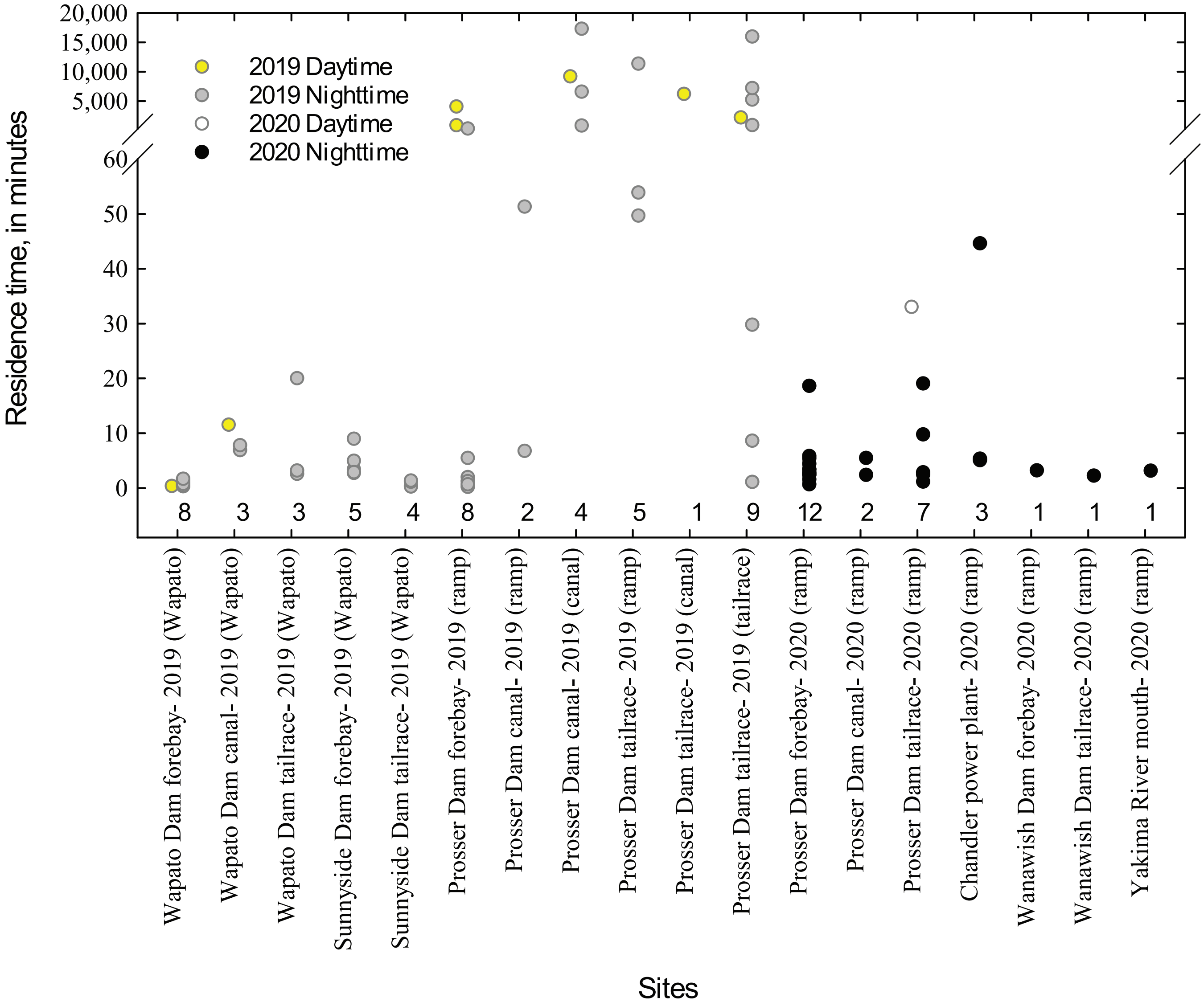

Figure 11. Residence time by diel arrival period for acoustically tagged juvenile Pacific Lamprey at fixed telemetry sites on the lower Yakima River, Washington, 2019 (daytime arrival, yellow circles; nighttime arrival, gray circles) and 2020 (daytime arrival. white circles; nighttime arrival, black circles). The x-axis is labeled as the detection location, followed by the year of release at the specific location site (in parentheses). Diel period is defined by civil twilight. Total number of fish detected are shown below the data points for each site. Residence time is the elapsed time from first detection at a site until the last detection at that same site.

Tests of transmitter life and fish condition using tagged lamprey were initiated in June 2019 and 2020 at the Yakama Nation Prosser Hatchery in Prosser, Washington, and monitoring continued for 32–35 days (table 8). Fungus was not observed on tagged lamprey in either year. Lamprey were energetic and appeared healthy, and the incision area was well healed in all fish at the time of the exams. No mortalities occurred in 2019 and one mortality occurred in 2020, 14 days after tagging. The dead lamprey had a large, circular abscess on the lateral body wall that was clearly visible as it was swimming in the container a few days prior to its death. Upon examination, we noted that the transmitter was situated immediately adjacent to the abscess and had an obvious bulge or swelling near the battery (fig. 15). The last detection of the tag was on June 29, about 3.5 days after the fish were tagged (table 8). The transmitter was returned to PNNL and, after examination, it was reported that there was a small hole in the battery seal that likely allowed water to penetrate the battery.

