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EVALUATION OF ADULT PACIFIC LAMPREY PASSAGE AT LOWER SNAKE RIVER DAMS

2015 Final Report

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EXECUTIVE SUMMARY

Declines in Columbia River basin anadromous fish have led to significant resource investments for the development of management actions intended to ameliorate these declines. More recently, efforts to understand declines in Pacific lamprey (*Entosphenus tridentatus*) abundance have received greater attention. Lamprey have been shown to play an important role in the ecology of the Basin, and like salmon and steelhead, they are integral to the culture of regional Native American tribes. While causes of Pacific lamprey declines are not well understood, studies indicate that passage at dams may be a primary limiting factor for adult lamprey escapement. As a result, U.S. Army Corps of Engineers (USACE) and other management and research organizations have focused lamprey data collection efforts on dam passage throughout the Columbia Basin. Initial efforts focused on lower Columbia River dams; however, a 2013 pilot experiment demonstrated similar patterns in passage behavior in the lower Snake River, the largest tributary to the Columbia River. Briefly, in the summer of 2013, Umatilla Tribal biologists collected adult lamprey at John Day Dam, implanted them with Passive Integrated Transponder (PIT) tags, and released them downstream of Lower Monumental Dam at river kilometer (rkm) 584. Roughly half of the 37 fish released were detected at monitoring sites within the fish ladders at Lower Monumental Dam, and 10 fish were detected at the top of the fish ladders. These results demonstrated that a similar large enough proportion of translocated lamprey are likely to migrate upstream to attempt passage of Snake River dams that translocation was a viable option for future studies.

The purpose of this study is to build upon the 2013 pilot experiment, evaluate passage success through the adult fish ladders, and quantify conversion rates at the four lower Snake River dams to identify potential passage impediments and opportunities for future fishway improvements. Due to low abundance of lamprey in the lower Snake River, translocation of lamprey from the mainstem Columbia River to the lower Snake River was necessary in order to ensure sufficient sample size for meaningful passage analysis. Protocols and procedures were put in place to ensure the translocated population matched the timing and distribution of lower Snake River lamprey populations.

In the summer of 2014 and 2015, Pacific lamprey were captured, radio tagged and half-duplex (HDX) PIT tagged at John Day Dam before being released in the lower Snake River (n = 199 in 2014 and 363 in 2015). These study fish were distributed among four release sites at Ice Harbor Dam; three in the tailrace and one in the forebay. In the tailrace, fish were released at dusk from the south shore (n = 61 in 2014 and 90 in 2015), north shore (n = 64 in 2014 and 90 in 2015) or from a boat mid-channel (n = 25 in 2014 and 90 in 2015), approximately 8.3 km downstream of the dam. In the forebay, fish were released at Levey Park approximately 4.5 km upstream of the dam (n = 49 in 2014 and 91 in 2015). Fish were monitored at numerous detection sites located within the fishways at each of the four lower Snake River dams, as well as along the upstream face of each dam. Passage timing at Ice Harbor Dam peaked in late July in 2014 and mid-August in 2015, concurrent with the number of fish released and available for passage. Passage timing at Lower Monumental Dam had a bimodal distribution with peaks in mid-July and mid-August in 2014 and was unimodal in 2015 with a single peak in mid-August. Detections at Little Goose Dam and Lower Granite Dam revealed passage occurring throughout the month of August, but the ability to describe passage timing distribution patterns was limited by small sample sizes for these two dams. In the majority of cases, lamprey ascended Snake River dams within one day of entering a fishway. Comparison of 2014 and 2015 lamprey passage metrics between Snake River dams revealed that entrance ratios progressively increased from Ice Harbor Dam (71%; n = 55 in 2014 and 79%; n = 141 in 2015) to Lower Granite Dam (100%; n = 8 and 9 in 2014 and 2015, respectively), while passage efficiency remained fairly consistent among dams (~53 to 65%; n = 5 to 41 in 2014 and ~47 to 67%; n = 6 to 85 in 2015). Passage metrics (approach, entrance and passage efficiency) were consistently higher at Lower Monumental, Little Goose, and Lower Granite Dams for fish released in Ice Harbor Dam tailrace compared with those released in the forebay. We also found that mid-channel tailrace release groups performed better than the north and south shore release sites at both Ice Harbor and Lower Monumental Dams. Ice Harbor Dam and Little Goose Dam had the highest fallback rates, with 10% of fish passing eventually detected downstream after passing in 2014 and 28% and 18%, respectively, in 2015. Only 3% and 2% of fish in 2014 and 2015, respectively, fell back below Lower Monumental Dam and none of the fish that passed Lower Granite Dam descended back into the Snake River hydropower system. Relative to studies completed between 2005 and 2010 at McNary Dam on the main stem Columbia River, lamprey entered and passed Lower Snake River dams at comparable rates, indicating that translocation of lamprey to the Snake River was not associated with large additional handling effects compared to similar tagging studies elsewhere in the Columbia Basin.

INTRODUCTION

The Snake River is the largest tributary to the Columbia River, and provides significant fisheries resources in the Basin (i.e., Hassemer et al. 1997). However, as with most watersheds in the Pacific Northwest, Snake River anadromous fish runs have been on a steady decline due to various climatic, environmental and anthropogenic factors. Declines in Snake River salmon and steelhead abundance led to significant resource investments to develop effective fisheries management actions intended to ameliorate decreased abundance. Although their abundance trend revealed similar declines, anadromous Pacific lamprey were not initially a primary concern for these efforts (USFWS 2011). However, concern for lamprey in the region increased as indications of their decline became more evident, particularly in inland areas such as the upper Snake River basin, where Lower Granite Dam counts have ranged from a high of 282 to a low of 12 individuals over the last ten years (Fish Passage Center; http://www.fpc.org/lamprey/adultladder_lamprey_query.html).

While causes of lamprey abundance declines are not well understood, early research indicates that dam passage might be a primary limiting factor for adult lamprey escapement throughout the Columbia River system (CRBLTWG 1995; and see Keefer et al. 2013a). As a result, improvements for lamprey passage at dams was emphasized by the Columbia Basin Pacific Lamprey Technical Workgroup (CRBLTWG 1995), tribal agencies (Close et al. 2002), the U.S. Army Corps of Engineers (USACE 2009), and the Northwest Power Planning Council (see section 7.5F of the 2000 Columbia River Basin Fish and Wildlife Program, and the 2008 Fish Accord Memorandum of Agreement related to effects of Federal Columbia River Power System (FCRPS) projects on passage of Pacific lamprey in the Columbia Basin).

Adult lamprey passage evaluations using radio telemetry were initiated in 1997 at Bonneville Dam by the Portland District of the USACE, and the lower Columbia River continues to be the primary focus for adult passage investigations in the system (Keefer et al. 2013a). Concurrent investigations of adult lamprey passage by the Walla Walla District USACE were initiated at McNary and Ice Harbor dams in 2005. Over time, research methods have expanded to include HDX PIT tags, optical video, acoustic imaging and juvenile salmon acoustic telemetry system (JSATS) technology. Adult Pacific lamprey must pass up to eight dams and reservoirs to reach historical spawning areas in the Snake River—four dams in the lower Columbia River and four in the Snake River (Close et al. 1995)–but until now the bulk of the work has continued to occur in the lower Columbia River because of the limited number of lamprey available for research in the upper basin. Despite large tagging efforts at downstream sites (summarized in Keefer et al. 2012; Keefer et al. 2014), low passage rates at lower Columbia River dams prevented accurate assessment of passage behavior at lower Snake River dams.

In 2008, tribal biologists began adult lamprey collection at lower Columbia River dams to be used in a translocation/reintroduction program (Ward et al. 2012). Fish collected were released into tributary streams as a means to boost escapement and natural production. This effort is ongoing, with annual agreements among the tribes and regional fish managers regarding the numbers and locations where adult lamprey are to be collected. Translocated adult lamprey have been monitored post-release in tributary streams using radio telemetry (Ward et al. 2012). Adult lamprey collected at Little Goose Dam were used to track behavior and distribution of adult migrants upstream of Lower Granite Dam (McIlraith et al. 2015). Results from those evaluations indicate that translocated adult lamprey will continue to migrate upstream post-release and that they behave similarly to non-translocated study animals. Based on these findings, regional managers agreed to explore the use of translocated lamprey as study animals to initiate passage evaluations for adult Pacific lamprey in the lower Snake River.

In 2013, a pilot study on the lower Snake River to demonstrated the efficacy of the proposed approach. Adult lamprey were collected by Umatilla Tribe biologists in the summer of 2013 at John Day Dam, PIT tagged, and released at Windust Park (rkm 584), 4.7 km downstream of Lower Monumental Dam. The results were summarized in a letter report provided to the Walla Walla District USACE on 5 November 2013 (Peery et al. 2013). Briefly, 17 of 37 (46%) PIT-tagged lamprey were detected at monitoring sites at Lower Monumental Dam and 10 (59%) of those 17 fish reached top-of-ladder sites, indicating likely dam passage. There was also the indication that up to 4 (40%) of the lamprey that passed the dam, fell back downstream, and later re-entered either the north or south shore fishways. Conclusions from this preliminary effort were that adult lamprey from downstream locations can be used in a Snake River passage evaluation and that lamprey passage concerns associated with success and fallback at Lower Monumental Dam should be further examined. A large-scale radio telemetry study was initiated during 2014, and this report summarizes the results of a two-year investigation to evaluate lower Snake River adult Pacific lamprey passage with emphasis on findings from monitoring in 2015. A similar report provides the detailed results of our 2014 monitoring effort (Stevens et al. 2015).

The purpose of this project was to evaluate passage behavior through the adult fish ladders and conversion rates at the lower Snake River dams in order to identify potential passage impediments and opportunities for fishway improvements. Specific study objectives were:

Objective 1. *Determine which of multiple ladder entrances slots attract the majority of migrating adult lamprey to aid in developing future entrance design modifications.*

Objective 2*. Estimate adult lamprey upstream passage success rates, relative fishway route use, passage times, turnaround/ladder fallout, and forebay fallback at Ice Harbor, Lower Monumental, Little Goose and Lower Granite dams using radio-telemetry, HDX-PIT technology, and visual counts.*

Objective 3. *Determine conversion rates of migrating adult lamprey between Snake River dams based on a combination of radio-telemetry and PIT-tag detections.*

METHODS

Adult Pacific lamprey were collected from John Day Dam by a combination of tribal biologists, US Fish and Wildlife Service, University of Idaho, US Army Corp of Engineers and Cramer Fish Sciences staff. Fish were outfitted with radio telemetry transmitters and HDX PIT tags by U.S. Fish and Wildlife Service (USFWS) personnel in 2014 and University of Idaho personnel in 2015, transported and released at locations in the tailrace and forebay of Ice Harbor Dam, and monitored at all four lower Snake River dams to identify potential passage impediments and areas for future fishway improvements (Figure 1). Fish movements were monitored using techniques similar to those used in previous radio-telemetry studies on the Columbia River (e.g., Naughton et al. 2007 Johnson et al. 2012; Caudill et al. 2013; Keefer et al. 2013a and 2013b). Results were compared to existing information from previous and concurrent studies conducted in the Columbia and Snake rivers. We also included monitoring of tributary streams within the upper Columbia River and within and upstream of the lower Snake River from unrelated studies to help determine final fates of fish.

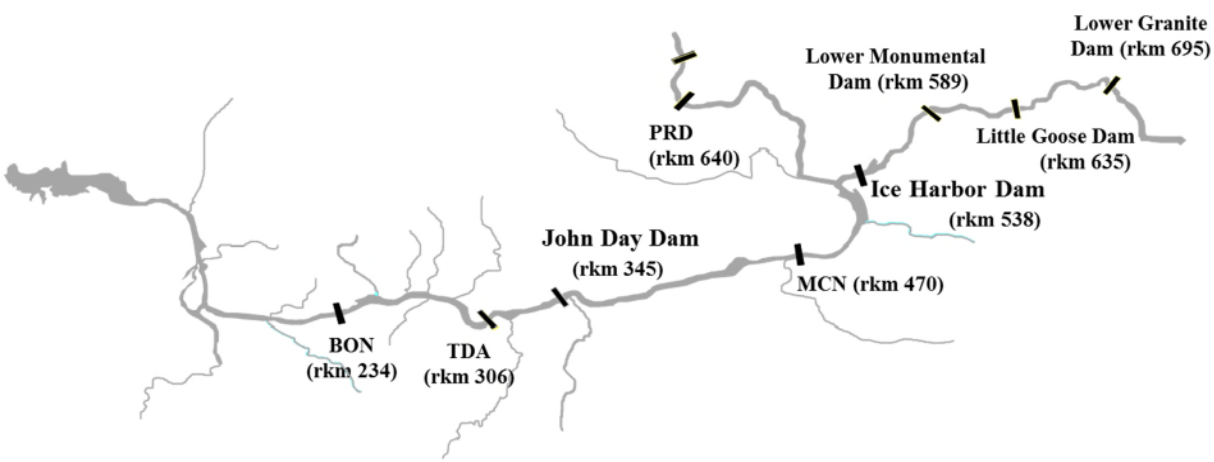

Figure 1. Schematic of the study area. Lamprey were collected at John Day Dam on the Columbia River and released at Ice Harbor Dam on the Snake River.

Fish Collection, Tagging, and Release

Our project team coordinated with regional managers, the USACE and tribal biologists to collect adult lamprey from lower Columbia River dams as part of the lamprey translocation/ reintroduction program. With assistance from tribal biologists, adult lamprey were collected by fixed trap in the south shore fishway, the Lamprey Passage Structure (LPS) of John Day Dam (rkm 347), which is operated in the north shore fishway entrance and from funnel traps on the John Day Dam north shore. The target sample size was 300-500 adult Pacific lamprey to be collected and outfitted with transmitters annually. The intent was to match tagging and telemetry operations with lamprey run timing at Ice Harbor Dam, which typically occurs July to mid-October (Figure 2). Fish were collected and radio-tagged between July and October. However, rapid spring warming at John Day Dam in 2015 resulted in an early period of no tagging due to temperature restrictions on collection and handling. Typically fish were collected four nights each week (traps set in the evening), Sunday/Monday and then Thursday/Friday. The following mornings the traps were checked and any fish collected were moved to holding tanks at the juvenile fish facility. The north shore LPS was run continuously. On days fish were tagged, LPS lamprey were transferred to the juvenile fish facility. Otherwise, trapped fish were released upstream of John Day Dam.

