Technical Report 2013-4

ADULT PACIFIC LAMPREY MIGRATION BEHAVIOR AND ESCAPEMENT IN THE BONNEVILLE RESERVOIR AND LOWER COLUMBIA RIVER MONITORED USING THE JUVENILE SALMONID ACOUSTIC TELEMETRY SYSTEM (JSATS), 2012

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Department of Fish and Wildlife Sciences

University of Idaho, Moscow, ID 83844-1136

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U.S. Army Corps of Engineers

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Table of Contents

Executive Summary

In 2012, we continued our evaluation of the Juvenile Salmon Acoustic Telemetry System (JSATS) for monitoring the migration and final fates of adult Pacific lamprey (*Entosphenus tridentatus*) in Bonneville Reservoir and the Bonneville Dam tailrace, two areas with high unaccounted loss in past telemetry studies. We tagged adult Pacific lamprey with Juvenile Salmon Acoustic Telemetry System (JSATS) tags and half-duplex (HD) PIT tags and monitored their upstream passage and migration behaviors. Our objectives were to calculate lamprey travel times, to estimate escapement past the monitored sites, to evaluate JSATS detection efficiency, and to test a mobile acoustic tracking device.

We double-tagged 299 adult Pacific lamprey collected at Bonneville Dam with both JSATS and HD-PIT transmitters from 5 June through 1 September. All fish were trapped and tagged (400 d transmitter) at the Adult Fish Facility at Bonneville Dam and were released at one of three tailrace locations: Dodson landing (rkm (225.6), Tanner Creek (rkm 232.0), Hamilton Island boat ramp (rkm 232.6) or one of two Bonneville reservoir loctions: Stevenson boat ramp (rkm 242.7) or Cascades Locks (rkm 239.1). We deployed 38 JSATS autonomous receivers between the Bonneville Dam tailrace and The Deschutes River. Receivers were deployed singly or in pairs as detection gates allowing us to calculate travel times and estimate distribution and final lamprey fates for multiple reaches within Bonneville Reservoir.

Estimated detection efficiencies for most of the acoustic receiver gates were 85% or higher, and individual receiver efficiencies ranged from 18% at Lyle, WA to 90% at Miller Island (near the Deschutes River).

The escapement estimate for lampreys released into the Bonneville Dam tailrace past the dam was 61.4% (n = 94), higher than estimates from previous HD-PIT studies (41-53%). The escapement estimate from release in Bonneville Reservoir past The Dalles Dam was 60.3% (n = 88). This was higher than JSATS-tagged adults released in the Reservoir in 2011 (n = 24, 38.7%).

Travel rates for tagged fish were variable and were higher in reservoirs than through dam reaches. Reservoir-released lamprey had a median travel time of 5.4 days (12.5 km/d) from release to The Dalles Dam ladder top. Tailrace-released fish moved rapidly once they passed Bonneville Dam. The median travel time for tailrace-released fish from release to the top of Bonneville Dam was 12.8 days (0.3 km/d), and was 38.2 days (2.0 km/d) from release to the top of The Dalles Dam. Movement through reservoir reaches was rapid (Stevenson to The Dalles Dam tailrace: *median* = 50.5 km/d, n = 61).

Distributions and final fates of tagged fish through early spring were similar to those seen in previous years. Thirty-six percent of tailrace-released fish and 60% of Reservoir-released fish passed The Dalles Dam. The majority of adults (86%) entering or released into Bonneville Reservoir were detected in the upper reservoir or tailrace of The Dalles Dam, indicating low migration mortality rates in the lower reservoir.

Acoustic monitoring continued from receiver deployment in mid-May 2012 through July 2013. The 400 d battery life transmitters provided additional data on spring movements of tagged lamprey that had not been collected previously. About 24% of the JSATS-tagged lamprey was detected in the spring, including several that entered spawning tributaries. Springtime records resulted in ~12% of the lamprey that were classified as unaccounted for in the fall being assigned as successfully entering tributaries, thereby improving our estimation of final fates compared to previous years. Mobile tracking efforts planned for spring 2013 were postponed while tracking equipment underwent necessary repairs.

Introduction

The populations of anadromous Pacific lamprey (*Entosphenus tridentatus*) in the Pacific Northwest, particularly in the Columbia River Basin, have been in a decades-long decline (Columbia River Inter-Tribal Fish Commission 2011; University of Washington 2012). Pacific lamprey are an important prey species for other fish (Poe et al. 1991) and may act as a buffer against predation by fish, birds and marine mammals on endangered salmon (Moser and Close 2003). As with many other anadromous fish species, it is likely that Pacific lamprey are important in nutrient cycling pathways (Gresh et al. 2000; Wilcove and Wikelski 2008). Pacific lamprey have also played a major role in the culture of many Native American tribes, particularly those of the Columbia Basin (Vladykov 1973; Close et al. 1995, 2002; Palacios 2007).

Results from both radiotelemetry (RT) and HD-PIT studies have indicated that Pacific lamprey do not readily pass dams and their poor passage efficiency may represent a critical limitation to their migration success (e.g., Moser et al. 2002b; Keefer et al. 2009c; Luzier et al. 2011). Specifically, Moser et al. (2002a, 2002b, 2003, 2005), Johnson et al. (2012), Clabough et al. (2011), and Keefer et al. (*in press*) found that fishway entrances, collection channel/transition pool areas, count stations, diffuser gratings, and serpentine weirs impede adult Pacific lamprey dam passage at lower Columbia River dams. These data have been used to design, implement, and test a number of passage improvements including Lamprey Passage Structures (LPS, Moser et al. 2011), and modified nighttime operations (Johnson et al. 2012).

In addition to identifying specific passage bottlenecks, these studies observed that many tagged adults failed to re-initiate upstream migration after tagging and that substantial proportions of tagged samples were unaccounted for between dams. For instance, dam counts, RT, and HD-PIT telemetry results all suggest considerable numbers of adult lamprey entering Bonneville Reservoir do not pass The Dalles Dam (TDA). Escapement estimates for tagged fish from studies in 2007 and 2008 were 25.3-62.8%, comparable to or higher than the conversion rates estimated from counts, and were generally higher in the HD-PIT than in the RT samples (Keefer et al. 2009b, 2009c). The HD-PIT method probably provides the best estimate of inter-dam conversion, and smaller tag effects than observed when using RT. Nonetheless, all estimates indicate considerable (>50%) loss in the Bonneville Reservoir in most years. In 2008, a year with the highest level of RT coverage (including at tributary mouths), 42% of RT adults that passed Bonneville Dam (BON) subsequently passed TDA, 22% were recorded at TDA but were not recorded passing, 5% were recorded in tributaries, and 35% had records indicating a final fate in Bonneville Reservoir (Keefer et al. 2009b). Values for 2009-2011 were similar based on evaluations using PIT-tagged (Keefer et al. 2010b, 2011a, 2012; Fox 2012) or JSATS-tagged adult lamprey (Noyes et al. 2012).

The unknown fate of many Pacific lamprey during their migration through tailraces and/or reservoirs may be attributed to: 1) overwintering in the reservoir and resuming upstream migration the following spring, 2) pre-spawn or predation mortality, 3) undetected spawning in reservoir tributaries, 4) and/or spawning in the tailrace of The Dalles Dam or elsewhere in the Reservoir. Lamprey are an attractive prey item to predators, and it is possible that these unaccounted for fish represent mortalities. White sturgeon (*Acipenser transmontanus*) are numerous in Bonneville and The Dalles Dam tailraces, and sea lions (*Zalophus californicus*, *Eumetopias jubatus*) are seasonally abundant in Bonneville Dam tailrace. However, unsuccessful dam passage does not necessarily mean lamprey fail to spawn. Lamprey may pass many suitable spawning tributaries during their migration up the Columbia River including those terminating in reservoirs on the main stem river, and it is possible that a significant number of the fish unaccounted for in reservoirs may represent successfully spawning individuals. Similarly, spawning in the tailraces of Columbia River dams has been observed in fall Chinook salmon (Mueller 2004; Skalicky 2009) and it is possible some lamprey also spawn in tailraces. Exploring any of these hypotheses requires knowing the final distribution of lamprey after the overwintering period.

Unfortunately, the deep bathymetry of Federal Columbia River Power System (FCRPS) reservoirs and the river below Bonneville Dam limits the ability to detect radio transmitters and thereby limits the ability to determine the final fates of many tagged lamprey. Acoustic telemetry has several advantages over RT and PIT technologies, including the ability to detect signals in deep water (>10 m). Acoustic transmitters also do not require a trailing antenna which may affect behavior and ultimately survival (Keefer et al. 2009d; Mesa et al. 2011). Until recently, transmitter design and battery size have precluded use of longer-lived acoustic transmitters on smaller species. Because of these limitations, the USACE initiated the development of a new juvenile salmonids acoustic telemetry system (JSATS; see McMichael et al. 2010 for description). The relatively small transmitter size and design of acoustic transmitters for salmonid smolts also make them suitable for other species. In 2010, we performed a pilot study with thirty JSATS-tagged adult Pacific lamprey to evaluate the technology for monitoring adult lamprey using fixed-site and mobile tracking hydrophone receivers (Naughton et al. 2011). In 2011, we continued the evaluation with a larger sample of tagged lamprey (n = 85) and increased monitoring effort (Noyes et al. 2012). The results demonstrated that the technology could be adapted readily to adult lamprey studies in deep water habitats, and that JSATS monitoring could be used to evaluate passage in some fishway environments.

In the 2012 study, we evaluated the use of JSATS for adult Pacific lamprey using a larger sample of tagged fish (n = 299), additional fixed receiver sites, and three additional release locations (in the Bonneville Dam tailrace at Hamilton Island and the mouth of Tanner Creek, and in Bonneville Reservoir at the Cascade Locks Marina). A small sample (n = 5) was released in the Bonneville Tailrace at Dodson, Oregon. Our primary objectives were to characterize lamprey migration behavior and estimate the fate of adult Pacific lamprey in Bonneville Reservoir and tailrace using the larger array of stationary acoustic JSATS receivers.

We had one secondary objective to evaluate an acoustic mobile tracking device for monitoring the migration and fate of JSATS-tagged adult Pacific lampreys in Bonneville Reservoir and the Bonneville Dam tailrace.

Methods

Fish capture and tagging

Pacific lamprey were captured at night using two traps installed in the Washington-shore fishway that collected fish as they passed weirs. We also deployed two portable pot traps between the two fixed traps in the fishway. A complete description of the collection and tagging methods is presented in Moser et al. (2002b) and Keefer et al. (2009c, 2012). Collected fish were anesthetized with 60 ppm (3 mL/50 L) clove oil, measured (length and girth to the nearest mm) and weighed (nearest g). Muscle lipid content (% lipid) was collected using a Distell fat meter. Fat meter readings from 2012 were converted to estimated % lipid (wet weight basis) using the regression equation 'percent lipid' = 3.618 * reading – 2.436 ($P < 0.01$; $r^2 = 0.4808$; $n = 33$). The regression equation was developed by comparing Fatmeter readings taken in 2008 on live lamprey captured at Bonneville ($n = 20$) and McNary ($n = 13$) dams to lipid levels determined by biochemical proximate analysis on the same individuals following euthanasia (B. Ho, unpublished data).