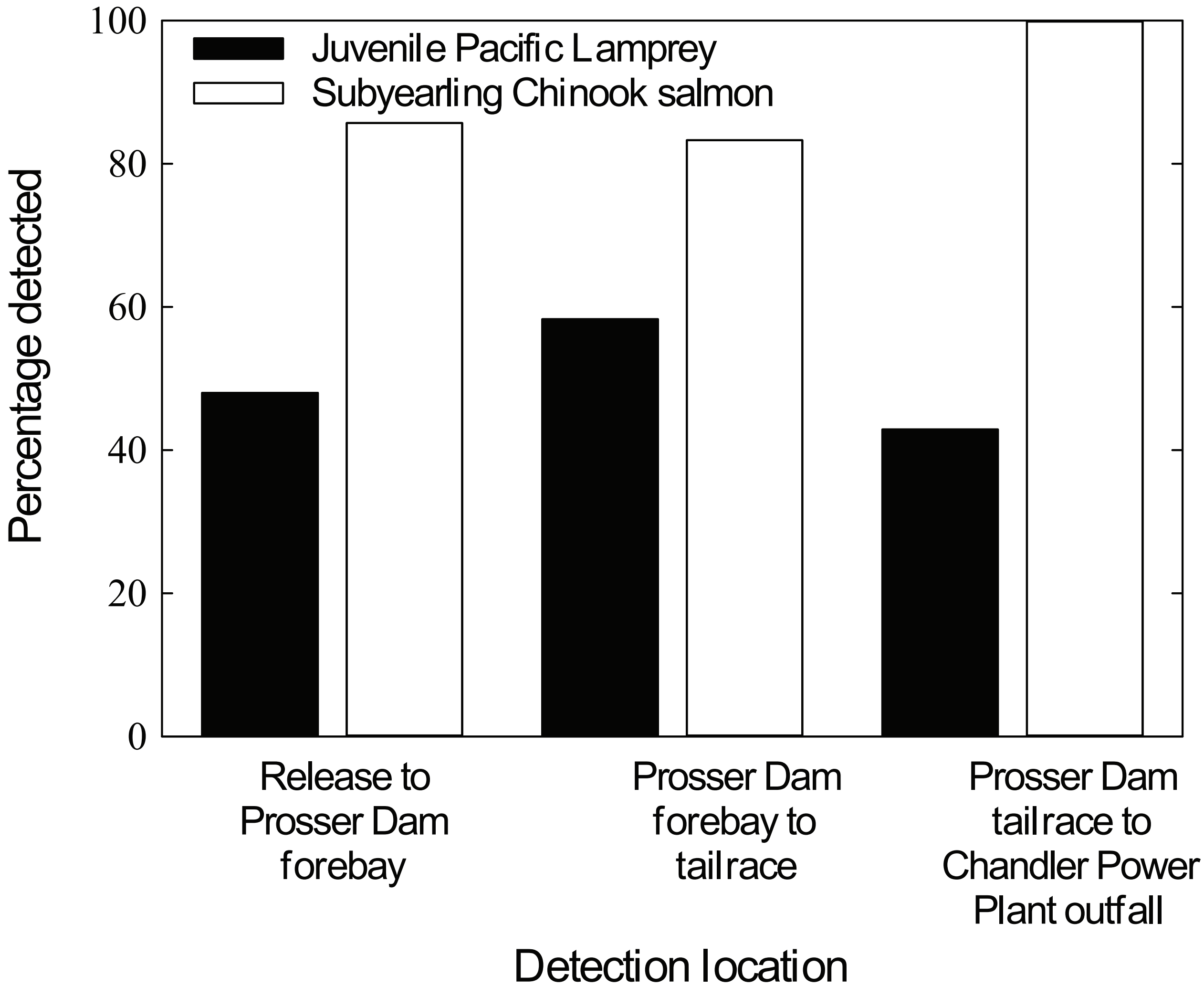

Figure 12. Percentage of juvenile Pacific Lamprey and subyearling Chinook salmon tagged with the eel-lamprey acoustic transmitter and detected following release at select sites in the lower Yakima River, Washington, 2020.

Table 7. Summary of transmitter-life evaluations conducted in the laboratory in 2019 and 2020.

[Transmitters that did not function beyond 15 days were defined as premature failures. Shelf-life is defined as the number of days between tag delivery and tag activation. Shelf-life based on end of production is defined as the number of days from the end of tag production to tag activation. Unknown indicates that value could not be determined. **Symbol:** <, less than]

Year	Batch number	Shelf-life (days)	Shelf-life based on end of production (days)	Number of tags in test	Median tag life (95-percent confidence interval) (days)	Number of tags that failed in less than 10 days	Number of tags that failed in 10–15 days	Number of tags that functioned beyond 15 days	Percentage of tags with premature failure
2019	1, 2, 3	<45	Unknown	23	18.2 (17.5–20.7)	1	1	21	8.7
2020	2	20	78	20	17.7 (16.6–19.4)	1	0	19	5
2020	2	62	140	20	15.2 (14.4–16.5)	0	8	12	40
2020	1	103	Unknown	10	16.7 (9.7–17.8)	1	3	6	40
2020	2	185	263	27	16.3 (13.7–17.0)	5	5	17	37

