Monitoring the Movements of Juvenile Pacific Lamprey (*Entosphenus tridentatus*) in the Yakima River, Washington, Using Acoustic Telemetry, 2018–2020

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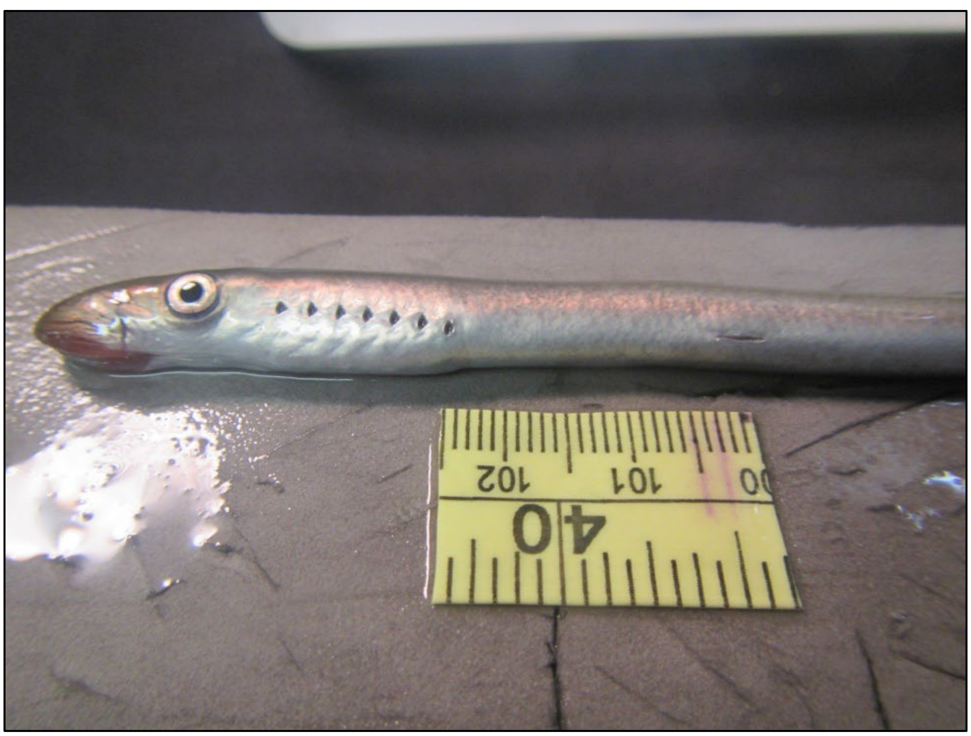

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14. ABSTRACT

Barriers to migration contribute to declining populations of Pacific Lamprey (Entosphenus tridentatus) throughout the West, but little is known about their migration patterns and effects of dams and water diversions. Telemetry has been used to describe dam-passage routes and survival of juvenile salmon and steelhead for decades. Juvenile The Dept. of Energy-Pacific Northwest National Laboratory has been developing a micro-transmitter specifically for use in juvenile lampreys, eels, and other small fishes. Through a collaborative research approach, we used prototype transmitters to do a pilot-level evaluation of tagged lamprey movements in the Yakima and Columbia Rivers. We partnered with an ongoing telemetry study being conducted by the U.S. Geological Survey (USGS), the Bureau of Reclamation (Reclamation), and Yakama Nation Fisheries (YNF). Our study goals 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, and (3) evaluate tag performance and test some survival model assumptions in preparation for future studies.

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Final Report No. ST-2022-19112

prepared by

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Monitoring the Movements of Juvenile Pacific Lamprey (Entosphenus tridentatus) in the Yakima River, Washington, Using Acoustic Telemetry, 2018–2020

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Executive Summary

The Yakima River originates from the Cascade Mountains in central Washington State, flowing over 200 miles through forest, range, and farmland until reaching the confluence with the Columbia River. The Bureau of Reclamation operates and maintains the Yakima Project which includes storage reservoirs, diversion dams, hydroelectric power plants, and fish passage facilities. The project provides water for over 400,000 acres of irrigated agriculture, the Yakama Nation Reservation, and municipal uses. The Yakima Basin also supports significant runs of salmon, trout, and other native fishes.

Pacific Lamprey (*Entosphenus tridentatus*) are a migratory fish species which were historically abundant throughout the Columbia River Basin. Lamprey were ecologically significant and important to Native American tribes reliant on fisheries. Adult lamprey spawn in freshwater streams where jueniles can live up to ten years before migrating to the ocean to grow, mature, and eventually return to freshwater to spawn. Among other factors, barriers to migration contributed to declining populations of Pacific Lamprey throughout their range, including the Yakima River Basin. Recovery of Pacific Lamprey populations is a regional fisheries management goal.

Little is known about the effects of dams and other facilities on juvenile lamprey migration. In 2018 a prototype micro-acoustic transmitter developed by the Dept. of Energy Pacific Northwest National Laboratory (PNNL) became available for research purposes. The micro-transmitter was suitable for tagging juvenile lamprey and was intended to be compatible with commercially available Juvenile Salmon Acoustic Telemetry System (JSATS) equipment.

A JSATS study known as the Lower Yakima River Smolt Survival Study was planned for 2018-2022. Study participants included fisheries staff from the Confederated Tribes and Bands of the Yakama Nation (YN Fisheries), Bureau of Reclamation (Reclamation), U.S. Geological Survey (USGS), and local irrigation districts. When participants of the JSATS study learned about the availability of micro-transmitters from PNNL they sought funding to acquire tags and add juvenile lamprey to the JSATS study.

The goals of tagging juvenile Pacific Lamprey were to (1) evaluate the feasibility of monitoring juvenile lamprey migration as part of the Lower Yakima River Smolt Survival Study and (2) evaluate the performance of the prototype micro-transmitter, using both field and laboratory methods. The study area included the lower Yakima River, 4 major diversion dams, and portions of the Columbia River. Lamprey were collected, tagged, and released during April-June from 2018-2020. Reclamation provided project management and field support, YN Fisheries collected, held, and tagged fish with support from USGS, and USGS was responsible for most data collection, analysis, and reporting. All agencies provided peer review of interim and final reports. The study received funding from various sources including the Reclamation Science and Technology Program (additional funding sources are identified in the appendices).

The study detected low numbers of lamprey released after tagging, in contrast to juvenile salmon which had high detection probability. Reasons for low detections of lamprey may include that juvenile lamprey migrate lower in the water column than salmon, where they are more difficult to

monitor. Some lampreys may not have migrated after being released or may have become mortalities. Tag battery life was approximately 18 days after which transmitters ceased operating.

Tagging effects appeared minimal, as most lamprey recovered from tag implantation surgery while being held for observation. Juvenile lamprey did not have as predictable and directed migration behavior as juvenile salmon, which may have limited the ability of JSATS to monitor lamprey behavior effectively. Field studies designed specifically to monitor lamprey, rather than salmon, may provide a better understanding of tagged lamprey behavior during migration.

Two USGS Open-File Reports were prepared for this study, an interim and final report. The reports contain detailed descriptions of the study background, methods, and results. The USGS reports are attached to this document as Appendix A and Appendix B and also available at the links below:

> Appendix A: *Movements of Juvenile Pacific Lamprey (Entosphenus tridentatus) in the Yakima and Columbia Rivers, Washington, 2018—A Pilot Study Using Acoustic Telemetry, USGS Open-File Report 2019-1058*
>
> Appendix B: *Monitoring the Movements of Juvenile Pacific Lamprey (Entosphenus tridentatus) in the Yakima River, Washington Using Acoustic Telemetry, 2019-20, USGS Open-File Report 2022–1052*

Data collected during the study is stored and publicly available at: Pacific States Marine Fisheries Commission, 2022, app.streamnet.org-/files/822/: Pacific States Marine Fisheries Commission, StreamNet—Fish Data for the Northwest data files, accessed May 9, 2022, at https://app.streamnet.org/files/822/.

Appendix A

Movements of Juvenile Pacific Lamprey (Entosphenus tridentatus) in the Yakima and Columbia Rivers, Washington, 2018—A Pilot Study Using Acoustic Telemetry, USGS Open-File Report 2019-1058

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

Movements of Juvenile Pacific Lamprey (*Entosphenus tridentatus*) in the Yakima and Columbia Rivers, Washington, 2018—A Pilot Study Using Acoustic Telemetry

Open-File Report 2019-1058

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

Cover: Downstream view of Yakima River at river kilometer 73, downstream of Interstate 82 bridge at Prosser, Washington. Photograph by Tyler Beals, Yakama Nation Fisheries, September 20, 2018.

Movements of Juvenile Pacific Lamprey (*Entosphenus tridentatus)* in the Yakima and Columbia Rivers, Washington, 2018—A Pilot Study Using Acoustic Telemetry

By Theresa L. Liedtke, Ralph T. Lampman, Daniel Z. Deng, Tyler E. Beals, Michael S. Porter, Amy C. Hansen, Tobias J. Kock, Ryan G. Tomka, and Patrick Monk

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

Open-File Report 2019-1058

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
mile (mi)	1.609	kilometer (km)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Travel rate	
mile per day (mi/d)	1.609	kilometer per day (km/d)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Volume	
liter (L)	33.81402	ounce, fluid (fl. oz)
	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:

$$°F = (1.8 \times °C) + 32.$$

Abbreviations

JSATS	Juvenile Salmon Acoustic Telemetry System
PNNL	Pacific Northwest National Laboratory
Reclamation	Bureau of Reclamation
SA	standard deviation
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
YNF	Yakama Nation Fisheries

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Movements of Juvenile Pacific Lamprey (*Entosphenus tridentatus)* in the Yakima and Columbia Rivers, Washington, 2018—A Pilot Study Using Acoustic Telemetry

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

Abstract

Telemetry has been an invaluable tool to improve our understanding of adult Pacific Lamprey (*Entosphenus tridentatus)* movements and to guide management approaches to protect and restore this species of concern. Juvenile and larval lamprey, however, are much smaller than adults, and have not been monitored with telemetry because available transmitters have traditionally been too large. With funding from the U.S. Department of Energy and the U.S. Army Corps of Engineers, the Pacific Northwest National Laboratory developed a prototype micro-transmitter of appropriate size for use in small fish such as juvenile lampreys and eels. Through a collaborative research approach, we used these prototype transmitters to do a pilot level evaluation of juvenile lamprey (macrophthalmia) movements in the Yakima and Columbia Rivers in 2018. Our project monitored tagged lamprey using acoustic monitoring arrays installed and maintained for juvenile salmon (*Oncorhynchus* spp.) migration studies done by our partners. The study was done in the lower Yakima River, Washington, from river mile 111 to the river mouth, and in the Columbia River, from the Yakima River mouth to Camas, Washington, downstream of Bonneville Dam. We released four groups of tagged lamprey from May 9 to 15, 2018. Two groups were released at the upper site (located at the State Route 24 bridge, about 4.5 river miles upstream of Wapato Dam), and two groups were released at the lower site (about 1.7 miles upstream of the Yakima River mouth). We detected 95.6 percent of the tagged lamprey, with more individuals detected in the Columbia River than in the Yakima River. Lamprey arrived at Bonneville Dam in an average of 8.0–9.6 days from the upper site (300 river miles) and in an average of 6.5 days from the lower site (193 river miles). Lamprey moved through the study area at an average rate of 30–35 miles per day and generally remained at each detection site for less than about 20 minutes. Most lamprey (63 percent) arrived at detection sites during periods of darkness, but some travel occurred during daylight and transitional light periods.

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[1] U.S. Geological Survey.
[2] Yakama Nation Fisheries.
[3] Pacific Northwest National Laboratory.
[4] Bureau of Reclamation.

Overall, lamprey moved more slowly than passive particles in the reach between McNary Dam and Bonneville Dam, but some individuals and one group of lamprey exceed particle travel rates. The estimated particle travel time from McNary Dam to Bonneville Dam was 3.3 days, and the mean travel time for the combined lamprey release groups was 4.4 days. This project is scheduled to complete a similar field study in 2019, continuing the partnership with the Yakima River juvenile salmon study.

Introduction

Telemetry is a powerful tool for monitoring animal movements. In the Columbia River Basin of the Pacific Northwest, telemetry has been used for decades to evaluate movements, dam passage, and survival of salmon and steelhead (*Oncorhynchus* spp.; hereinafter "salmon") to inform management decisions to protect and preserve these species. As technology advanced, manufacturers designed and produced smaller and smaller transmitters, responding to the need to monitor the movements of smaller fishes. Small, light transmitters are required for studies of small fishes because telemetry studies assume that tagged individuals behave and perform similarly to untagged individuals. This assumption is not met when the weight of the transmitter relative to the weight of the fish, referred to as transmitter burden, exceeds about 2–5 percent (Liedtke and Wargo-Rub, 2012). In addition to transmitter burden, the size and shape of the transmitter must be considered relative to the fish. Specifically, the transmitter should not disrupt normal swimming or be positioned where it encroaches on internal organs or structures. For example, in laterally compressed fishes, the weight of a transmitter may be appropriate when considering burden, but the transmitter may be too large to fit inside the body cavity. Small transmitters are desirable because they allow a wide range of fishes to be monitored.

Pacific Lamprey (*Entosphenus tridentatus*), and other lamprey species (*Lampetra* spp.) pose unique challenges for telemetry studies (Moser and others, 2007), but meeting these challenges is a priority because these unique fishes are not well understood and applying this powerful tool will help to fill knowledge gaps and guide management decisions. Lampreys have long, tube-shaped bodies with cartilaginous skeletons and swim with undulating body movements. All life stages of Pacific Lamprey are associated with substrates and have benthic-oriented behavior including burrowing into sediments or attaching to rocks. Combined, these traits can make attachment and retention of a transmitter challenging (Moser and others 2007). Transmitters attached externally could be dislodged by their swimming movements or their regular association with hard substrates. Surgical implantation of the transmitter into the body cavity reduces the risk of transmitter loss (Liedtke and Wargo-Rub, 2012), but the tube-shaped body of lampreys can limit the space available for a transmitter and possibly impede swimming ability (Moser and others, 2002, 2007). Adult Pacific Lamprey commonly are monitored using telemetry (Keefer and others, 2013; Starcevich and others, 2014; McIllraith and others, 2015; Clemens and others, 2017), as implantation techniques have been developed and transmitter burden and dimensions are within defensible limits. We have learned much about adult lamprey movements in and around barriers and in spawning habitats using telemetry (Moser and others, 2002; Johnson and others, 2012; Starcevich and others, 2014; Clemens and others, 2017). Innovative lamprey passage devices have been designed and tested by monitoring how adult lamprey approach and use them (Moser and others, 2011; Keefer and others, 2013). Telemetry has been an invaluable tool to inform adult lamprey movements and to guide management approaches to protect and restore them. Juvenile (macrophthalmia) and larval (ammocoete) lamprey, however, are much smaller than adults, and have not been monitored with telemetry

because available transmitter models were too large. Juvenile lamprey are of special interest because they are migratory, moving downstream to the ocean, and their migration may be affected by barriers such as dams or water diversions. Managers 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 (USACE) developed the Juvenile Salmon Acoustic Telemetry System (JSATS) and a micro-transmitter that used micro-battery technology (Deng and others, 2015). The use of micro-battery technology enabled advances in transmitter miniaturization, which previously was limited by the size of available batteries. This new transmitter was reported to be "injectable" owing to its small size, which was a benefit because it could reduce the handling typically required to surgically implant a transmitter (Deng and others, 2015). This innovative transmitter weighed 30 percent less than other acoustic transmitters (Deng and others, 2015) and was designed to allow studies of small salmon. Despite the reduction in size, the "injectable" JSATS transmitter was still too large to be used in juvenile lampreys. To address this need, PNNL developed another, smaller transmitter, specifically for use in juvenile lampreys and eels (Deng and others, 2018) with funding from the U.S. Department of Energy and USACE. 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. We partnered with an ongoing study by U.S. Geological Survey (USGS), the Bureau of Reclamation (Reclamation), and Yakama Nation Fisheries (YNF) that used JSATS to monitor juvenile salmon. The juvenile salmon study had a series of acoustic receivers in the lower 110 mi of the Yakima River that could detect the new lamprey transmitters because they used the JSATS system. Additionally, PNNL had JSATS receivers positioned at several locations in the Columbia River, downstream of the Yakima River. Working collaboratively, we did a pilot-level juvenile Pacific Lamprey evaluation within the study area monitored by these acoustic receivers to begin addressing critical information gaps for this life stage. Some of the information gaps we were especially interested in were (1) movement rates of juvenile lamprey that are relatively weak swimmers (Moursund and others, 2000; Moser and others 2015), and (2) diel movement patterns, as Pacific Lamprey are primarily nocturnal (Moursund and others, 2000).

Methods

Study Area

The study was done in the lower Yakima River, from river mile 111 to the river mouth, and in the Columbia River, from the Yakima River mouth to Camas, Washington, downstream of Bonneville Dam. Personnel from the juvenile salmon study installed and maintained acoustic monitoring receivers at eight sites in the Yakima River (fig. 1). Receiver deployments were designed to detect fish as they approached and passed dams or were entrained into irrigation canals. In the Columbia River, the juvenile salmon study and our other study partners maintained acoustic receivers at nine monitoring sites (table 1), including at McNary and Bonneville Dams,

the Blue Bridge (Pioneer Memorial Bridge) that crosses the Columbia River as U.S. Route 395, and the Cable Bridge (Ed Hendler Bridge) that crosses the Columbia River as State Route 397. Both of these two bridges are near Kennewick, Pasco, and Richland (hereinafter, the "Tri-Cities"), Washington.