Lamprey were surgically implanted with a 4-mm × 32-mm glass-encapsulated HD-PIT transmitter (134.2 kHz; Texas Instruments, Dallas, Texas) and a modified JSATS transmitter (Advanced Telemetry Systems, Isanti, MN). The JSATS transmitter was 4.0 mm × 8.0 mm × 23.0, weighed 1.7 g in air, and had an estimated battery life of 400 d with a 10 s burst rate. Both the JSAT transmitter and HD-PIT tag were inserted through a small (<1 cm) incision in the body cavity along the ventral midline, in line with the anterior insertion of the first dorsal fin. Incisions were closed with a single suture (3-0 monofilament), and fish were placed in a post-surgery holding tank.

Tagged adults were allowed to recover for at least 2 h post surgery and were released between 12:00 – 13:00 ($n = 22$) and 18:00-23:00 ($n = 278$). Lamprey were released in either the Bonneville Dam tailrace or Bonneville Reservoir. Tailrace release sites included two located at rkm 232.3: Hamilton Island on the Washington shore and near the mouth of Tanner Creek on the Oregon shore. A small sample ($n = 5$) was released at Dodson, OR (rkm 225.6) for purposes of mobile tracker testing. Lamprey were released at two sites in Bonneville Reservoir: the Stevenson boat ramp on the Washington shore (rkm 242.7) and the Cascade Locks Marina on the Oregon shore (rkm 239.1). The reservoir sites were selected as the nearest sites to the dam that also minimized the potential for tagged fish fallback over Bonneville Dam. The Hamilton Island and Tanner Creek tailrace sites have been frequently used in RT and HD PIT studies (e.g., Clabough et al. 2010; Johnson et al. 2012).

Telemetry monitoring

JSATS-tagged fish were monitored with autonomous receivers (Advanced Telemetry Systems, Trident SR5000) which contained an internal rechargeable lithium battery pack (rated for 34 d), an externally-mounted hydrophone, water temperature and pressure sensor, and analog and digital circuit boards (see McMichael et al. 2010 for descriptions). The receivers were deployed to position the hydrophone about 3 to 4 m above the river or reservoir bottom. The standard deployment configuration consisted of the receiver affixed at a single point to a short section of wire cable (3/16 in. stainless steel) with two small floats for additional buoyancy. The receiver was then attached to an acoustic release mechanism (Inter-Ocean Model 111 or Teledyne Model 875-TD). JSATS receivers (*n* = 12) were used to monitor major tributary mouths and The Dalles Dam tailrace throughout the winter of 2011-12. Additional JSATS receivers (*n* = 17) were deployed starting on 31-May 2012 to form additional gates across Bonneville Reservoir and the Bonneville Dam tailrace, and to monitor the area around the mouth of the Deschutes River. Monitoring at nearly all sites continued through October 2012. Receivers were not deployed over the winter of 2012-13. Monitoring resumed at major tributaries and the tailraces of Bonneville and The Dalles Dam in March 2013. Data obtained from the autonomous receivers were used to record final locations, to partition final locations within the reservoir, and to estimate reach travel times of tagged lamprey.

The study area encompassed the lower Columbia and Snake rivers monitored by HD-PIT antennas. JSATS monitoring included the reach from the Bonneville Dam tailrace to the tailrace of The Dalles Dam (rkm 304.9) (Figure 1). JSATS receivers were deployed as gates of one to three nodes mid-channel or on either the Washington or Oregon shores of the Columbia River, at each of eleven locations (Table 1). Data were also collected on JSATS arrays operated by Pacific Northwest National Laboratory at each of 11 locations used in other studies (Table 1).

Lamprey detections on HD-PIT antennas were also used to monitor passage at Columbia and Snake River dams, and to determine final locations of Pacific lamprey. HD-PIT antennas were located at the tops of fish ladders at Bonneville, The Dalles, John Day, McNary, Priest Rapids, Wanapum, Rock Island, and Rocky Reach Dams on the Columbia River, and at Ice Harbor, Lower Monumental, Little Goose, and Lower Granite Dams on the Snake River. These sites were maintained by UI (lower Columbia and Snake River dams), and the Chelan and Grant County PUD's (upper Columbia River dams). Additional HD-PIT antennas were located in Fifteenmile Creek, a small tributary that empties into the Columbia River in The Dalles Dam tailrace, Hood River, and in some Deschutes River tributaries (maintained by the Confederated Tribes of Warms Springs Reservation of Oregon [CTWSRO]).

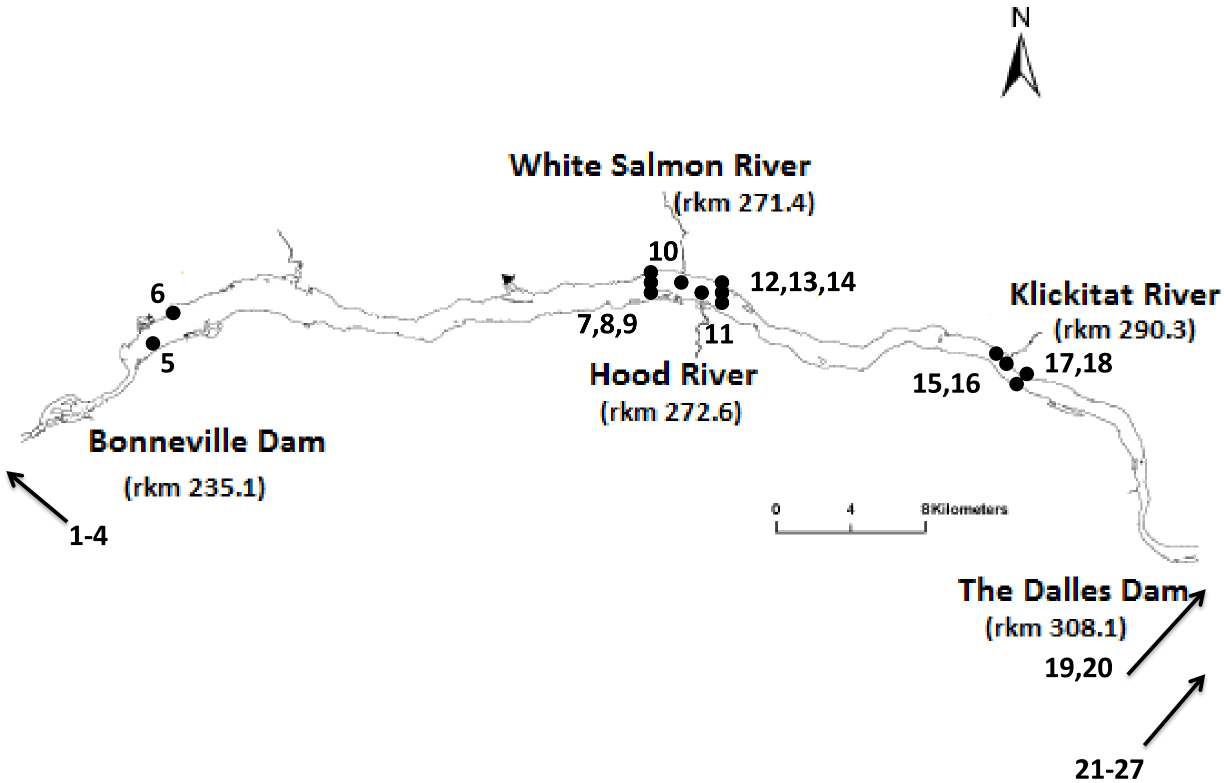

Figure 1. Receiver locations (numbered circles) used to monitor JSATS-tagged adult Pacific lamprey in 2012: 1-2) Rooster Rock; 3-4) Dodson; 5) Cascade Locks; 6) Stevenson; 7-9) White Salmon R.; 10) White Salmon R. mouth; 11) Hood R. mouth; 12-14) Hood R.; 15-16) Klickitat R. mouth; 17-18) Lyle; 19-20) The Dalles Dam tailrace; 21-26) Miller Island and Deschutes R. mouth; 27) John Day River.

Table 1. Locations JSATS receivers were deployed by University of Idaho (UI) and Pacific Northwest Laboratories (PNNL) in 2012. River mile kilometer (RKM) zero = mouth of Columbia River.

Agency	River	Location	RKM
UI	Columbia	Rooster State Park	209.7
UI	Columbia	Dodson, OR	225.6
UI	Columbia	Skamania, WA	225.6
UI	Columbia	Bonneville Dam tailrace	232.0
PNNL	Columbia	Bonneville Dam tailrace	233.0
PNNL	Columbia	Bonneville Dam	235.1
PNNL	Columbia	Bonneville Dam forebay	236.0
UI	Columbia	Bonneville Dam forebay	236.5
UI	Columbia	Cascade Locks, OR	239.1
UI	Columbia	Stevenson, WA	243.0
UI	Columbia	White Salmon River, WA shore	269.6
UI	Columbia	White Salmon River, mid-river	269.7
UI	Columbia	White Salmon River, OR shore	269.8
UI	Columbia	White Salmon River, mouth	271.4
UI	Columbia	Hood River, mouth	272.4
UI	Columbia	Hood River, WA shore	273.0
UI	Columbia	Hood River, mid-river	273.0
UI	Columbia	Hood River, OR shore	273.0
PNNL	Columbia	Hood River, OR	275.0
UI	Columbia	Klickitat River, downstream of mouth	289.8
UI	Columbia	Klickitat River, mouth	290.3
UI	Columbia	Lyle, upstream of Klickitat R. mouth WA shore	291.8
UI	Columbia	Lyle, upstream of Klickitat R. mouth OR shore	291.9
UI	Columbia	The Dalles Dam tailrace, WA shore	304.9
UI	Columbia	The Dalles Dam tailrace, OR shore	304.9
PNNL	Columbia	The Dalles Dam tailrace	307.0
PNNL	Columbia	The Dalles Dam	308.1
PNNL	Columbia	The Dalles Dam forebay	311.0
PNNL	Columbia	Celilo, OR	325.0
UI	Columbia	Miller Island downstream, WA shore	325.9
UI	Columbia	Miller Island downstream, OR shore	326.0
UI	Columbia	Deschutes River, mouth	328.2
UI	Columbia	Miller Island, north channel	329.3
UI	Columbia	Miller Island upstream, OR shore	333.6
UI	Columbia	Miller Island upstream, WA shore	333.7
PNNL	Columbia	John Day Dam tailrace	346.0
PNNL	Columbia	John Day Dam	346.9
PNNL	Columbia	John Day Dam forebay	351.0
UI	Columbia	John Day River, ~1200 m upstream from mouth	352.0
PNNL	Columbia	Crowe Butte State Park	422.0
PNNL	Columbia	McNary Dam tailrace	468.0
PNNL	Columbia	McNary Dam	469.8
PNNL	Columbia	McNary Dam forebay	472.0
PNNL	Snake	Snake River, mouth	524.6
PNNL	Snake	Ice Harbor Dam forebay	538.6
PNNL	Snake	Sheffler, WA	561.6
PNNL	Snake	Lower Monumental tailrace	586.6
PNNL	Snake	Lower Monumental forebay	589.6
PNNL	Snake	Ayers Landing	603.6
PNNL	Snake	Little Goose tailrace	633.6
PNNL	Snake	Little Goose forebay	635.6
PNNL	Snake	Lower Granite tailrace	692.6
PNNL	Snake	Lower Granite forebay	695.6
PNNL	Snake	Red Wolf Crossing Bridge	742.6

Data downloading and processing

Data were loaded into a database maintained at the University of Idaho. Autonomous nodes were downloaded monthly by transferring data to a portable computer. Clocks on all receivers and readers were synchronized to assure comparability between data collected between different sites. Records were screened to remove obvious error (noise) records and detections that occurred before fish were released. Records were inspected for accuracy, and assigned codes summarizing the movements of tagged fish. After the study season, we exchanged data with other researchers (e.g., PNNL) using JSATS transmitters and receivers to ensure the most complete migration histories for all JSATS-tagged fish.