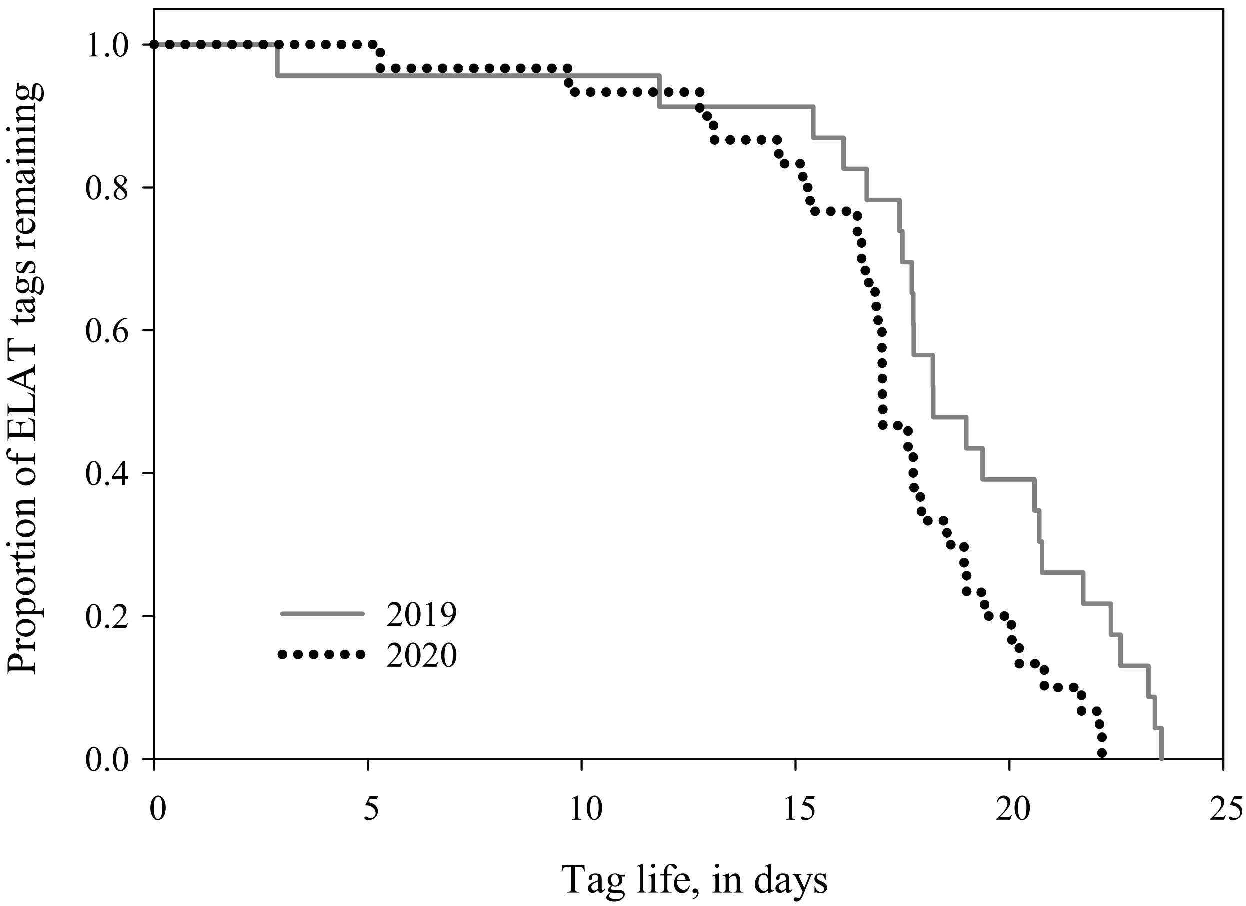

Figure 13. Kaplan-Meier survivorship plot of eel-lamprey acoustic transmitter (ELAT) tag life empirically measured in a laboratory study, 2019 and 2020.

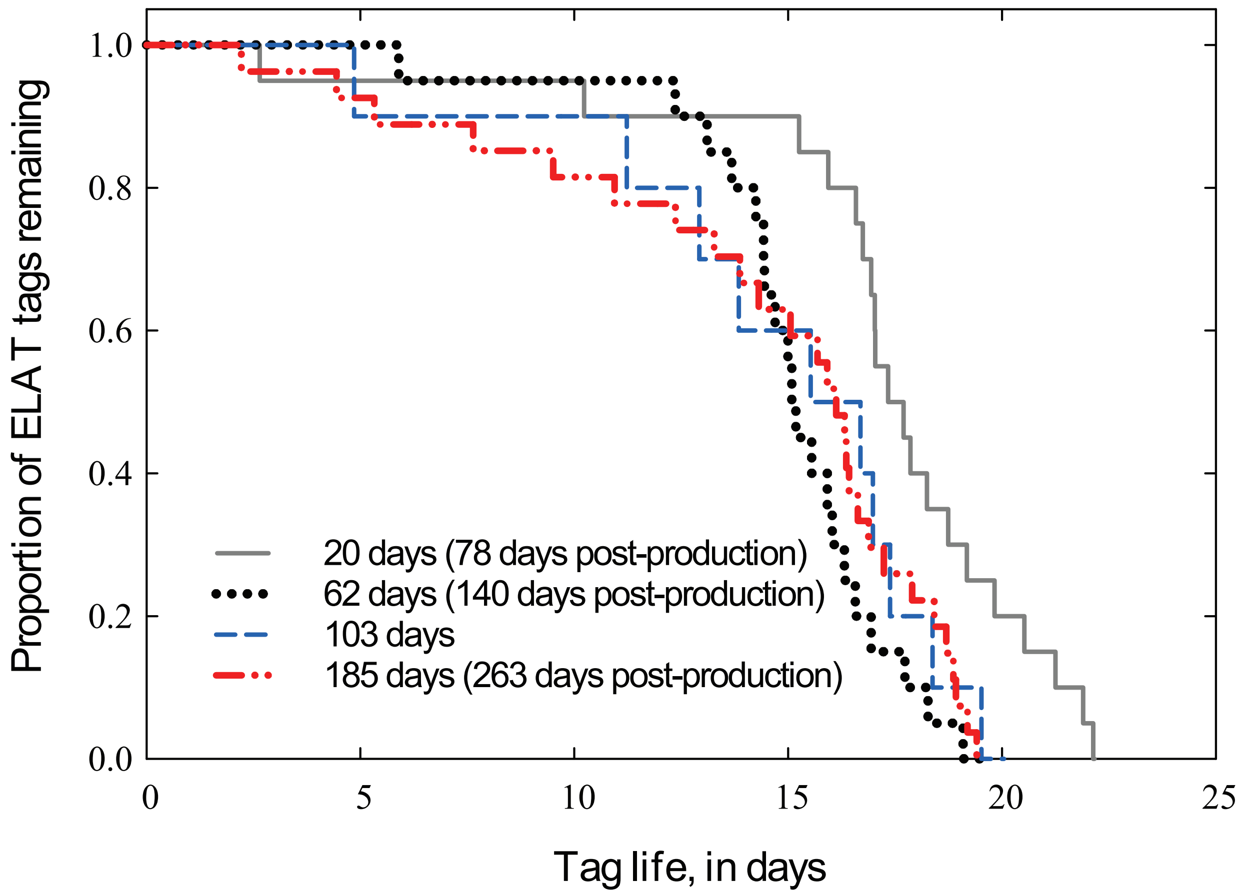

Figure 14. Kaplan-Meier survivorship plot of eel-lamprey acoustic transmitter (ELAT) tag life empirically measured in a laboratory study, by days from delivery to tag activation, 2020.