Lamprey were surgically outfitted with radio transmitters (Lotek Wireless; NTC-4-2L, 79 day battery life with 5 sec burst rate; 18.3 ×8.3 mm, 2.1 grams in air) and HDX PIT tags (Texas Instruments; 23 mm×3.8 mm, 0.6 grams) using standard procedures (Moser et al. 2002; Moser 2007). Study animals were individually anesthetized using (60 ppm eugenol (2014; INAD Study Number 11-741-14-166F) or 90 mg/L AQUI-SE 20 (2015, INAD Study Number 11-741-15-121F), their length, weight and girth was measured and then each was placed head down into a 10 cm diameter polyvinyl chloride (PVC) cradle that maintained the head and gills submerged, but allowed access to the ventral surface of the lamprey for surgery. An incision approximately 2 cm long was made just left of the ventral midline directly below the anterior insertion of the first dorsal fin. The HDX PIT tag was inserted first into the body cavity followed by a catheter, which was pushed through the body wall about 5 cm posterior to the incision. The radio tag antenna was threaded through the catheter and the catheter was removed, leaving the antenna protruding through a small hole in the skin. The incision was closed with two or three simple interrupted Monocryl™ 3-0 sutures. After surgery, tagged fish were returned to the holding tanks where they were held until transported to the Snake River for release. In the evenings, tagged fish were moved to aerated coolers and driven 185 river kilometers upstream for release below Ice Harbor Dam (rkm 538). Temperatures were monitored during transport and ice was added to the coolers if temperatures increased by more than 1°C en route. Occasionally, when fewer than 10 fish were collected in a night, they would be held overnight at John Day Dam and combined with the following day's collection of fish for transport and release.

Radio-tagged lamprey were distributed among four release sites at Ice Harbor Dam; three in the tailrace and one in the forebay. In the tailrace, fish were released either from the south shore, north shore, or from a boat mid-channel approximately 8.3 km downstream from the dam. The three tailrace release sites were intended to distribute released lamprey to prevent bias based on an individual release location and to limit any negative effects of aggregation (e.g. – predation). In the forebay, fish were released at Levey Park, approximately 4.5 km upstream of the dam. The single release site in the Ice Harbor Dam forebay was intended to increase the likelihood that fish would ascend to the upper dams in the hydrosystem. Fish were typically released at dusk.

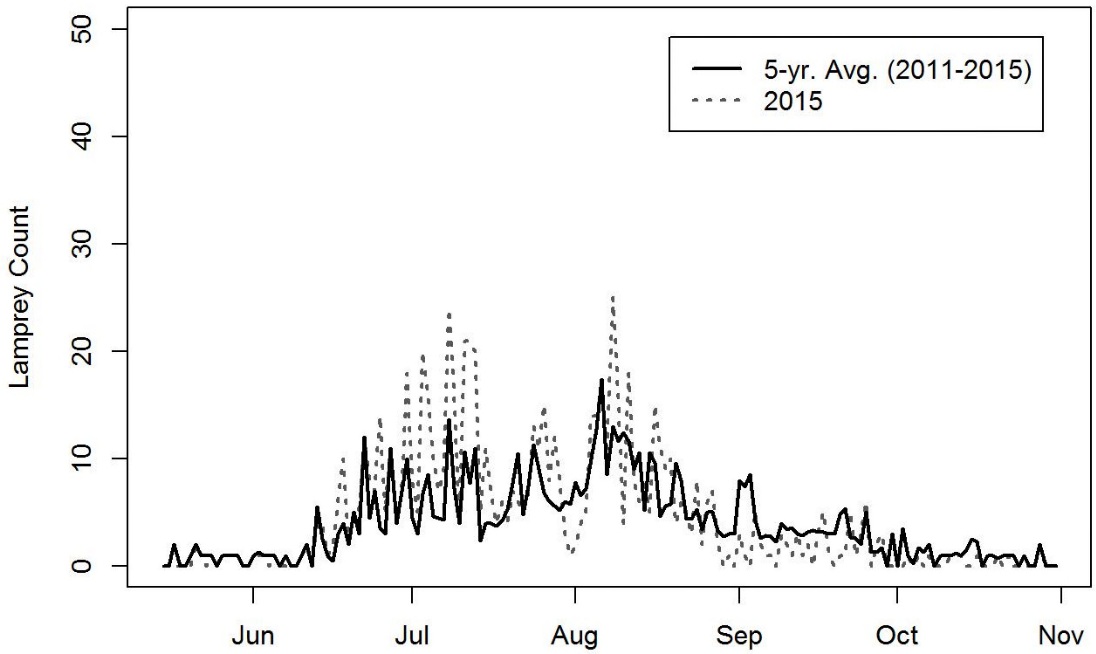

Figure 2. Numbers of adult Pacific lamprey counted at Ice Harbor Dam during 2015 and the five year average during 2011to 2015.

Installation and Maintenance of Radio Telemetry Systems

An array of fixed-site Lotek SRX 400 single antenna receivers and DSP 500/SRX 400 multi-antenna receivers were used at the four lower Snake River dams and other sites to monitor movements of radio-tagged adult Pacific lamprey (Table 1). Monitoring locations included the approach to the tailrace, approach to fishways, entrance to fishways, transition pool areas, ladder exits, and tributary mouths (Figure A-1 thru Figure A-4). In total, 38 receivers were deployed at sites identified in the Performance Work Statement. An additional 4 receivers operated by the USFWS and Nez Perce Tribe were also monitored to document fish dispersing into the Palouse or Tucannon Rivers or moving upstream into the Clearwater or upper Snake River. All main fishway openings, transition pool(s), and the ladder top(s) were monitored with underwater radio antennas connected to radio receivers except where access or fish passage concerns required the use of Yagi aerial antennas. Tailrace areas were monitored with six-element Yagi antennas. Tailrace sites were located ~0.5- 1.0 km downstream of each dam, with one on each side of the river. All receivers were deployed and tuned to provide detection ranges similar to those used in past studies (e.g., ~10 m detection range for underwater antennas; see Keefer et al. 2013a) prior to the arrival of tagged adult lamprey.

Table 1. Radio-telemetry monitoring locations for evaluating radio-tagged adult Pacific lamprey passing Snake River dams in 2015.

Location	Description	Receiver	Antenna	Purpose
Snake River	SNR NORTH SHORE WEST FENCE OF TIDEWATER TERMINAL	SRX	Aerial	Downstream migration
Snake River	SNR SOUTH SHORE EAST FENCE OF HOOD PARK	SRX	Aerial	Downstream migration
Ice Harbor Dam	SOUTH SHORE TAILRACE SITE	SRX	Aerial	Project entrance and fallback
Ice Harbor Dam	NORTH SHORE TAILRACE SITE	SRX	Aerial	Project entrance and fallback
Ice Harbor Dam	SOUTH SHORE ENTRANCE	SRX with DSP	Underwater	Passage
Ice Harbor Dam	SOUTH SHORE TRANSITION POOL	SRX with DSP	Underwater	Passage
Ice Harbor Dam	SOUTH LADDER COUNT WINDOW	SRX with DSP	Underwater	Turn-around
Ice Harbor Dam	SOUTH LADDER EXIT AND BELOW SERPENTINE SECTION	SRX with DSP	Underwater	Project exit
Ice Harbor Dam	NORTH POWERHOUSE ENTRANCE	SRX with DSP	Underwater	Passage
Ice Harbor Dam	NORTH SHORE ENTRANCE	SRX with DSP	Underwater	Passage
Ice Harbor Dam	NORTH LADDER EXIT AND COUNT WINDOW	SRX with DSP	Underwater	Turn-around and Project exit
Snake River	BIG FLAT HMU NORTH END	SRX	Aerial	Ice Harbor reservoir monitoring
Snake River	FISH HOOK PARK	SRX	Aerial	Ice Harbor reservoir monitoring
Lower Monumental Dam	SOUTH SHORE TAILRACE SITE	SRX	Aerial	Project entrance and fallback
Lower Monumental Dam	NORTH SHORE TAILRACE SITE	SRX	Aerial	Project entrance and fallback
Lower Monumental Dam	SOUTH LADDER ENTRANCE AND TRANSITION POOL AND DOWNSTREAM END OF TURN POOL	SRX with DSP	Underwater	Passage
Lower Monumental Dam	SOUTH LADDER EXIT AND BELOW COUNT POOL AND UPSTREAM END OF TURN POOL	SRX with DSP	Underwater	Turn-around and Project exit
Lower Monumental Dam	SOUTH POWERHOUSE ENTRANCE	SRX with DSP	Underwater	Passage
Lower Monumental Dam	NORTH LADDER ENTRANCE /COLLECTION CHANNEL EXIT NSE	SRX with DSP	Underwater	Passage
Lower Monumental Dam	BOTTOM NORTH LADDER/ TRANSITION POOL AND COUNT WINDOW	SRX with DSP	Underwater	Turn-around
Lower Monumental Dam	NORTH LADDER EXIT AND 2ND TURN POOL FROM TOP	SRX with DSP	Underwater	Project exit
Tucannon River	TUCANNON RIVER APPROX. 2.6 KM UPSTREAM FROM MOUTH	SRX	Aerial	Tributary monitoring
Palouse River	LYONS FERRY HATCHERY PUMP STATION 2.75 KM UPSTREAM FROM MOUTH	SRX	Aerial	Tributary monitoring
Little Goose Dam	NORTH SHORE TAILRACE SITE	SRX	Aerial	Project entrance and fallback
Little Goose Dam	SOUTH SHORE TAILRACE SITE	SRX	Aerial	Project entrance and fallback
Little Goose Dam	NORTH POWERHOUSE ENTRANCE	SRX with DSP	Underwater	Passage
Little Goose Dam	NORTH SHORE ENTRANCE	SRX with DSP	Underwater	Passage
Little Goose Dam	SOUTH POWER HOUSE ENTRANCE	SRX with DSP	Underwater	Passage
Little Goose Dam	SOUTH TRANSITION POOL	SRX with DSP	Underwater	Passage
Little Goose Dam	COUNT WINDOW AND TURN POOL	SRX with DSP	Underwater	Turn-around
Little Goose Dam	SOUTH LADDER EXIT AND BELOW SERPENTINE WEIR SECTION	SRX with DSP	Underwater	Project exit
Lower Granite Dam	SOUTH SHORE TAILRACE SITE	SRX	Aerial	Project entrance and fallback
Lower Granite Dam	NORTH SHORE TAILRACE SITE	SRX	Aerial	Project entrance and fallback
Lower Granite Dam	NORTH SHORE ENTRANCE	SRX with DSP	Underwater	Passage
Lower Granite Dam	NORTH POWERHOUSE ENTRANCE	SRX with DSP	Underwater	Passage
Lower Granite Dam	SOUTH SHORE ENTRANCE	SRX with DSP	Underwater	Passage
Lower Granite Dam	TRANSITION POOL-BOTTOM OF LADDER	SRX with DSP	Underwater	Passage
Lower Granite Dam	COUNT WINDOW AND TURN POOL ABOVE AND BELOW TRAP ENTRANCE/EXIT	SRX with DSP	Underwater	Turn-around
Lower Granite Dam	SOUTH LADDER EXIT AND BELOW SERPENTINE WEIR SECTION	SRX with DSP	Underwater	Project exit
Clearwater River	CLEARWATER RIVER S SHORE UPSTREAM OF POTLATCH	SRX	Aerial	Tributary monitoring
Asotin Creek	ASOTIN CITY PARK 0.45 KM UPSTREAM FROM MOUTH	SRX	Aerial	Tributary monitoring
Snake River	SNAKE RIVER W SHORE UPSTREAM OF 3-MILE ISLAND	SRX	Aerial	Tributary monitoring

Telemetry Site Downloading and Data Management

Receivers were regularly downloaded to minimize data loss from outages and prevent loss due to full memory banks. In 2014, initial data processing was performed by NOAA-Fisheries as part of a concurrent radio telemetry study of adult Pacific lamprey migration in the lower Columbia FCRPS. Data was transferred to an Oracle database on a Linux server housed and operated by NOAA-Fisheries Northwest Fisheries Science Center (Seattle, WA), where a copy of the long-term radio telemetry dataset for the project was initially processed and housed. Programs using standardized rules for processing data (e.g., filtering noise) were used to ensure data quality and compatibility with data from previous years. All data (original files and summarized data) were backed up nightly and validated prior to analysis. Processed files were then transferred to University of Idaho for further analysis. In 2015, all initial data processing work was taken over by University of Idaho using similar data management protocols. In both years, UI used an automated program to assign activity codes (e.g. – fishway approach and entry, dam passage and fallback, etc.) to the time-stamped detections. Each detection history then underwent manual quality assurance/quality control (QA/QC) to ensure proper assignment of activity codes. These detection history files were then assembled into a final, processed file, which was used for statistical analyses by Cramer Fish Sciences.

HDX PIT Tag Monitoring

HDX PIT tag detection data were collected from three of the lower Snake River dams (Ice Harbor, Lower Monumental and Lower Granite), as well as McNary Dam on the middle Columbia River and Priest Rapids, Wanapum and Rock Island Dams on the upper Columbia River. These data were processed and coded using similar methods as described above for radio telemetry data. Detections of lamprey at these sites were primarily used to identify fish that had lost or nonfunctioning transmitters, and/or passed dams after radio tag batteries expired.

HDX PIT tag data from fish translocated and released in the lower Snake River for this study, as well as fish tagged during concurrent studies in the mainstem Columbia River, were used, where feasible and appropriate, to corroborate the results of radio-telemetry data. Fish collected, tagged and released in the mainstem Columbia River as part of concurrent studies were captured, tagged and released using comparable methods and protocols at Bonneville Dam (similar to Keefer et al. 2014) such that lack of translocation are the only substantial differences. While lampreys released into the Columbia River volitionally entered the lower Snake River at low rates, they nonetheless provided a useful comparison to migration behaviors of translocated fish.