Data analysis

Lamprey travel times (d) and migration rates (km/d) were calculated from the last record at a receiver site to the first record at upstream receiver sites. We estimated detection efficiency for each receiver site by comparing detections at the site with all lampreys detected on JSATS receivers and HD-PIT antennas at upstream sites. Detection on individual JSATS receivers required assumptions about valid versus invalid ("noise"). Valid detections were defined as those with three detections within a fifteen minute time block within a plausible spatial range. Coded data were used to estimate several passage metrics. We estimated residence times at receiver sites and described the final locations of individual fish using both JSATS and HD-PIT detection records. We tested for associations between lamprey migration rate and tag date, temperature, and fork length using univariate regression. We compared the passage frequencies of JSATS and HD-PIT only tagged adults to test whether there was evidence of a greater tag burden in the JSATS-tagged adults (i.e., adults were double tagged with JSATS + HD-PIT or HD-PIT only) using Chi-square tests. Travel time, migration rate, detection efficiency, diel behavior, and residence time analyses were based on data collected from May 2012 through October 2012. Final fates and distributions were determined from JSATS and HD-PIT records in fall 2012 and spring 2013.

Results

Lamprey tagging and release

The total number of adult lamprey recorded at Bonneville Dam in 2012 was 93,462 (daytime count = 29,230; night video count = 49,647; LPS count = 10,372; collected and released upstream = 4,213). A sample of 299 lampreys, representing 0.32% of the total count at Bonneville Dam, was double-tagged with 400-day estimated battery life JSATS transmitters and HD-PIT tags. The sample was in approximate proportion to the run (Figure 2). Fish were released into the Bonneville tailrace at Hamilton Island (*n* = 74), Tanner Creek (*n* = 74), Dodson, OR (*n* = 5), Bonneville Reservoir at Stevenson, WA (*n* = 73) and Cascade Locks, OR (*n* = 73).

Size metrics and percent lipid were similar between JSATS-tagged fish and fish that were HD-PIT-tagged only in 2012 (Table 2).

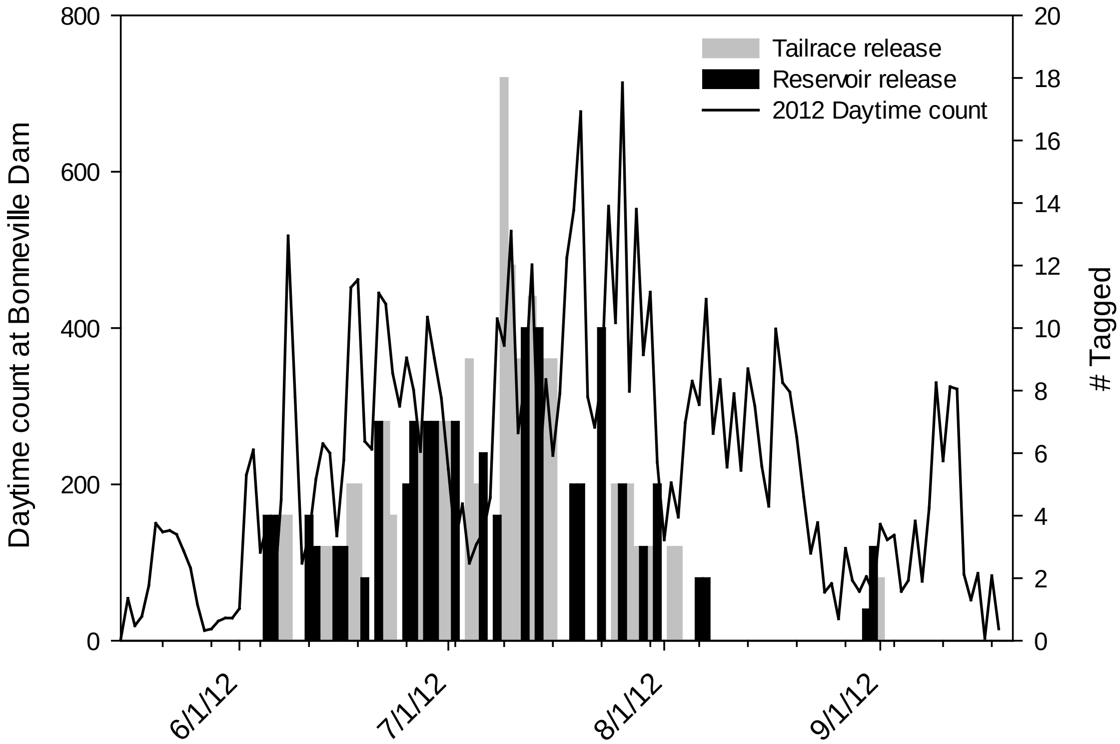

Figure 2. Distribution of JSATS-tagged Pacific lamprey and daily daytime count at Bonneville Dam, 2012. Tagging effort was suspended between August 8th and 29th due to water temperatures in excess of 22.2 °C.

Table 2. Length, weight, girth, and percent lipid of adult Pacific lamprey double tagged with HD-PIT and JSAT transmitters at Bonneville Dam in 2012. For comparison, data from lampreys that were tagged only with HD-PIT tags in 2012 are shown; details for the HD-PIT sample are reported in Keefer et al. (*in review*).

	Length (cm)			Girth (cm)			Weight (g)			Percent lipid (%)		
Study group	*n*	Mean	*sd*	*n*	Mean	*sd*	*n*	Mean	*sd*	*n*	Mean	*sd*
Tailrace release	152	67.1	3.6	152	11.2	0.8	151	485	84.4	152	28.7	12.5
Reservoir release	146	66.9	4.2	146	11.1	0.8	146	474	82.5	144	28.1	12.7
All releases	298	67.0	3.9	298	11.2	0.8	297	479	83.5	296	28.4	12.5
HD PIT only	894	65.2	4.2	892	10.8	0.8	805	445	89.8	891	25.6	9.0

Telemetry monitoring

Monitoring began with a set of eight autonomous nodes which had been deployed continuously since the fall of 2011 (Figure 3). These eight nodes were deployed in the Bonneville Dam tailrace and forebay, at Lyle, WA, in The Dalles Dam tailrace, and in the John Day River. These locations were selected to detect overwintering movement of the 2011 cohort of tagged lamprey. In February 2012, seven additional receivers were deployed near the mouths of the Hood, White Salmon, Klickitat, and Deschutes Rivers to monitor tributary entry by tagged lamprey. In late May 2012, before the 2012 tagging effort began, receiver locations were adjusted and new receivers were deployed at Miller Island near the mouth of the Deschutes River, Hood River, and White Salmon River in Bonneville Reservoir, at the Stevenson, Cascade Island, and Dodson release sites, and near Rooster Rock State Park downstream from Bonneville Dam. Coverage at most sites remained in place through October of 2012. The Rooster Rock site was abandoned in early September due to interference with purse seining operations conducted by Washington Department of Fish and Wildlife. Most sites had nearly continuous coverage, with short (<1 h) periods of no coverage for receiver maintenance, while other sites had some significant gaps in coverage, usually due to battery or electronics failure (Figure 3).

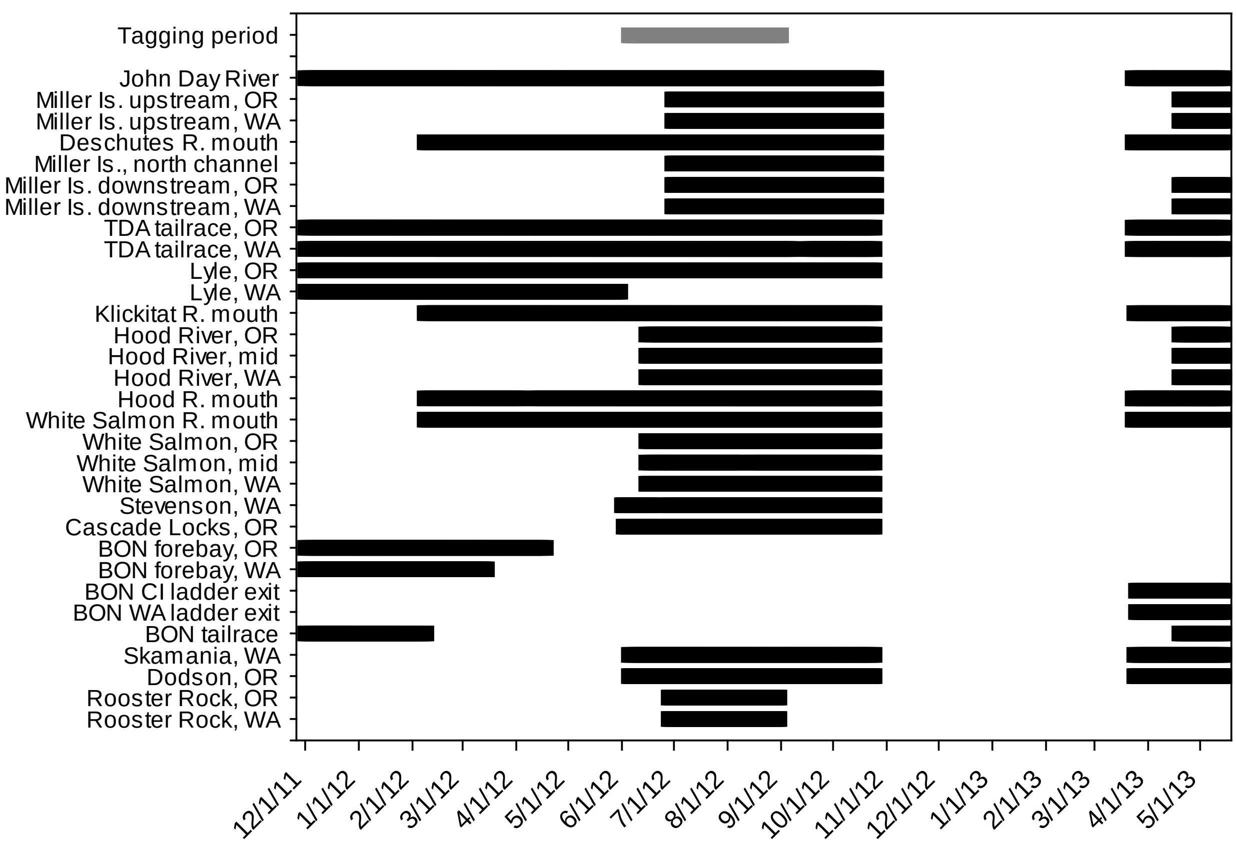

Figure 3. Autonomous node deployment schedule by site, December 2011 to May 2013.