Lamprey Collection, Tagging, and Release

Juvenile Pacific Lamprey were collected at five locations and transported to the Chandler Juvenile Monitoring Facility (hereinafter "the Chandler facility") in Prosser, Washington, for tagging. 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 facilities. When juvenile lamprey were collected at these sites within a few days of our tagging date, we transported them to the Chandler facility. All study fish ideally 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 creeks and only tagged lamprey from the Columbia River dams when fish from these sources were limited.

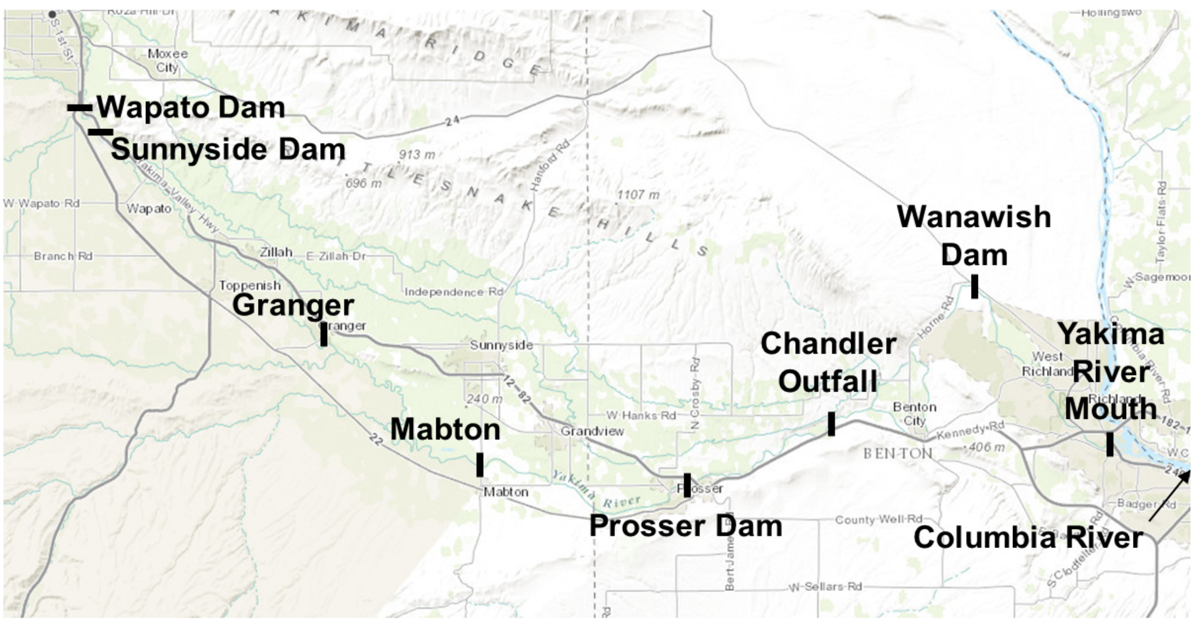

Figure 1. Schematic showing eight acoustic telemetry monitoring sites for juvenile Pacific Lamprey in the Yakima River, Washington, 2018. Monitoring sites on the Columbia River are shown in table 1.

Table 1. Acoustic telemetry monitoring sites (shown in Columbia River miles) for juvenile Pacific Lamprey in the Columbia River, Washington, 2018.

Monitoring site	Columbia River mile
Blue Bridge	329.5
Cable Bridge	327.9
McNary Dam forebay	292.7
McNary Dam tailrace	290.8
Crow Butte	262.2
Klickitat River mouth	179.9
Bonneville Dam forebay	146.0
Bonneville Dam tailrace	143.5
Camas	119.3

Acoustic transmitters were surgically implanted in the body cavity of juvenile lamprey using techniques described in Mesa and others (2012). Fish handling and aseptic techniques followed principles in Liedtke and others (2012). The prototype transmitter was 12 × 2 mm, weighed 80 mg, and had a 30-day battery life with a pulse rate interval of 5 seconds. The transmitter was developed to match the dimensions of a 12-mm Passive Integrated Transponder, which had been successfully implanted in juvenile lamprey (Mesa and others, 2012). A single experienced tagger was used for all study fish to minimize variability. Fish holding times prior to tagging were variable to allow fish collected over a short period (3–4 days) to be combined in a larger group. Fish were anesthetized individually in a solution of tricaine methanesulfonate (MS-222, 100–150 mg/L) buffered with an equal amount of sodium bicarbonate. When fish started to become unresponsive, they were removed from the anesthetic, weighed to the nearest 0.1 g, and measured to the nearest 1 mm. Each fish was then placed in 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. 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 between 90 and 110 percent. Water temperature in the transport tote was maintained within 2 °C of the recovery tank and river temperature at the release site.

Tagged lamprey were released at two locations. The upper release site was at the State Route 24 bridge, about 4.5 mi upstream of Wapato Dam. The lower release site was about 1.7 mi upstream of the Yakima River mouth. We decided to release tagged lamprey at both sites to manage the risk that the macrophthalmia released at the upper site might not reach the river mouth within the 30 days of transmitter life available. The upper release site allowed fish to be monitored within the Yakima River, and the lower release site was intended to increase the likelihood that some tagged fish would be detected at the monitoring sites at McNary Dam or

further downriver. We completed releases during daylight conditions at the lower release site and included both a daytime and a nighttime release for the upper release site to facilitate comparisons of lamprey movement behavior. 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 potential tagging effect, we did a controlled laboratory assessment using non-functional ("dummy") transmitters. The dummy tags were the same dimensions as the tags for the field evaluation, and all aspects of fish collection, holding, and tagging up to the time of release matched the field study procedures. When field study fish were loaded for transport to the release sites, dummy-tagged fish were moved to the Yakima Nation Prosser Hatchery (adjacent to the Chandler facility) and transferred to glass aquaria. Tagged and untagged lamprey were held for about 30 days to evaluate tagging or handling effects. As has been reported by other researchers (Mueller and others, 2006; Mesa and others, 2012), some held lamprey developed fungal infections. To better understand potential options for controlling fungal outbreaks, we tested anti-fungal treatments on both tagged and untagged lamprey. The methods and results of the laboratory evaluation are described in Beals and Lampman (2019).

Monitoring of Tagged Lamprey

Tagged juvenile lamprey were monitored as they moved through the Yakima and Columbia Rivers by a series of acoustic receivers deployed at selected monitoring sites. All monitoring sites were selected, installed, and maintained by our study partners for their own research objectives prior to the start of our pilot study. Our study used these existing sites to monitor tagged lamprey. The juvenile salmon study (USGS-Reclamation-YNF) had eight monitoring sites in the Yakima River (fig. 1) and two sites at bridges in the Columbia River in the Tri-Cities, Washington (table 1). Monitoring sites at McNary Dam, Crow Butte, Bonneville Dam, and Camas, Washington (table 1), were installed and maintained by PNNL. The monitoring site on the Columbia River at the mouth of the Klickitat River was maintained by USGS. Multiple acoustic receivers typically were deployed 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 a series of studies because all the study partners used the JSATS, which is required to detect the prototype lamprey transmitters. All detections of tagged lamprey were gathered, and we compiled a dataset that was reviewed and proofed for analyses.

Analyses

We calculated travel time, travel rate, and residence time at and between several detection sites throughout the study area. Travel time was calculated as the difference between the last detection at one site, or the time of release, and the first detection at another site. Travel rate was expressed as miles per day and was calculated by dividing the distance between sites by the travel time for an individual fish between those sites. Residence time was the time between the first and last detection of a lamprey at a given detection site. We present travel metrics at selected detection sites—five sites for the upper site releases and four sites for the lower site releases. These sites were selected based on the number of fish detected at that site (minimum of about 20 individuals) and their spatial separation (minimum of about 2 mi).

To evaluate lamprey movements relative to light and dark periods, we characterized the light condition at the time lamprey arrived at a series of detection sites. We defined four categories for light condition at time of arrival: (1) “light” began 30 minutes prior to sunrise, (2) “dark” began 30 minutes after sunset, (3) “a.m. low light” began 1 hour prior to the start of light, and (4) “p.m. low light” began 1 hour prior to the start of darkness. Using these categories, the dark condition excludes any transitional light periods.

Lamprey Compared to Passive Particle Travel Metrics

Passive particle travel times and rates were calculated from McNary to Bonneville Dams using data from the USACE (Douglas Baus, U.S. Army Corps of Engineers, written commun., December 2018). The USACE calculator required a flow input and generated a travel time and rate for a given reach. The mean daily discharge was determined for the dates on which lamprey were first and last detected at McNary and Bonneville Dams (May 10–26, 2018) and was used as the flow input to calculate passive particle travel times and rates. Particle travel times and rates were compared to lamprey travel times and rates, both as release groups and overall for all lamprey combined. The release groups moved through the McNary-to-Bonneville reach at different times within the period from May 10 to 26, but the flow conditions they experienced were similar. We compared the mean flow for each of the four release groups using the dates each group moved through the McNary-to-Bonneville reach. The means for the four groups had a maximum difference of 12,000 ft^3/s, or 2.5 percent. The mean daily discharge for all lamprey release groups combined was used for the particle travel time and rate calculations. The distance between the dams, used to calculate travel rates for both the particles and lamprey, was 145.3 river miles.

Lamprey travel times between McNary and Bonneville Dams were compared to the predicted passive particle travel times. At these large Columbia River dams, acoustic receivers were deployed in the forebay and tailraces to improve detection capability. Ideally, lamprey travel time would be calculated as the difference between the last time a fish was detected in the McNary Dam tailrace and the first time it was detected in the Bonneville Dam forebay. This approach is ideal because it eliminates any time incurred during dam passage. We detected 26 lamprey moving between these dams that could be compared with particle travel times. At Bonneville Dam, all 26 fish were detected in the dam forebay. At McNary Dam, however, only six fish were detected in the tailrace. Using the ideal approach, the limited detections at the McNary Dam tailrace would have allowed only six fish to be used for the comparison. To estimate the potential influence of using detections in the McNary Dam forebay, we calculated the passage time at the dam as the difference between the last detection in the forebay and the first detection in the tailrace. The maximum passage time was 2.8 hours for a group of 25 lamprey that had matching detections for which the calculation could be made. Over the course of the multi-day travel time between the dams, we considered the influence of passage time to be nominal, so we accepted McNary Dam forebay detections as valid for calculation of travel time from McNary to Bonneville Dams. In cases where both a forebay and a tailrace detection were available for an individual, the tailrace detection was used for the calculation to minimize the potential bias of passage time.

Night-Only Travel Scenario

To better understand diel lamprey movements, especially as they relate to the comparison with passive particle movement metrics, we calculated travel rates under an artificial scenario where we assumed that lamprey only traveled at night (hereinafter, “night-only travel scenario”). The night-only travel scenario assumed that lamprey only traveled during darkness, with a constant rate of travel, and stopped downstream movement during daylight periods. Our question for this scenario was how travel rates measured for the tagged lamprey in our study compared to the theoretical scenario. For this comparison, we used 26 lamprey that moved between McNary and Bonneville Dams—the same data used for the comparison with passive particle travel times and rates. We reviewed the time of last detection at McNary Dam and the time of first detection at Bonneville Dam and calculated, for each individual, the total hours of darkness and light available within this window. We defined dark to include both crepuscular periods, beginning 30 minutes prior to sunset and continuing until 30 minutes after sunrise. We used the length of the reach (145.3 river miles) and the total hours of darkness available for an individual to calculate a travel rate for the night-only travel scenario.

Results and Discussion

We completed four releases of tagged lamprey from May 9 to 15, 2018 (table 2). Two groups were released at the upper site and two groups were released at the lower site. The May 9 release at the upper release site was done at night to allow some comparison of fish behavior with the May 15 release at the upper site, which occurred during light conditions (table 2). Both releases at the lower site were done during light conditions.

River Environment

Environmental conditions in the Yakima River during our study generally were similar to the conditions during the 10-year period from 2008 to 2017. Overall, discharge during 2018 was typical of previous years, but our study activities in May occurred during the highest flows of the year (fig. 2). The May 9 and 10 releases occurred as flows were decreasing, between a peak flow on May 9 and a low flow on May 13 (fig. 3). Lamprey were released at 2130 hours on May 9, so their exposure to flow conditions began primarily on May 10. The May 15 releases were on an ascending limb of the hydrograph, with the peak flow for 2018 occurring on May 17 at 11,642 ft^3/s (fig. 3). Water temperatures in 2018 were about average relative to the previous 10 years (fig. 2). In May 2018, the mean Yakima River discharge was 8,053 ft^3/s (standard deviation [SD], 2,914 ft^3/s), and the mean water temperature was 14.6 °C (SD, 1.4 °C).

Table 2. Summary of acoustically tagged juvenile lamprey released at two sites on the Yakima River, Washington, May 2018.

[Upper site was at the State Route 24 bridge, about 4.5 miles upstream of Wapato Dam. Lower site was about 1.7 miles upstream of the Yakima River mouth]

Site	Date	Time (hours)	Number released	Number of active tags
Upper	May 9	2130	19	18
Lower	May 10	1326	24	19
Upper	May 15	1017	29	29
Lower	May 15	1328	25	25

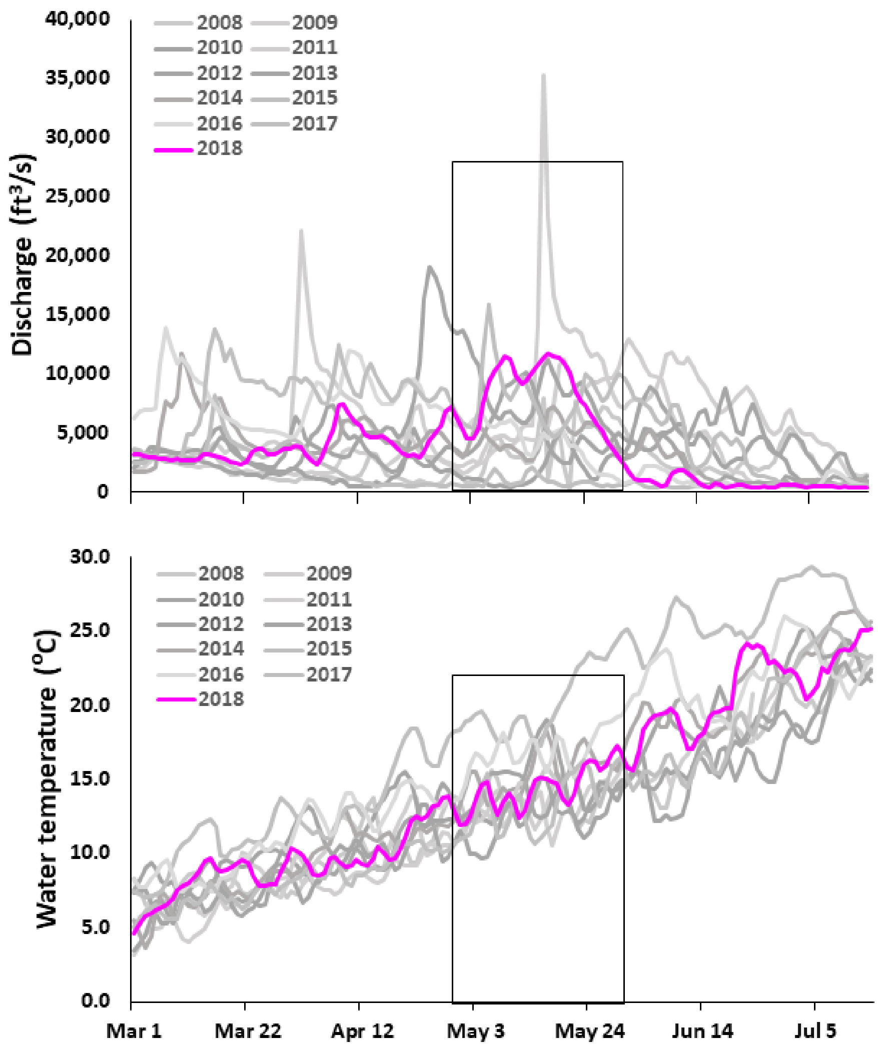

Figure 2. Graph showing discharge and water temperature in Yakima River, Washington, March–July 2018. Study period is shown in the boxed areas. ft^3/s, cubic foot per second; °C, degrees Celsius. Data from https://www.usbr.gov/pn/hydromet/.