Given the limited detection ranges inherent in HDX PIT technology and fewer receivers deployed at each dam (i.e. – two to three per fishway), as compared with the radio-telemetry array, a limited suite of passage metrics was calculated from HDX PIT data. For release group metrics, entry and dam passage ratios were calculated. For fishway passage metrics, only fishway passage ratios could be calculated. For dam-wide passage metrics, only fallback ratios could be calculated. Approach and dam passage ratios could not be calculated for any of these classes of metrics due to the absence of approach detections from the HDX PIT data. For hydrosystem metrics, conversion ratios were calculated. Though we were unable to account for tributary entry, HDX PIT data was used to supplement and corroborate "final" fate information. One important note is that the top-of-ladder receiver at the south-fishway of Lower Monumental Dam was taken off-line to prevent interference with a nearby full-duplex (FDX) PIT tag receiver. As such, no fish were detected at this receiver for the duration of our study, which is why fishway-specific metrics are not provided at this location. It should also be noted that, for this same reason, HDX dam-wide or hydrosystem-wide metrics represent minimum estimates.

Passage Metrics and Data Analyses

Passage metrics calculated for this study fall into five broad categories: release group metrics, fishway use metrics, fishway-specific metrics, dam-wide metrics and reach-scale metrics (Table 2). For compatibility with previous studies, passage metrics were calculated using methods similar to those used in recent evaluations at McNary and lower Columbia River dams and as described in Keefer et al. (2012) though nomenclature may differ slightly. Release group metrics were used to analyze behavioral differences, if any, between release groups/locations. Release group metrics, combined with measures of biological factors such as size distributions, were used to determine if results have been biased by heterogeneity in biology or behavior between release groups/locations.

Release group metrics were calculated based on unique (i.e. – individual-based) detections of approaches, entries or passages by both release location and fishway. These metrics were only calculated for Ice Harbor and Lower Monumental dams since they were the only dams with lamprey released directly into their tailraces. Lamprey released in the Ice Harbor tailrace were only used to calculate metrics for Ice Harbor Dam and the same was true for Lower Monumental Dam. All fishway openings and fishways were combined for a given dam unless otherwise noted. Release group metrics (Table 2) include:

- Approach Ratio: estimate of lamprey success at locating fishway openings.
- Entry Ratio: estimate of lamprey success at entering fishway openings.
- Dam Passage Ratio: estimate of lamprey passage success for entire dam from fishway approach to exit at top of fishway.

Table 2. Calculation formulas for important passage metrics.

Metric Category	Passage Metric	Calculation Method
Release Group	Approach Ratio	Unique approached / # released in tailrace
	Entry Ratio	Unique entered / # released in tailrace
	Dam Passage Ratio	Unique passed / # released in tailrace
Fishway Use	Approach	Unique approaches at opening / unique approaches all openings at dam
	Entrance	Unique entrances at opening / unique entrances all openings at dam
	Exit	Unique exits at opening / unique exits all openings at dam
	Turnarounds	Total turnarounds in a given segment / total turnarounds in fishway
Fishway-specific	Entry Ratio	Unique entered / Unique approached
	Passage Ratio	Unique passed / Unique entered
Dam-wide	Passage Ratio	Unique passed / Unique approached
	Fallback Ratio	Unique fallbacks / Unique passed
Reach-scale	Conversion Ratio	Unique passed current dam / (Unique passed previous dam – (Unique fallbacks + Unique Tributary diversions))

Fishway use metrics were calculated based on unique (i.e. – individual-based) detections of approaches, entries or exits at the base of a fishway. These metrics describe the distribution of lamprey use at different fishway openings. These metrics were calculated for all four lower Snake River dams. Fishway openings were analyzed and presented separately. Fishway use Metrics include:

- Fishway Approach – lamprey approaching a given fishway opening as a proportion of total lamprey approaching all openings.
- Fishway Entrance – lamprey entering a given fishway opening as a proportion of total lamprey entering all openings.
- Fishway Exit – lamprey exiting a given fishway opening as a proportion of total lamprey exiting all openings.
- Fishway Turnarounds – lamprey turning around in a given segment of a fishway as a proportion of total turnarounds in that fishway

Fishway-specific metrics were calculated based on unique (i.e. – individual-based) detections of approaches, entries at the base of a fishway or exits at the top of a fishway (i.e. – passages) either by individual fishway or combined across fishways in the case of Ice Harbor and Lower Monumental dams. These metrics were calculated for all four lower Snake River dams. All fishway openings were combined. Fishway-specific metrics include:

- Fishway Entry Ratio: estimate of lamprey success at entering fishway openings. Note that this metric differs from the release group metric of the same name in that only those fish that approach the fishway are available for entry (i.e. – factored into the denominator) NOT all fish released or present in the tailrace.
- Fishway Passage Ratio: estimate of lamprey success passing individual fishways or aggregate fishways at a given dam. Note that this metric considers only fish that enter the fishway as candidates for passage (i.e. – denominator) meaning it accounts for passage barriers within the fishway, but not attraction flow, fishway location, etc.

Dam–wide metrics were calculated based on unique (i.e. – individual-based) detections for approaches, exits at the top of a fishway (i.e. – passages) or fallbacks from the top of a fishway back to the tailrace aggregated for a single dam. These metrics were calculated for all four lower Snake River dams. All fishway openings were combined and all fishways were combined in the case of Ice Harbor and Lower Monumental dams. Dam-wide metrics include:

- Dam Passage Ratio: estimate of lamprey success passing a given dam. Note that this metric differs from fishway passage ratio in that any lamprey that approaches a fishway entrance is considered a candidate for passage (i.e. – denominator) as opposed to only those lamprey that enter a fishway. As a result, this metric captures a more complete suite of potential passage barriers (i.e. – attraction flows, fishway location, fishway construction, etc.).
- Dam Fallback Ratio: estimate of lamprey falling back into the tailrace of a dam following a confirmed passage.

Also, median dam-wide entrance and passage times were calculated for Ice Harbor and Lower Monumental Dams. All unique (i.e. – individual-based) detections were used and all fishway openings at a given dam were combined. These passage times included:

- Entrance Time: the amount of time from first approach of a fishway opening to the first entrance at that opening.
- Passage Time: the amount of time from first approach of a fishway opening to the first exit at the top of fishway (i.e. – passage).

A Wilcoxon Rank Sum test was used to test for differences in median entrance or passage time between years for a given dam. Entrance or passage time was not tested between dams as differing physical conditions between dams make such comparisons non-sensical.

The hydrosystem metric, conversion ratio, was calculated based on unique detections for exits at the top of a fishway (i.e. – passages), fallbacks from the top of a fishway back to the tailrace and diversions into tributaries. Conversion ratio estimates lamprey success in passing successive dams within the entire hydrosystem. Note that only lamprey which successfully pass the immediate downstream dam were considered candidates for passage at the current dam (i.e. – denominator). Also, note that lamprey recorded falling back over the previous dam or moving into a monitored tributary were removed from the candidates for passage at the current dam. A “final” fate was determined for each lamprey released in this study based on its last detected location on or prior to December 28, 2015[1]. These final fates incorporate all fish tagged during the 2014 season which over-wintered in the hydrosystem and were subsequently detected on HDX PIT receivers throughout 2015. For fish tagged in 2015, fates could only be assigned using detections through December 28, 2015. Fish that may over-winter in 2015 and move in spring 2016 are not included. Radio-telemetry receivers at all lower Snake River dams, monitored tributaries on the lower Snake River and main stem and upper Columbia River (i.e. – McNary and Priest Rapids Dams) were interrogated for detections. These last known locations were then cross-referenced to HDX PIT tag interrogations, particularly for upper Columbia River dams (i.e. – Wanapum and Rock Island Dams) where radio-telemetry systems were not installed. Final fates for dams with both radio-telemetry and HDX PIT tag systems were consistent.

Analyses focused on developing passage metrics as described above for each fishway and dam on the lower Snake River, and on classifying passage behavior for migrants which did or did not pass individual or multiple dams successfully. Data collected for this evaluation also included biological and environmental variables likely to be related to lamprey migration behavior and success. Biological variables were primarily related to fish condition and included fish length, weight, girth, presence of injuries, and collection and release sites. Environmental factors included water temperature, flow, spill, and migration timing.

Associations were analyzed between passage rates and success at each dam and biological conditions (i.e. - fish size, source). Length by capture site and by release location were compared using Tukey’s Honest Significance Test to determine if lamprey size differed between capture or release location in such a way as to bias study results. Environmental conditions (i.e. - water temperature, flow/spill, release date) were considered for statistical analysis but exploratory analyses revealed insufficient sample size and/or insufficient variability in thermal and spill data to conduct meaningful analyses. Results were visually and qualitatively examined and compared. Logistic regression was performed on length distributions of fish that did versus did not pass lower Snake River dams but the results should be viewed as preliminary given the replication and sample size issues noted above. Other results were compared visually and described qualitatively with no attempt to assign statistical significance to direction or magnitude of effects.

[1] The batteries in all radio-telemetry tags implanted in adult lamprey during the 2014 and 2015 field seasons were expected to expire before December 28, 2015.

RESULTS & DISCUSSION

Lamprey Capture, Tagging & Release

A total of 373 lamprey were captured at John Day Dam and surgically implanted with radio tags and HDX PIT tags in 2015. However, manufacturing defects in the radio tags substantially impacted detection efficiencies for some fish (n = 12). As a result, analysis and reporting is limited to a total of 361 fish. One hundred and ten fish were captured in the John Day Dam north funnel, 73 were caught in the John Day north lamprey passage structure (LPS) and 178 were captured in the John Day south trap. Two-hundred and seventy of these fish were released into the Ice Harbor Dam tailrace and 91 were released into the Ice Harbor Dam forebay (Table 3).

Fish tagging efforts generally followed the trend in fish availability at John Day Dam (Figure 3). However, passage at John Day Dam peaks roughly one month earlier than passage in the lower Snake River. To compensate, we began tagging in mid-July, coincident with lamprey passage increases at Ice Harbor Dam. However, the abundance of lamprey at John Day Dam in mid-July skewed the number of fish released more heavily towards the early portion of the Snake River adult lamprey migration. Additional efforts in September to capture lamprey at multiple locations at John Day Dam were successful in both years, and we were able to release more fish during the later portion of the Snake River migration. This also served to increase our sample size following temperature restrictions on tagging during July-August, and reductions in lamprey availability in the John Day Dam LPS commensurate with high summer water temperatures.

During the 2015 radio-tagging season, average daily water temperatures ranged from a low of 17.5 ^{o}C to a high of 23.5 ^{o}C at Ice Harbor Dam from June 24 through October 10 (Figure 4). Water temperatures recorded at the other three Snake River Dams tended to be 1-2 ^{o}C cooler on average than those recorded at Ice Harbor Dam. Water temperatures were substantially higher in 2015 compared to 2014 and the onset of high temperatures was much earlier than recorded in the past decade. Between June 25 and July 27, 2015, lamprey radio-tagging at John Day Dam was suspended due to excessive water temperatures. Researchers in the Columbia River Basin have reached a consensus that water temperatures above 72 °F (22.2 ^{o}C) create conditions that are stressful for lamprey. Above that threshold, handling and surgical procedures are not advised (CRBLTWG 2005).

Flow conditions in the lower Snake River ranged from ~35,000 cfs to ~10,000 cfs during the 2015 field season (Figure 5). Flows generally declined throughout the summer and fall and were substantially lower in 2015 compared to 2014. Some deviations from this general flow trend are worth noting, such as the 10,000 cfs flow increase that occurred in late July 2014, which happened to coincide with the majority of our radio-tagged lamprey releases in the Ice Harbor Dam tailrace and forebay.

Table 3. Numbers of radio-tagged adult Pacific lamprey released into the tailrace (three sites) and forebay of Ice Harbor Dam, 2015.

	Release Location				
Date	Ice Harbor Tailrace - North shore	Ice Harbor Tailrace - Mid-channel	Ice Harbor Tailrace – South shore	Ice Harbor Forebay – Levy Park	Total
24-Jun-15+	4	4	4	-	12
28-Jul-15	10	9	9	-	28
30-Jul-15	12	11	10	-	33
04-Aug-15	11	6	-	-	17
05-Aug-15	-	-	-	20	20
08-Aug-15	7	12	10	-	29
10-Aug-15	13	14	14	-	41
12-Aug-15	-	-	5	6	11
13-Aug-15	6	-	6	8	20
25-Aug-15	3	5	4	7	19
27-Aug-15	1	3	4	6	14
04-Sep-15	3	6	4	7	20
09-Sep-15	4	4	4	6	18
11-Sep-15	4	5	4	6	19
15-Sep-15	4	4	3	5	16
17-Sep-15	3	3	4	4	14
22-Sep-15	2	2	2	2	8
24-Sep-15	5	5	6	11	27
30-Sep-15	1	1	1	2	5
10-Oct-15	1	-	-	1	2
Total	90	90	90	91	361

+ June 24 release group had faulty tags. They are included here for reference but omitted from further discussion or analysis.

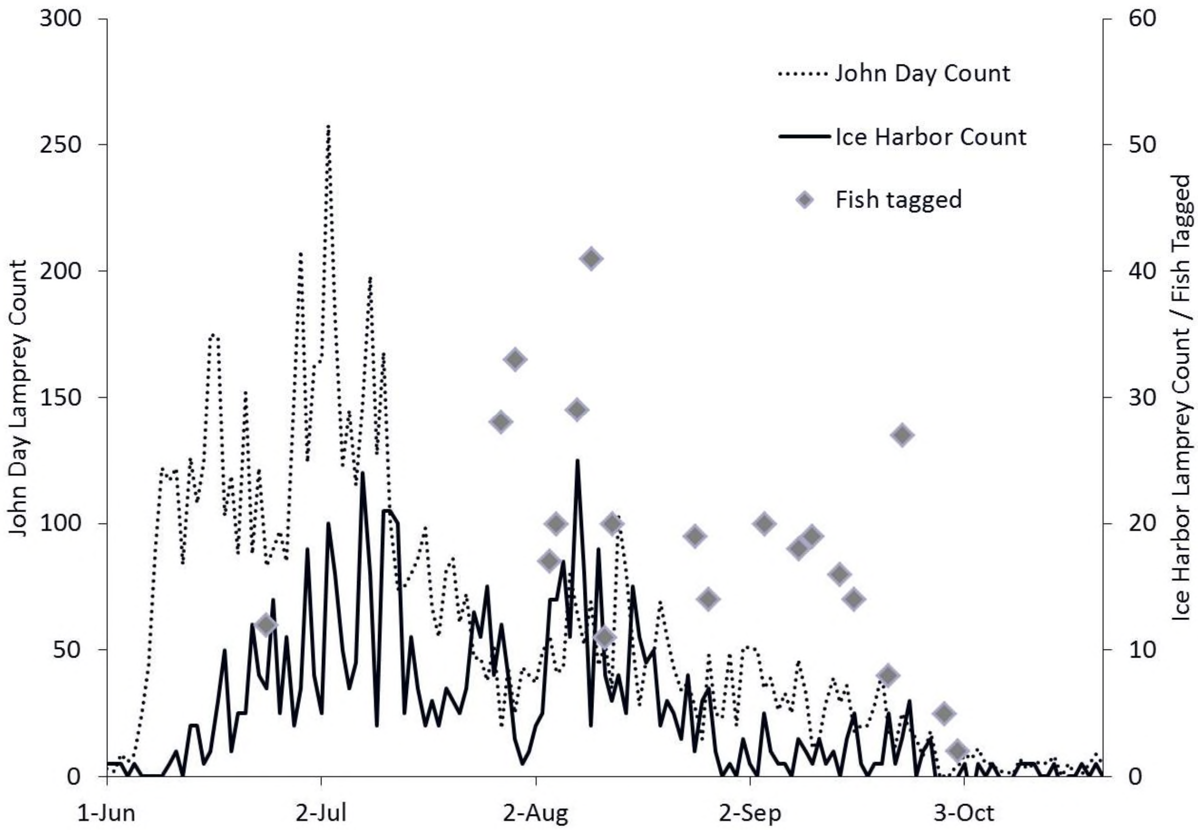

Figure 3. Daily number of lamprey recorded passing John Day Dam and Ice Harbor Dam, and the number of radio-tagged lamprey released into Ice Harbor Dam tailrace and forebay, 2015. Secondary y-axis used for both Ice Harbor Dam fish counts and tagged fish counts.