Detection efficiencies differed by location. Of the 299 lamprey released, 296 (99%) were detected on at least one autonomous node receiver. All three undetected tagged lamprey had been released at Hamilton Island or Tanner Creek, where we did not have a release site receiver deployed. Detection efficiency of reservoir-released fish was 100% at the receiver near the Cascade Locks Marina release site, and 88% at the receiver near the Stevenson, WA release site. Among the other receiver gates, detection efficiencies ranged from 18% at the Lyle, WA receivers to 90% at the Miller Island receivers (Figure 4). One tagged lamprey was last detected moving downstream at the Rooster Rock site and presumably left the study area.

Most (86%) of the adults detected in the Bonneville Reservoir were later detected at upper reservoir sites (Figure 5). The proportion of adults detected at upstream sites differed among release locations because many lamprey released to the tailrace did not pass Bonneville Dam (Figure 5). The distribution of adults upstream of Bonneville Dam was similar between those released to the tailrace that passed Bonneville Dam and those released in Bonneville Reservoir (Figure 5).

Within Bonneville Reservoir, detection efficiency ranged from 18% at the Lyle site to >90% at the Hood River site (Figure 4). Of the 153 fish released into the Bonneville Dam tailrace, 146 (95%) were detected on the tailrace receiver. Of the tailrace-released fish, 59 (39%) were never detected at top-of-fishway HD antennas or at JSATS receivers upstream from Bonneville Dam.

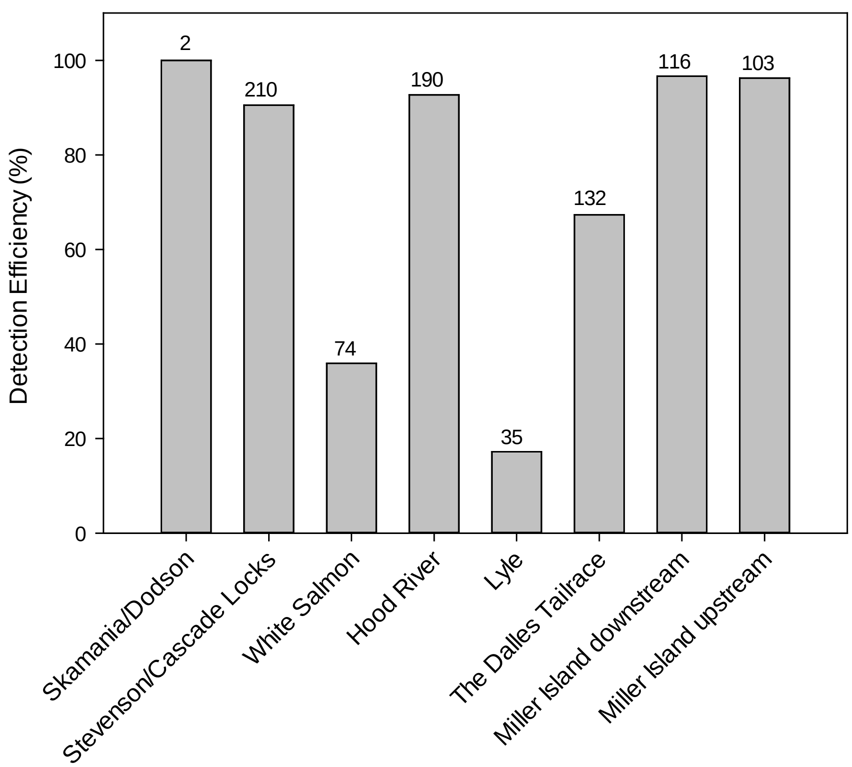

Figure 4. Detection efficiencies of JSATS receivers, by gate, for all tagged Pacific lamprey. Sample sizes detected upstream are shown above each bar.

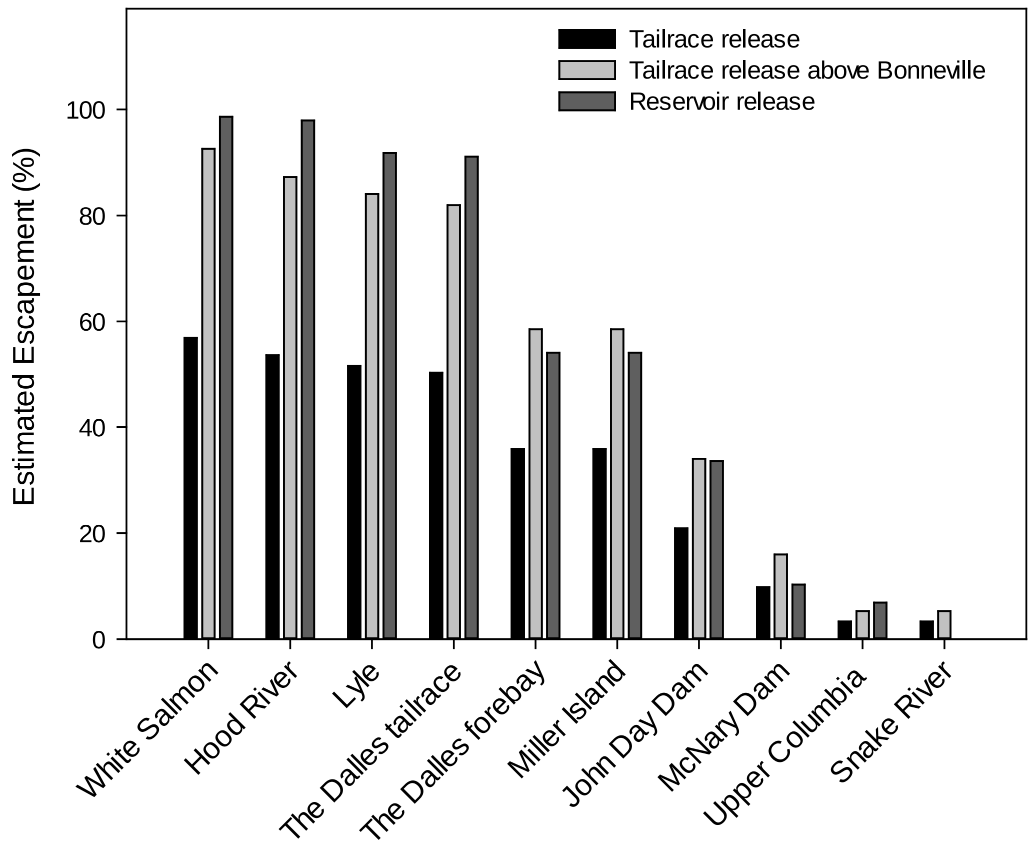

Figure 5. Percentage of JSATS tagged Pacific lamprey detected at Bonneville Reservoir and upriver receiver gates, by release group.

Diel activity

Tagged lampreys moved upstream during daytime and nighttime, but patterns differed among sites. First and last detections at the Hood River gate showed most movement occurred during midday, regardless of release group. Similarly, detections at other mid-reservoir sites frequently occurred during daytime hours. First and last detections for both release groups at The Dalles tailrace gate occurred primarily overnight and in early morning (Figure 6).

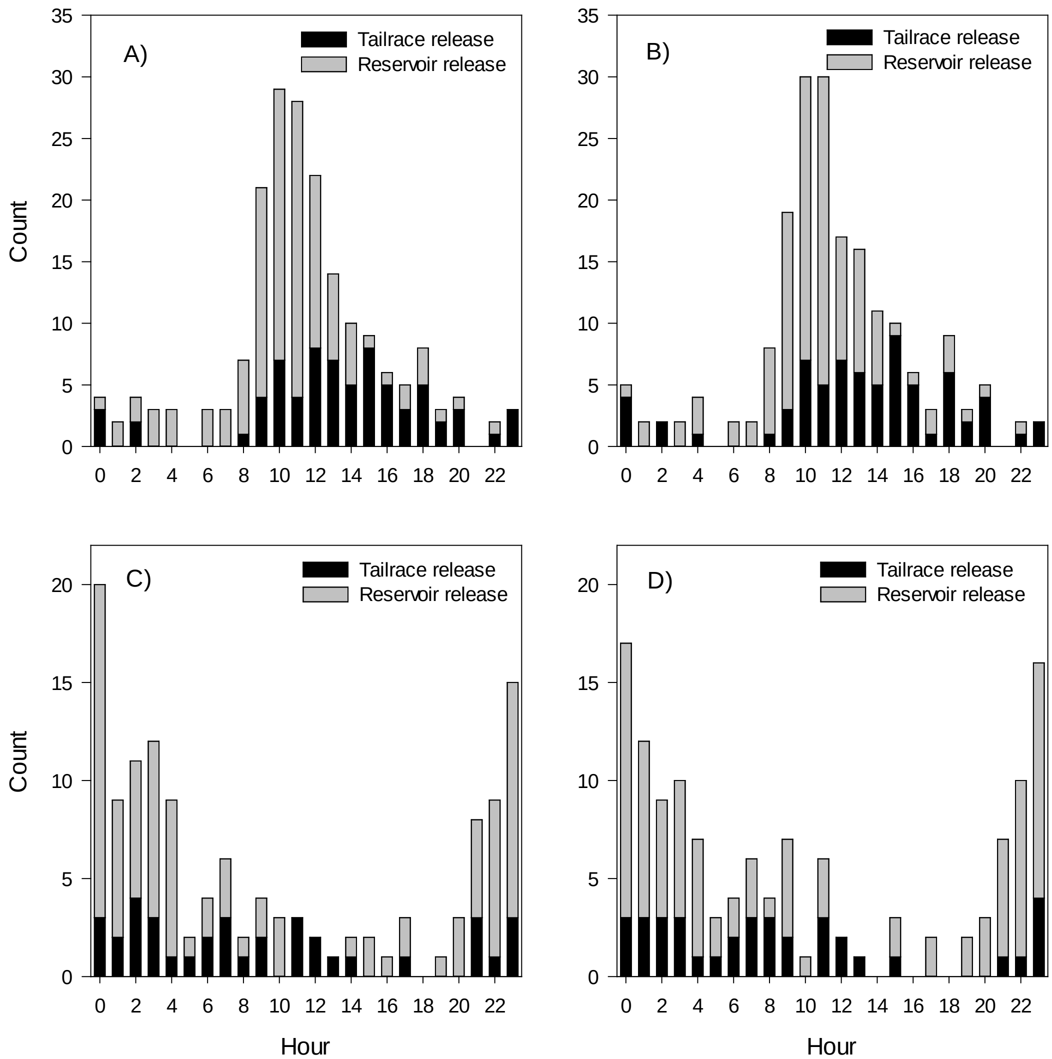

Figure 6. Distribution of first (left) and last (right) detections by hour of JSATS-tagged Pacific lamprey on receivers at the Hood River (A and B) and The Dalles Dam tailrace (C and D) sites (Washington and Oregon shores, combined).