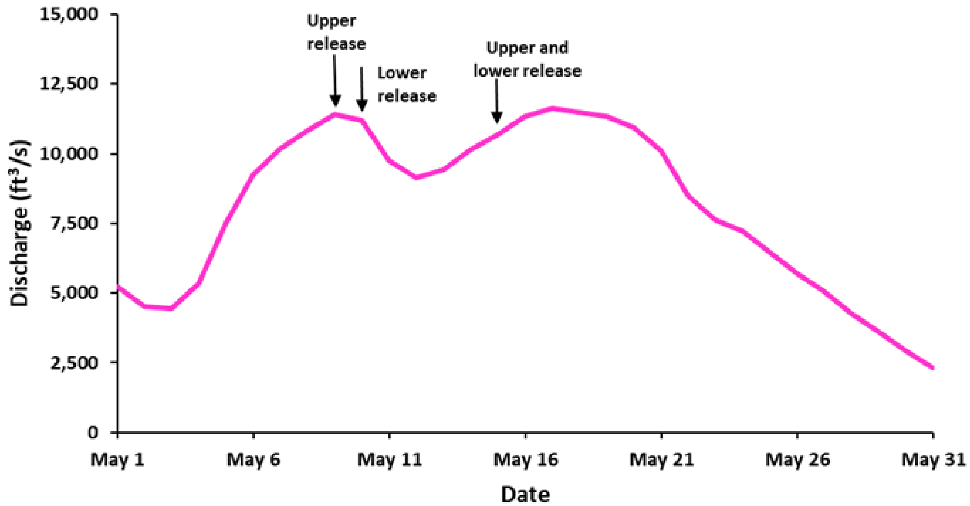

Figure 3. Graph showing releases of acoustically tagged juvenile lamprey (indicated with arrows) and discharge in Yakima River, Washington, May 2018. ft^3/s, cubic foot per second. Data from https://www.usbr.gov/pn/hydromet/.

In the Columbia River, we compared discharge and water temperature during May 2018 to the 10-year average for the reach between McNary and Bonneville Dams. The 2018 discharge in this reach was higher than the 10-year average on all dates in May (fig. 4), with an overall mean for May of 436,000 ft^3/s. Water temperatures in this reach were similar to the 10-year average and increased from McNary to Bonneville Dams (table 3).

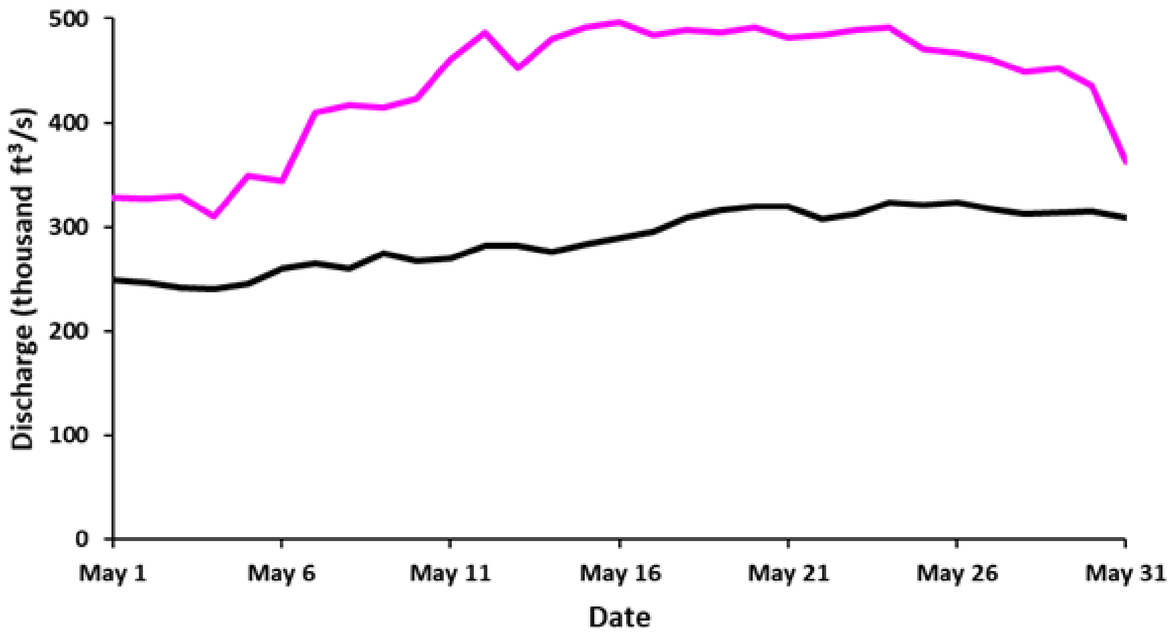

Figure 4. Graph showing mean daily discharge between McNary Dam tailrace and Bonneville Dam forebay, on the Columbia River, Washington, May 2018 (pink top line) compared to the 10-year (2008–17) mean for May (black bottom line). thousand ft^3/s, thousand cubic foot per second. Data from http://www.cbr.washington.edu/dart.

Table 3. Mean daily water temperatures for the Columbia River between McNary Dam and Bonneville Dams, on the Columbia River, for May 2018, and for May during the 10-year period, 2008–17.

[Data from http://www.cbr.washington.edu/dart. ±, plus or minus standard deviation]

Site	May 2018	May 2008–17
McNary Dam forebay	12.7±1.1	12.3±1.0
McNary Dam tailrace	12.7±1.2	12.4±1.0
John Day Dam forebay	12.7±1.1	12.3±1.0
John Day Dam tailrace	13.2±1.1	12.8±1.1
The Dalles Dam forebay	13.4±1.0	13.0±1.0
The Dalles Dam tailrace	13.4±1.1	13.0±1.0
Bonneville Dam forebay	13.5±1.1	13.0±1.1

Lamprey Collection, Tagging, and Release

We tagged and released 97 juvenile lamprey from May 9 to 15, 2018 (table 2). One juvenile Western River Lamprey (*Lampetra ayresii*), collected at the Chandler facility, was included with the May 15 release at the upper release site and all other study fish were Pacific Lamprey. One lamprey tagged on May 9 died prior to release but no other mortalities were observed. The overall mean total length for tagged lamprey was 150.0 mm and ranged from 138 to 176 mm (table 4). The overall mean weight for tagged lamprey was 4.6 g and ranged from 3.2 to 7.4 g (table 4). The mean transmitter burden (transmitter weight relative to body weight) was 1.7 percent and ranged from 1.1 to 2.5 percent. The Western River Lamprey was 154 mm long and weighed 3.5 g. The sizes of lamprey for each release group were similar (table 4).

Table 4. Juvenile lamprey total length and mass for groups of acoustically tagged fish released at two sites on the Yakima River, Washington, May 2018.

[Upper site was at the State Route 24 bridge, about 4.5 miles upstream of Wapato Dam. Lower site was about 1.7 miles upstream of the Yakima River mouth]

Site	Date	Length (millimeter)		Mass (gram)	
		Mean	Range	Mean	Range
Upper	May 9	147.4	138–173	4.3	3.2–6.4
Lower	May 10	149.3	139–164	4.7	3.6–6.5
Upper	May 15	150.6	140–176	4.6	3.5–7.4
Lower	May 15	150.6	139–164	4.7	3.7–6.5

Lamprey were collected for tagging from 3–4 sites for each tagging date (table 5). 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 tagging-release group. For the first release group, juvenile lamprey were collected from four sites and the mean holding time was 3.1 days. Two lamprey were held for 10 days, which was the maximum holding time for the group (table 5). When lamprey from this group were examined and handled for tagging, we noted that some fish showed evidence of an early fungal infection. Previous studies have reported that fungus commonly is an issue for juvenile lamprey (Mueller and others, 2006; Mesa and others, 2012). Of the 20 fish tagged, 9 (45 percent) showed some indication of fungus, ranging from a small area of fungus near the first dorsal fin to small white or clear dots on their body. The mean holding time for fish that had fungus was 5.9 days (maximum of 10 days), and the mean holding time for fish that showed no signs of fungus was 0.9 days (maximum of 4 days). We reviewed the detection records and travel metrics for the nine fish with fungus; noted few differences compared to the remainder of the release group; and, therefore, now present pooled (fungus and non-fungus) summaries for this release group. To limit the risk of fungal infections, future tagging sessions limited the pre-tag holding time to 4 days (table 5). None of the lamprey released on May 10 or 15 had signs of fungus. Overall, 49.4 percent of the study fish came from McNary Dam, 25.7 percent came from the Chandler facility, 14.4 percent came from John Day Dam, and about 5 percent each came from Ahtanum and Toppenish Creeks.

Six tagged fish were removed from the dataset because their tags were not detected in the recovery tank prior to release or at any monitoring station downstream. All analyses were done with the 91 tags that were confirmed to be functioning (table 2).

Table 5. Release sites and dates, collection sites and dates, and number of days fish were held prior to tagging for groups of acoustically tagged lamprey released at two sites on the Yakima River, Washington, May 2018.

[Upper site was at the State Route 24 bridge, about 4.5 miles upstream of Wapato Dam. Lower site was about 1.7 miles upstream of the Yakima River mouth]

Site	Release date	Tag date	Collection site	Number of fish	Collection date	Number of days held
Upper	May 9	May 8	Ahtanum Creek	4	May 8	0
	May 9	May 8	Chandler facility	1	April 29	9
	May 9	May 8	Chandler facility	5	May 7	1
	May 9	May 8	John Day Dam	1	April 28	10
	May 9	May 8	John Day Dam	3	May 4	4
	May 9	May 8	McNary Dam	1	April 28	10
	May 9	May 8	McNary Dam	1	May 1	7
	May 9	May 8	McNary Dam	2	May 5	3
	May 9	May 8	McNary Dam	1	May 7	1
Lower	May 10	May 9	Ahtanum Creek	1	May 9	0
	May 10	May 9	Chandler facility	10	May 9	0
	May 10	May 9	Toppenish Creek	5	May 9	0
	May 10	May 9	McNary Dam	8	May 9	0
Upper	May 15	May 14	Chandler facility	1	May 10	4
	May 15	May 14	Chandler facility	1	May 11	3
	May 15	May 14	Chandler facility	4	May 12	2
	May 15	May 14	John Day Dam	4	May 14	0
	May 15	May 14	McNary Dam	9	May 11	3
	May 15	May 14	McNary Dam	10	May 13	1
Lower	May 15	May 14	Chandler facility	2	May 10	4
	May 15	May 14	Chandler facility	1	May 12	2
	May 15	May 14	John Day Dam	6	May 14	0
	May 15	May 14	McNary Dam	16	May 13	1

Detection Summary

Overall, we detected a high proportion of tagged lamprey, with more individuals detected in the Columbia River than in the Yakima River (fig. 5). Of the 91 lamprey with confirmed functioning tags, we detected 87 (95.6 percent) on at least one acoustic telemetry receiver within our study area (table 6). Detections in the Yakima River were low overall, with most detections occurring at two locations. In the Columbia River, lamprey were detected at each of the nine monitoring sites, with the number of fish detections generally decreasing as lamprey moved downstream.

In the Yakima River, lamprey most commonly were detected in the Wanawish Dam forebay and at the river mouth. We released 47 lamprey at the upper site, and these fish potentially could have been detected on any of the monitoring sites in the Yakima River. Only 10 of these sites detected lamprey, most of them with low numbers of individuals (table 6). The site that detected the most lamprey was the Wanawish Dam forebay (38 lamprey, 80.9 percent). More than one-half (27 lamprey, 57.4 percent) of the fish from the upper release site were detected at the Yakima River mouth (table 6, fig. 5). The remaining sites in the Yakima River detected lamprey in low numbers, ranging from 1 to 12 individuals per site (table 6). Lamprey were not detected at 16 monitoring sites in the Yakima River (table 7). No lamprey were detected at monitoring sites downstream of irrigation canal fish diversion screens, including Wapato canal, Sunnyside canal, Prosser canal, and Wanawish West canal (table 7).

In the Columbia River, lamprey were detected most commonly at McNary Dam, Crow Butte, the Yakima River mouth, and Blue Bridge (table 6, fig. 5). These sites detected between 84.6 percent (McNary Dam) and 61.5 percent (Yakima River mouth and Blue Bridge) of the study fish. Small numbers of lamprey were detected at the Klickitat River mouth (five individuals), Bonneville Dam tailrace (1 individual), and Camas (2 individuals).

Lamprey released at the lower site were detected in higher proportions than lamprey released at the upper site. At all monitoring sites downstream of the lower release site, more individuals from the lower site were detected than from the upper site (fig. 5). The only exception was in the tailrace of Bonneville Dam, where only one lamprey was detected (table 6). All lamprey released at the lower site and 91.5 percent of all lamprey released at the upper site were detected somewhere in the study area (table 6). For fish released at the upper site, 100 percent of the May 9 release was detected, and 86.2 percent of the May 15 release was detected (table 6).

The Western River Lamprey released as part of our study was only detected in the forebay of Wapato Dam. It was released at the upper site on May 15 and was first detected in the dam forebay on June 3, 19.5 days after it was released. The last time we detected this lamprey was on June 5, 1.3 days after it had first been detected in the forebay. There were no other detections of this fish in our study area.

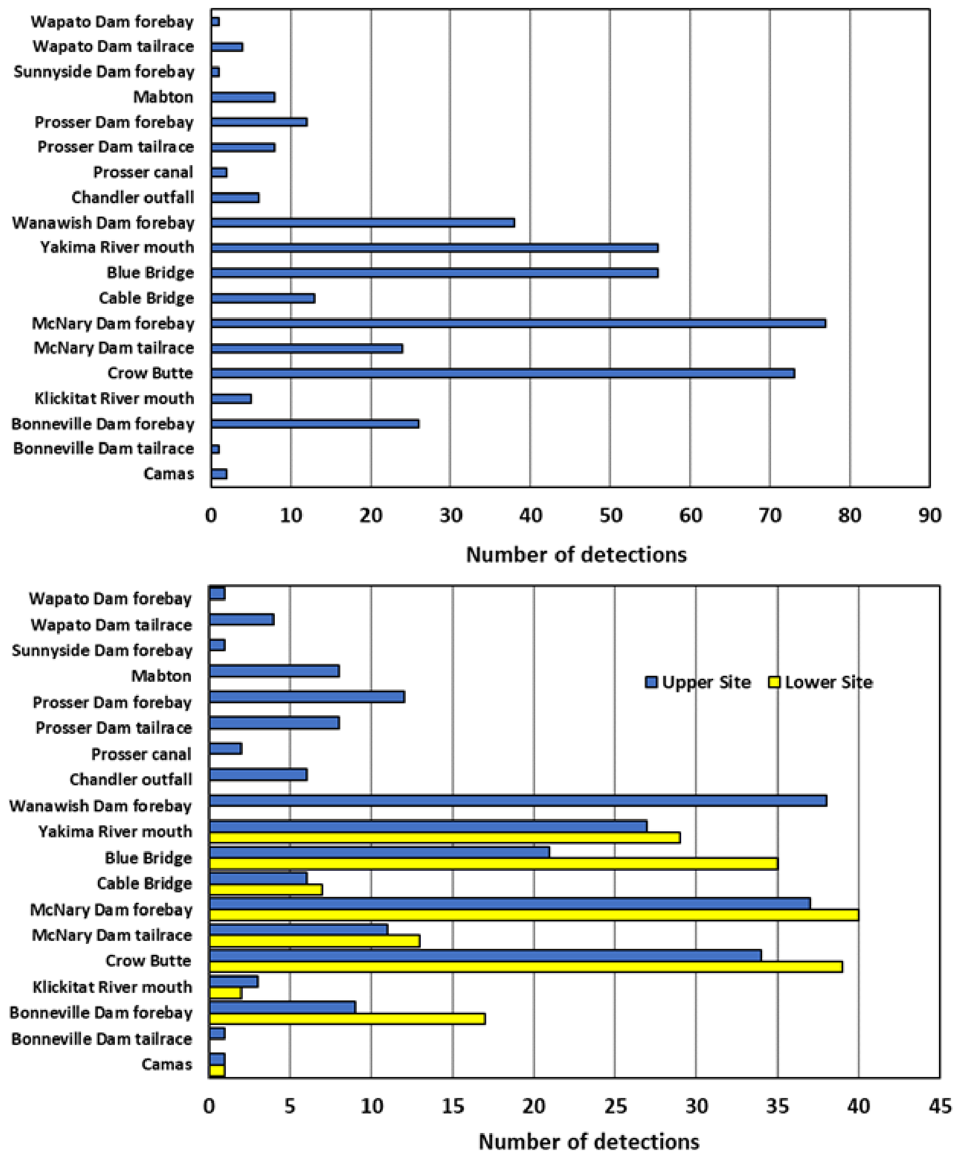

Figure 5. Graphs showing number of detections and sites where acoustically tagged juvenile lamprey were detected following release, Yakima and Columbia Rivers, Washington. Upper graph shows all releases combined and lower graph shows upper and lower sites separately. Bars represent number of individuals detected at each detection site.

Table 6. Monitoring sites where lamprey were detected in the Yakima and Columbia Rivers, by release site and date in 2018, for groups of acoustically tagged lamprey released at two sites on the Yakima River, May 2018.