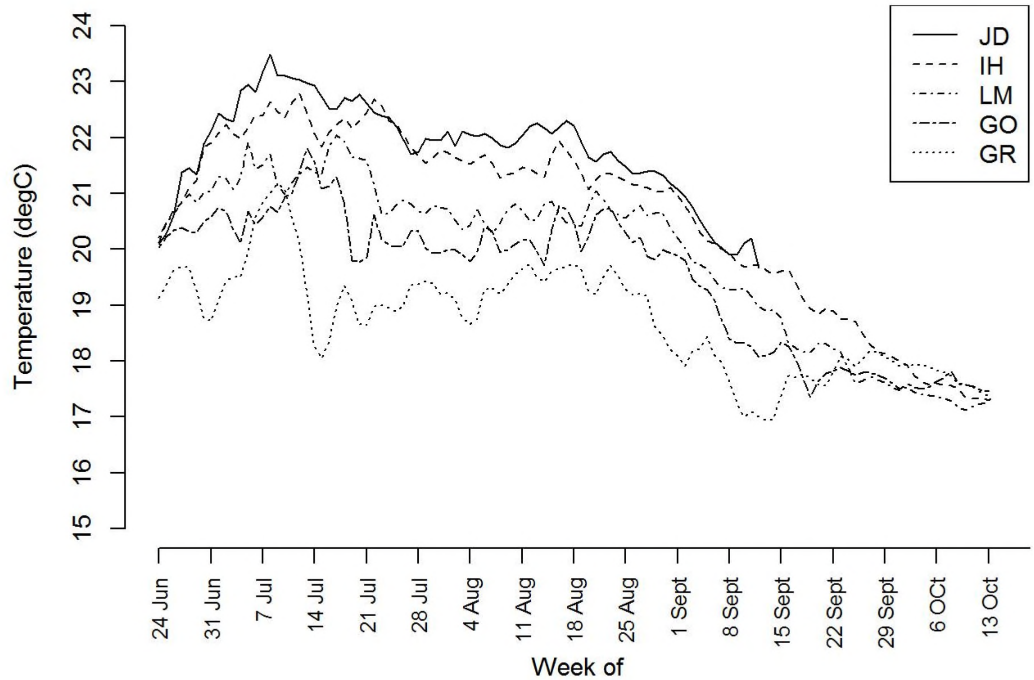

Figure 4. Average daily water temperature conditions during the tagging period (24 June to 10 October 2015) at lower Snake River dams and John Day Dam on the Columbia River. JD=John Day, IH=Ice Harbor, LM=Lower Monumental, GO=Little Goose, GR=Lower Granite.

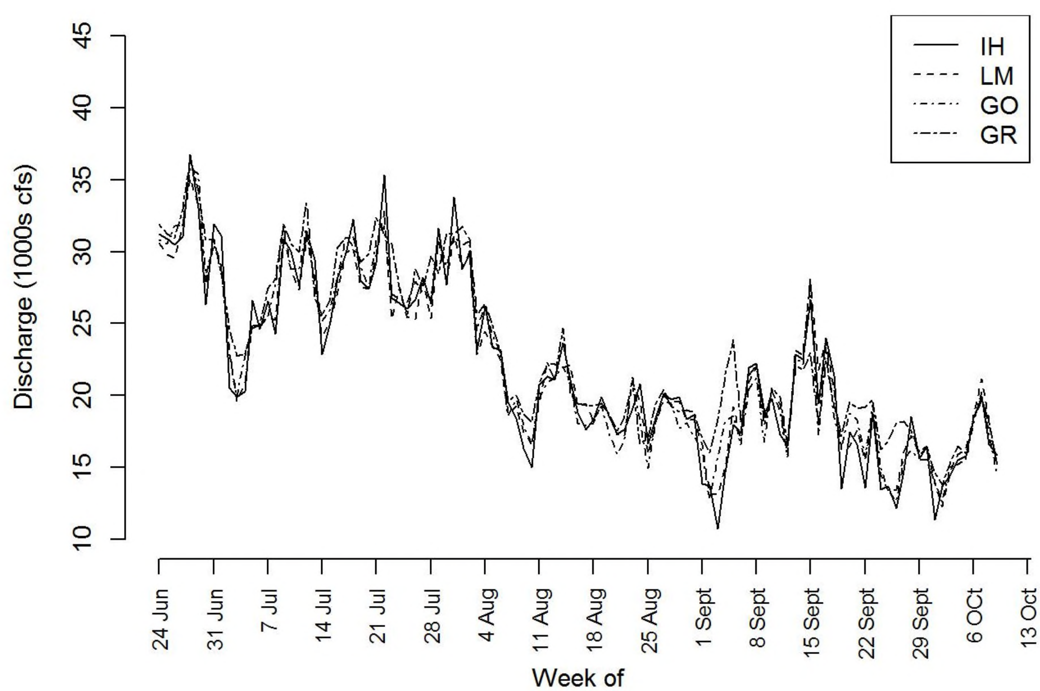

Figure 5. Total daily discharge for lower Snake River Dams during the tagging period (24 June to 10 October 2015). IH=Ice Harbor, LM=Lower Monumental, GO=Little Goose, GR=Lower Granite.

Capture & Release-group Effects & Potential Sampling Biases

The influence of body size on lamprey upstream migration distance and passage of Columbia River main stem dams has been well documented (Keefer et al. 2013a; Keefer et al. 2013b). Fish released at Ice Harbor Dam in 2015 averaged 65 cm in length and ranged between 55 and 77 cm, respectively (Figure 6). Fish captured in funnel traps along the north shore at John Day Dam were significantly larger than fish collected the John Day LPS or south shore trap (Figure 7; Table 4). However, differences in size among collection locations were homogenized across release locations. There were no significant differences in size between fish released at any of the four release locations (Figure 8; Table 5).

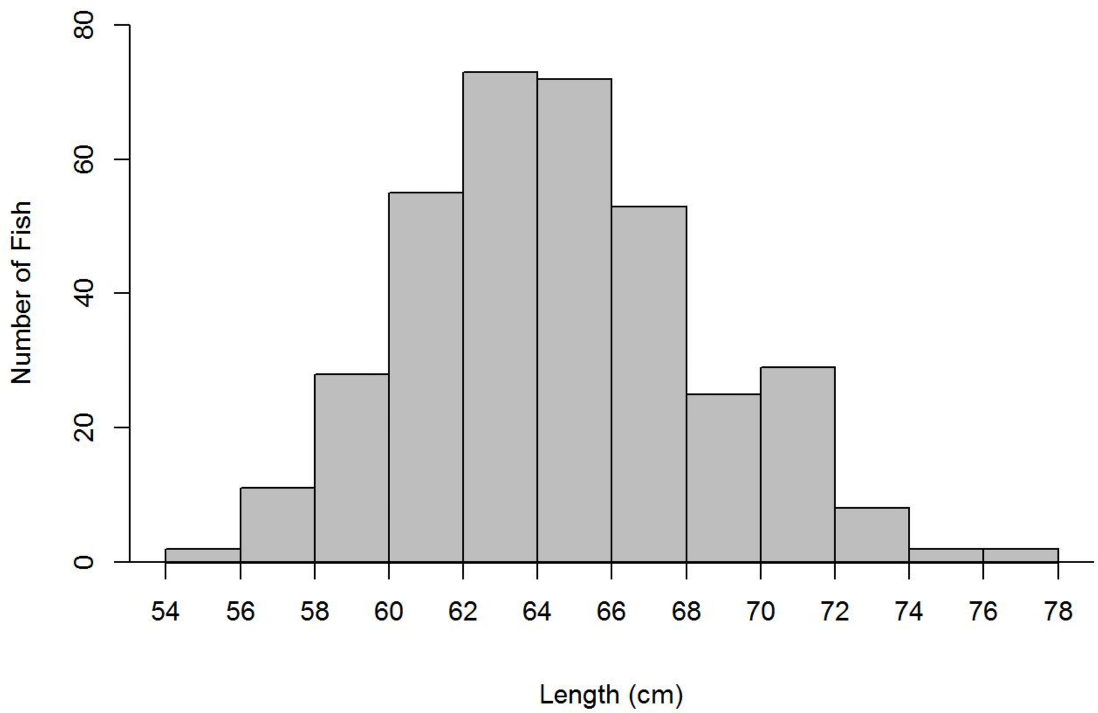

Figure 6. Size distribution of adult Pacific lamprey released in the Ice Harbor Dam forebay and tailrace, 2015.

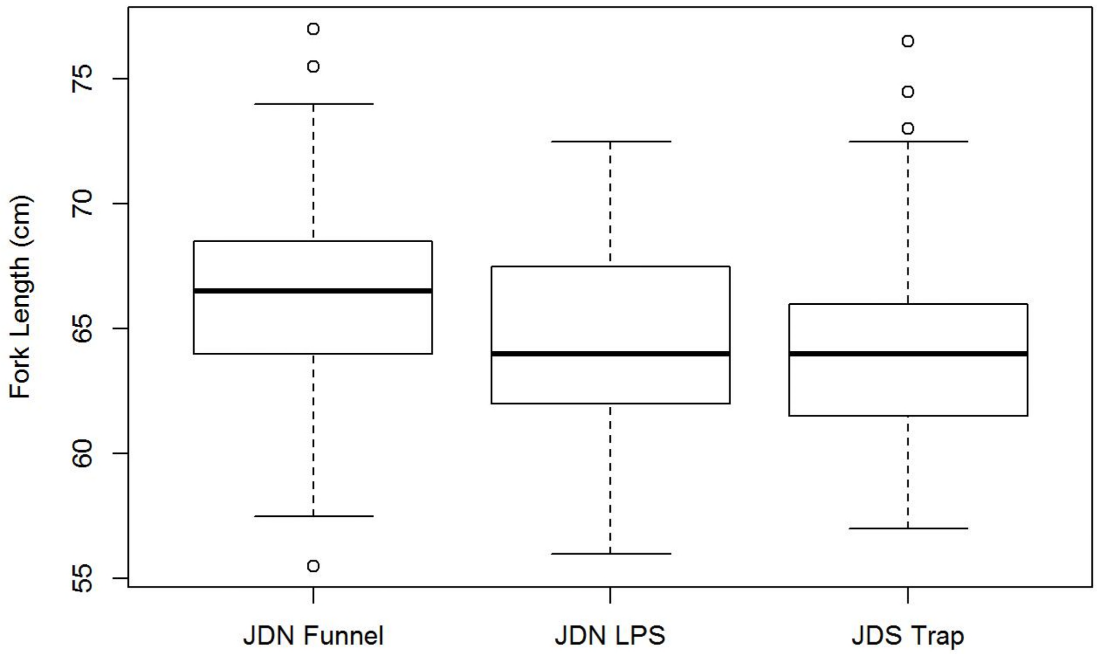

Figure 7. Lamprey size by capture location at John Day Dam, 2015. JDN Funnel = John Day north shore funnel trapping, JDN LPS = John Day north shore lamprey passage structure, JDS Trap = John Day south shore lamprey trap.

Table 4. Tukey's Honest Significant Difference multiple comparison of means for lamprey size by capture location at John Day Dam, 2015. JDN Funnel = John Day north shore funnel trapping, JDN LPS = John Day north shore lamprey passage structure, JDS Trap = John Day south shore lamprey trap.