Travel times and migration rates

Tagged lamprey released downstream from Bonneville Dam passed the dam slowly, but then migrated rapidly through all Reservoir reaches (Figures 7 and 8). Similarly, reservoir-released lamprey moved quickly through the Reservoir reaches. Median migration rates for downstream-released fish were 40.6-62.1 rkm/d through the Reservoir reaches versus 0.3 rkm/d from release past Bonneville Dam (Table 3). Median Reservoir rates for reservoir-released samples were 47.2-60.7 rkm/d.

Analyses using univariate linear regression found weak, but significant correlations between migration rate through the reservoir reach with the largest sample size (White Salmon to Hood River) and release date (n = 63, r^2 = 0.173, P < 0.001), and water temperature (n = 63, r^2 = 0.152,

$P = 0.002$) (Figure 9). We found a marginally significant correlation between migration rate and lamprey fork length ($n = 63$, $r^2 = 0.053$, $P = 0.068$) (Figure 9).

Table 3. Travel times (d) and migration rates (km/d) of JSATS-tagged adult Pacific lamprey released in the Bonneville Dam tailrace (top) and Bonneville Reservoir (bottom), 2012.

		Travel time (d)			Migration rate (km/d)		
Reach	*n*	Mean	Median	Range	Mean	Median	Range
Tailrace-released fish							
Release – BON ladder top	66	18.9	12.8	0.4-78.3	0.6	0.3	0.04-8.7
BON ladder top – White Salmon	21	2.8	1.5	0.6-19.3	38.3	40.6	3.2-101.8
White Salmon – Hood River	25	0.1	0.1	0.04-0.5	45.3	47.9	6.4-72.8
Hood River – Lyle	23	1.2	0.3	0.2-18.7	55.9	62.1	1.0-62.1
Lyle – TDA Tailrace	3	0.3	0.3	0.2-0.4	46.7	50.0	33.2-56.8
Reservoir-released fish							
Release – White Salmon	43	0.7	0.5	0.4-2.3	51.3	56.6	11.8-72.5
White Salmon – Hood River	42	0.1	0.1	0.05-0.09	47.2	47.2	34.2-61.7
Hood River – Lyle	12	0.4	0.3	0.3-1.0	52.2	55.6	19.4-65.9
Lyle – TDA tailrace	2	0.2	0.2	0.21-0.22	60.7	60.7	59.9-61.5

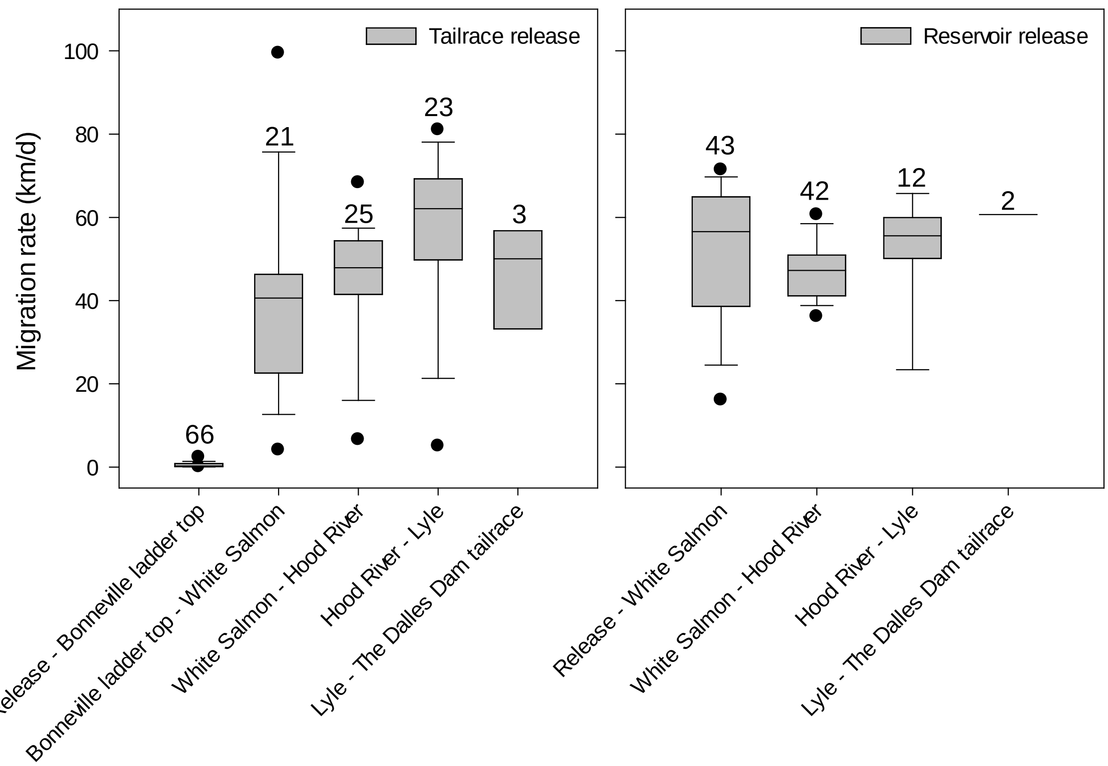

Figure 7. Migration rates (km/d) by reach for JSATS-tagged Pacific lamprey released into the Bonneville Dam tailrace (left) or Bonneville Reservoir (right). Sample sizes are shown above each bar. Box plots show 5th, 25th, 50th, 75th and 95th percentiles.

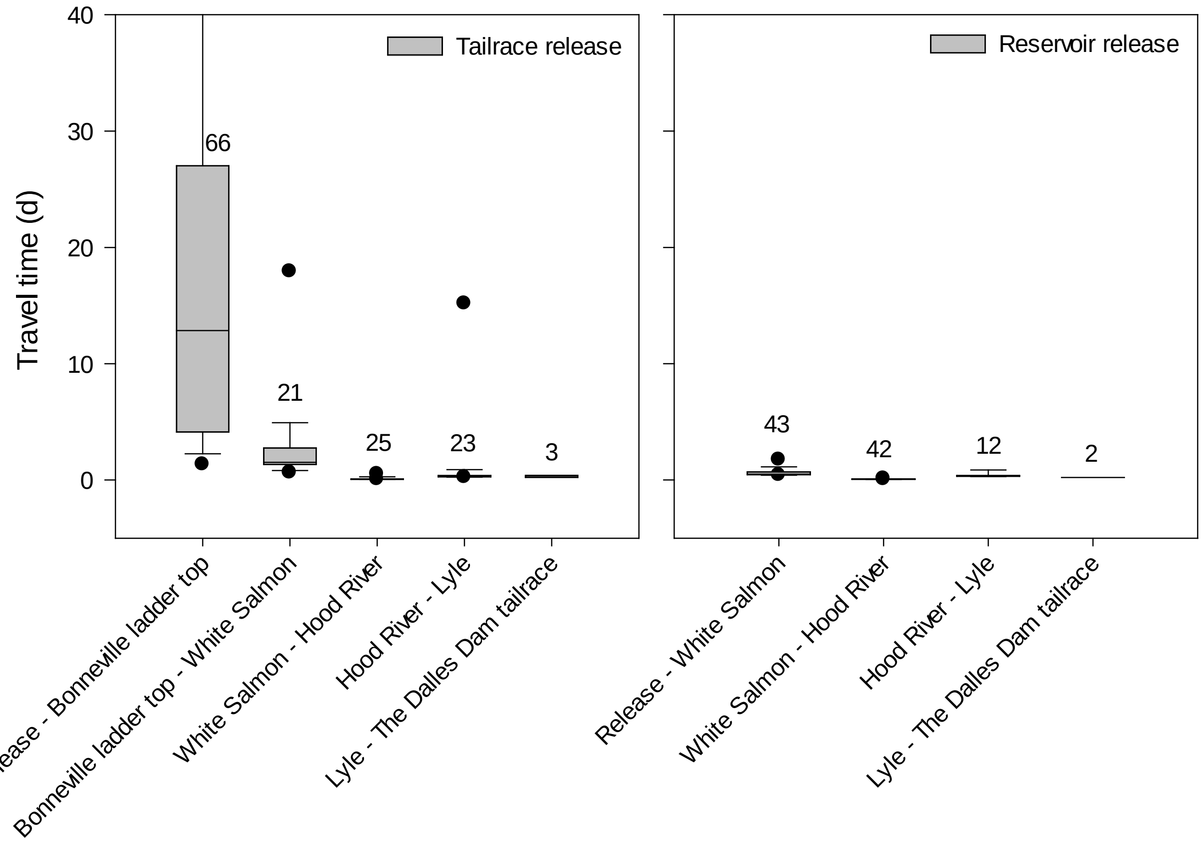

Figure 8. Travel times by reach for JSATS-tagged Pacific lamprey released into the Bonneville Dam tailrace (left) or Bonneville Reservoir (right). Four outliers omitted for clarity. Sample sizes are shown above each bar. Box plots show 5th, 25th, 50th, 75th and 95th percentiles.

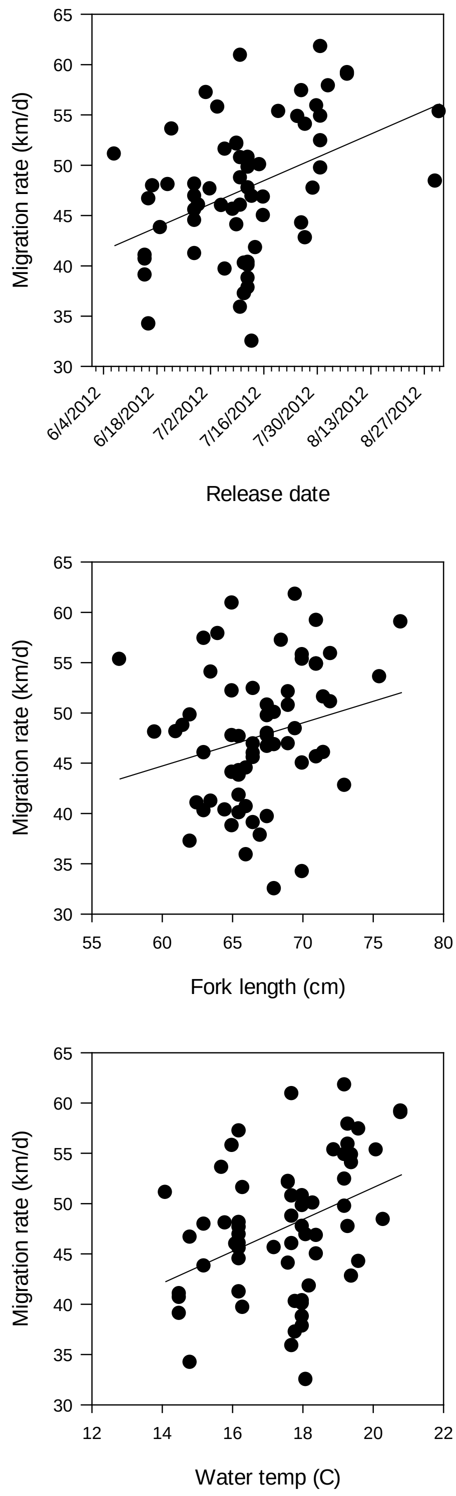

Figure 9. Relationships between migration rate (White Salmon River-Hood River reach) and release date (A), fork length (B), and water temperature at release (C) for adult Pacific lamprey tagged in 2012 (both release groups combined).