[Upper site was at the State Route 24 bridge, about 4.5 miles upstream of Wapato Dam. Lower site was about 1.7 miles upstream of the Yakima River mouth. Total fish available for detection is the sum of lamprey released upstream of the monitoring site. Total number of individual lamprey detected and percentage of total available for detection (in parentheses) are presented for each release site and date, and overall. –, not applicable]

Monitoring site	Upper site May 9	Lower site May 10	Upper site May 15	Lower site May 15	Total detected	Total available for detection
Yakima River						
Wapato Dam forebay	0	–	1	–	1	47
Wapato Dam tailrace	3	–	1	–	4	47
Sunnyside Dam forebay	1	–	0	–	1	47
Mabton	3	–	5	–	8	47
Prosser Dam forebay	8	–	4	–	12	47
Prosser Dam tailrace	4	–	4	–	8	47
Prosser canal	1	–	1	–	2	47
Chandler outfall	3	–	3	–	6	47
Wanawish Dam forebay	16	–	22	–	38	47
Yakima River mouth	4	13	23	16	56	91
Columbia River						
Blue Bridge	12	18	9	17	56	91
Cable Bridge	3	5	3	2	13	91
McNary Dam forebay	16	16	21	24	77	91
McNary Dam tailrace	7	6	4	7	24	91
Crow Butte	13	15	21	24	73	91
Klickitat River mouth	1	0	2	2	5	91
Bonneville Dam forebay	2	6	7	11	26	91
Bonneville Dam tailrace	1	0	0	0	1	91
Camas	0	1	1	0	2	91
All sites combined (percentages in parentheses)						
All sites combined	18 (100)	19 (100)	25 (86.2)	25 (100)	87 (95.6)	–

Table 7. Monitoring sites where no acoustically tagged lamprey were detected in the Yakima River, Washington.

Monitoring site
Wapato canal
Wapato canal downstream of screens
Wapato bypass outlet
Wapato tailrace
Sunnyside tailrace
Sunnyside bypass outlet
Sunnyside canal
Sunnyside canal downstream of screens
Granger
Prosser bypass outlet
Prosser canal downstream of screens
Wanawish West canal
Wanawish West canal downstream of screens
Wanawish East canal
Wanawish tailrace
Wanawish bypass outlet

Travel Times, Travel Rates, and Residence Times

Travel times increased with increasing distance from the release sites, as expected, and some groups had large ranges, even with relatively large numbers of fish (table 8). For example, 29 individuals released at the lower site were detected at the Yakima River mouth with a mean travel time of 1.0 day. The range of travel times for these 29 fish was from 0.02 to 16.5 days, although the distance between sites was only 1.7 mi (table 8). Each release group generally had similar travel times to a detection site and the variability was due to a single fish or a few fish that moved much more quickly or slowly than the remainder of the group. For example, for the lower release site group detected at the Yakima River mouth, if the fish with the 16.5-day travel time is removed, the mean travel time for the group is 95.0 minutes instead of 1.0 day.

Lamprey arrived at Bonneville Dam in an average of 8.0–9.6 days from the upper site (about 300 river miles) and in an average of 6.4 days from the lower site (about 193 river miles). All lamprey detected at Bonneville Dam arrived within about 10–11 days (table 8). The shortest travel time to Bonneville Dam was 4.0 days for a lamprey released at the lower site (table 8).

Mean travel rates for groups of lamprey ranged from 23.7 to 38.8 mi/d (table 8). Individual lamprey traveled as slowly as 0.1 mi/d and as quickly as 72.5 mi/d. Like the travel times on which they were based, travel rates for a given group most commonly were very similar, with a few outliers. Considering the range of distances and flow conditions the different groups were exposed to, travel rates were consistently near 30 mi/d (table 8). The overall mean travel rate, pooled for all release groups and detection sites, was 31.4 mi/d.

Table 8. Travel time, travel rate, and residence time for groups of acoustically tagged lamprey released under dark (shaded rows) and light (unshaded rows) conditions from two release sites on the Yakima River, Washington, May 2018.

Release condition	Detection site	Distance from release site (miles)	Number of fish	Travel time (days)		Travel rate (miles per day)		Residence time minutes)	
				Mean	Range	Mean	Range	Mean	Range
Upper release site									
Dark	Wanawish Dam forebay	92.8	16	3.3	2.2–5.2	29.4	17.8–42.2	3.1	1.4–5.2
Light	Wanawish Dam forebay	92.8	22	3.0	1.5–4.5	32.7	20.5–61.1	2.2	0.3–3.3
Dark	Yakima River mouth	108.9	4	2.9	2.5–3.1	37.6	35.0–44.5	1.1	0.4–2.6
Light	Yakima River mouth	108.9	23	3.5		33.0	20.0–64.6	2.6	1.0–6.5
Dark	McNary Dam forebay	153.5	16	5.2	3.5–7.0	30.8	22.1–43.4	33.0	5.0–268.0
Light	McNary Dam forebay	153.5	21	4.6	2.7–6.8	34.4	22.5–56.1	11.0	5.0–32.0
Dark	Crow Butte	184.0	13	5.9	4.6–7.4	31.9	24.7–39.9	5.6	4.0–10.0
Light	Crow Butte	184.0	21	5.4	3.3–7.5	35.7	24.4–56.3	5.7	3.0–10.0
Dark	Bonneville Dam forebay	300.2	2	9.6	9.1–10.0	31.5	30.0–33.1	1.0	0.5–1.0
Light	Bonneville Dam forebay	300.2	7	8.0	6.2–10.9	38.8	27.4–48.7	1.1	0.5–2.0
Lower release site									
Light	Yakima River mouth	1.7	29	1.0	0.02–16.5	23.7	0.1–72.5	2.6	0.5–5.9
Light	McNary Dam forebay	46.3	40	1.7	0.9–5.4	30.7	8.6–50.3	13.5	6.0–69.0
Light	Crow Butte	76.7	39	3.5	1.4–26.4	30.1	2.9–54.0	28.1	3.0–884.0
Light	Bonneville Dam forebay	192.9	17	6.4	4.0–9.9	31.9	19.4–48.1	1.2	0.5–2.0

Residence times at detection sites were consistently low. Mean residence times for groups ranged from 1.0 to 33.0 minutes (table 8). The two highest mean residence times (33.0 and 28.1 minutes) were both influenced by a single fish in the group with exceptionally high residence time. One lamprey was resident at McNary Dam forebay for 4.5 hours (268 minutes) and another was resident at Crow Butte for 14.7 hours (884 minutes) (table 8). The next highest residence time we measured for any site was 69.0 minutes, and there were only 11 instances (of 270 total movements) of residence times longer than 20 minutes in the dataset. The overall mean residence time, pooled for all release groups and detection sites, was 10.6 minutes.

The two upper site releases, one during the day and one at night, showed some differences in movement metrics. Overall, travel times for upper site release groups differed more than residence times. There were five detection sites at which these groups could be compared, from Wanawish Dam to Bonneville Dam (table 8). The group released during the day had slightly faster mean travel times than the group released at night at 4 of the 5 detection sites (table 8). The magnitude of the difference was 0.3 days at Wanawish Dam and 1.6 days at Bonneville Dam, with the other detection sites falling between these extremes at 0.5–0.6 days (table 8). Residence times were short, and similar at 4 of the 5 detection sites (table 8). The highest residence times for both groups occurred at McNary Dam, where the night release group had a mean of 33.0 minutes and the day group had a mean of 11.0 minutes. The night release group had one fish with an extended residence time of 268 minutes. When that fish was excluded, the adjusted mean residence time for the night release group was 17.6 minutes, and the difference between the groups was 6.6 minutes. The group released at night, overall, had slower travel times at most detection sites and a slightly longer residence time at one site, compared to the group released during the day.

Light Condition at Time of Arrival at Detection Sites

Most lamprey arrived at detection sites during periods of darkness. Across all release groups and detection sites, 63.0 percent of lamprey arrivals occurred during darkness (table 9). The remainder of arrivals were 28.5 percent light, 3.3 percent a.m. low light, and 5.2 percent p.m. low light (table 9). Only 8.5 percent of lamprey arrivals occurred during the two transitional light conditions combined. The combination of release site and detection site resulted in 14 groups that were used to summarize light condition at time of arrival. Of these 14 groups, 11 groups arrived predominantly in the dark, and 3 groups arrived predominantly in the light (table 9). The detection sites where groups arrived predominantly in the light were the low reaches in our study area, at Crow Butte and Bonneville Dam. One group detected at Bonneville Dam was released at the lower site during the day and had predominantly night arrival for the Yakima River mouth, McNary Dam, and Crow Butte before arriving at Bonneville Dam primarily under light conditions (table 9). Both upper site release groups (one day and one night release) arrived predominantly under dark conditions at the Wanawish Dam forebay, 93 mi downstream of the release location (table 9). As lamprey moved downstream, both groups continued to arrive predominantly under dark conditions at the Yakima River mouth and at McNary Dam, although the numbers of individuals arriving under light and transitional light categories increased (table 9). At Crow Butte and Bonneville Dam the day release arrived predominantly under light conditions, and the night release arrived predominantly in the dark.

Table 9. Light condition at time of arrival for groups of acoustically tagged juvenile lamprey released under dark (shaded rows) and light (unshaded rows) conditions at two sites on the Yakima River, Washington, May 2018.

[–, not applicable]

Release condition	Detection site	Number of fish	Light condition at time of arrival					Change of light condition
			Dark	Low light (a.m.)	Light	Low light (p.m.)	Summary (percentage)	
Upper release site								
Dark	Wanawish Dam forebay	16	13	0	1	2	81.3 Dark	0
Light	Wanawish Dam forebay	22	20	0	0	2	90.9 Dark	0
Dark	Yakima River mouth	4	3	0	1	0	75.0 Dark	0
Light	Yakima River mouth	23	19	0	1	3	82.6 Dark	0
Dark	McNary Dam forebay	16	8	0	6	2	50.0 Dark	1
Light	McNary Dam forebay	21	15	1	5	0	71.4 Dark	1
Dark	Crow Butte	13	8	0	4	1	61.5 Dark	0
Light	Crow Butte	21	6	0	15	0	71.4 Light	0
Dark	Bonneville Dam forebay	2	2	0	0	0	100.0 Dark	0
Light	Bonneville Dam forebay	7	1	0	5	1	71.4 Light	0
Lower release site								
Light	Yakima River mouth	29	17	0	11	1	58.6 Dark	0
Light	McNary Dam forebay	40	28	2	10	0	70.0 Dark	0
Light	Crow Butte	39	26	5	7	1	66.7 Dark	4
Light	Bonneville Dam forebay	17	4	1	11	1	64.7 Light	0
Both release sites (percentages in parentheses)								
Light and dark	All sites combined	270	170 (63.0)	9 (3.3)	77 (28.5)	14 (5.2)	–	6 (2.2)

Lamprey released on two dates at the lower site had different light conditions on arrival at the Yakima River mouth, 1.7 mi downstream of the release site. The two releases occurred on May 10 and 15 at about 1330 hours (table 2). For the May 10 release, 13 lamprey were detected at the Yakima River mouth (table 6), and 10 of these fish (76.9 percent) arrived in less than 1 hour, under light conditions. The first lamprey to arrive was detected 33.2 minutes after release. Three lamprey had longer travel times; two were detected from 4 to 8.5 hours after release and one did not arrive for 16.5 days (table 8). For this group, most lamprey moved quickly downstream following release and arrived at the river mouth during daylight. For the second release, on May 15, 16 lamprey were detected at the Yakima River mouth (table 6), and the first fish to arrive had a travel time of 7 hours and arrived under p.m. low-light conditions. A total of 13 lamprey had travel times from 7 to 8.6 hours, with 12 of these lamprey arriving after dark (75 percent). Three lamprey had longer travel times, ranging from 2.3 to 2.4 days, all arriving after dark. For this group, most lamprey delayed downstream movement or moved more slowly, arriving at the river mouth about 6 hours later than the first release group, and in the dark. When the groups were pooled, the dominant light condition on arrival was dark (table 9), but the behavior of the fish seemed to be different between these releases. We have no evidence that the groups had different handling, tagging, or transport experiences. The May 15 release had lower flow conditions and warmer water temperature than the May 10 release, but the differences were nominal. Mean discharge was 11,176 ft^3/s on May 10 and 10,698 ft^3/s on May 15, a difference of 478 ft^3/s, or 4.4 percent. Water temperature was 13.7° C on May 10 and 15.1 °C on May 15, a difference of 1.4 °C.

Few lamprey experienced a change in light condition while they were resident at a detection site; that is, they moved into a detection area (first detection time) and out of the same detection area (last detection time) under the same light condition. Overall, across all release groups and detection sites, 2.2 percent of these movements (6 of 270) occurred across a change of light condition (table 9). The low incidence of these events likely was due to the consistently low residence times at detection sites. Short residence times, however, did not preclude a change of light, as 4 of the 6 events that had a change of light condition had residence times less than 18 minutes. These four fish arrived at Crow Butte (table 9) during a transitional light condition and were last detected at the light or dark condition that immediately followed. The remaining two events were in the McNary Dam forebay and had more extended residence times. One lamprey released at the upper site at night arrived at McNary Dam under p.m. low-light conditions, about 1 hour prior to full darkness, was resident for 4.5 hours, and was last detected under dark conditions. The final fish to experience a change of light condition was released at the upper site during the day, arrived at McNary Dam under a.m. low-light conditions, was resident for 32 minutes, and was last detected under full daylight.

We detected one lamprey that remained at a detection site through the full daylight period, apparently only moving downstream when it became dark. This lamprey was released on May 10 at the lower site and was detected at Crow Butte on May 13. It arrived early in the morning, about 30 minutes after daylight, remained resident at the site for 14.7 hours, and departed under p.m. low-light conditions, about 40 minutes prior to darkness. This extended residence time was the highest we recorded (table 8) and was fully within light or transitional light periods. This lamprey arrived at Crow Butte as the light was increasing and remained there until the light was decreasing. No other fish in the study had a similar profile.

Lamprey Compared to Passive Particle Travel Metrics

Overall, lamprey moved more slowly than passive particles in the reach between McNary and Bonneville Dams, but some individuals and one group exceeded particle travel rates. All four release groups experienced similar Columbia River flow conditions as they traveled between McNary and Bonneville dams (fig. 6). The difference in mean flow between the groups was a maximum of 12,000 ft^3/s, or 2.5 percent. The two releasees on May 15 had the highest mean flows and the May 10 release had the lowest mean flow (fig. 6). The predicted particle travel rate was 43.6 mi/d, which was faster than 3 of the 4 lamprey release groups as well as the overall lamprey travel rate for all groups combined (fig. 6). The May 15 upper site release group had a mean travel rate of 48.7 mi/d, which exceeded the particle travel rate. Overall, seven individual lamprey (27.0 percent) met or exceeded the particle travel rate, with travel rates ranging from 47.9 to 70.3 mi/d (fig. 6). However, the sample size for the overall group was 26 fish, and individual release groups had sample sizes ranging from 2 to 11 lamprey. Comparisons of individual release groups with particle travel rates should be interpreted cautiously.

The estimated particle travel time from McNary to Bonneville Dams was 3.3 days, and the mean travel time for the combined lamprey release groups was 4.4 days (fig. 6). The lamprey were, on average, 1.1 days slower in this reach than passive particles. The fastest lamprey group, from the upper release site on May 15, arrived at Bonneville Dam in a mean of 3.2 days. The seven lamprey that did not exceed particle travel time arrived between 7 and 30 minutes faster than the particles. The group with the longest travel time was the May 10 release, and it arrived with a mean of 4.9 days, lagging behind the particle time by 1.6 days.