Capture Location	Difference	p-value
JDN Funnel compared to JDN LPS	1.90	0.003*
JDN Funnel compared to JDN Trap	2.40	<0.001*
JDN LPS compared to JDN Trap	-0.50	0.60

* Significant at the $\alpha = 0.05$ level

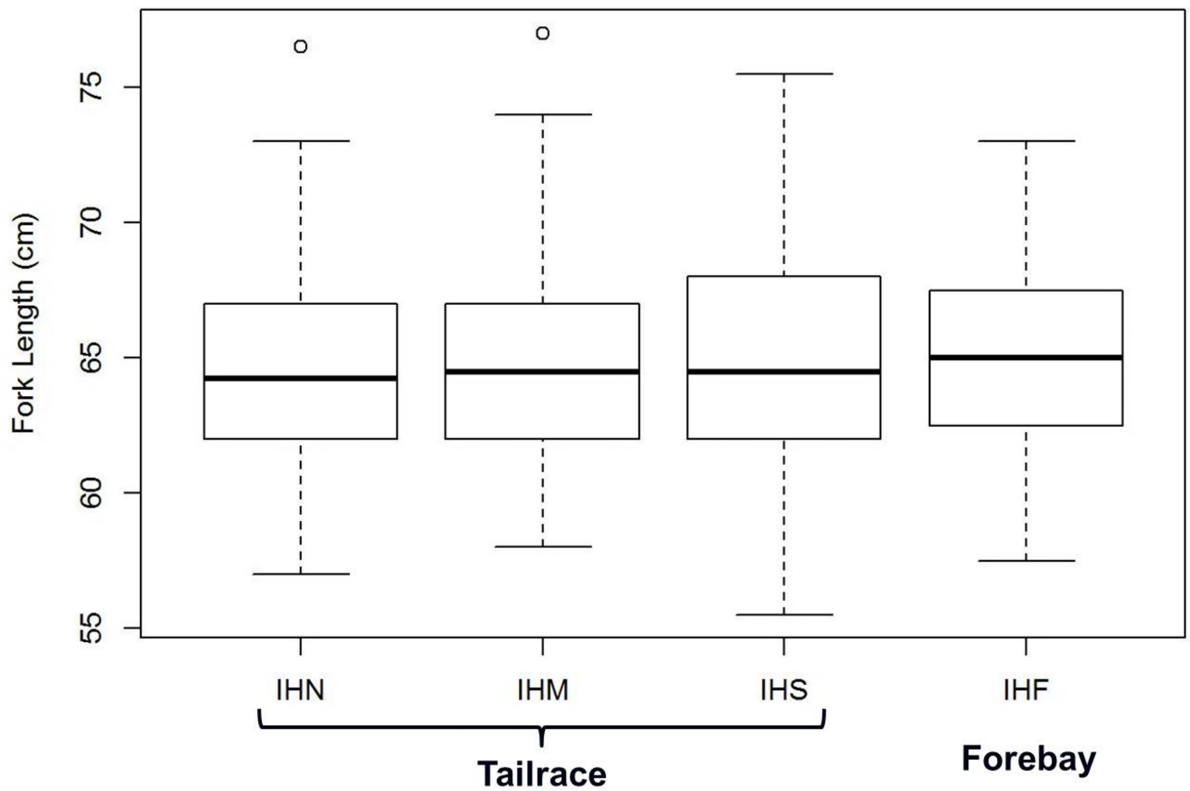

Figure 8. Lamprey size by release location/group at Ice Harbor Dam tailrace and forebay, 2015. IHN = north shore, IHM = mid-channel, IHS = south shore, IHF = forebay.

Table 5. Tukey's Honest Significant Difference multiple comparison of means for lamprey size by release location/group at Ice Harbor Dam tailrace and forebay, 2015. IHN = north shore, IHM = mid-channel, IHS = south shore, IHF = forebay.

Release Location/Group	Difference	p-value
IHN compared to IHM	-0.23	0.98
IHN compared to IHS	-0.42	0.89
IHN compared to IHF	-0.43	0.88
IHM compared to IHS	-0.19	0.99
IHM compared to IHF	-0.19	0.99
IHS compared to IHF	-0.004	0.99

* Significant at the $\alpha = 0.05$ level

Intra - Dam Comparisons

Fishway Use Metrics and Rates

Fish approach, entrance and exit distributions appear to show clear patterns within individual dams. Approach and entrance distributions at Ice Harbor Dam are highest at the north fishway entrance with lower rates at the north powerhouse and south fishway entrances. However, exit rates are consistently highest at the north powerhouse entrance (Figure 9). Approach, entrance and exit distributions at Lower Monumental Dam are relatively consistent across all entrances (Figure 10). Approach, entrance and exit distributions at Little Goose are higher at the north or south entrances than at the north powerhouse (Figure 11). Finally, approach, entrance and exit distributions are highest at the south fishway entrance at Lower Granite dam with the north entrance and north powerhouse entrance lower and comparable to each other (Figure 12). However, the ratio for Lower Granite Dam are calculated based on very low sample sizes ($n < 10$) so trends should be interpreted cautiously as they may simply reflect random variation.

In contrast, when examining the differential use of north and south shore fishways at Ice Harbor and Lower Monumental Dams for only the fish released below each dam, no clear pattern emerged across the three metrics for Ice Harbor Dam (Figure 13 and Figure 14). In contrast, the north shore fishway at Lower Monumental Dam produced consistently higher values for all three passage metrics when considering both radio and HDX PIT telemetry.

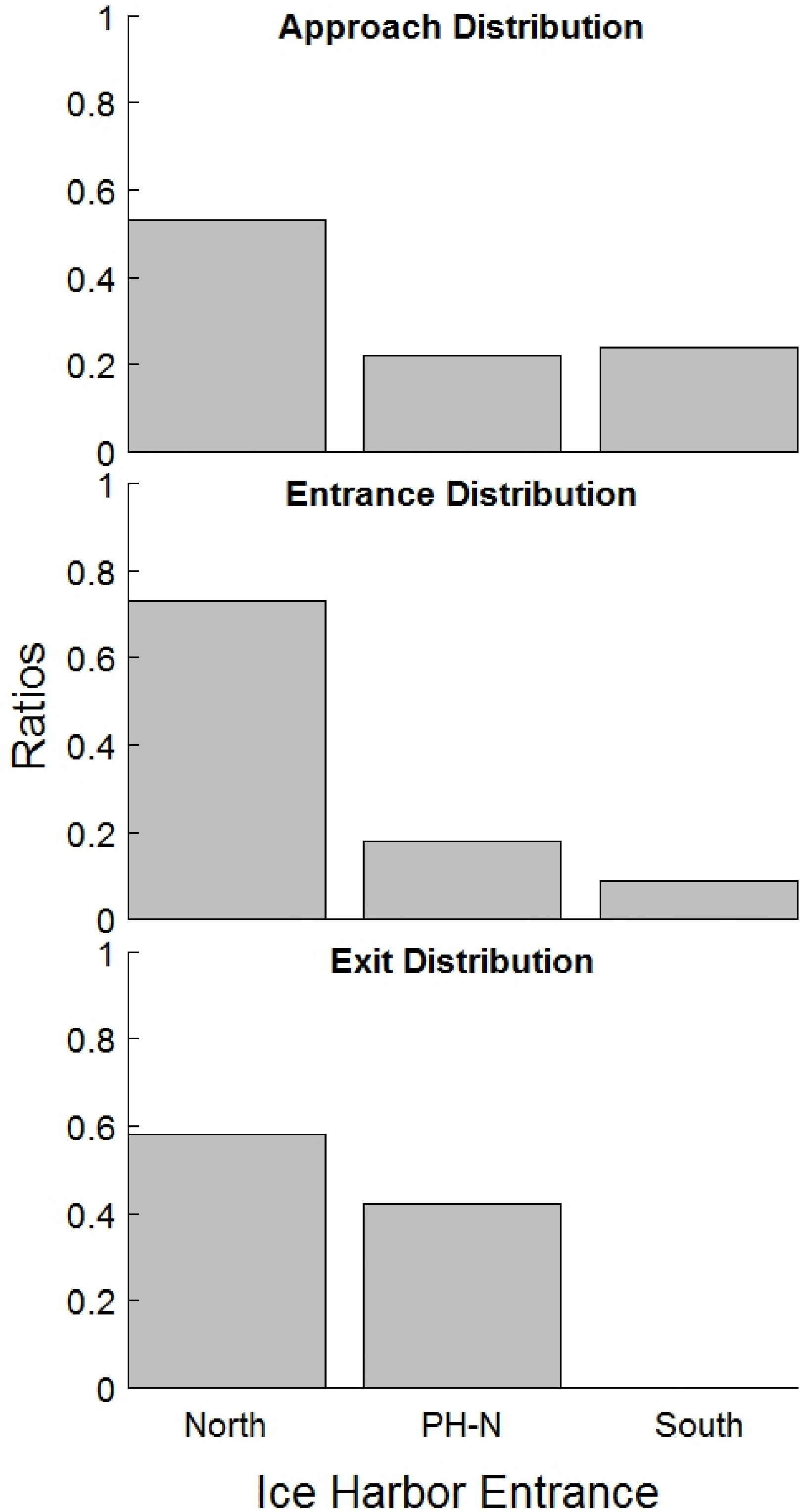

Figure 9. Approach, entry, and exit distributions (# unique approaches, entrances or exits at entrance / total # unique approaches, entrances or exits at dam) of translocated lamprey by fishway entrances at Ice Harbor Dam calculated using radio-telemetry data, 2015. North = north ladder entrance, PH-N = north powerhouse entrance and South = south fishway entrance.

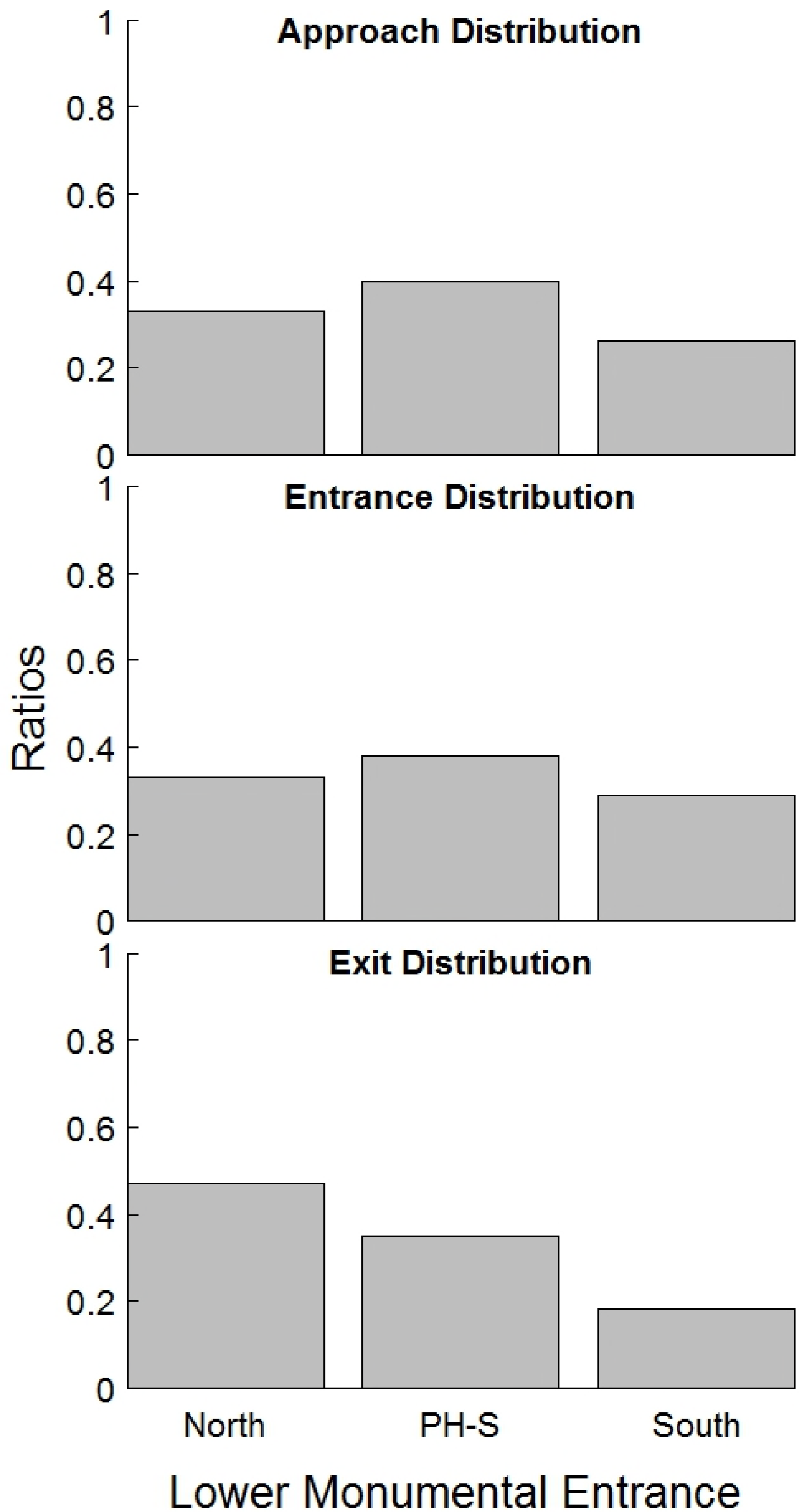

Figure 10. Approach, entry, and passage distributions (# unique approaches, entrances or exits at entrance / total # unique approaches, entrances or exits at dam) of translocated lamprey by fishway entrances at Lower Monumental Dam calculated using radio-telemetry data, 2015. North = north ladder entrance, PH-S = south powerhouse entrance and South = south fishway entrance.

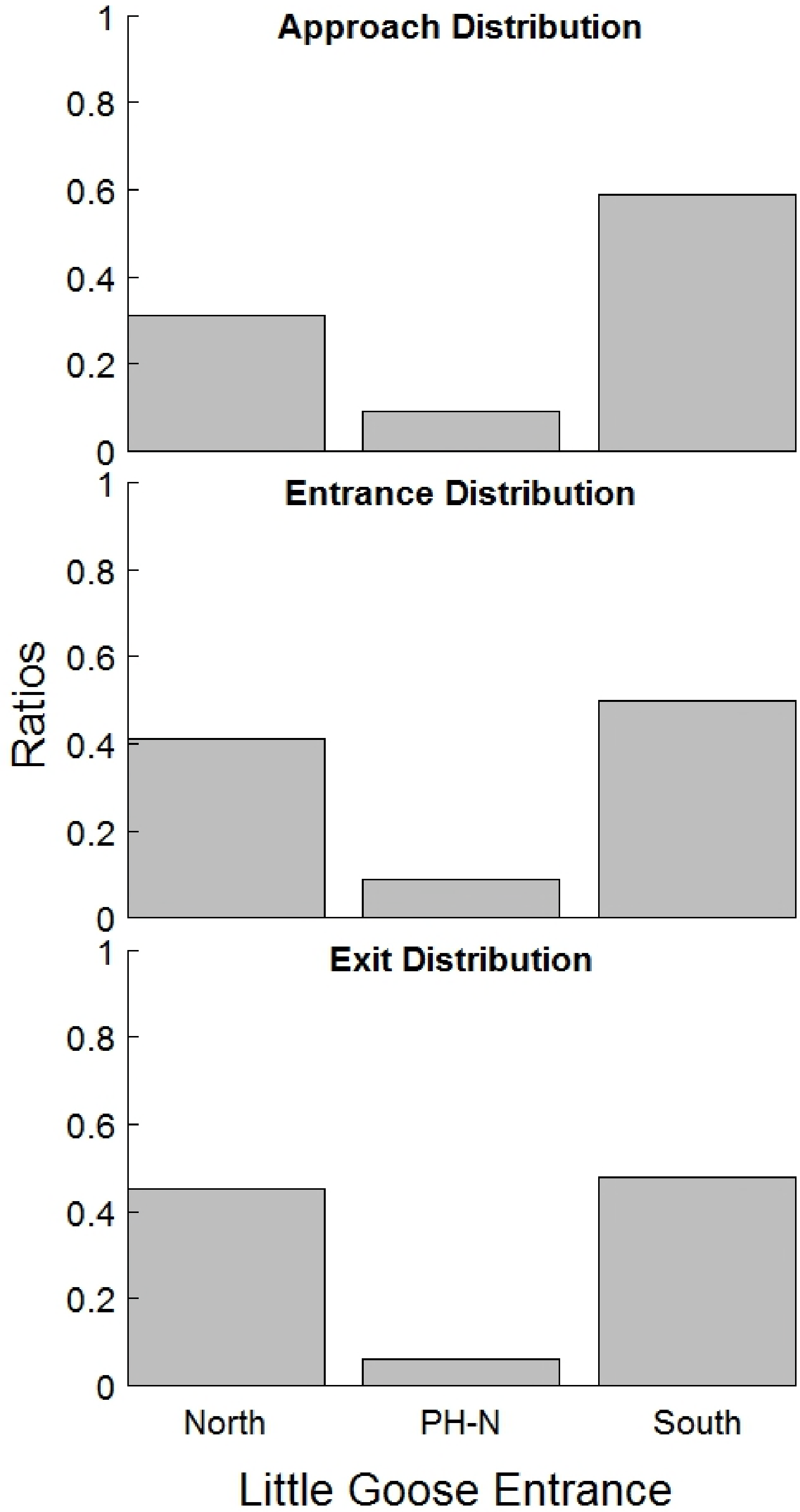

Figure 11. Approach, entry, and exit distributions (# unique approaches, entrances or exits at entrance / total # unique approaches, entrances or exits at dam) of translocated lamprey by fishway entrances at Little Goose Dam calculated using radio-telemetry data, 2015. North = north ladder entrance, PH-N = north powerhouse entrance and South = south fishway entrance.