Residence times

We examined residence time within the detection range of individual autonomous nodes as a secondary measure of migration rate. Lampreys were present near the Cascade Locks release site for the longest period (minutes to an hour), but were present at other sites for fifteen minutes or less in nearly all cases (Figure 10). Median residence time at the Cascade Locks and Stevenson release site receivers was 0.2 h (*mean* = 0.4 h; *range* = 0.01 – 1.6 h) and 0.2 h (*mean* = 0.4 h; *range* = 0.02 – 4.0 h), respectively (Figure 10). Median residence times at other Bonneville Reservoir receivers ranged from 0.04 h at the White Salmon site to 0.13 h at the Lyle site (Figure 10). Median residence times at Miller Island receivers were 0.11 h at the downstream site and 0.16 h at the upstream site (Figure 10).

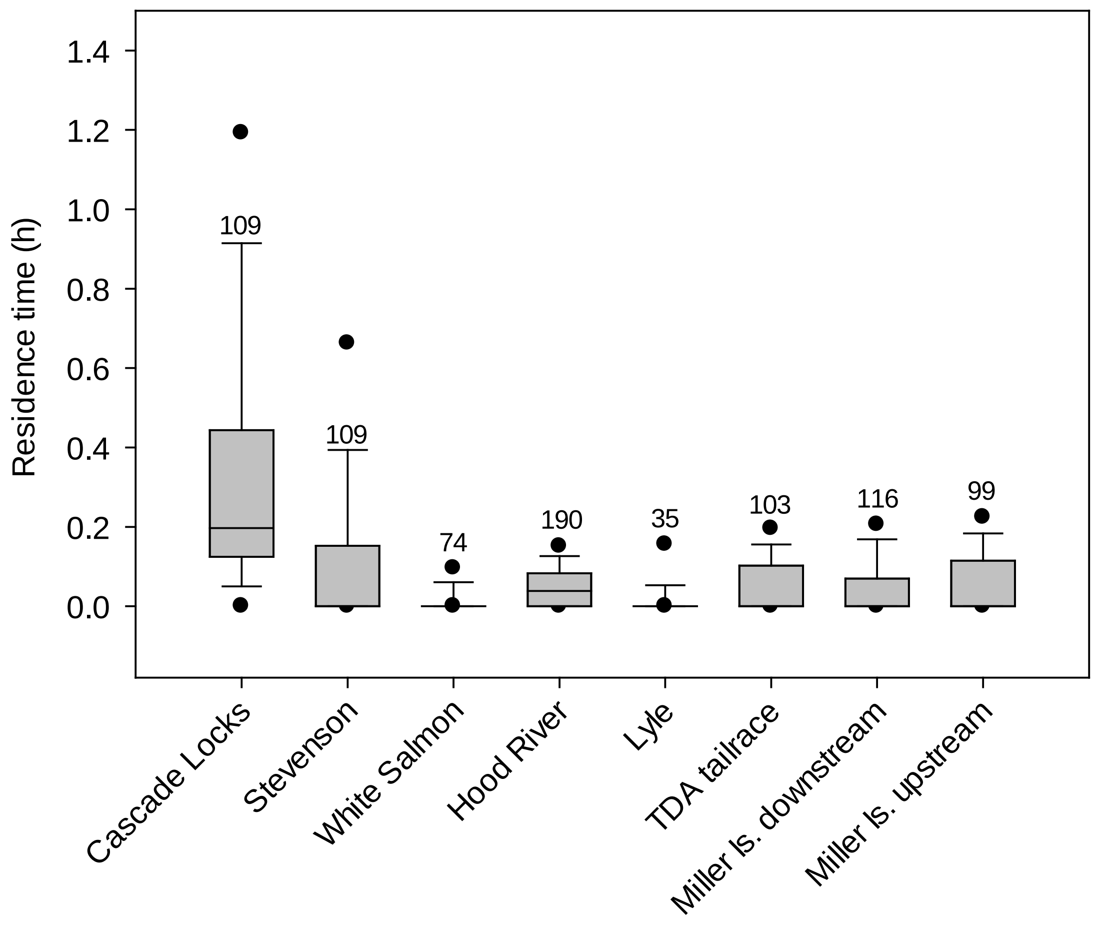

Figure 10. Residence times for JSATS-tagged Pacific lamprey on receivers in Bonneville Reservoir. Sample sizes are shown above each bar. Box plots show 5th, 25th, 50th, 75th and 95th percentiles.

Final distribution and escapement

The probability of passing Bonneville, John Day, or McNary dams did not differ ($P > 0.10$, χ^2 test) between adult lampreys double-tagged with JSATS + HD-PIT tags versus adults tagged with only an HD-PIT tag 2012 (Table 4). However, JSATS-tagged adults were more likely to pass The Dalles Dam than HD-PIT only fish ($P = 0.009$).

Table 4. Results of Pearson's chi-square tests of upstream dam passage proportions between JSATS (*n* = 153) and HD-PIT (*n* = 823) tagged Pacific lamprey released in the Bonneville Dam tailrace.

	HD-PIT		JSATS			
	n	%	*n*	%	*Chi-square*	*P*
% past Bonneville	447	54.3	94	61.4	2.65	0.104
% past The Dalles	212	25.8	55	35.9	6.74	0.009
% past John Day	177	21.5	32	20.9	0.03	0.869
% past McNary	69	8.4	13	8.5	0.002	0.964

Final records of lampreys from JSATS and HD-PIT antennas were used to estimate the final distribution of lamprey (Figure 11). At the broadest scale, the 153 downstream-released lamprey were classified as: passing Bonneville Dam (*n* = 91, 59.5%); exiting the Bonneville Dam tailrace downstream (*n* = 12, 7.8%); last detected in the Bonneville tailrace (*n* = 47, 30.7%); or undetected (*n* = 3, 2.0%). Eighty-seven fish (56.9%) were detected on the White Salmon gate or above. Seventy-nine fish (51.6%) made it as far as the Lyle, WA receivers, and seventy-seven tagged lampreys (50.3%) were detected on or above The Dalles Dam tailrace receivers. Fifty-five fish (35.9%) were detected on top of the ladder HD-PIT antennas at The Dalles Dam and at the Miller Island downstream gate; 42 fish (27.5%) were subsequently detected at the Miller Island upstream gate, thirty-two (20.9%) continued to John Day Dam and fifteen fish (9.8%) were detected passing McNary Dam. Five fish (3.3%) were detected in the Snake River at Ice Harbor Dam, and three (2.0%) were last detected passing Lower Granite Dam. Five fish (3.3%) were detected in the mid-Columbia River at Priest Rapids Dam. Two fish (1.3%) were detected at Wanapum Dam, and a single lamprey was detected passing Rocky Reach Dam. Eleven tailrace-released lampreys had last detections in or at the mouths of tributaries (7.2% of total, 11.7% of 94 entering the reservoir). Tailrace-released fish were last recorded on JSATS receivers at the mouths of the White Salmon River (*n* = 1, 0.7%), Hood River (*n* = 3, 2.0%), Klickitat River (*n* = 3, 2.0%), and Deschutes River (*n* = 3, 2.0%). Four tailrace-released fish (2.6%) were also last recorded on HD-PIT antennas located within Fifteenmile Creek (Table 5, Figure 12).

Over half (*n* = 92, 63.0%) of the 146 reservoir-released fish were detected at or above The Dalles Dam. Nearly all of the reservoir-released fish were last recorded as far upstream as the White Salmon gate (*n* = 144, 98.6%) and the majority were detected as far as The Dalles Dam tailrace (*n* = 133, 91.1%). Seventy-nine fish (54.1%) were detected as far as the Miller Island downstream gate, and seventy-one (48.6%) were detected at the gate upstream of Miller Island.

Forty-nine fish (33.6%) were detected on HD-PIT antennas at John Day Dam or upstream, and fifteen fish (10.3%) were detected as far as McNary Dam. Ten lamprey (6.8%) were detected passing Priest Rapids Dam, four fish (2.7%) were detected at Wanapum Dam, and one fish (0.7%) was detected passing Rocky Reach Dam. No reservoir-released lamprey were detected at any Snake River dams. Seventeen reservoir-released lampreys (11.6%) were last detected at the mouths or within tributaries of Bonneville Reservoir. Tagged lamprey were last detected on JSATS receivers at the mouths of the White Salmon River (*n* = 1, 0.7%), Hood River (*n* = 2, 1.4%), Klickitat River (*n* = 7, 4.8%), and Deschutes River (*n* = 8, 5.5%). Lamprey were also last detected on HD-PIT antennas in Hood River (*n* = 1, 0.7%), Fifteenmile Creek (*n* = 6, 4.1%), and the Deschutes River at Sherar's Falls (*n* = 1, 0.7%) (Table 5, Figure 13).

Final locations of reservoir-released lamprey were determined based on their last detection (Figure 13). Reservoir-released lamprey were classified as passing The Dalles Dam (*n* = 92, 63.0%), entering a tributary to the reservoir (*n* = 17, 11.6%), or last detected in the reservoir with unknown final fate (*n* = 37, 25.3%).

Once above Bonneville Dam, both release groups showed similar patterns in reach escapement, particularly when passing dams (Figure 14). The tailrace-release group had a distribution pattern similar to reservoir-released fish within Bonneville Reservoir.

JSATS receivers located immediately upstream and downstream of Miller Island and at the mouth of the Deschutes River were used to monitor lamprey behavior as they approached the tributary. Nearly half of all tagged lamprey (*n* = 131, 43.8%) were detected approaching Miller Island. Twelve (9.2%) of these were last detected on the Deschutes River mouth receiver, 7 (5.3%) were last detected at downstream sites, and another 12 (9.2%) were last detected on the Miller Island receivers. The remaining fish that approached Miller Island (*n* = 100, 76.3%) were last detected at upstream sites. Nearly all of the lamprey that were recorded upstream of Miller Island passed the island with no evidence of milling in the area. Milling behavior was defined as any downstream movements or residence times in excess of 15 minutes. Two lamprey (2%) were recorded making downstream movements before resuming upstream migration, and no tagged fish were recorded residing at the Deschutes River mouth or Miller Island receivers for longer than 20 minutes.