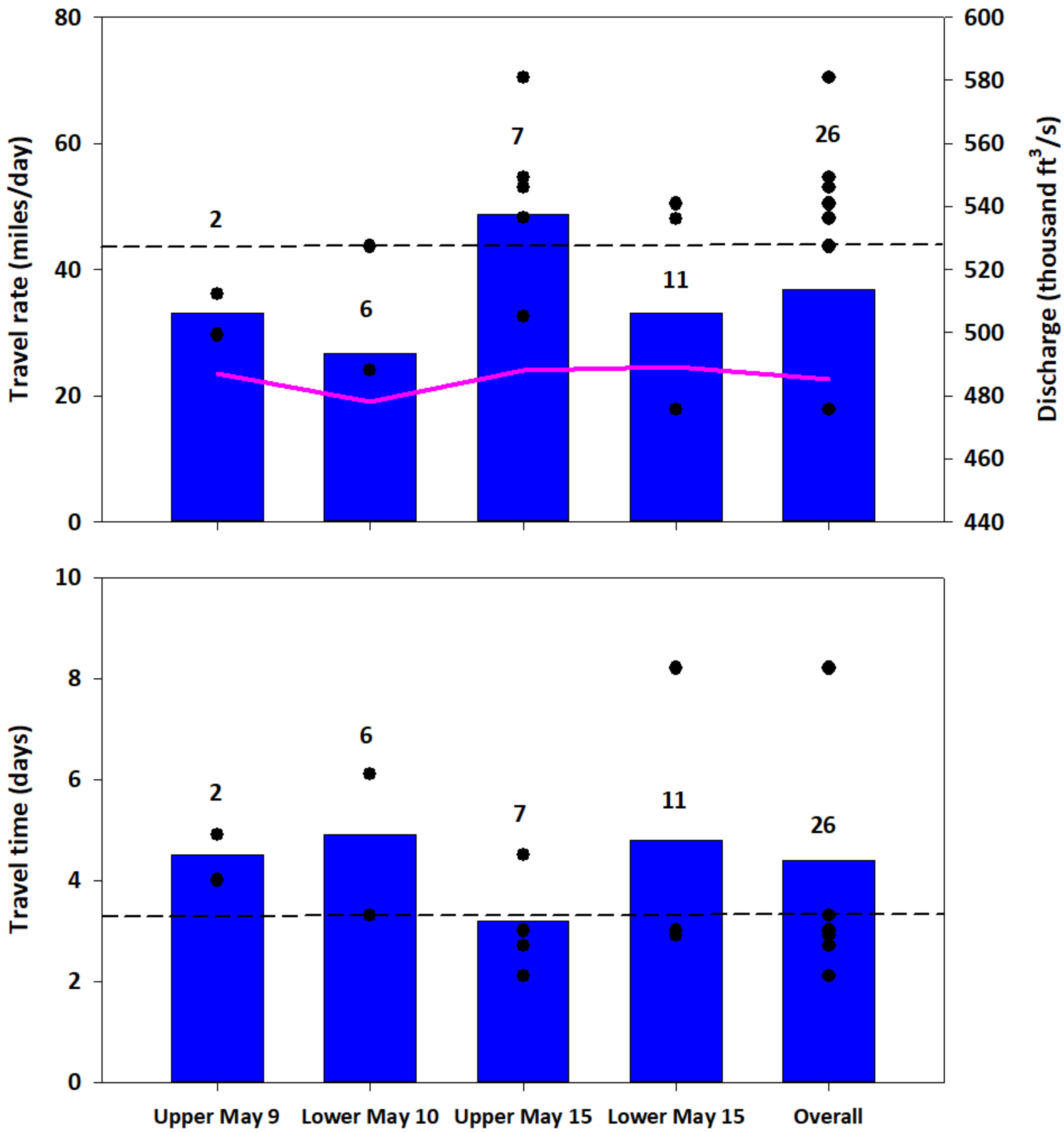

Figure 6. Graphs showing mean juvenile lamprey travel rates (in miles per day [miles/day]; upper graph) and travel times (in days; lower graph) between McNary and Bonneville Dams for four groups of fish released at two locations in the Yakima River, Washington, May 2018. Mean flow for each group and for overall (all groups pooled) is shown on the secondary axis (pink curved line). Passive particle travel rate and travel time are shown with a dashed line in each graph. Samples sizes for each bar are presented over the bar. Circles represent the minimum and maximum for each group and outliers. thousand ft^3/s, thousand cubic foot per second.

Night-Only Travel Scenario

Scenario Rationale and Approach

The findings from the comparison of lamprey travel times and rates with those of passive particles led to questions about lamprey movement strategies. Although studies of juvenile lamprey movements have been limited, it is assumed that lamprey prefer to travel at night and may have limited or no movements during daylight periods. Our summary of light condition at time of arrival at detection sites provides some support for this assumption as lamprey arrived predominantly under dark conditions. The detection data, however, provide snapshots of movement timing, with limited residence time spent near detection sites. A true picture of a travel pattern cannot be visualized with the detection data alone. For example, the detection data consist of the date and time that a lamprey arrived at and departed from McNary Dam, and the date and time that the same lamprey arrived at Bonneville Dam. Although we can calculate the travel time and rate and describe the light conditions at both detection sites while the lamprey was present, we lack any information about movements within the reach between the dams or whether the travel rate was steady or variable over time. The comparison of mean lamprey travel times with particle travel times showed that lamprey arrived at Bonneville Dam 1.1 days after passive particles would have arrived. This result could be explained by at least two potential movement scenarios: (1) lamprey moving nonstop through the reach, at an average rate less than the passive particle rate; or (2) lamprey moving at the particle rate or faster, but for a period less than the total travel time (that is, there are some periods of non-movement). Considering the assumption that lamprey tend to move only at night, and our finding that lamprey arrived at detection sites predominantly in the dark, we were interested in investigating the second scenario, where the non-movement periods occurred during daylight hours. To evaluate the night-only travel scenario, we used the 26 lamprey that moved between McNary and Bonneville Dams and divided their total travel time into periods of darkness and light. We divided the distance between the dams (145.3 river miles) by the total hours of darkness available to an individual fish to get the theoretical rate for the night-only travel scenario. This theoretical travel rate is assumed to be constant over the hours of darkness.

Scenario Summary

The theoretical travel rate generated under the night-only travel scenario was more than double the mean travel rate we measured for lamprey that moved between McNary and Bonneville Dams. The theoretical mean travel rate under the night-only travel scenario was 89.2 mi/d (range, 42.2–165.3 mi/d). The mean lamprey travel rate through the McNary-to-Bonneville reach, as measured during this study, was 36.7 mi/d (range, 17.7–70.3 mi/d). The highest travel rate we observed in this reach was 70.3 mi/d, and the highest rate we measured anywhere in our study area was 72.5 mi/d (table 8), both of which are 16–19 mi/d less than the mean rate for the scenario.

The mismatch between the theoretical travel rates and the observed travel rates has several possible explanations. One explanation is that lamprey traveled at least partially during daylight periods. There is some evidence for this based on the time of arrival at detection sites. Another explanation is an elevated nighttime travel rate, exceeding the observed overall travel rate. Our dataset cannot evaluate this potential explanation as our detection sites were widely separated and lamprey moved through several day-night cycles as they transited between the dams. This comparison ideally would be made in a study reach that lamprey could transit in a

short period (less than about 8 hours) so that daytime- or nighttime-specific travel rates could be estimated. Our 2018 pilot study was limited in this regard, but we expect that the 2019 evaluation will provide additional opportunities to describe juvenile lamprey migration behavior.

Lamprey movements likely are a combination of the two potential explanations. They likely travel at least somewhat during daylight (perhaps at a reduced rate or with periods of rest) and travel at higher rates at night.

Additional Discussion

This 2018 pilot acoustic telemetry study, done in a collaborative setting, provided valuable insights into the movements of juvenile Pacific Lamprey. We detected a high proportion of our study fish (95.6 percent), and three of the four release groups had 100 percent detection. Detections of lamprey in the Yakima River were limited at most sites, but larger groups of fish (15+) were detected at two sites, and these became the primary sites used for our summary and comparisons between groups. The detection arrays in the Yakima River were not designed to provide detailed passage route information for lamprey, but it was difficult to describe even broad patterns of routing such as potential entrainment into irrigation diversions owing to the limited detections at many sites. Large groups of lamprey were detected at several sites in the Columbia River, allowing us to define a series of reaches over which we could summarize lamprey travel behavior. Without the collaborative approach that allowed access to detection data from the arrays in the Columbia River, much less would have been learned. The combination of the detection sites in both the Yakima and the Columbia Rivers allowed us to more fully describe lamprey movements over a series of reaches and a wide range of distances. We estimate that our detections, especially in the Yakima River, could have been improved using a transmitter with a 3-second pulse rate interval, rather than the 5-second-interval transmitter that we used. We anticipate that a transmitter using a 3-second pulse rate interval will have a battery life of about 18 days. Nothing was known about the travel rate of juvenile lamprey to guide a decision on a pulse rate interval that might maximize detections and because we wanted to maximize transmitter life, we selected the 5-second pulse rate interval for the pilot study. Transmitter testing and development have advanced, and we now know that lamprey are capable of high movement rates, at least under the study conditions present in 2018, so future studies may benefit from a transmitter with a modified pulse rate interval.

Lamprey moved through our study area at an average rate of 30–35 mi/d and generally remained at each detection site for less than about 20 minutes. Groups of lamprey showed variability, but the common trend was for most fish in a group to have very similar travel rates or residence times, and 1–2 fish in the group to have very different movement patterns with much longer or shorter rates or times. For our dataset, river conditions (flow and water temperature) do not seem a likely driver of this difference in behavior because all lamprey in a group typically moved through our study reaches within a day or so of the rest of the group and river conditions were relatively stable over that interval. Perhaps the differences we observed are similar to the findings of Deng and others (2018) that small numbers of their study fish did not seem to be disposed to move downstream following release. With few studies of juvenile lamprey movements, little was known about their travel rates. Deng and others (2018) used the same transmitter in a field test in the Columbia River and reported median travel rates from 43.2 to 69.6 mi/d over a 7-km study area. Our study groups traveled from 2 to 300 river miles (3.3–482.8 km) and had mean travel rates from about 30 to 39 mi/d. The maximum travel rates we observed ranged from about 40 to about 73 mi/d, and compare well with Deng and others (2018).

The residence times at our detection sites were consistently low (most commonly 1–3 minutes), suggesting that lamprey moved directly past these sites without delay. Residence times may have been influenced by the limited detection range for this tag, estimated at 80–140 m (Deng and others, 2018) if the lamprey was near the detection site, but out of detection range.

Passive particle travel rates exceeded lamprey travel rates for most groups that traveled between McNary and Bonneville Dams. The mean travel rate for all the release groups combined was about 7 mi/d slower than the particle travel rate, but one of the release groups exceeded the particle rate by about 5 mi/d. Expressed as travel time, particles made the trip in 3.3 days, and the pooled lamprey groups took 4.4 days. The fastest lamprey group arrived in 3.2 days, just slightly faster than the particle travel time. We made this comparison because the lamprey travel rates we observed were high, and lamprey are not strong swimmers (Moursund and others, 2000; Moser and others, 2015), so our hypothesis was that they might be traveling with the bulk flow, either by choice or because it was so powerful that they could not resist. The results suggest that lamprey are not moving passively with the bulk flow through the entire reach. They may match or exceed particle travel rates at times and then have periods of non-travel, or they may be traveling at reduced rates throughout the reach. The passive particle travel rates were generated using data from the USACE that were developed to help manage the hydropower system. Although the particle travel rate information was useful and interesting, it may not accurately predict the flow conditions experienced by juvenile lamprey. We are likely to learn a lot more in the coming years about the depth profiles of migrating juvenile lamprey now that we can monitor their movements with telemetry, but from what is currently known, lamprey seem to be deeper in the water column than juvenile salmonids. Without an air bladder, juvenile lamprey tend to sink unless they are actively swimming. Additionally, they show a strong affinity to be attached to substrate during daylight hours (Moursund and others, 2000). Mesa and others (2015) summarized juvenile lamprey migration and passage findings in the Columbia and Snake Rivers and reported that very few juvenile lamprey would be routed into juvenile bypass systems and were much more likely to be entrained into turbines because they approached the dams deeper than juvenile salmon. Deng and others (2018) did field testing with the lamprey-eel transmitter and reported a median depth of 8.5 m for juvenile lamprey. The particle travel rates are based primarily on surface water, and since lamprey tend to be deeper in the water column and are likely to be spending time attached to hard substrates on the bottom of the river, lamprey likely experience different flow conditions.

Lamprey arrived at detection sites predominantly during the dark, but we also found evidence that some travel occurred during daylight and transitional light periods. Our detection sites were widely separated, lamprey needed 1 day or more to transit between them (several day-night cycles), and they did not remain near our sites for more than about 20 minutes. Our detection records, therefore, give us a simplified view of lamprey movements between detection sites. If lamprey had extended residence times at our sites, we could compare the fraction of the resident time that was light and dark to learn when movements were initiated and terminated. Lacking extended residence times, we summarized the light condition at the time lamprey were first detected at our sites to learn more about their diel movements. Overall, about 63 percent of lamprey arrival times at detection sites were in the dark, about 29 percent were during daylight, and about 9 percent were during transitional light periods. Considering that in May, each 24-hour period is composed of 60–65 percent light (based on the light categories we defined), the high proportion of night arrivals for juvenile lamprey supports the premise that they tend to travel after dark. Goodman and others (2015) also reported that most macrophthalmia moved at night

and in the early morning hours, especially associated with high-flow events. These authors suggest that turbidity associated with high-flow events effectively extends the low-light conditions lamprey prefer for movement (Goodman and others, 2015). We looked at lamprey movement rates under the night-only travel scenario. The scenario showed that lamprey would have required travel rates faster than any travel rate we measured during our study. Based on the difference between theoretical and observed travel rates, we concluded that the night-only travel scenario was not a good fit to our data, and that lamprey likely completed some travel during daylight hours or moved at higher rates than the observed rate during darkness. Lamprey are primarily nocturnal, and Moursund and others (2000) estimated that more than 90 percent of juvenile lamprey activity occurred during dark periods. These authors also noted that during laboratory studies, juvenile lamprey had a strong affinity for the substrate or the bottom of the tank during daylight hours (Moursund and others, 2000). Although they show a preference for activity at night, juvenile lamprey do not swim continuously throughout dark periods but stop intermittently and attach to substrates (Moser and others, 2015). In laboratory studies, about 15 percent of macrophthalmia remained attached throughout a 12-hour dark period (Moursund and others, 2000). We saw similar variability in our dataset, with a preference for movements at night, but evidence that some lamprey were actively moving during the daylight hours.

Our 2018 pilot study generated new data on juvenile lamprey travel rates and diel movement patterns in the Yakima and Columbia Rivers, and helped address critical information gaps for this life stage. The project is scheduled to do a similar field study in 2019 and 2020, continuing the partnership with the lower Yakima River juvenile salmon study. One of the goals of our pilot study was to improve our understanding of how to best conduct a telemetry study of juvenile lamprey to guide future field efforts. We plan to use a transmitter with a shorter (3-second) pulse rate interval in 2019 to improve our ability to detect lamprey at sites in the Yakima River. Additional detections will help us to describe routes that lamprey use to move around or through dams, irrigation diversions, or barriers. We hope that additional detections will also allow more detailed descriptions of daytime- and nighttime-specific travel rates. For the pilot study, we explored the option to collect fish from various sources and hold them until there were enough fish for a rigorous release group. We found some fish with fungus, likely attributable to extended holding. For 2019, we plan to limit pre-tag holding to a maximum of 4 days, at which we did not observe negative effects in 2018. Ideally, if enough fish are available, we would tag fish the day they were collected to control the risk of fungal infections. Only the upper release site will be used in 2019 so that all study fish will have the potential to be detected at the monitoring arrays in the Yakima River. We expect that 2019 will have different environmental conditions and, therefore, will be a useful addition to the 2018 pilot study.

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Appendix B

Monitoring the Movements of Juvenile Pacific Lamprey (Entosphenus tridentatus) in the Yakima River, Washington Using Acoustic Telemetry, 2019-20, USGS Open-File Report 2022–1052

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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

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Open-File Report 2022–1052

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

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

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

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

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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

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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.

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

[1]U.S. Geological Survey

[2]Yakama Nation Fisheries

[3]Bureau of Reclamation

[4]Pacific Northwest National Laboratory

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.

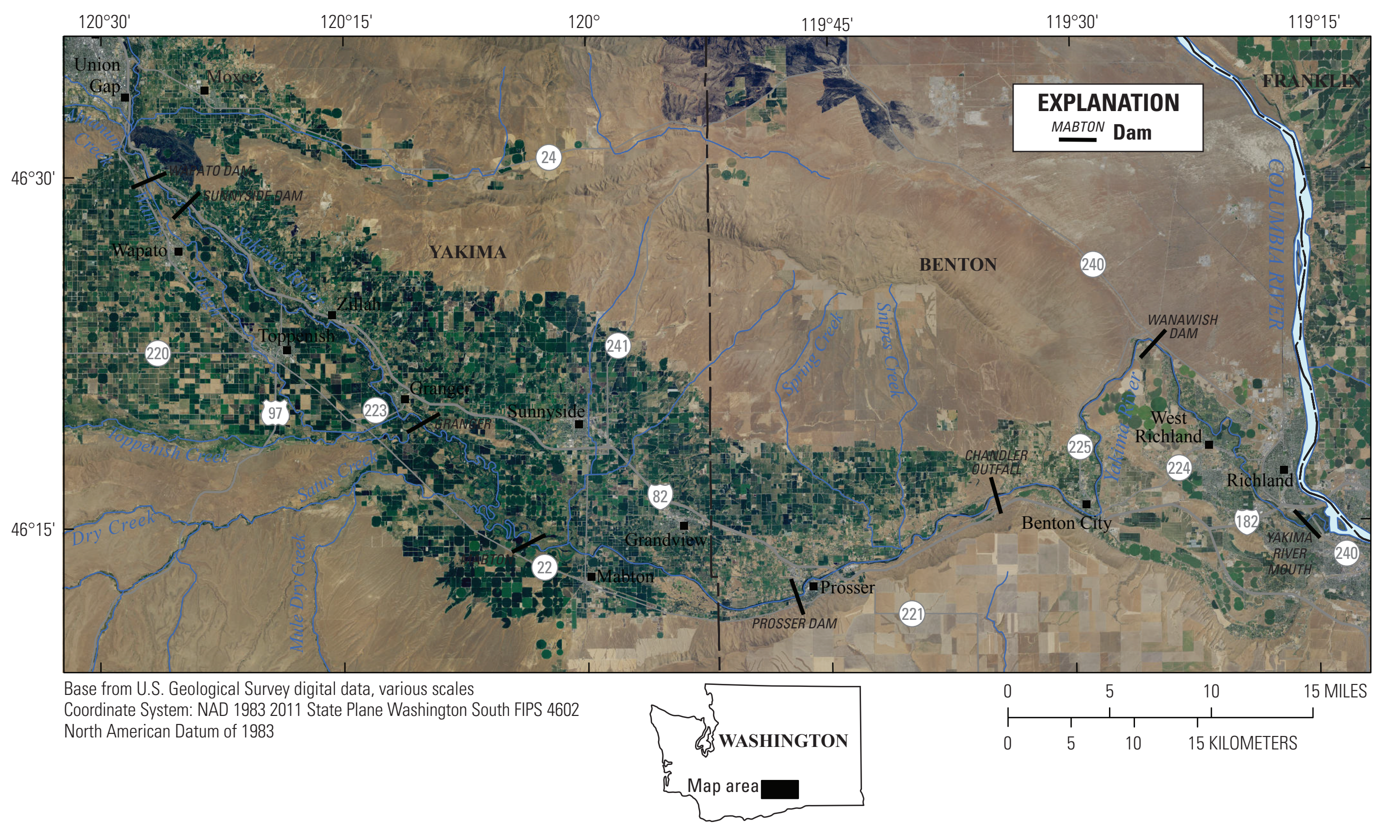

Figure 1. Eight acoustic telemetry monitoring sites (indicated by black lines, perpendicular to the river) for juvenile Pacific Lamprey in the Yakima River, Washington, 2019 and 2020.