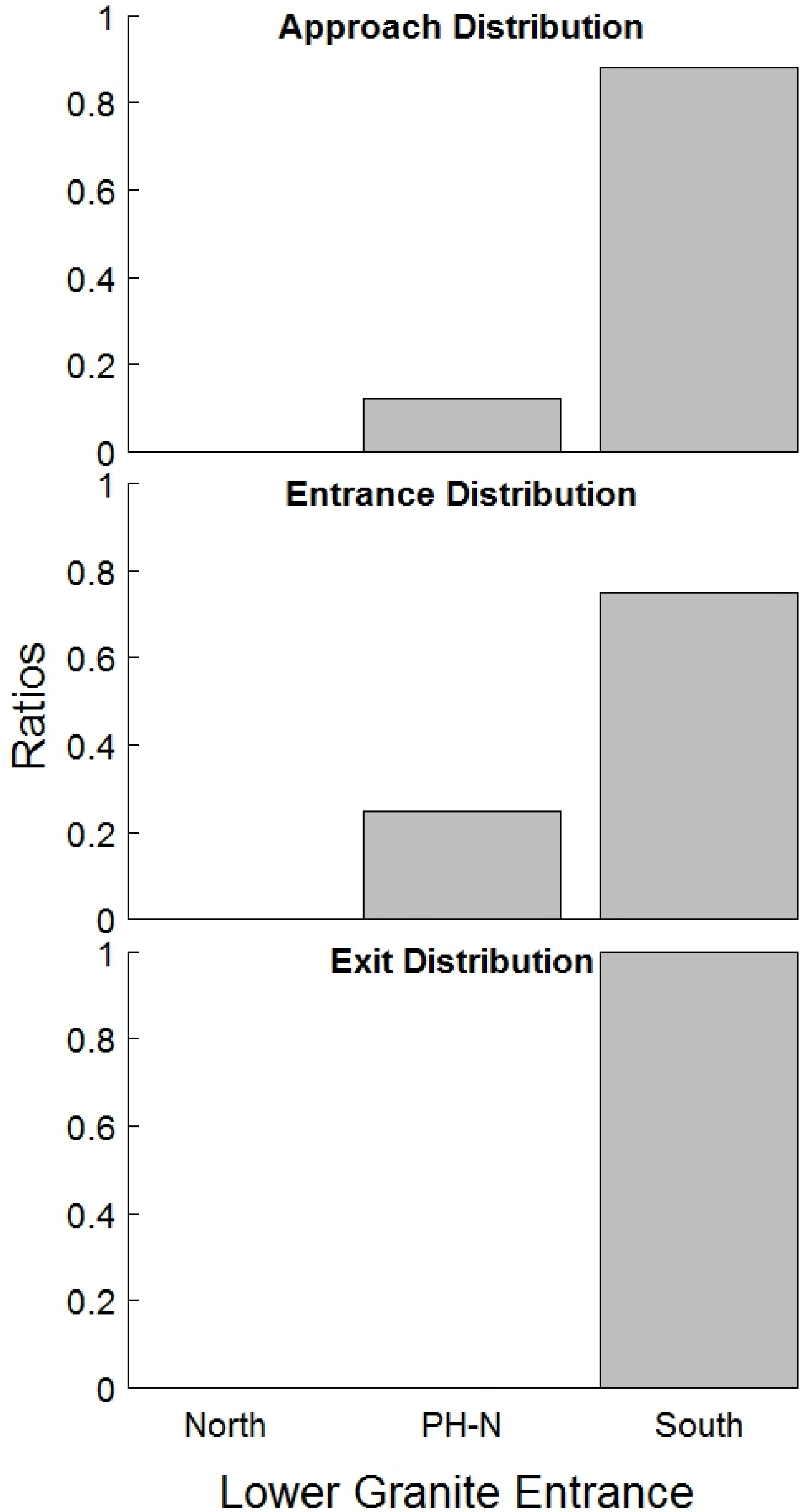

Figure 12. Approach, entry, and exit distributions (# unique approaches, entrances or exits at entrance / total # unique approaches, entrances or exits at dam) of translocated lamprey by fishway entrances at Lower Granite Dam calculated using radio-telemetry data, 2015. North = north ladder entrance, PH-N = north powerhouse entrance and South = south fishway entrance.

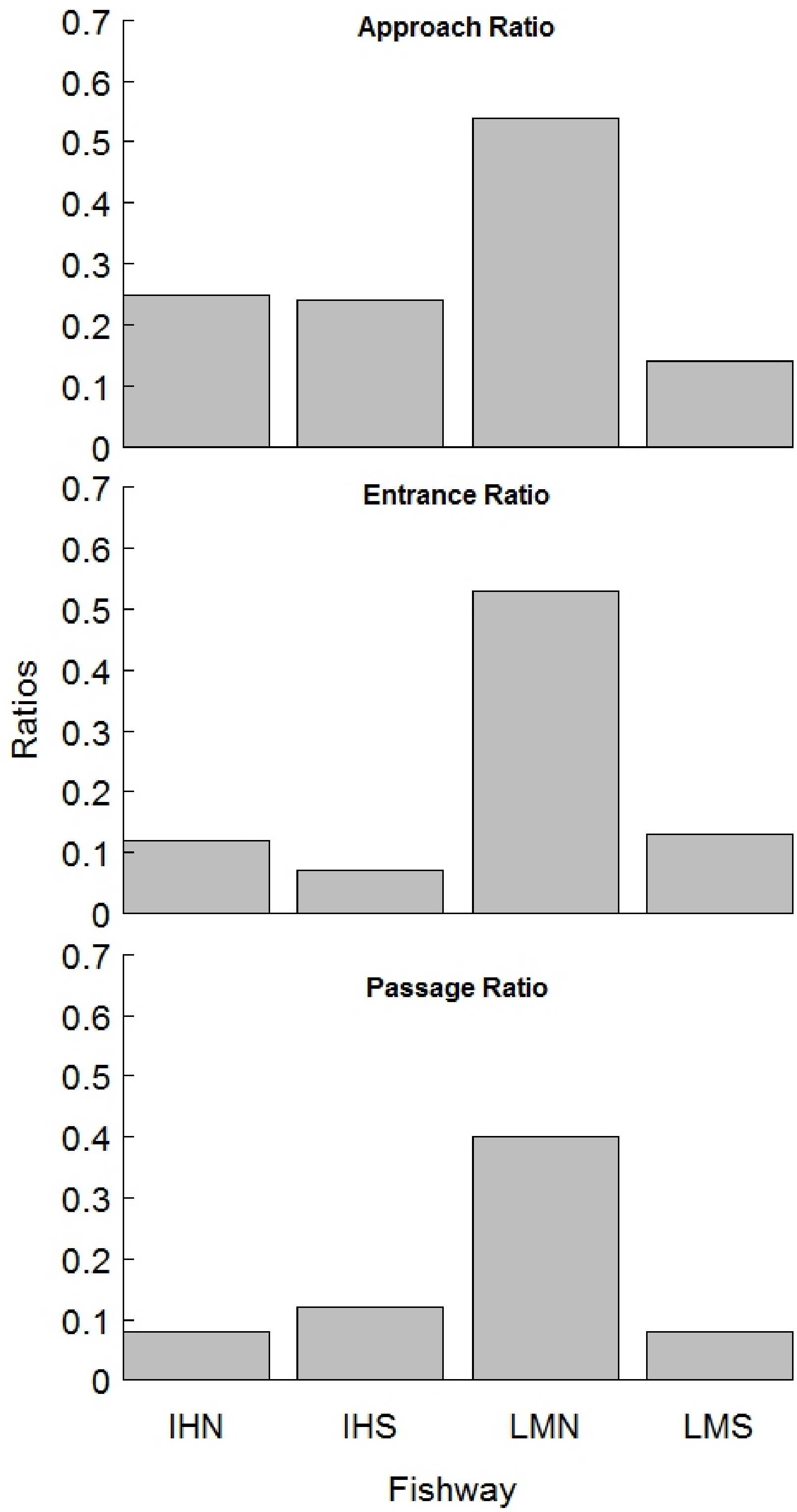

Figure 13. Fishway approach, entry, and passage ratios of translocated lamprey released in the tailrace of Ice Harbor and Lower Monumental dams (# unique approaches, entrances or passages / # released in Ice Harbor tailrace or Ice Harbor forebay, respectively) calculated using radio-telemetry data, 2015. IH=Ice Harbor, LM=Lower Monumental.

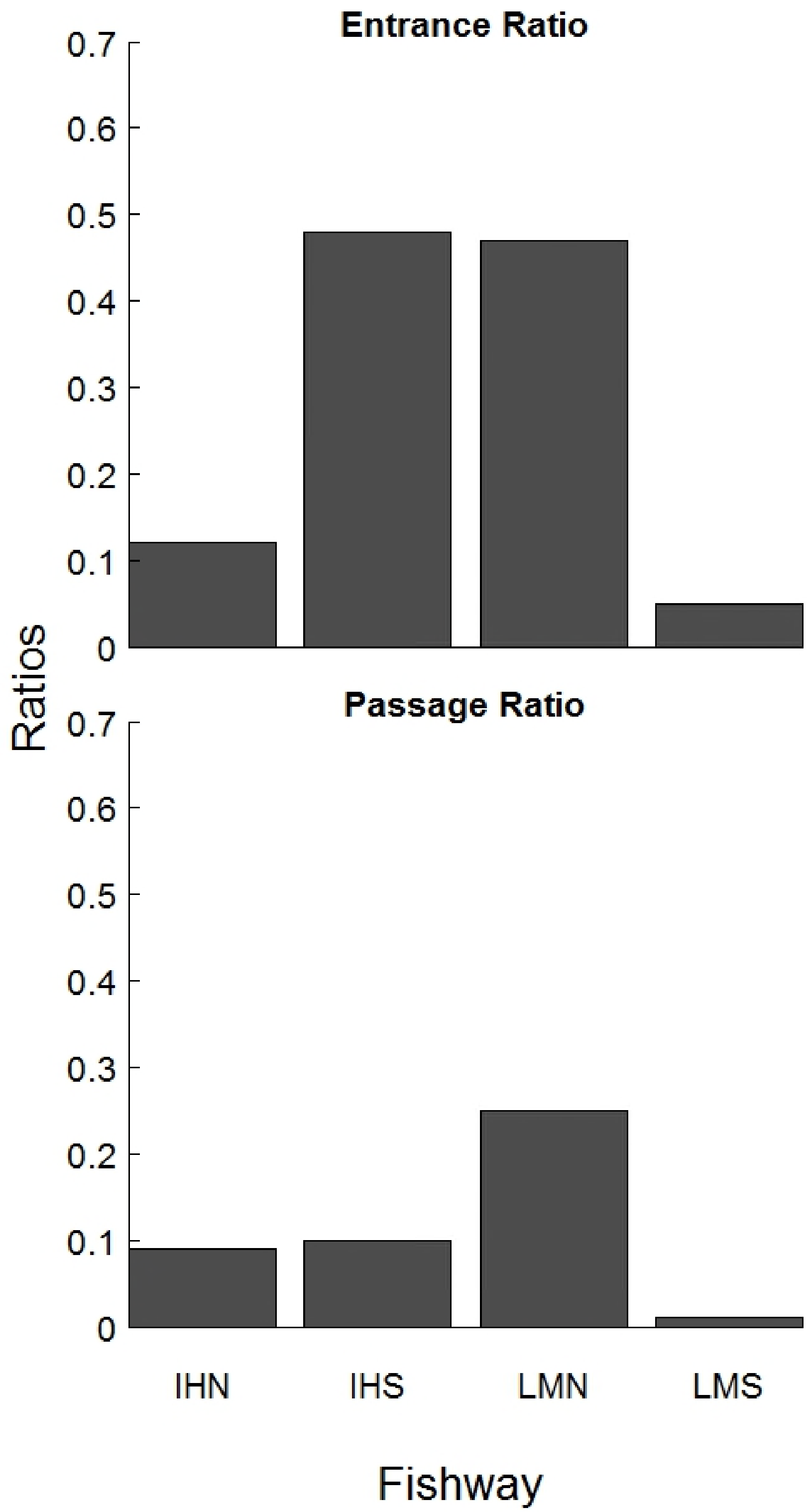

Figure 14. Entry and passage ratios for tailrace passage of translocated lamprey by fishway at Ice Harbor and Lower Monumental dams (# unique entrances or passages / # released in Ice Harbor tailrace or Ice Harbor forebay, respectively) calculated using HDX PIT data, 2015. IH=Ice Harbor, LM=Lower Monumental.