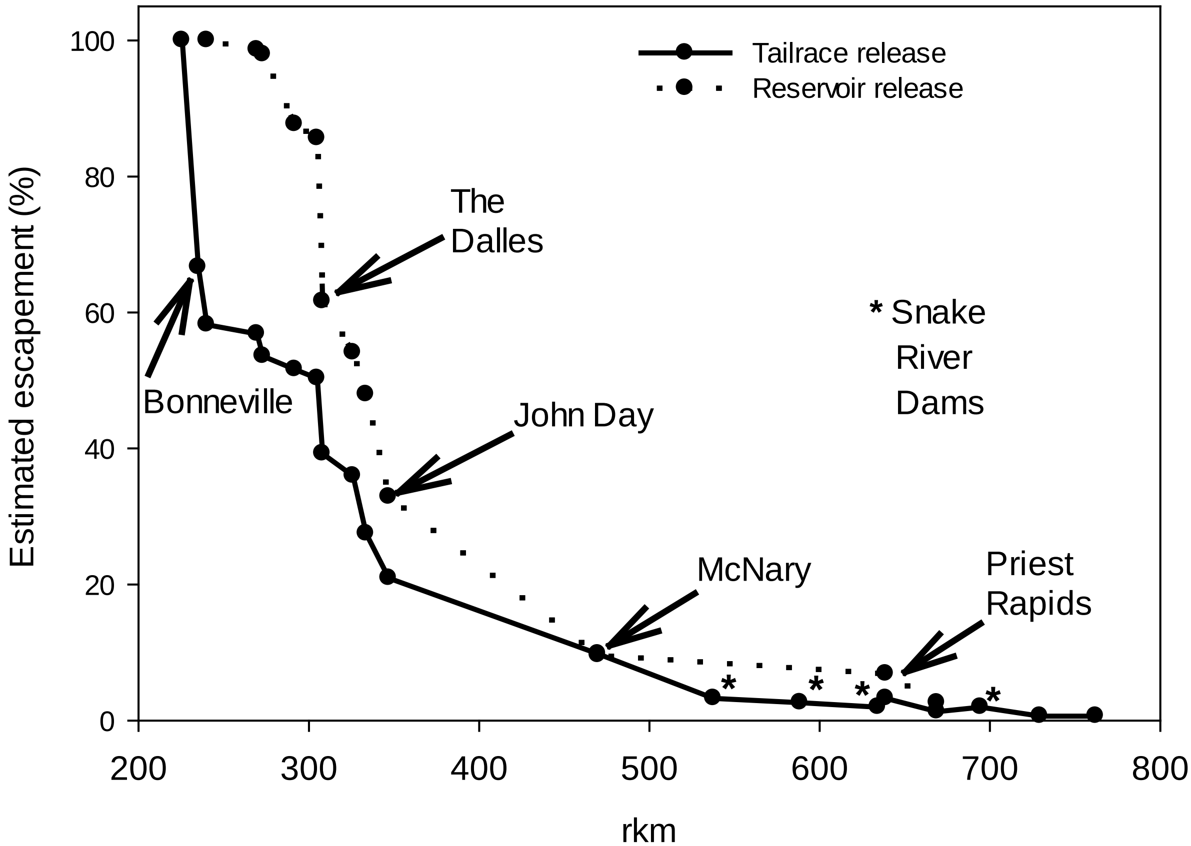

Figure 11. Escapement estimates for JSATS-tagged Pacific lamprey for the Bonneville Dam tailrace release group and Bonneville Reservoir release group. Estimates were made using JSATS and HD-PIT detection records.

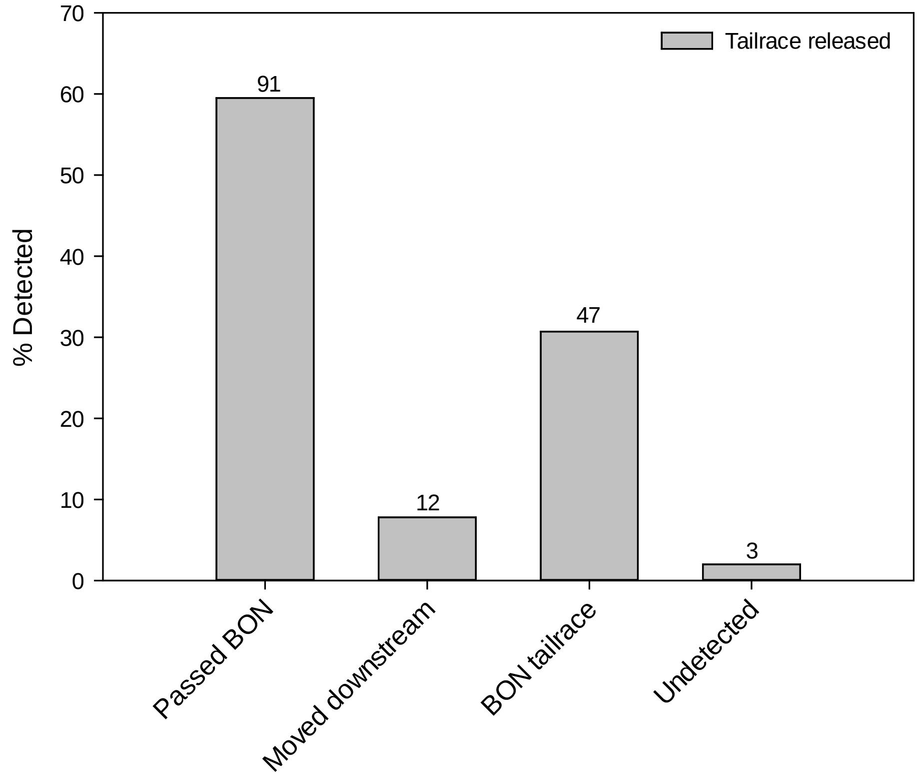

Figure 12. Final locations of JSATS-tagged Pacific lamprey released in the Bonneville Dam tailrace. Estimates were made using final records on JSATS and HD-PIT receivers.

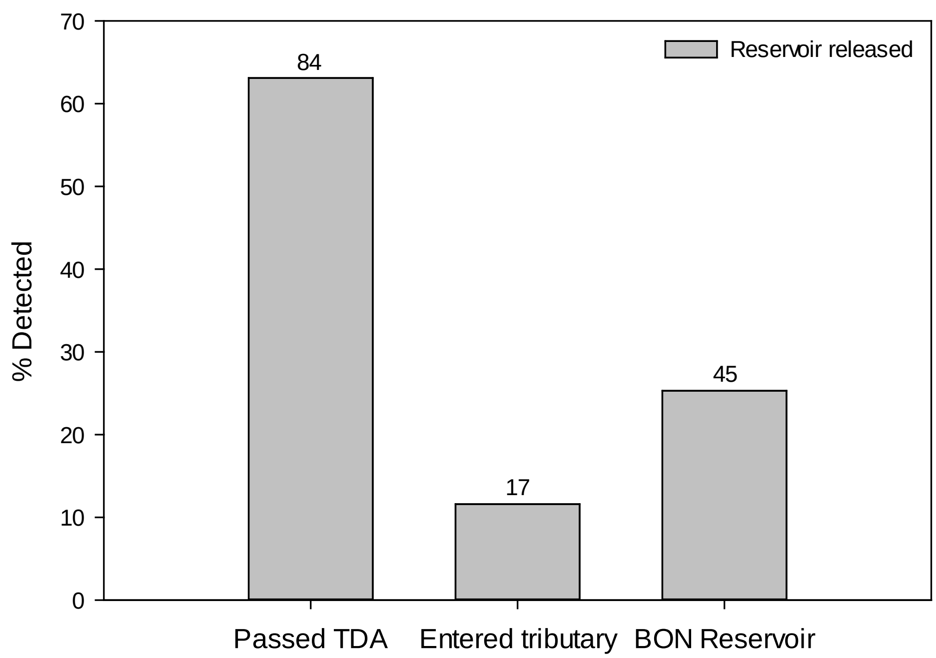

Figure 13. Final locations of JSATS-tagged Pacific lamprey released in Bonneville Reservoir. Estimates were made using final records on JSATS and HD-PIT receivers.

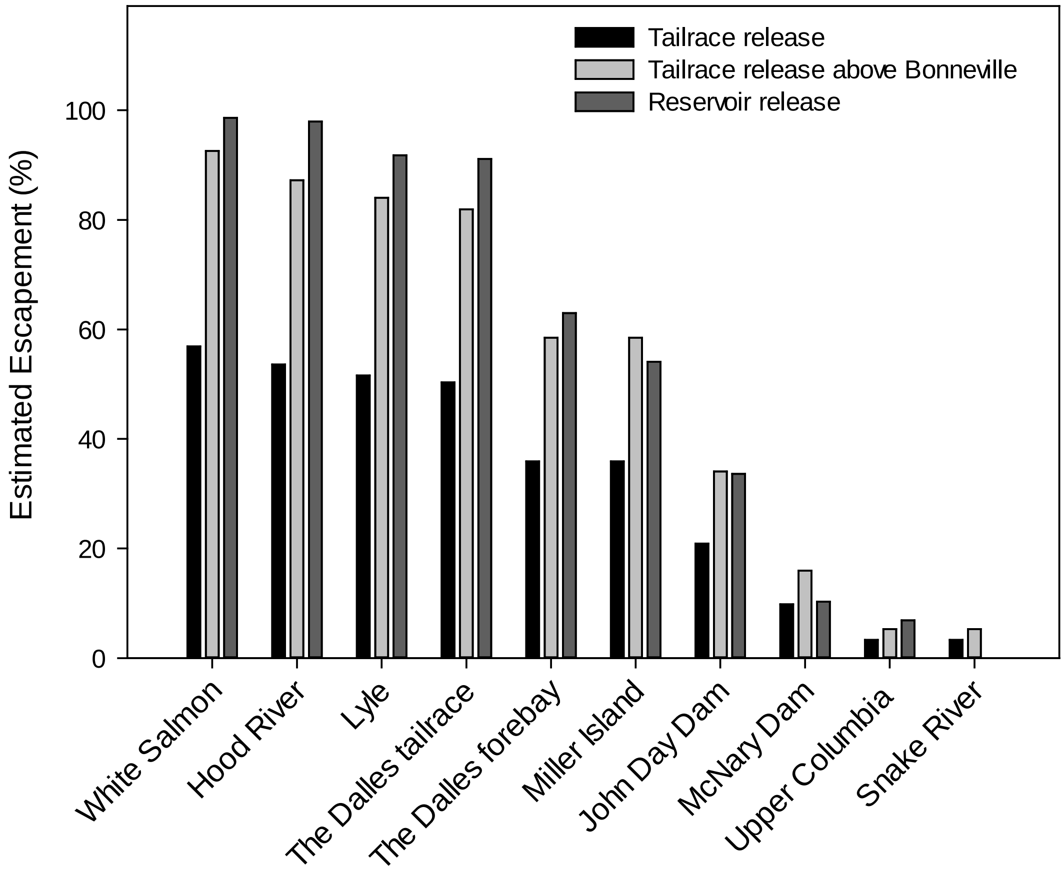

Figure 14. Escapement estimates for JSATS-tagged Pacific lamprey for the Bonneville Dam tailrace release group, tailrace-released lamprey known to have passed Bonneville Dam, and Bonneville Reservoir release group. Estimates were made using JSATS and HD-PIT detection records.

Table 5. Escapement estimates by reach for JSATS-tagged Pacific lamprey.