Table 8. Summary of transmitter-life and fish-condition evaluations, 2019 and 2020.

[**Abbreviations:** g, grams; mm, millimeters]

Metric	2019	2020
Number of fish	6	10
Collection date	June 2, 2019	June 10–18, 2020
Collection source	Chandler	John Day Dam
Tagging date	June 3, 2019	June25, 2020
Initial size		
Length (mm) mean	148.2	147.6
Length (mm) range	143–155	138–162
Mass (g) mean	4.4	4.3
Mass (g) range	3.5–4.9	3.6–5.1
Exam date	Jul. 8, 2019	Jul. 27, 2020
Test duration	35 days	32 days
Final size		
Length (mm) mean	147.8	144.3
Length (mm) range	144–157	135–158
Mass (g) mean	4.2	4.2
Mass (g) range	3.6–4.7	3.5–5.2

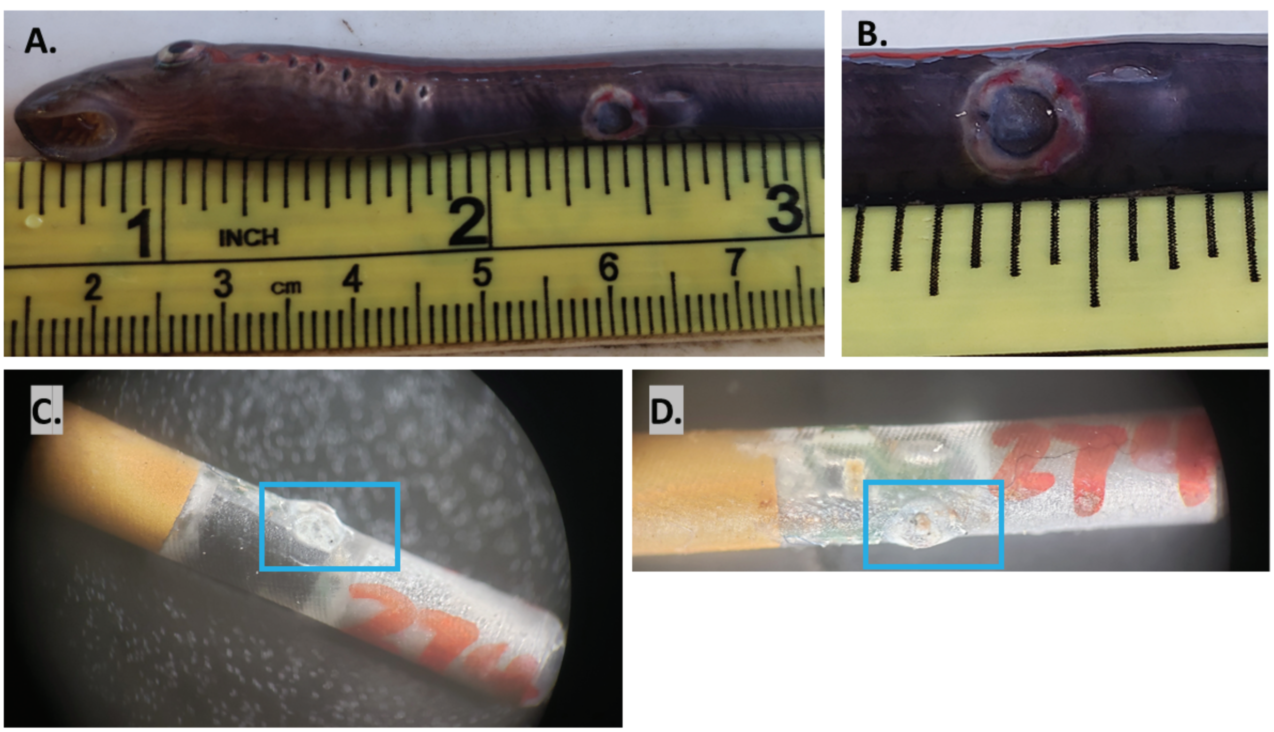

Figure 15. Juvenile Pacific Lamprey implanted with an acoustic transmitter that developed an abscess (A and B) and died 14 days after being tagged. The transmitter had an obvious bulge or swollen area (C and D) near the battery. Photographs A and B. by T. Beals, Yakama Nation Fisheries. Photographs C and D by Theresa Liedtke, U.S. Geological Survey.