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).

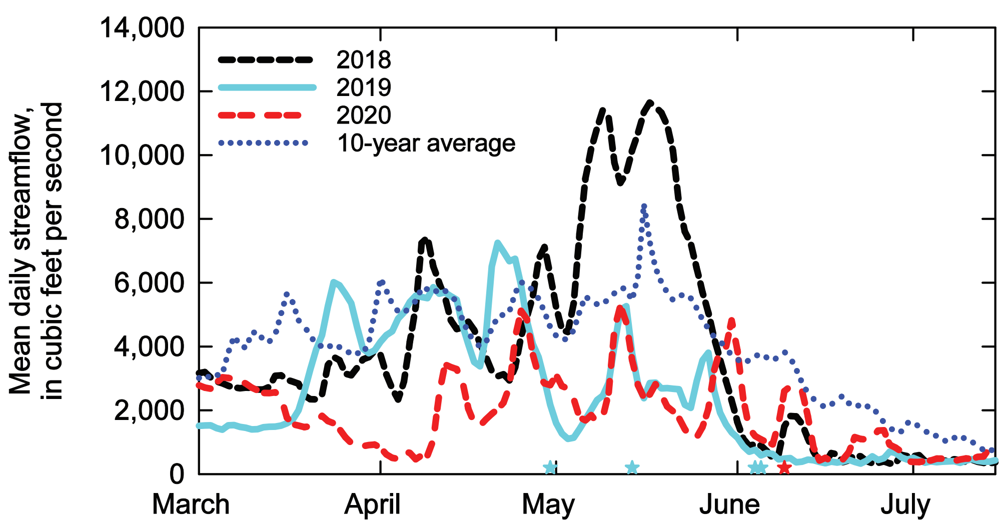

Figure 3. Mean daily streamflow in the Yakima River, Washington, in 2018, 2019, and 2020 and the 10-year average (2011–20; Bureau of Reclamation, 2021b). Colored stars indicate acoustically tagged Pacific Lamprey release dates by year.

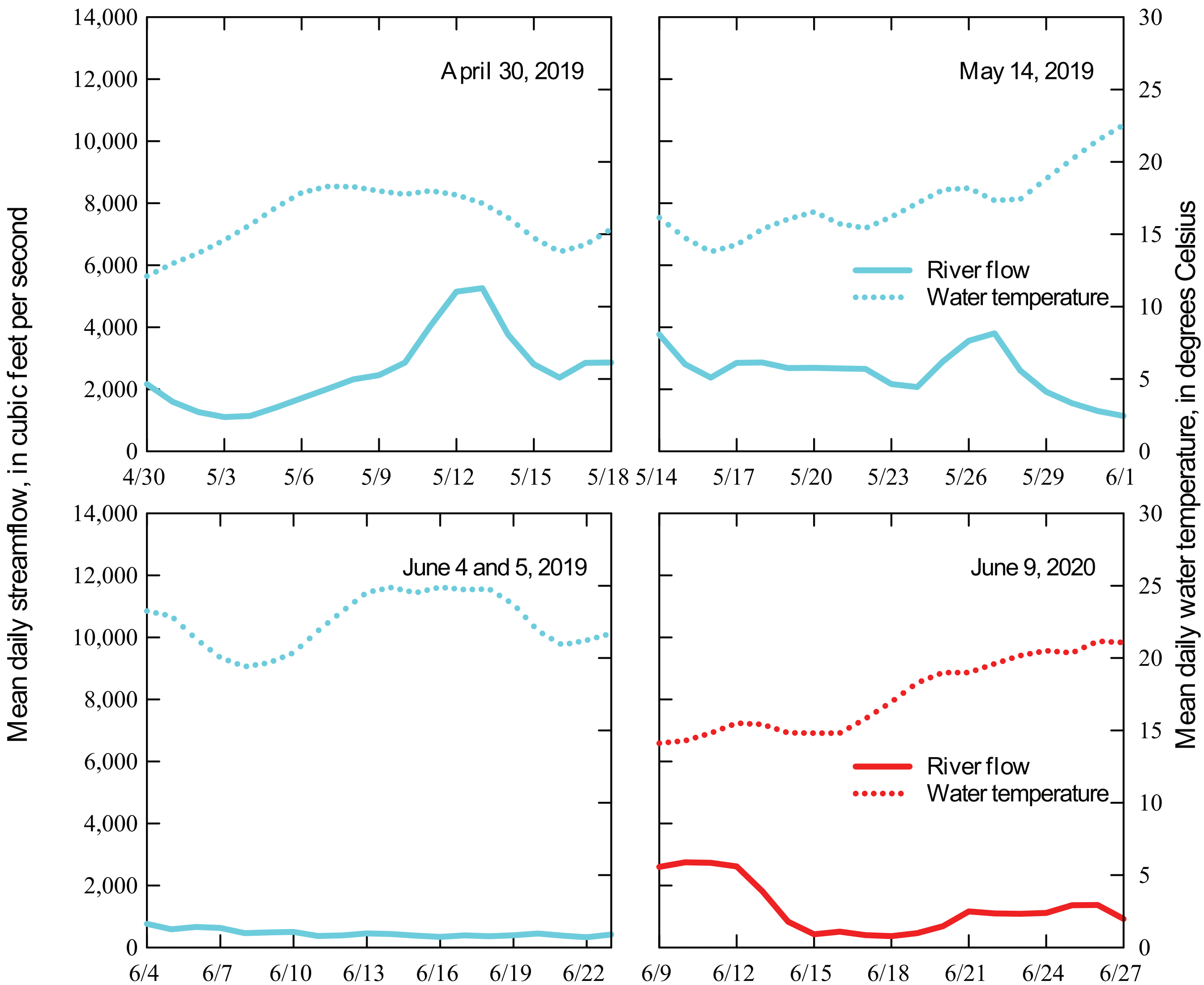

Figure 4. Mean daily streamflow and mean daily water temperature in the Yakima River, Washington, in 2019 and 2020 (Bureau of Reclamation, 2021a, 2021b). Each graph describes conditions for one lamprey release, indicated by the date in the upper right-hand corner. Blue lines represent 2019 conditions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

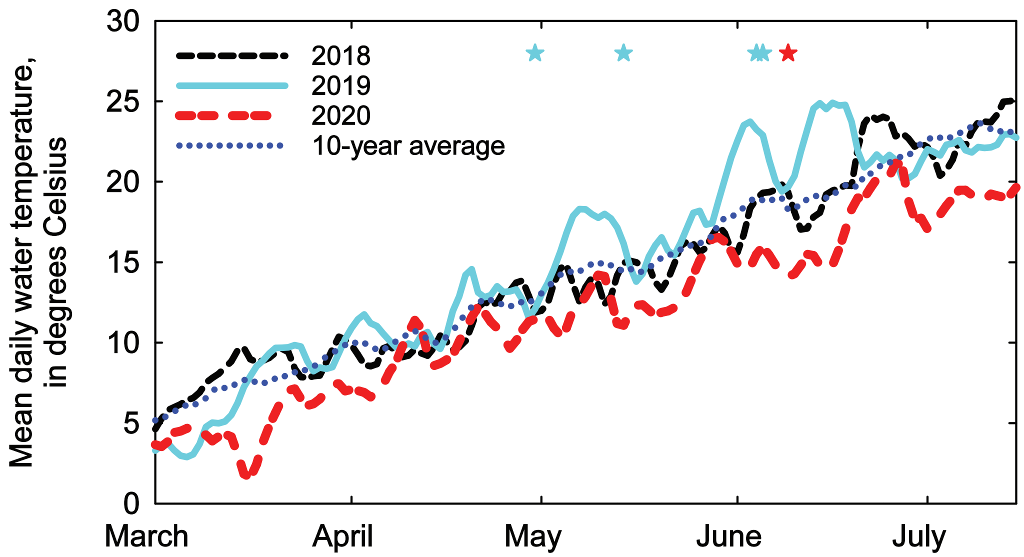

Figure 5. Mean daily water temperature in the Yakima River, Washington, in 2018, 2019, and 2020, and the 10-year average (2011–20; Bureau of Reclamation, 2021a). Colored stars indicate acoustically tagged Pacific Lamprey release dates by year.

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

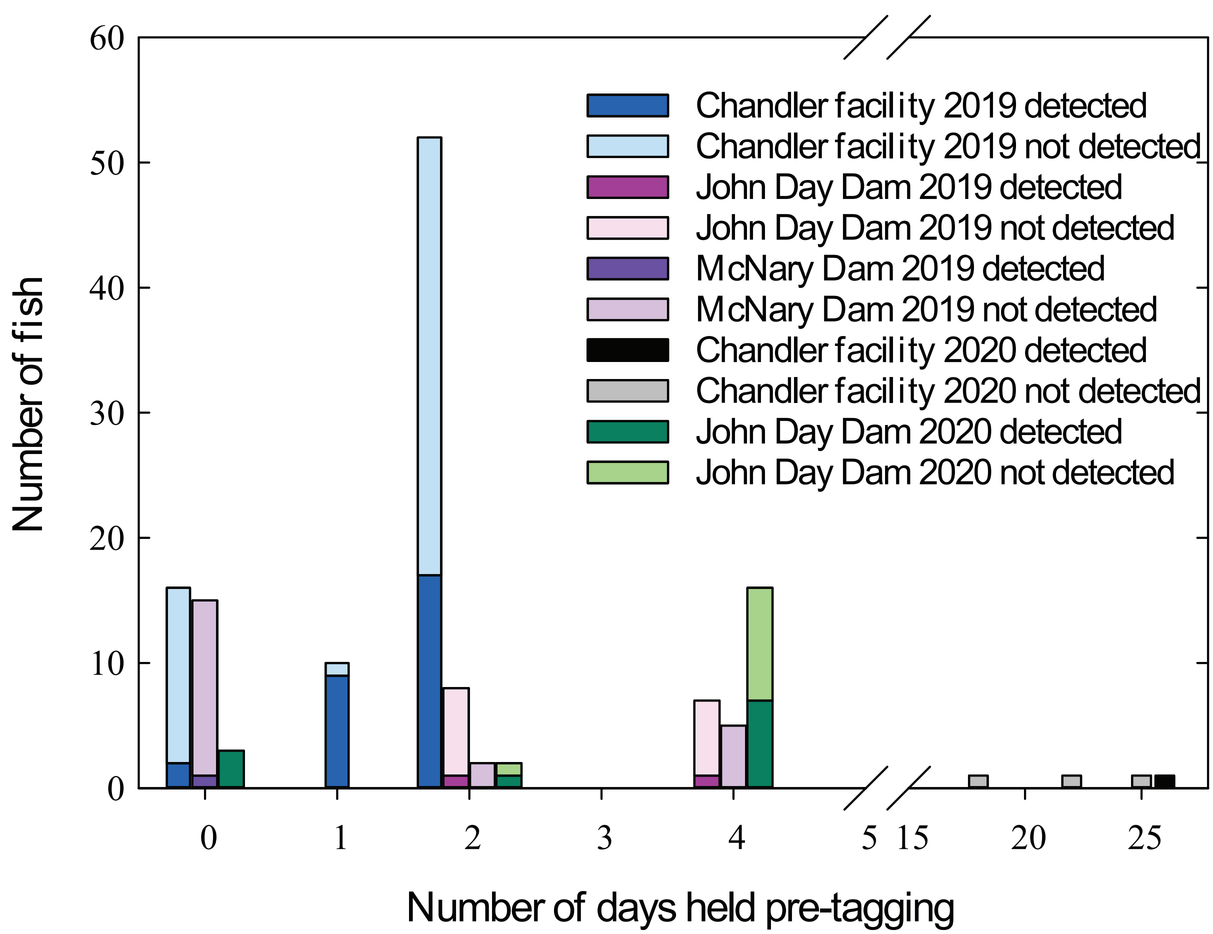

Figure 6. Acoustically tagged juvenile Pacific Lamprey in the study area, detected and not detected, by collection site and number of days held prior to tagging and release into the Yakima River, Washington, 2019 and 2020. Euthanized fish were omitted from this graph.

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).

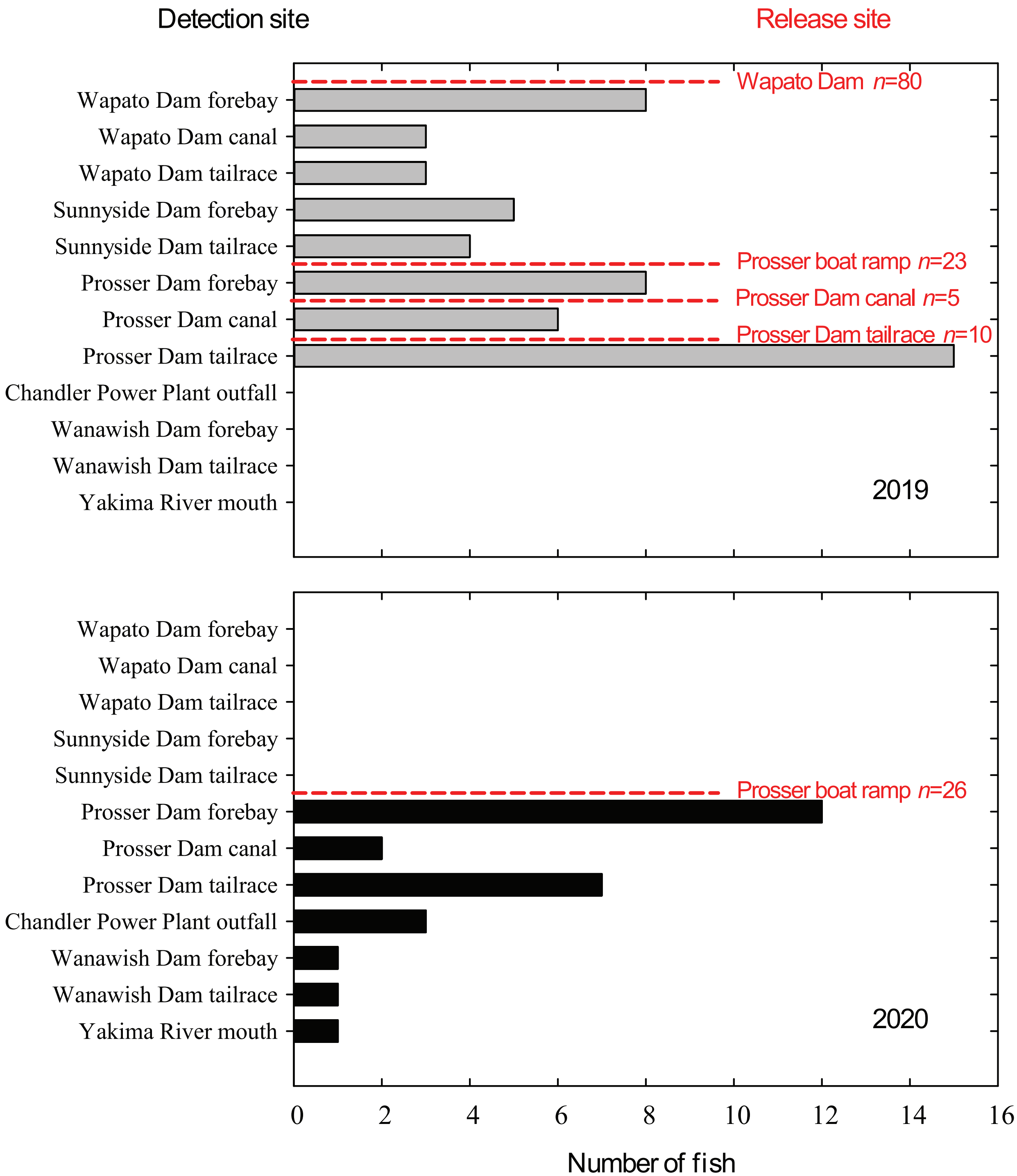

Figure 7. Number of fish and sites where acoustically tagged juvenile Pacific Lamprey were detected following release in the Yakima River, Washington, 2019 and 2020. *n*, number of tagged lamprey released.