Tailrace release (*n* = 153)			Reservoir release (*n* = 146)		
Reach	*n*	%	Reach	*n*	%
Release to Bonneville Dam tailrace	149	97.4			
Release to Bonneville Dam	102	66.7			
Release to Bonneville forebay	94	61.4			
Release to White Salmon River gate	87	56.9	Release to White Salmon River gate	144	98.6
Release to White Salmon River mouth	1	0.7	Release to White Salmon River mouth	1	0.7
Release to Hood River mouth	3	2.0	Release to Hood River mouth	3	2.1
Release to Hood River gate	82	53.6	Release to Hood River gate	143	97.9
Release to Klickitat River mouth	3	2.0	Release to Klickitat River mouth	7	4.8
Release to Lyle, WA	79	51.6	Release to Lyle, WA	134	91.8
Release to The Dalles Dam tailrace	77	50.3	Release to The Dalles Dam tailrace	133	91.1
Release to Fifteenmile Creek	4	2.6	Release to Fifteenmile Creek	6	4.1
Release to The Dalles Dam	60	39.2	Release to The Dalles Dam	92	63.0
Release to The Dalles Dam top of the ladder HD-PIT antennas	55	35.9	Release to The Dalles Dam top of the ladder HD-PIT antennas	88	60.3
Release to downstream of Miller Island	55	35.9	Release to downstream of Miller Island	79	54.1
Release to Deschutes River mouth	3	2.0	Release to Deschutes River mouth	9	6.2
Release to upstream of Miller Island	42	27.5	Release to upstream of Miller Island	71	48.6
Release to John Day Dam	32	20.9	Release to John Day Dam	49	33.6
Release to McNary Dam	15	9.8	Release to McNary Dam	15	10.3
Release to Ice Harbor Dam	5	3.3	Release to Ice Harbor Dam	--	--
Release to Lower Monumental Dam	5	3.3	Release to Lower Monumental Dam	--	--
Release to Little Goose Dam	3	2.0	Release to Little Goose Dam	--	--
Release to Priest Rapids Dam	5	3.3	Release to Priest Rapids Dam	10	6.8
Release to Wanapum Dam	2	1.3	Release to Wanapum Dam	4	2.7
Release to Lower Granite Dam	3	2.0	Release to Lower Granite Dam	--	--
Release to Rock Island Dam	1	0.7	Release to Rock Island Dam	2	1.4
Release to Rocky Reach Dam	1	0.7	Release to Rocky Reach Dam	1	0.7

2011 JSATS-tagged lamprey

Monitoring for 2011 JSATS-tagged lamprey continued through the winter of 2011 and spring of 2012. Of the 85 lamprey tagged in 2011, seven (8.2%) were detected in 2012. Two of these fish were detected moving downstream from potential spawning areas in late June 2012 and were likely post-spawn carcasses. One fish last detected in 2011 in the Bonneville Dam tailrace was detected in 2012 at the same location. The remaining four fish were last detected in Bonneville Reservoir in 2011 and had been previously classified as having unknown final fates based on records through fall 2011. These four lamprey represent 8.3% of the total number of unaccounted for fish in 2011 (*n* = 48), and 12.1% of all fish last detected in Bonneville Reservoir in 2011 (*n* = 33). All four of these lamprey were last detected in early spring 2012 on receivers at the mouth of the Klickitat River (*n* = 3) or Hood River (*n* = 1).

2012 JSATS-tagged lamprey detected in 2013

Twenty-four percent (*n* = 72) of lamprey tagged with JSATS transmitters in 2012 were detected again in 2013. Eight of these fish (11.1%) were recorded entering spawning tributaries in early spring 2013, representing 12.5% of those classified as having unknown fate in the Bonneville Reservoir based on detections through fall of 2012. Fifteen fish (20.8% of those detected in 2013) had been recorded entering spawning tributaries in 2012 and were detected in late spring and early summer 2013 exiting these tributaries and moving downstream. The remaining forty-nine fish (68.1%) were detected moving between mainstem receivers. The majority of these were recorded moving downstream (*n* = 42, 80%), although seven lamprey (20%) were detected passing Bonneville Dam in 2013.

Mobile tracker testing

Field testing of the mobile tracking unit in 2012 revealed several flaws. Stationary test JSATS transmitters were deployed at varying depths (bottom, mid-water column, and surface) by affixing them to ropes attached to surface buoys. We also released a small sample (*n* = 5) of tagged lamprey within detection range of the boat mounted mobile tracker. The mobile tracker failed to detect any of the tagged lamprey and only detected the rope mounted transmitters sporadically. Transmitters successfully detected by the mobile tracker were inaccurately displayed by the included mapping software. Further field testing was halted and the unit was returned to the manufacturer for necessary modifications. The primary limitations appeared to be related to software and high noise generated when attempting to track in a moving boat in areas with current.

Discussion

Past monitoring of adult Pacific lamprey in the Columbia River using radio- and HD-PIT telemetry systems has revealed low dam passage rates, unaccounted losses in Bonneville Reservoir and tailrace, and relatively rapid travel rates through reservoirs compared to passage rates at dams. Radio- and HD-PIT telemetry studies have been unable to determine the final distribution and fate of tagged lamprey that either failed to pass Bonneville Dam or that were last detected in Bonneville Reservoir. These limitations resulted in part from the inability of radio or HD-PIT technologies to monitor adult Pacific lamprey in deep-water habitats including Columbia River reservoirs and tailraces or through the winter and into the final spring migration and spawning period. Primary aims of this multi-year study have been to determine if the JSATS tag reduced tagging effects compared to radio-tags and simultaneously to evaluate the potential for the JSATS technology to monitor lamprey movements in deep-water habitats through the spawning period.

An important element of the 2010 -2012 JSATS evaluations has been to assess whether JSATS-tagged adult lamprey exhibit evidence of smaller or larger tag effects with respect to available comparison groups (HD-PIT only groups sampled concurrently and radio-only and radio+HD PIT double-tagged groups from previous studies). Past studies have consistently indicated that radio-tags are associated with a decreased probability of dam passage compared to HD-PIT tag groups (e.g., Keefer et al. 2010). We anticipated that the JSATS tag might decrease the magnitude of this effect because the tag is slightly smaller and flatter in profile than radio transmitters used in previous studies and because lamprey behavior may be affected by the external antenna and catheter required for radio transmitters. No lampreys were radio-tagged in 2012, precluding direct comparison. The best available analysis is the comparison of conversion rates between the exit of Bonneville Dam to exit of The Dalles for HD-PIT-only samples vs. double-tagged samples (RT+HD-PIT in 2007-2009 or JSATS+HD-PIT in 2012) released below Bonneville Dam. In 2012, the Bonneville exit-to-The Dalles exit estimates were 58.5% for JSAT+HD-PIT fish versus ~50% for HD-PIT-only fish. The slightly higher conversion for JSATS+HD fish was at least partially a result JSATS fish being collected earlier in the migration, on average, than the HD-PIT-only fish. In 2007-2009, the RT+HD-PIT samples had consistently lower Bonneville exit-to-The Dalles exit conversions than HD-PIT-only samples (RT+HD-PIT: 25-40%; HD-PIT only: 52-63%; annual difference in conversion was 12-38% higher in HD-PIT-only samples). As in the 2012 studies, there were differences in all previous years in the timing of sample collection for the different tag groups, making direct comparisons potentially misleading. Overall, however, we provisionally conclude that the JSATS tag had no additional tag effects over the HD-PIT only tagging protocol and appeared to have less effect than RT protocols.

In the spring of 2013 we monitored for movements of lampreys tagged with the 400 day JSATS tag in 2012. We expected some lamprey to resume migration in spring, and receivers were redeployed with an increased emphasis on tributary locations. Detection of lampreys in the spring further confirmed the ability of the JSATS technology to provide information on lamprey movements during the spring spawning season, including some evidence of post-spawn downstream movements by adults or spawned out carcasses. The high detection efficiencies at most locations and concordance between HD-PIT detections and JSATS records demonstrate that quantitative estimates of reach conversions and final distributions are possible for migrating adult Pacific lamprey using the JSATS system.

Travel times and migration rates

JSATS monitoring provided the opportunity to estimate migration rates of lamprey within the reservoir without the influence of dam passage time (a complicating factor for HD-PIT only samples). Within-reservoir travel times and migration rates varied greatly among individual lamprey, but were typically rapid. Medians were similar to those observed in the 2010 and 2011 JSATS studies (Naughton et al. 2011; Noyes et al. 2012).

Distribution

Determining the final distribution of lamprey with last records in FCRPS reservoirs was a primary biological objective of this study. Distributions of tagged fish in both release groups were similar to distributions seen in previous years. The distribution patterns reported in previous years were mostly determined from detections on radio and HD-PIT antennas located at dams, and only showed if a tagged fish approached, entered, exited, or passed a dam, or entered a tributary in the fall for radio-tagged adults. Generally, of the tagged fish observed to successfully migrate past a given dam in past studies about half were not detected at upstream dams (e.g., Keefer 2009a, d). Little is known from past studies of the final fates of the lampreys last detected entering Bonneville Reservoir, though past radiotelemetry studies indicate that relatively few adults moved into spawning tributaries that empty into Bonneville Reservoir in the fall or early winter (prior to the expiration of radio tag battery life; e.g., Moser et al. 2002; Keefer et al. 2010).

Monitoring in and at the mouths of the Hood, White Salmon, Klickitat, Deschutes, and John Day Rivers (JSATS) and in Fifteenmile Creek (HD-PIT) determined or implied that forty-one of the JSATS adults (13.7%) entered one of these tributaries in 2012. An additional eight lamprey (2.7%) were detected entering these tributaries in the spring of 2013. Past radiotelemetry studies suggest movements into the Klickitat River and Fifteenmile Creek are more common than into other Bonneville Reservoir tributaries during late summer and fall (Keefer et al. 2010).

A key finding of this study is the observation that the vast majority (89.2%) of adults that entered or were released to Bonneville Reservoir rapidly and successfully passed ~80% the length of the reservoir and were detected at the Lyle gate, approximately 16 rkm downstream from The Dalles Dam. This suggests that migration conditions and factors such as predation did not strongly contribute to the overall unaccounted-for fates in the Bonneville Reservoir during the summer and fall migration, and that fish probably were not overwintering in the downstream two-thirds of Bonneville Reservoir. Potential mechanisms include: 1) Lampreys are overwintering in The Dalles Dam tailrace and resuming upstream migration in the spring, 2) Lampreys are overwintering in The Dalles Dam tailrace and returning to downstream spawning tributaries in the spring, 3) Lampreys are spawning in The Dalles Dam tailrace in the spring, 4) adults with final records at Lyle and The Dalles Dam tailrace were prespawn mortalities or predation mortalities. Previous HD-PIT studies show little evidence that fish resume upstream movement in the main stem in the spring following tagging, and the high percentages of fish that reach upper Bonneville Reservoir sites suggest that prespawn and predation mortality in the lower reservoir accounts for few missing fish, at least in summer or fall. Fixed receiver sites in the Bonneville Dam tailrace and Bonneville Reservoir detected movements in spring and summer 2013 of tagged lamprey that were unaccounted for at the end of monitoring in fall 2012. These lamprey were detected entering monitored tributaries in 2013 at rates similar to those recorded by fish that were tagged in 2011 and redetected in 2012. Overall, these movements may account for 12.5% of the lamprey that were unaccounted-for in Bonneville Reservoir at the end of 2012. Future monitoring efforts should work to further resolve the fates of adults last detected in tailrace reaches and further refine estimates of tributary entry, particularly during the spring period prior to spawning.

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