The transmitter-life estimates from the tests that evaluated transmitter life and fish condition were unique because they were the only tests in our study that measured tag performance while implanted in lamprey. The holding conditions for the lamprey, and thus the setting for these tag-life studies, were different than the conditions for the other evaluations of tag life. In 2019, the six tags in the test had a median tag life of 19.9 days (95-percent confidence interval [CI], 8.0–24.1 days). One tag failed in less than 10 days, and five tags were still functioning after 15 days (fig. 16). The premature failure rate for tags in this test was 16.7 percent (1 of 6). In 2020, there were 10 lamprey implanted with tags, but one tag was not detected in the first 24 hours following tagging, so it was removed from the tag-life analysis. The median tag life for the remaining nine tags was 13.3 days (95-percent CI, 3.5–15.5 days). Two tags failed in less than 10 days, including the tag that sustained battery damage because of water intrusion (fig. 15), five tags failed from 11 to 15 days, and two tags were still functioning after 15 days (fig. 16). Seven of nine tags (77.8 percent) met our definition of premature failure. Shelf-life substantially influenced this test, as it used the second batch of tags, the delivery of which was delayed. The test was initiated 14 days after tag delivery, which was 93 days after the end of tag production. Comparison of the Kaplan-Meier survivorship plots for 2019 and 2020 tests showed a significant difference (Wilcoxon, Z=4.5315, P=0.0333).

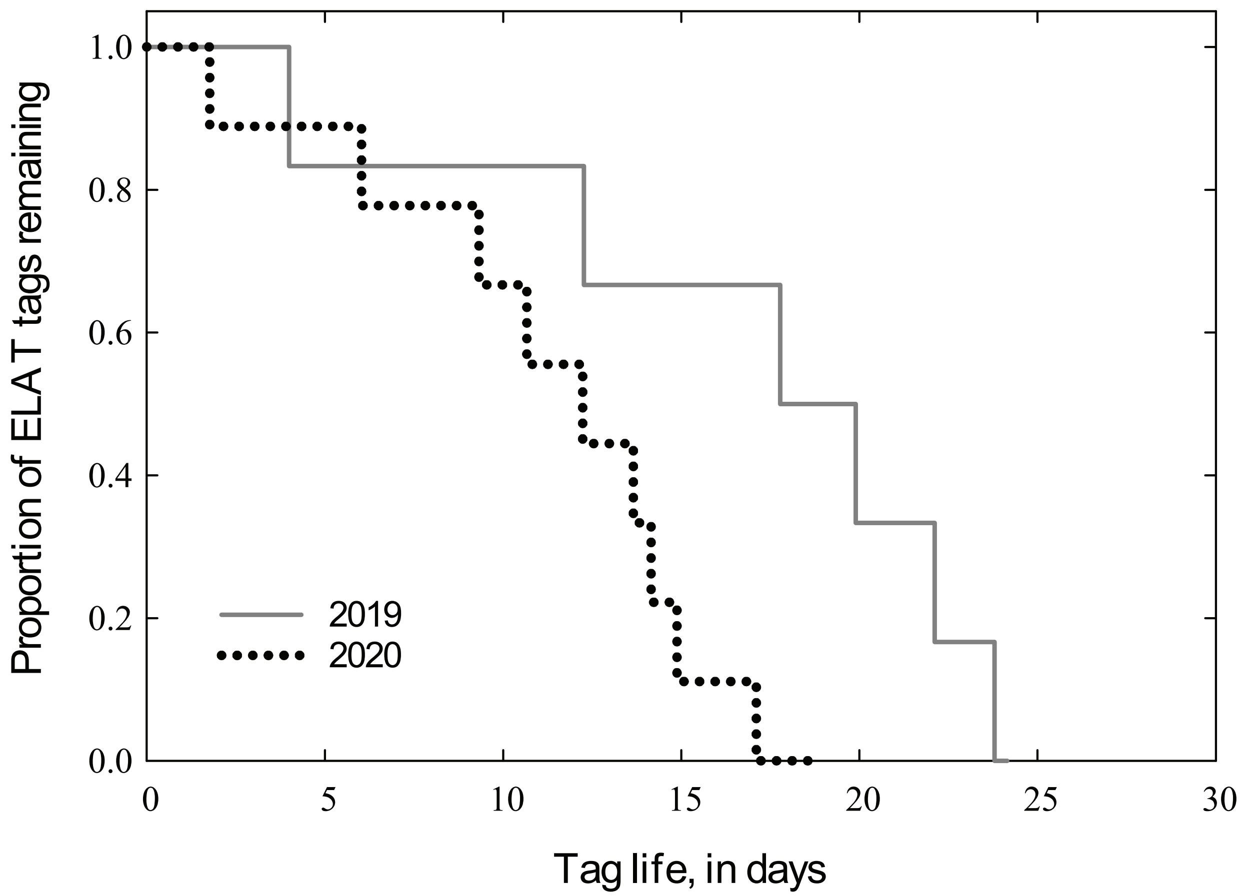

Figure 16. Kaplan-Meier survivorship plot of eel-lamprey acoustic transmitter (ELAT) tag life empirically measured in fish during a laboratory study at the Yakama Nation Prosser Hatchery in Prosser, Washington, 2019 and 2020.