Fishway Turnaround Locations

We observed 53 entry events in which fish exited the downstream end of the fishway, returning to the Ice Harbor Dam tailrace (Table 6). These behaviors were referred to as “fallouts.” Sixteen (30%) fallouts occurred in the north fishway and 38 (70%) occurred in the south fishway. Lamprey turned around in nearly all fishway segments, except for IHN3 and IHS6. However, most turnarounds occurred in lower fishway segments prior to ladder ascension (Figure 15). A total of 90 entry events resulted in fallouts at Lower Monumental Dam (Table 7). Seventy-eight (87%) fallouts occurred in the north fishway and 12 (12%) occurred in the south fishway. Lamprey turned around in nearly all fishway segments, except for the LMN5 and LMS3. However, most turnarounds occurred in lower fishway segments prior to ladder ascension (Figure 16). Finally, a total of 103 entry events resulted in fallouts at Little Goose Dam (Table 8) and four entry events resulted in fallouts at the Lower Granite Dam (Table 9). All lamprey turned around in lower fishway segments prior to ladder ascension (Figure 17 and Figure 18).

It should be reiterated that entries as reported in this section are distinct from the unique entries calculated and reported elsewhere in the document. The entries reported here represent all entries at a given location by a given fish (i.e. - a single fish may enter and be counted multiple times) not just a single unique entry for each fish.

Substantial numbers of lamprey, in some cases, were assigned “unknown” entrance locations (e.g. – IH South – UNK). These are lamprey that were detected for the first time at a receiver inside the fishway with no corresponding detection at any of the entrances. When a fishway had multiple entrances, these lamprey could be assign to a given fishway but not a specific entrance at that fishway hence the “unknown” designation.

Figure 15. Schematic of Ice Harbor Dam denoting fishway segments analyzed for turnaround events.

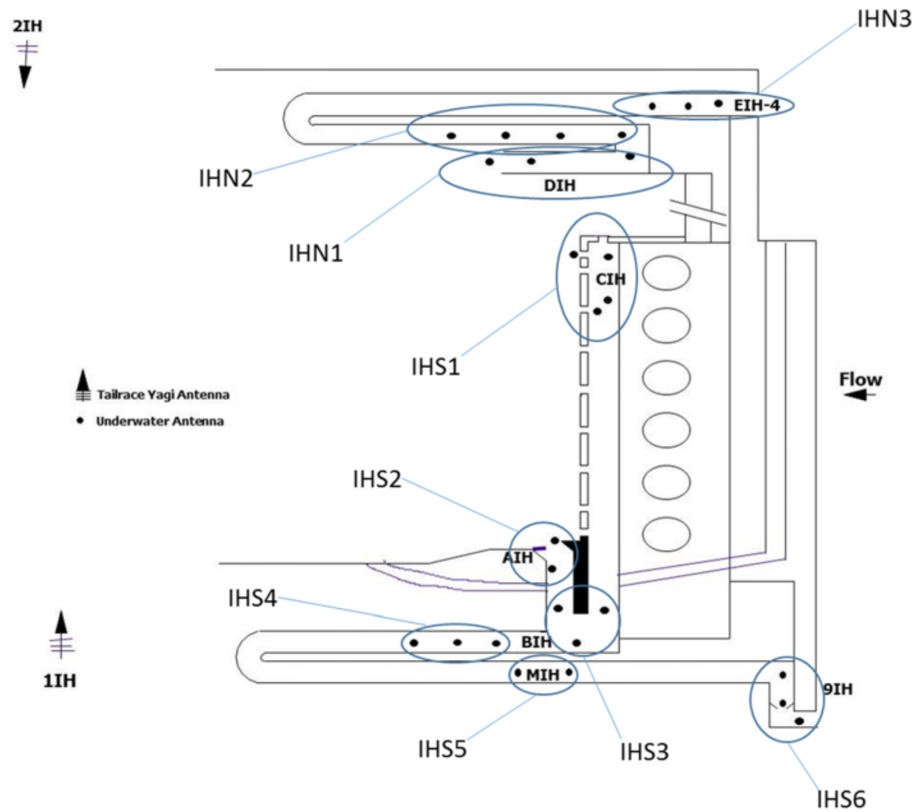

Table 6. Total number of fishway entrance events, turnaround locations and turnaround percentages by fishway segment for all entries that did not result in a successful passage at Ice Harbor Dam, 2015. Grey-shaded areas represent turnaround location numbers greater than those that exist within a given fishway.

		Turnaround Location					
Entrance	**Entry (*n*)**	**1**	**2**	**3**	**4**	**5**	**6**
North Fishway							
IH North	43	12	3				
IHN Sub-total	*43*	*12*	*3*	*0*			
IHN (% of 15 Total Turns)		*80%*	*20%*	*0%*			
South Fishway							
IH PH – N	11	7					
IH South	13		2		3		
IH South -UNK	100	6	3	1	11	5	
IHS Sub-Total	*124*	*13*	*5*	*1*	*14*	*5*	*0*
IHS (% of 38 Total Turns)		*34%*	*13%*	*3%*	*37%*	*13%*	*0%*

Figure 16. Schematic of Lower Monumental Dam denoting fishway segments analyzed for turnaround events.

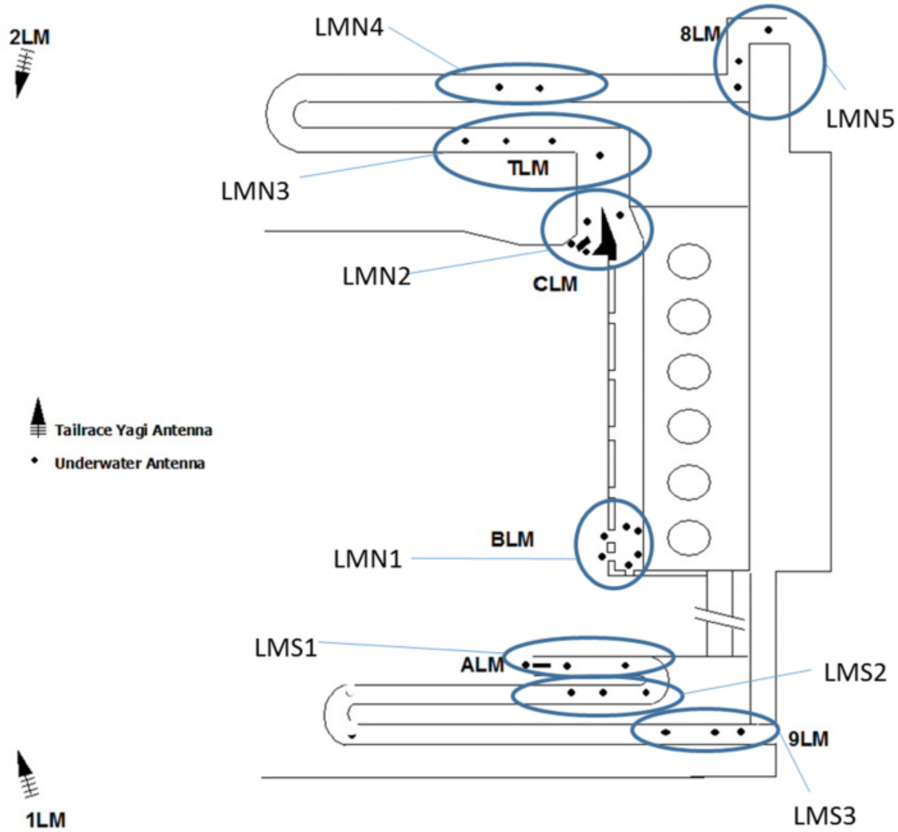

Table 7. Total number of fishway entrance events, turnaround locations and turnaround percentages by fishway segment for all entries that did not result in a successful passage at Lower Monumental Dam, 2015. Grey-shaded areas represent turnaround location numbers greater than those that exist within a given fishway.

		Turnaround Location					
Entrance	**Entry (*n*)**	**1**	**2**	**3**	**4**	**5**	**6**
	North Fishway						
LM North	73	10	8	16	5		
LM PH – S	54	18	1	20			
LM North - UNK	0						
LMN Sub-total	*127*	*28*	*9*	*36*	*5*	*0*	
LMN (% of 78 Total Turns)		*36%*	*12%*	*46%*	*6%*	*0%*	
	South Fishway						
LM South	25	10	2				
LMS Sub-total	*25*	*10*	*2*	*0*			
LMS (% of 12 Total Turns)		*83%*	*17%*	*0%*			

Figure 17. Schematic of Little Goose Dam denoting fishway segments analyzed for turnaround events.

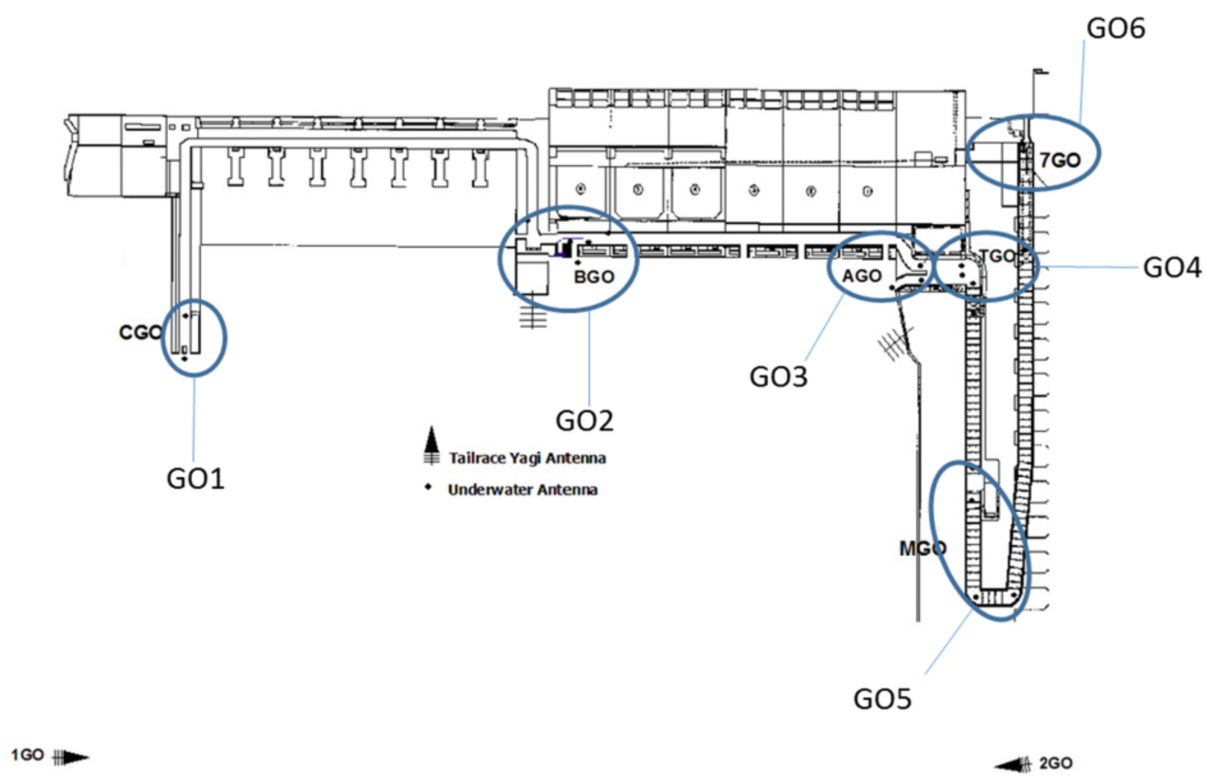

Table 8. Total number of fishway entrance events, turnaround locations and turnaround percentages by fishway segment for all entries that did not result in a successful passage at Little Goose Dam, 2015.

		Turnaround Location					
Entrance	**Entry (*n*)**	**1**	**2**	**3**	**4**	**5**	**6**
GO North	22	13	7	1			
GO PH – N	9		4	2	2		
GO South	93	7	3	38	24		
GO- UNK	2			1	1		
GO Sub-total	*126*	*20*	*14*	*42*	*27*	*0*	*0*
GO (% of 103 Total Turns)		*19%*	*14%*	*41%*	*26%*	*0%*	*0%*

Figure 18. Schematic of Lower Granite Dam denoting fishway segments analyzed for turnaround events.

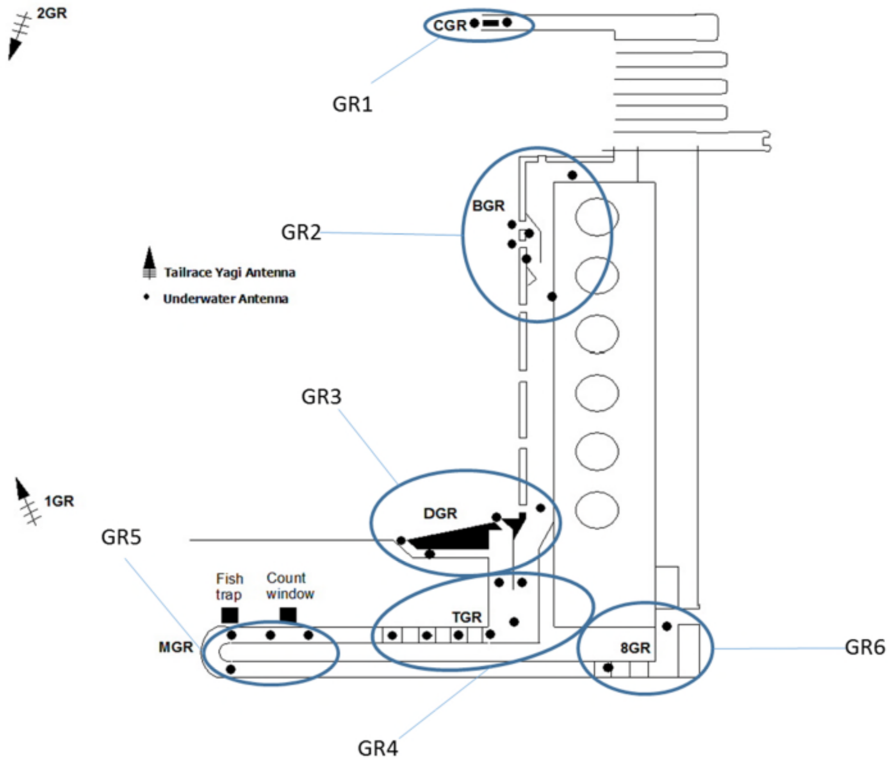

Table 9. Total number of fishway entrance events, turnaround locations and turnaround percentages by fishway segment for all entries that did not result in a successful passage at Lower Granite Dam, 2015.