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

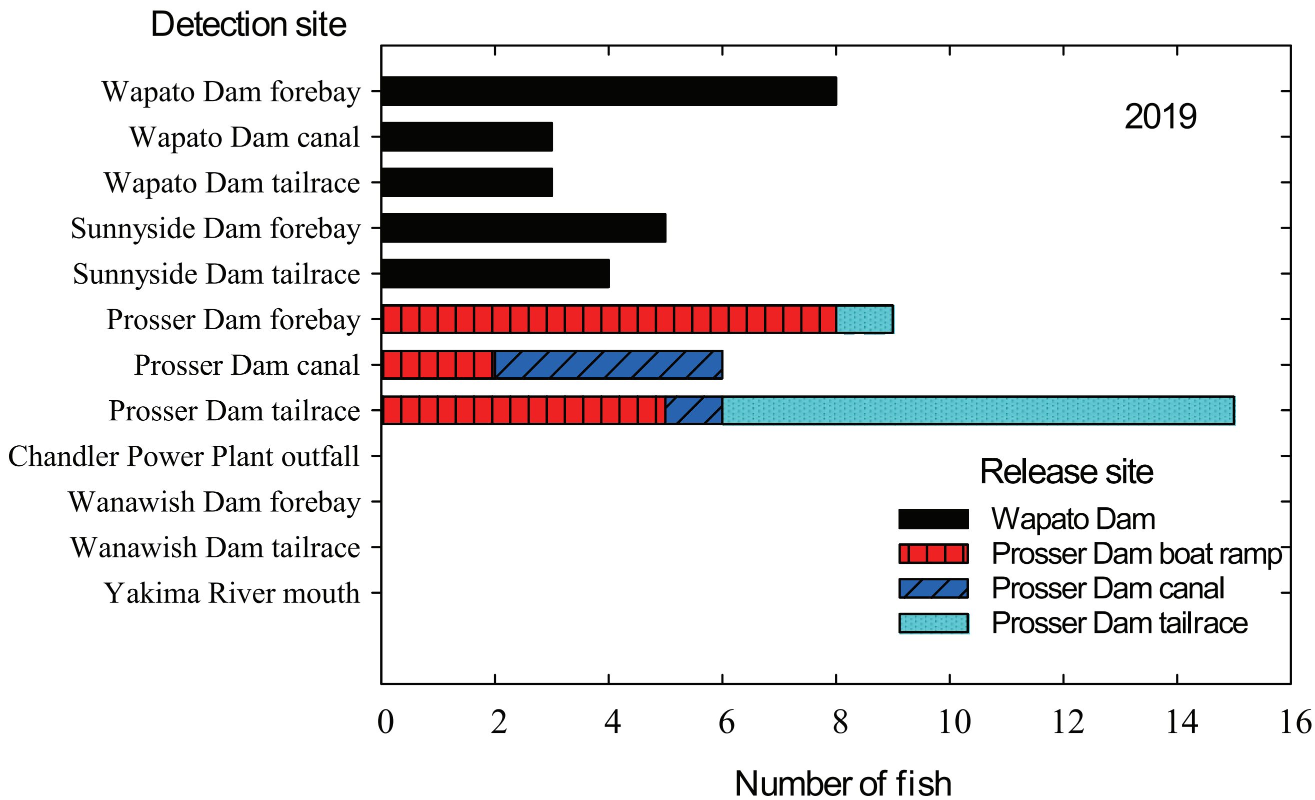

Figure 8. Number of fish and sites where acoustically tagged juvenile Pacific Lamprey were detected following release, by release location, in the Yakima River, Washington, 2019. All 2020 study fish were released at a single location and are not shown.

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

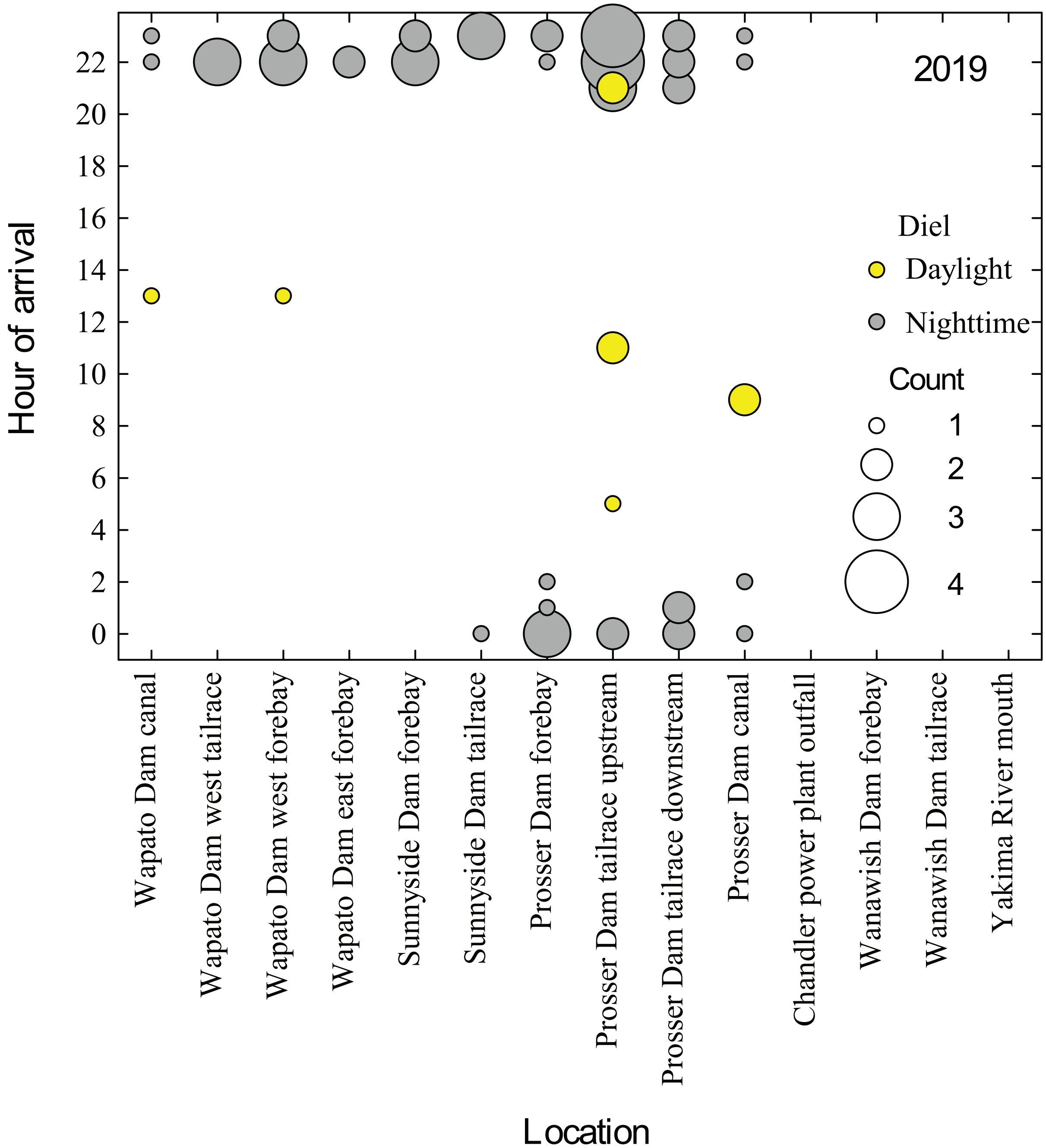

Figure 9. Hour of acoustically tagged juvenile Pacific Lamprey arrival at each acoustic telemetry site in the Yakima River, Washington, 2019. Diel period is defined by civil twilight and the size of circles is proportional to the number of fish represented in each value.

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

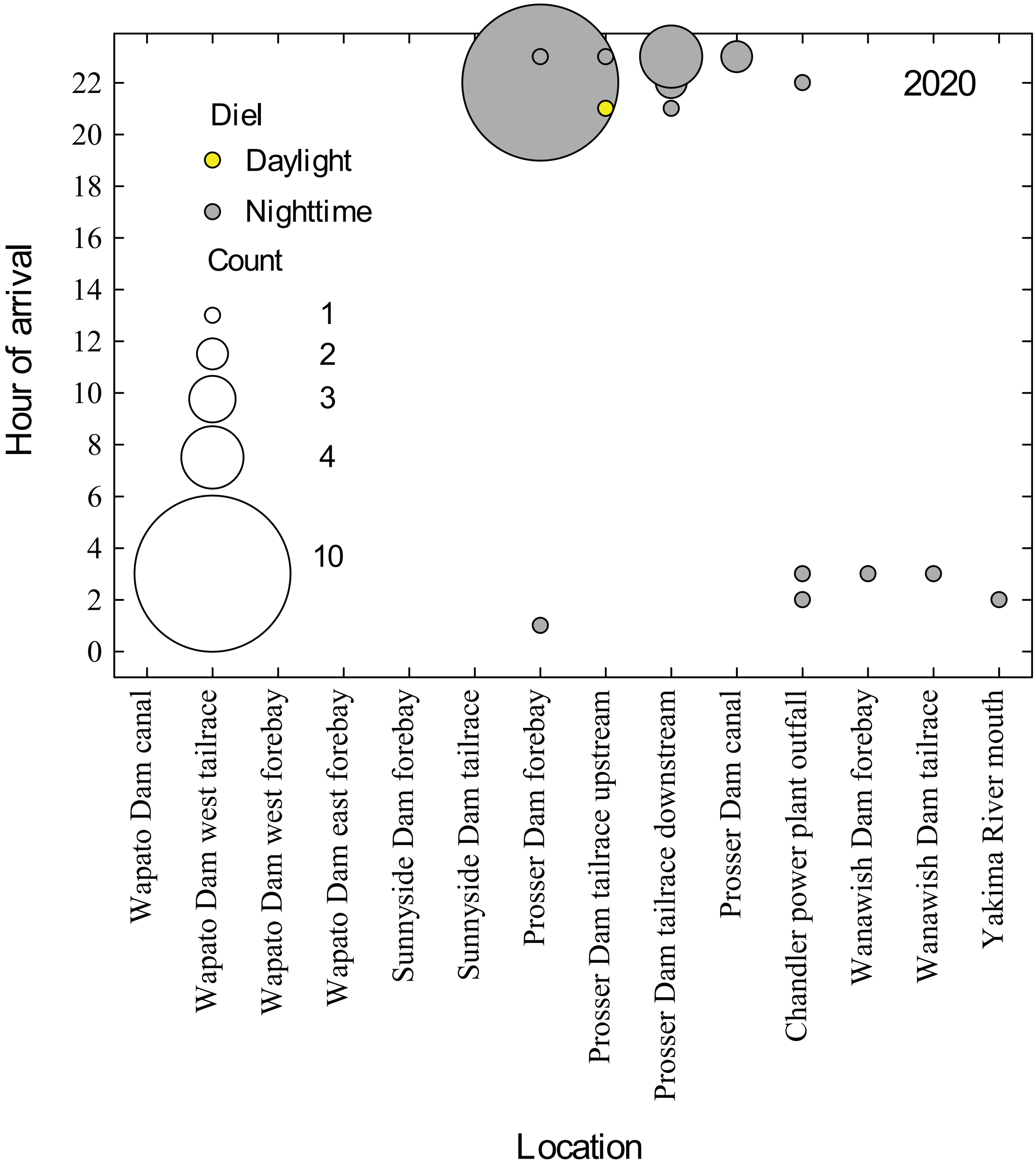

Figure 10. Hour of acoustically tagged juvenile Pacific Lamprey arrival at each acoustic telemetry site in the Yakima River, Washington, 2020. Diel period is defined by civil twilight and the size of circles is proportional to the number of fish represented in each value.

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).

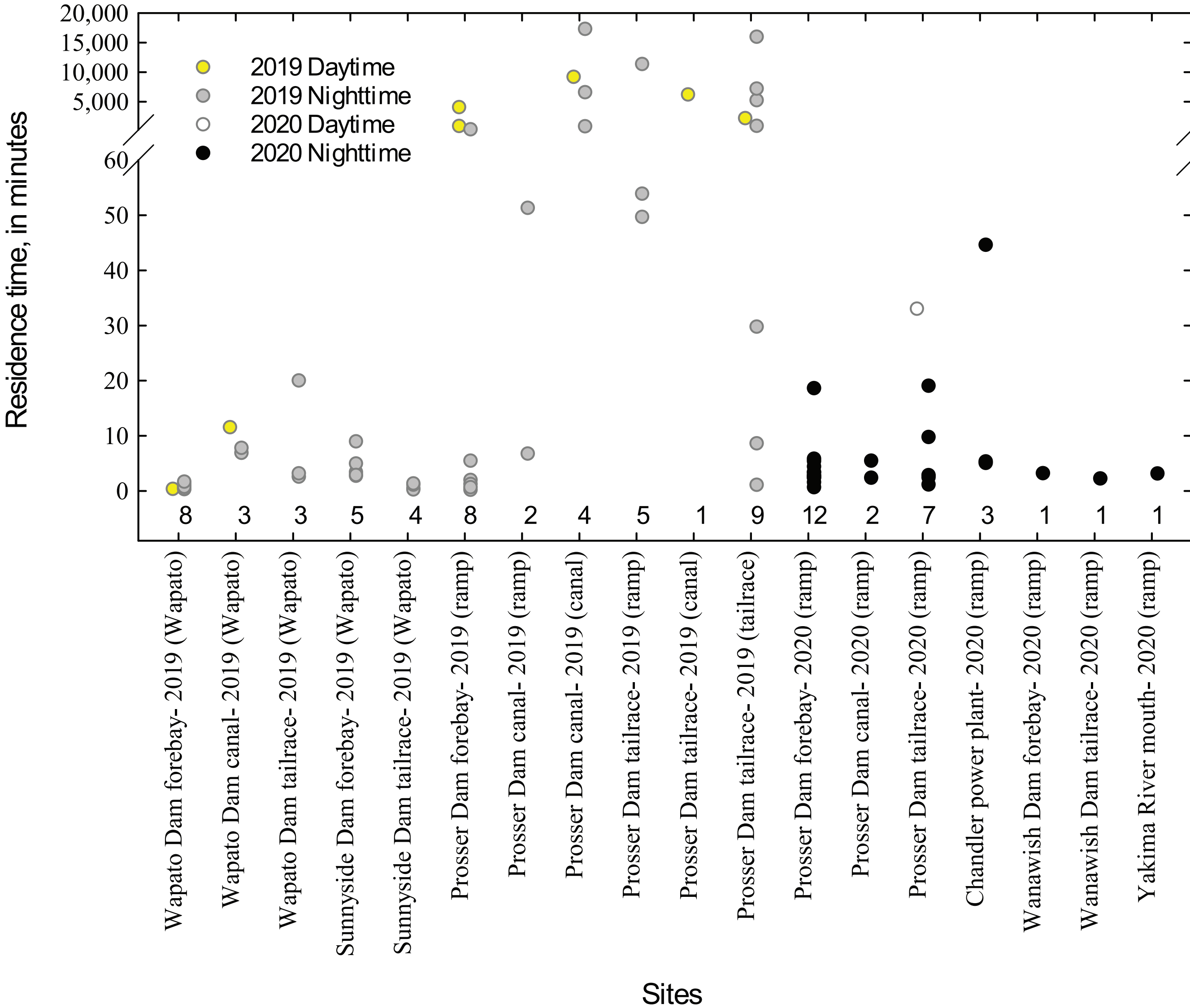

Figure 11. Residence time by diel arrival period for acoustically tagged juvenile Pacific Lamprey at fixed telemetry sites on the lower Yakima River, Washington, 2019 (daytime arrival, yellow circles; nighttime arrival, gray circles) and 2020 (daytime arrival. white circles; nighttime arrival, black 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.