Discussion

Most tagged lamprey did not initiate downstream movements within the 18 days of tag life, and we detected limited numbers of fish at monitoring sites other than near where they were released. In our 2018 evaluation of juvenile lamprey movements in the Yakima and Columbia Rivers, we detected 95.6 percent of the tagged fish (Liedtke and others, 2019), but overall detections were 27.0 percent in 2019 and 48.0 percent in 2020. Detections of tagged lamprey in 2018 were limited at monitoring sites in the Yakima River, and most detections occurred at sites in the Columbia River, including McNary and Bonneville Dams, where intensive monitoring arrays were used (Liedtke and others, 2019). Although the Columbia River monitoring arrays were more limited for the current study, few fish reached the lower Yakima River. In 2018, tagged fish released at the Wapato release site were detected in low numbers at Wapato and Sunnyside Dams, but detections increased at Prosser and Wanawish Dams and the Yakima River mouth (Liedtke and others, 2019). The highest numbers of detections in 2018 were at the Wanawish Dam forebay and the Yakima River mouth (Liedtke and others, 2019). Tags used in the 2018 evaluation had a pulse rate of 5 seconds, which likely contributed to the finding that lamprey were not detected at some sites but detected at other sites farther downstream (Liedtke and others, 2019). As a result of our observations in 2018, tags were programmed to a 3-second pulse rate during 2019–2020 to increase detection probabilities when tagged fish were within detection ranges of telemetry receivers. Thus, the low proportion of fish detected in 2019 and 2020 was unexpected. The pattern of detections showed no evidence of missed detections (that is, low numbers of fish detected at an upstream monitoring site followed by an increased number of fish detected at downstream sites). Lamprey were detected in the highest numbers at the first monitoring site downstream from their release site, followed by limited or no detections at sites farther downstream. No fish were detected at Wanawish Dam and one fish was detected at the Yakima River mouth for the current study, despite the high numbers of detections at these sites in 2018. Although there is the possibility that lamprey moved past monitoring sites undetected, our testing of tag detection range (pre-season) and the suite of monitoring sites downstream from the release sites without any detections are evidence that many lamprey remained near their point of release for extended periods in 2019 and 2020. The ELAT tags used in the current study had an estimated tag life of 18 days at the 3-second pulse rate. If lamprey failed to initiate substantial downstream movement within that period, they would not be detected. Because we did not observe extended holding near the point of release during our 2018 evaluation, we estimate that the variable detection patterns between the studies were related to lamprey behavior, environmental conditions, or a combination of both, rather than the location, configuration, or performance of the monitoring arrays.

Differences in the hydraulic conditions between the 2018 and 2019–20 studies was likely a contributing factor to the variable findings across the studies. Yakima River flows during 2018 overall were similar to the 10-year average, but the period when tagged lamprey were monitored in May occurred during the highest flows of the year, with a monthly mean of more than 8,000 ft^3/s (Liedtke and others, 2019). The 2019 and 2020 flow conditions were less than the 10-year average, and releases of tagged lamprey occurred after the annual peak-flow event. Peak flows in 2019 were about 2,000 ft^3/s, with a brief peak of about 5,300 ft^3/s in mid-May. In 2020, our single release in early June had flows of about 2,600 ft^3/s initially, which then decreased to about 1,000 ft^3/s. The high flow conditions in 2018 may have encouraged lamprey to initiate downstream movement. Conversely, the decreased flows in 2019 and 2020 may have had the opposite effect. The hydrographic trend at the time lamprey were released may also have played a role. Although it is not well documented, there is some suggestion that lamprey initiate movements in anticipation of, or in response to, a rising hydrograph. Little is known, however, about how lamprey respond to a falling hydrograph. In 2018, four releases of tagged fish occurred: two on descending limbs of the hydrograph and two on an ascending limb (Liedtke and others, 2019). Lamprey released on the descending limbs, however, had a rising hydrograph within the period in which we anticipated that the tags would be functional. In 2019, releases at Wapato occurred on descending limbs (April and May releases) or under stable, low flows (June). The hydrograph increased within the 18 days of expected tag life for the April and May releases but remained stable for the June release. Detection rates at Wapato Dam were low and similar for all three release groups, ranging from 8.0 to 9.7 percent. The May 14, 2019, release was interesting in that the hydrograph was in precipitous decline. The flow decreased by about 1,500 ft^3/s in the 24 hours prior to release, which was the largest flow change observed for the year. In 2020, lamprey had stable, low flows at release, with a small increase in flows during the anticipated 18-day tag life. We detected 48.0 percent of the tagged fish at Prosser Dam, which was the highest rate of detection of any release group in the study. The overall low detections of lamprey for this study limited our ability to rigorously analyze relations between lamprey movements and hydrographic conditions. As more information is collected on the movements of juvenile lamprey relative to environmental conditions, we are hopeful that more will be learned about conditions that may cue juvenile lamprey to initiate downstream movements.

Lamprey movement metrics varied among years. Lamprey travel rates observed in our 2018 evaluation ranged from 38 to 56 km/d (Liedtke and others, 2019), which were comparable to the only other study that reported movement rates for juvenile lamprey (Deng and others, 2018). In 2020, a group of three fish had a median travel rate of 45.3 km/d, which was within the range of the 2018 rates, but the remaining release groups in 2019 and 2020 traveled more slowly (medians ranging from 0.2 to 6.7 km/d). The flows in 2018 were higher than those for the current study and likely influenced lamprey travel rates. Another example of flow influence on travel rate was observed for releases at the Prosser boat ramp in 2019 and 2020. In 2019, lamprey traveled at a median rate of 0.2 km/d to the forebay and 1.2 km/d to the tailrace of Prosser Dam. In 2020, lamprey released at the same location had a mean rate of 4.6 km/d to the forebay and 6.7 km/d to the tailrace. In both years the releases occurred in early June under low-flow conditions, but flows were higher in 2020 than in 2019. Overall, across all release groups and detection sites, we noted that most lamprey from a release group arrived at monitoring sites with similar timing, with a few individuals that moved substantially faster or slower. The variability in travel time and rates was owing primarily to these especially fast or slow lamprey. Our 2018 evaluation had a similar finding (Liedtke and others, 2019) and Deng and others (2018) reported that some of their study fish did not seem to be disposed to move downstream following release. Perhaps the limited number of individuals detected in the current study represents the lamprey most inclined to migrate. Residence times at monitoring sites generally were brief and comparable to the 2018 evaluation. Lamprey released at Wapato spent about 10–20 minutes near detection sites, which was similar to the finding of residence times of less than 20 minutes reported in 2018 (Liedtke and others, 2019). Median residence times were longer for lamprey released at the Prosser boat ramp and detected in the canal (29 minutes) and tailrace (2.3 hours). The small groups of lamprey released in the Prosser Dam canal and tailrace, however, had protracted residence times near their release sites, ranging from 11 to 12 days. The residence times for these groups started at the time of release, so the fish may have limited their movements following transport and release as they adjusted to the river environment. A consistent finding among study years was that lamprey most commonly arrived at monitoring sites under dark conditions. The 2018 evaluation reported that 63 percent of arrivals occurred at night, even after fish traveled several hundred river kilometers, over several day-night cycles from release sites in the Yakima River to McNary and Bonneville Dams in the Columbia River (Liedtke and others, 2019). The proportion of nighttime arrivals was higher in 2019 (85 percent) and 2020 (97 percent) than in 2018, perhaps because the detections were restricted to the Yakima River, where the distances between the release and monitoring sites was shorter than in 2018. We might also hypothesize that lamprey migration behavior may be different in tributaries compared to the main-stem Columbia River based on their variable flow regimes. For example, in the relatively high flows of the Columbia River (or other large river systems), juvenile lamprey may travel during both day and night periods, whereas in tributaries, with lower flows, they may restrict their movements to nighttime. This question remains to be answered as we learn more about juvenile lamprey migration behaviors.

The low detection rates and lack of movement we observed for tagged lamprey may justifiably raise concerns that fish condition could have been negatively affected by tagging. We tagged and released 97 lamprey in 2018 (Liedtke and others, 2019) and 152 lamprey in the current study. One lamprey died prior to release in 2018, and there were no mortalities in the current study. The overall pre-release mortality rate (2018–20) was 0.4 percent. One lamprey was removed from a release group in 2019 because of concerns about its condition. Its swimming behavior was atypical, with one side of the body showing limited movement. If we classify this fish as a mortality, the overall pre-release mortality rate would be 0.8 percent. We developed and followed a strict standard operating procedure for transmitter implantation and fish handling and have used a single experienced tagger for all tagging efforts (2018–20). Minimum lamprey size was tightly controlled to limit tag burden (mean of 1.8 percent pooled for 2018–20) and risk of transmitter effects (Liedtke and Wargo-Rub, 2012). Further evidence that lamprey were in good condition after tagging comes from two small laboratory trials that evaluated fish condition and tag life. We tagged 16 juvenile lamprey with active ELAT tags and held them for about 30 days after tagging. One fish in these tests died 14 days after tagging, but the cause of death was clearly linked to water intrusion into the transmitter, which caused the battery to swell. The tissue adjacent to the transmitter developed an abscess, leaving little doubt about the cause of death. Internal and external exams of the remaining 15 fish revealed consistent incision healing and no obvious organ damage or injuries. Lamprey in the laboratory trials showed no signs of fungus, which has been an issue in other studies of juvenile lamprey (Mueller and others, 2006; Mesa and others, 2012; Liedtke and others, 2019). Our study team has extensive experience working with juvenile lamprey, and we are confident that we have been taking all appropriate steps to minimize negative outcomes from tagging. One variable that occasionally has been challenging to control is the length of time lamprey are held after collection and before tagging. We commonly have collected lamprey over several days and combined them into a larger group for tagging. In 2018, most fish were held less than 4 days before tagging, but a few fish were held for as long as 10 days (Liedtke and others, 2019). Several of these fish developed mild-to-moderate fungal infections, and fungus was the most likely cause of death for the single mortality in 2018 (Liedtke and others, 2019). In 2019, we were able to select fish from the various collection locations and limit holding time to a maximum of 4 days (mean of 1.6 days). The facility closures and work limitations that occurred in 2020 made fish collection more challenging, and we held fish for longer periods. Most of the 2020 lamprey were held for 4 days or less, but four lamprey were held for 18–26 days. No sign of fungus was present when these fish were tagged or released, but only one of the four fish was detected in the study area. We recognize that protracted holding of juvenile lamprey prior to tagging is not ideal, but 2020 was an exceptionally challenging year, and future tagging efforts will seek to limit pre-tag holding to a maximum of 4 days.

Secondary objectives for this study included releasing purposely killed lamprey and empirically measuring tag life in the laboratory to facilitate future evaluations where lamprey survival may be estimated. We released eight euthanized lamprey at Wapato in 2019, two fish in May, and six fish in June. We developed a procedure for euthanizing lamprey without distorting their tissues so they would drift in the river like lamprey that died naturally. Although releases of purposely killed fish are commonly used in survival studies for juvenile salmonids, no existing procedures were available for lamprey. Additionally, some euthanasia procedures used for juvenile salmon have been problematic, resulting in salmon reviving after release and traveling long distances (see Tomka and others, 2020). We tested several approaches in the laboratory before we defined our procedures for the field study and confirmed that none of the lamprey were able to revive. We did not detect any of the euthanized lamprey at any monitoring sites in the study area, which is a good first step toward testing the survival model assumption that all detected fish are alive (Skalski and others, 2010; Tomka and others, 2020). During these initial tests, however, our sample sizes were small. Future studies could benefit from releasing additional euthanized lamprey, over a range of hydrographic conditions, and in combination with live study fish to further evaluate this survival model assumption.

The second part of our efforts to facilitate future survival studies was the measurement tag life under laboratory conditions. We conducted seven tag-life tests, five with ELAT tags in containers (our standard approach) and two with tags implanted in lamprey. Three tag-life tests produced median tag-life estimates that met or exceeded the expected 18 days of battery function. The 2019 standard test and the 2020 standard test with 20-days of shelf-life (78 days since the end of production) had tag-life estimates of about 18 days and were not significantly different. The 2019 test in lamprey was not robust (six tags) but had a median tag life of 19.9 days, which was significantly higher than the 2020 test in lamprey (13.3 days). The shelf-life tests showed that the 62-, 103-, and 185-day groups had significantly reduced tag life compared to the 20-day shelf-life group. Premature failure rates also increased with shelf-life duration, from 5 percent for the 20-day group to 37–40 percent for the longer shelf-life groups. Researchers cannot conduct cost-effective and defensible telemetry studies with premature tag failure rates near 40 percent. During our 3 years working with the ELAT tag, we have discovered several tags with physical damage (cracked coating or exposed wires) or that failed to activate and function as expected. In 2020, we documented our most extreme example of tag failure when water penetrated the tag components and caused a lesion on the body wall of the lamprey. Some of these challenges are to be expected because the tag is a prototype that still is in the development and testing phases. The ELAT tags are manufactured at PNNL which is a research setting, not a production facility. The variability we report in tag performance among production years and batches is explained by the production process. The plan for the ELAT tag beyond development and testing is to make it available through commercial vendors who will establish quality-control measures during production. Studies that use the ELAT, or any other transmitter model, could consider conducting tag-life tests under controlled settings to validate field observations and improve the rigor of the evaluation, using randomly selected tags from each production batch.