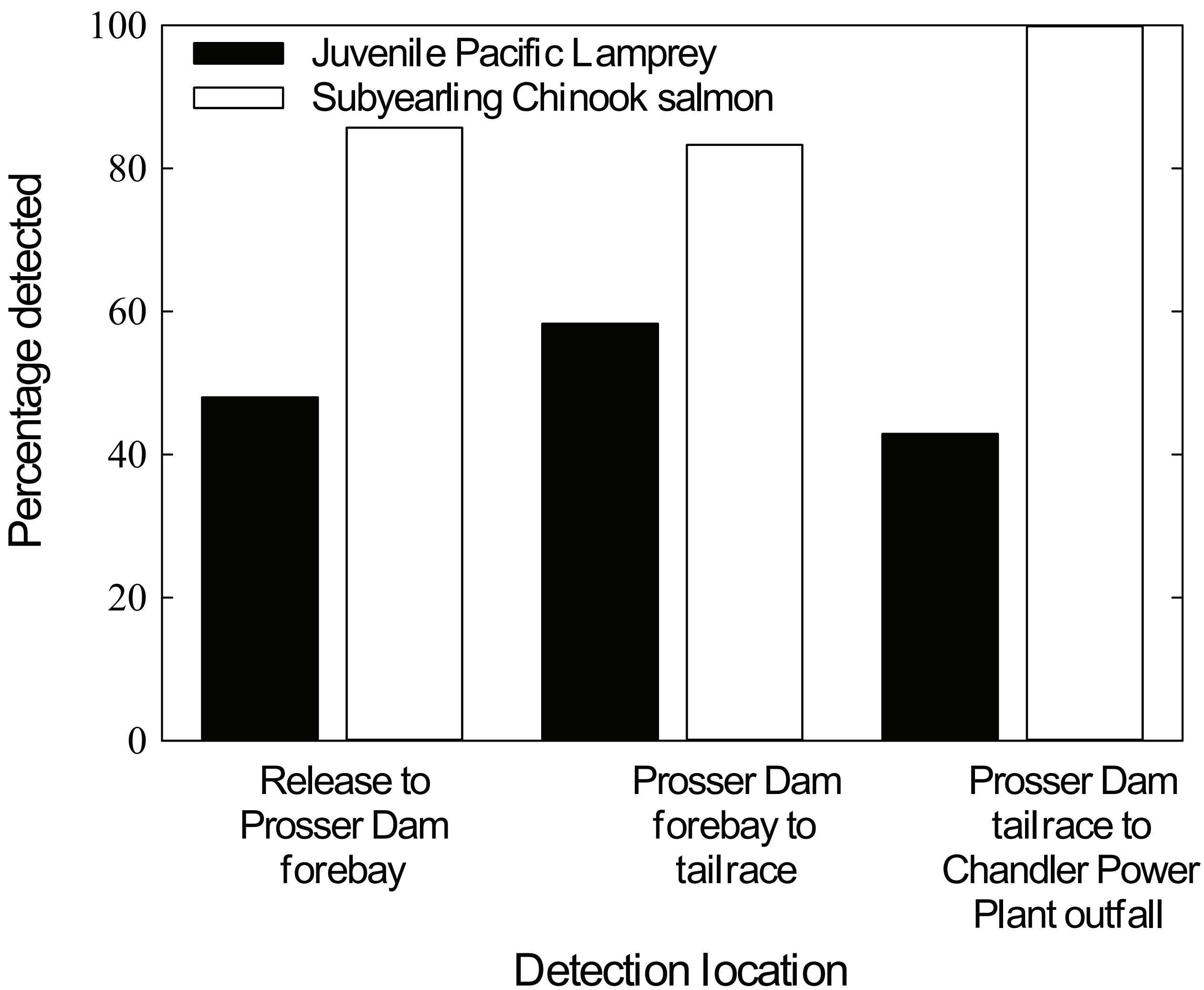

Figure 12. Percentage of juvenile Pacific Lamprey and subyearling Chinook salmon tagged with the eel-lamprey acoustic transmitter and detected following release at select sites in the lower Yakima River, Washington, 2020.

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

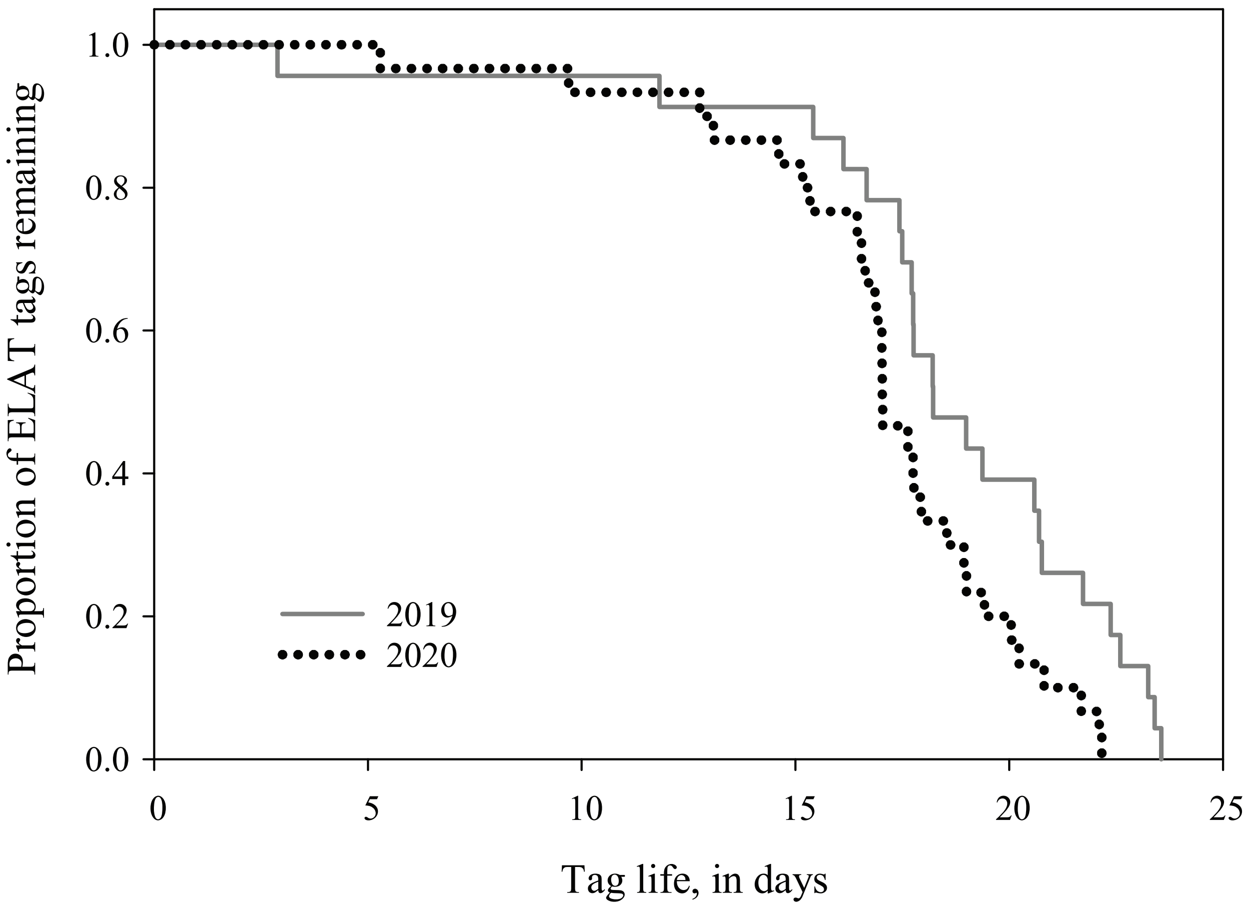

Figure 13. Kaplan-Meier survivorship plot of eel-lamprey acoustic transmitter (ELAT) tag life empirically measured in a laboratory study, 2019 and 2020.

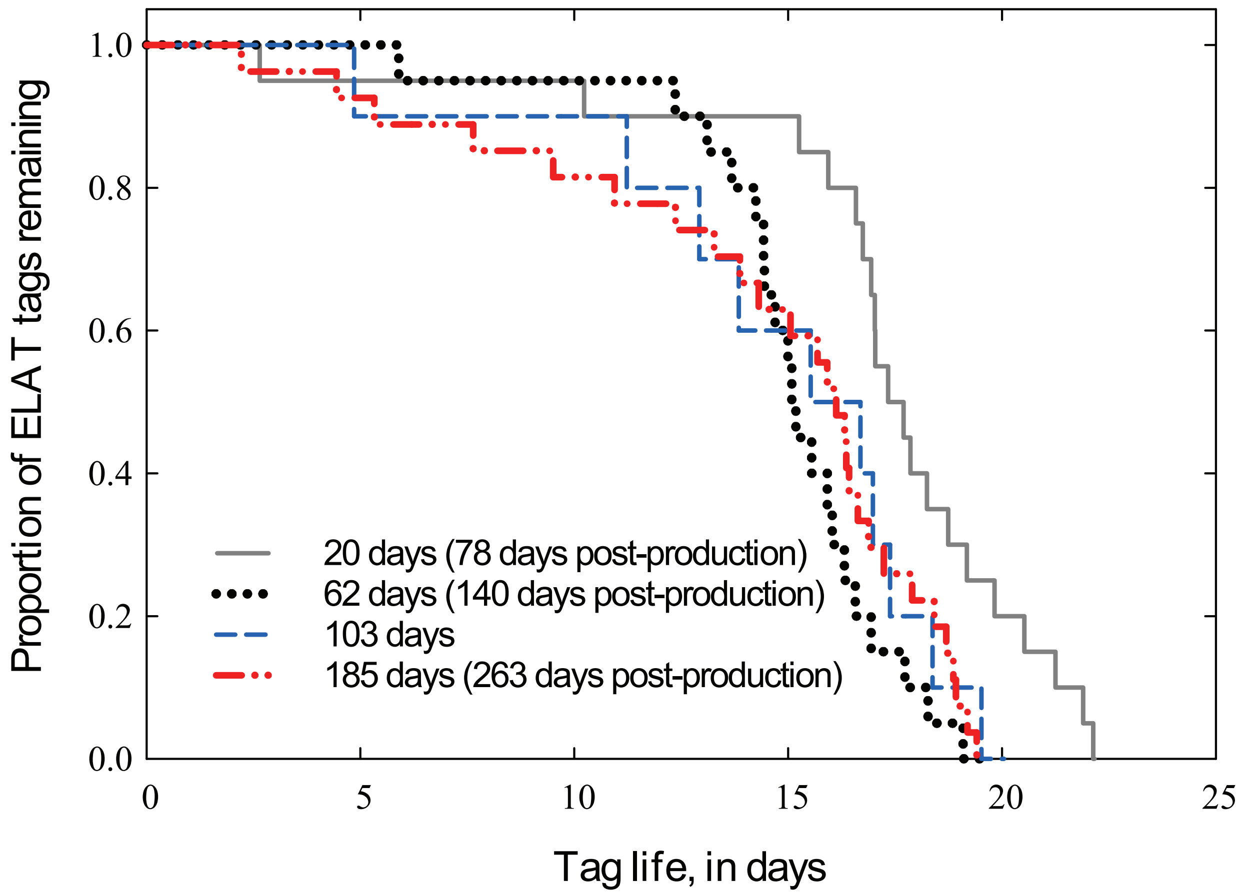

Figure 14. Kaplan-Meier survivorship plot of eel-lamprey acoustic transmitter (ELAT) tag life empirically measured in a laboratory study, by days from delivery to tag activation, 2020.

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

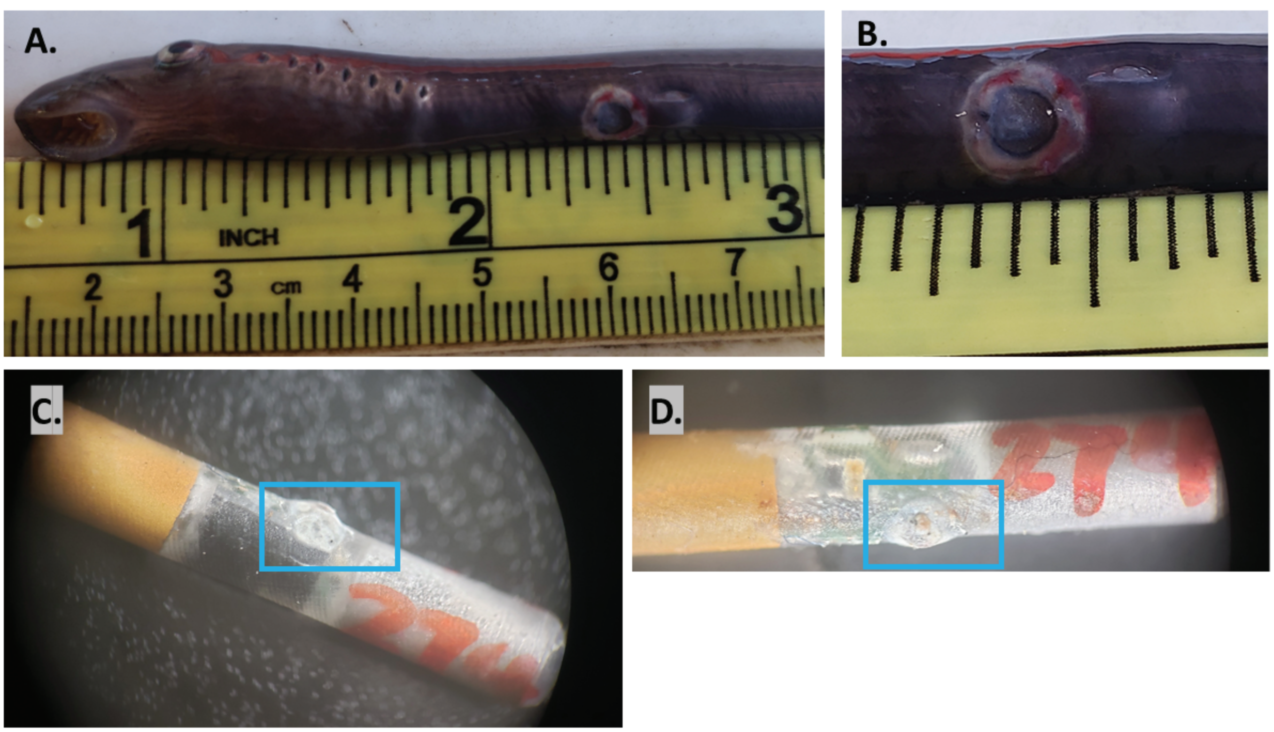

Figure 15. Juvenile Pacific Lamprey implanted with an acoustic transmitter that developed an abscess (A and B) and died 14 days after being tagged. The transmitter had an obvious bulge or swollen area (C and D) near the battery. Photographs A and B. by T. Beals, Yakama Nation Fisheries. Photographs C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

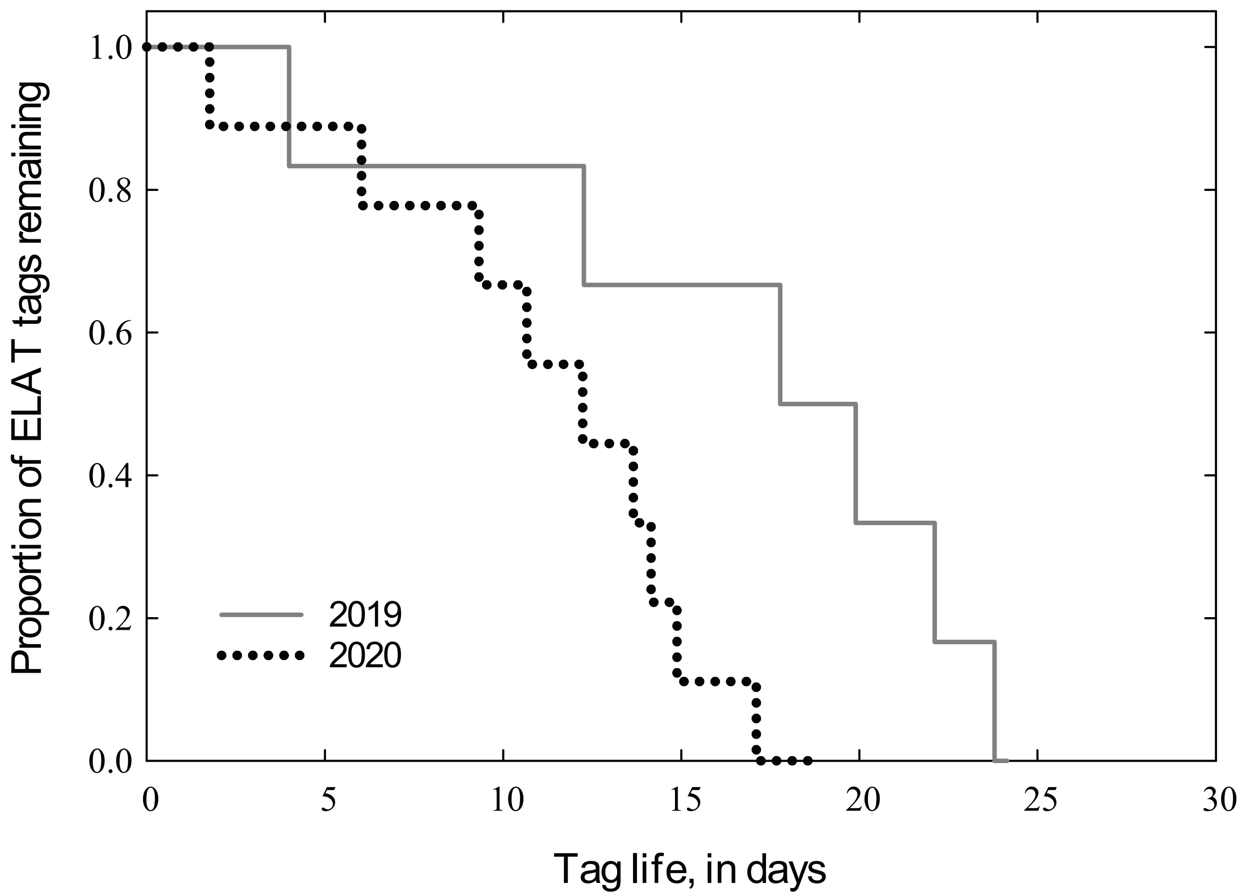

Figure 16. Kaplan-Meier survivorship plot of eel-lamprey acoustic transmitter (ELAT) tag life empirically measured in fish during a laboratory study at the Yakama Nation Prosser Hatchery in Prosser, Washington, 2019 and 2020.

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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