The timing and location of our planned releases of tagged lamprey were adaptively modified to adjust to changing conditions. In 2018, about one-half of the lamprey were released at Wapato and the remainder were released at the Yakima River mouth to increase the probability of detections in the Columbia River (Liedtke and others, 2019). With limited detections in the Yakima River in 2018 (mostly at two monitoring sites), we initially planned to release all 2019 study groups upstream from Wapato Dam to maximize our ability to describe fish behavior at the full range of detection sites in the lower river. We conducted testing using the ELAT tag at several of the monitoring sites and were confident that the detection ranges were appropriate. Following two releases of lamprey and in-season review of the detection histories, the study team modified the release strategy. We selected a release site in the forebay of Prosser Dam because the distance from the release site to the first downstream monitoring site was reduced (compared to the Wapato release site) and because the monitoring array near the dam had documented high performance. We released small groups of tagged fish directly into the Prosser Dam canal and tailrace to evaluate if different release conditions might result in larger proportions of lamprey initiating downstream movements than in the past. In 2020, we simplified the release strategy to accommodate facility closures and work restrictions associated with the Covid-19 pandemic. All study partners were affected at some level, resulting in delayed tag delivery and challenges with the ability to collect, tag, and release lamprey. Tags were allocated to a single release effort in June and then used for additional testing including the tag-life tests and the use of the ELAT tags in subyearling Chinook salmon. Like our adaptive approach to release locations, we were compelled to modify our planned approach to release timing relative to the migration timing. In 2018, releases were conducted in early to mid-May (Liedtke and others, 2019). Our goal in 2019 was to release study fish from March to May to capture the early parts of the juvenile lamprey migration period in the lower Yakima River. Manufacturing of the tags was delayed and our earliest release in 2019 was at the end of April. Similarly, in 2020 the pandemic caused substantial delays in tag manufacturing and delivery and the single release we conducted was in early June. We have thus far been unable to monitor juvenile lamprey in the early part of the migration period, and this monitoring remains a high-priority research need because we anticipate that different components of the migration likely will have different behaviors.

As part of our adaptive management of the 2020 study objectives, our study partners with the USGS-Reclamation-YNF juvenile salmon study implanted ELAT tags in subyearling Chinook salmon. The goals of this test were to compare ELAT performance to another transmitter commonly used in salmon and to compare detections of salmon with detections of lamprey. This report summarized findings comparing salmon and lamprey with the ELAT tag. Other comparisons between salmon tag models are outside the scope of the study. We selected the salmon release group that was best aligned with a lamprey release to make the comparison, but the sample size for the salmon group was small (seven fish). The trend was clear that detections rates for the salmon exceeded those for lamprey at three monitoring locations, including 100-percent detection of salmon at one site. We concluded that the monitoring arrays could reliably detect ELAT tags, so reduced detections of tagged lamprey likely were attributable to differences in fish behavior between lamprey and salmon. One difference in behavior is that lamprey are more bottom-oriented than salmon, which typically migrate in the upper part of the water column. Lamprey also may travel in more shallow water closer to the shoreline than juvenile salmon, although this behavior has not been evaluated in tributaries. Detecting lamprey in the shallow water near the shoreline or very close to the substrate can be challenging because the multiple reflective surfaces (substrate and water surface) or objects between the tag and the hydrophone (rocks or debris) block or reflect the tag signal. The monitoring arrays for this study were designed by the juvenile salmon study to optimize detections of juvenile salmon and, based on the detections for the Chinook salmon with ELAT tags, they performed well. The arrays also detected lamprey effectively, as there was no evidence for missed detections in our 2019–20 evaluation. An opportunity exists, however, for future studies to refine array configuration to optimize performance based on lamprey behavior.

Few studies have used acoustic telemetry to monitor the movements of juvenile lamprey and much remains to be learned. Prior to this study, the only evaluations were our pilot study in 2018 (Liedtke and others, 2019) and the Deng and others (2018) study in the Columbia River. The state of knowledge on the best approaches to conduct juvenile lamprey studies using telemetry is in its infancy. Although telemetry studies are currently a common tool to monitor the movements and survival of juvenile salmon, in the early development years, the approach was refined through trial and error (Hockersmith and Beeman, 2012). The approach to optimal monitoring of juvenile lamprey, likewise, will be refined through experience. This study would not have been possible without our partnership with the salmon survival study, but future studies may benefit from designing monitoring approaches specific to lamprey. Transmitter performance also is expected to improve, with additional battery life and a commercial manufacturing process (Liedtke and Wargo-Rub, 2012). For the current study, the most substantial knowledge gap was the conditions under which lamprey initiate downstream movements. Environmental conditions commonly are cited as a movement cue for lamprey (Liedtke and others, 2019) and we described some differences based on hydraulic conditions. We plan to pursue additional analyses with water temperature and turbidity to understand their potential role. Other considerations include the variable collection methods and locations, the stage of the migration, and the stage of development of the lamprey used in the study. Future studies of juvenile lamprey movements should consider documenting these conditions for their study fish to add to the state of the science and enhance restoration efforts.

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