		Turnaround Location					
Entrance	**Entry (*n*)**	**1**	**2**	**3**	**4**	**5**	**6**
GR North	0						
GR PH – N	1						
GR South	4		1	1			
GR - UNK	5		1	1			
GR Sub-total	*10*	*0*	*2*	*2*	*0*	*0*	*0*
GR (% of 4 Total Turns)		*0%*	*50%*	*50%*	*0%*	*0%*	*0%*

Inter-Dam Comparisons

Fishway Entrance, Fishway Passage and Dam Passage Ratios

Entrance ratio and dam passage ratios were highest at the north shore fishways at both Ice Harbor and Lower Monumental Dams (Figure 19 and Figure 20). Although fish tended to enter the south shore fishway at Lower Monumental Dam more frequently in 2015, they were more likely to pass via the north shore fishway, consistent with our observations in 2014 (Stevens et al. 2015), resulting in higher dam passage ratios for north shore routes of passage in both study years. Also, it is worth noting that lamprey were observed approaching multiple times, sometimes at different fishways. Therefore, initial approach was not a reliable indicator of fishway entrance or passage. Any patterns in fishway entrance and passage must be interpreted cautiously given low sample sizes, particularly at Little Goose and Lower Granite Dams.

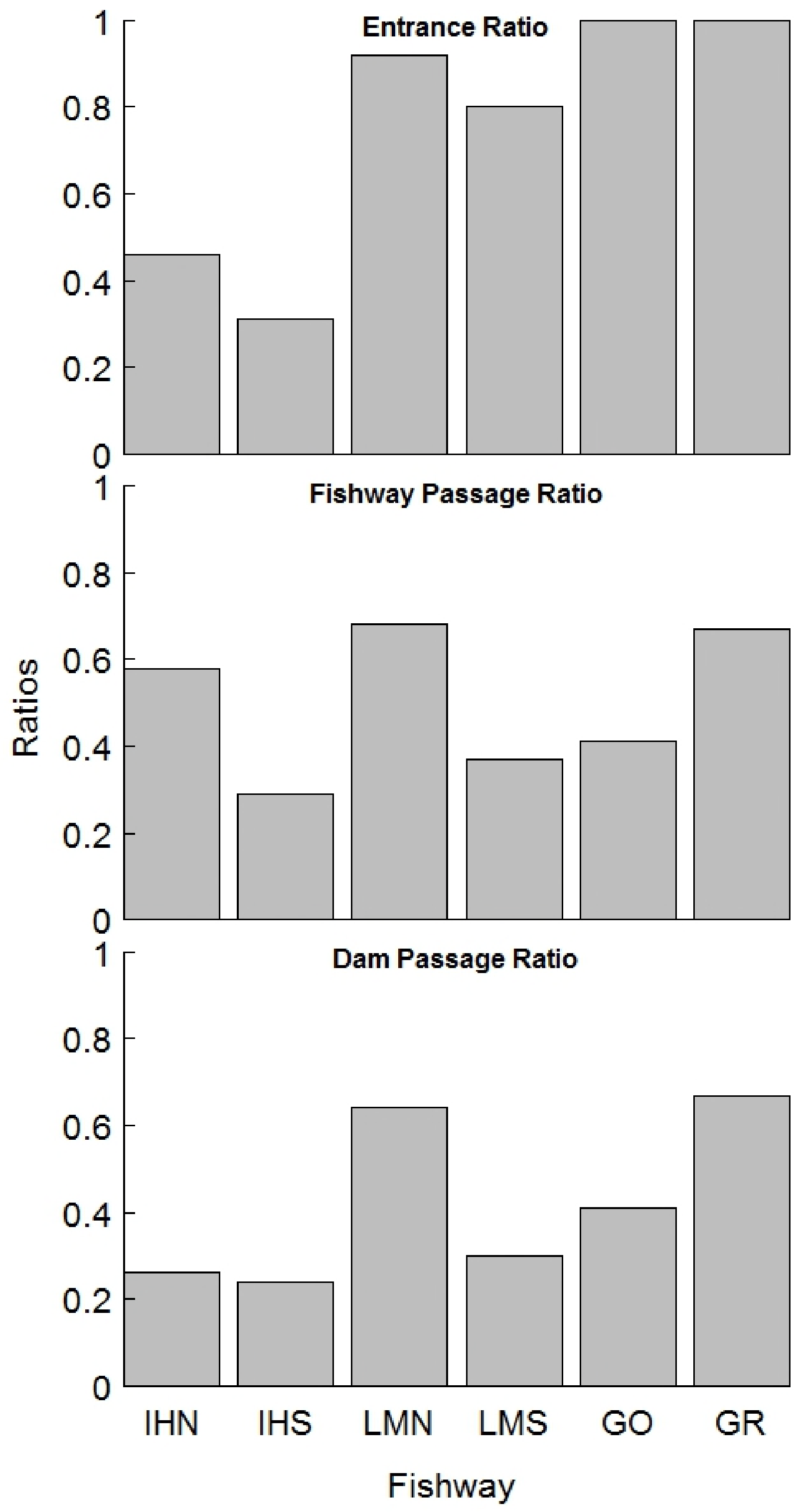

Figure 19. Entrance ratio (# unique entrances / # unique approaches), fishway passage ratio (# unique passages / # unique entrances), and dam passage ratio (# unique passages / # unique approaches) for translocated lamprey at lower Snake River dams calculated using radio-telemetry data, 2015. IHN=Ice Harbor north fishway, IHS=Ice Harbor south fishway, LMN=Lower Monumental north fishway, LMS=Lower Monumental south fishway, GO=Little Goose, GR=Lower Granite.

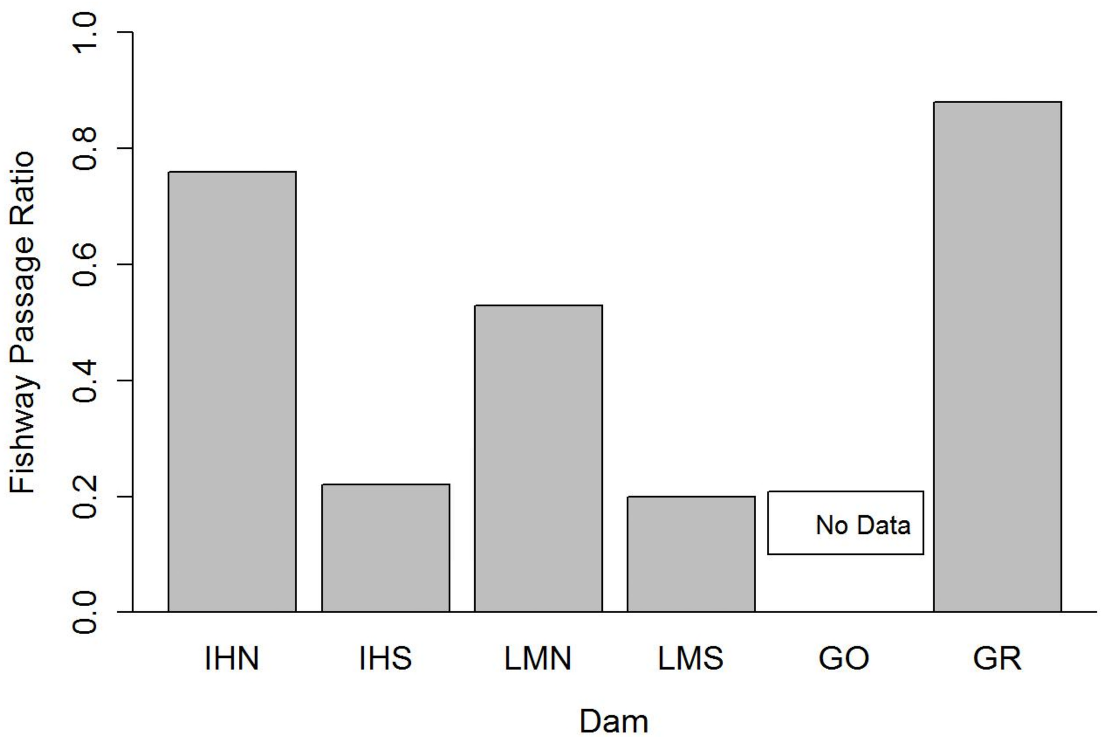

Figure 20. Fishway passage ratios (# unique passages / # unique entrances) for translocated lamprey at lower Snake River dams calculated using HDX PIT detections, 2015. IHN=Ice Harbor north fishway, IHS=Ice Harbor south fishway, LMN=Lower Monumental north fishway, LMS=Lower Monumental south fishway, GO=Little Goose, GR=Lower Granite.

Dam Entrance and Passage Ratio

Lamprey monitoring in 2015 revealed that Snake River dam entrance ratios progressively increased from Ice Harbor Dam to Lower Granite Dam, while passage remained fairly consistent between dams (Figure 21; Table 10). Entrance ratios were slightly higher in 2015 relative to those measured previously at McNary Dam for the mainstem Columbia River (Keefer et al. 2013). However, both years of monitoring in the Lower Snake River produced entrance and passage ratios that were similar to those measured previously at McNary Dam. Exceptions were slightly higher passage ratios at Lower Granite Dam and slightly lower passage ratios at Ice Harbor and Little Goose Dams in 2015.

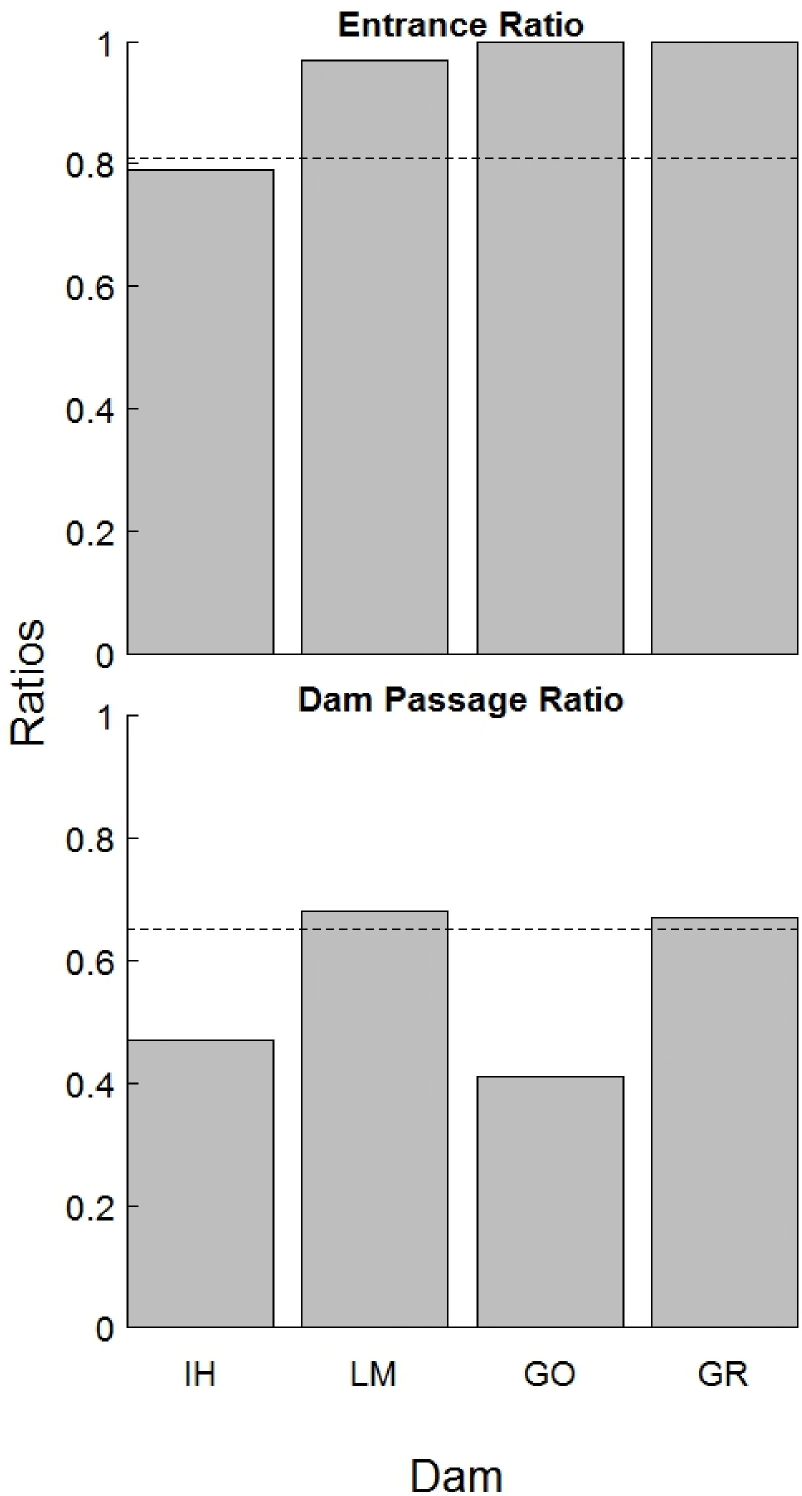

Figure 21. Entrance (# unique entrances / # unique approaches) and passage (# unique passages / # unique approaches) ratios of translocated lamprey at lower Snake River dams calculated using radio-telemetry data, 2015. IH=Ice Harbor, LM=Lower Monumental, GO=Little Goose, GR=Lower Granite. Horizontal dashed lines at 0.81 and 0.65 are the entrance and passage ratio, respectively, for McNary Dam from 2005 – 2010 (Keefer et al. 2013) for reference.

Table 10. Entrance and passage ratios of translocated lamprey at lower Snake River dams 2015, compared to observations of non-translocated lamprey at McNary Dam from 2005 to 2010 (Keefer et al. 2013a). All metrics were calculated using radio-telemetry data. Sample sizes are in parentheses. IH=Ice Harbor, LM=Lower Monumental, GO=Little Goose, GR=Lower Granite, MN=McNary.

	Snake River Dams				
	IH	LM	GO	GR	MN*
Approached	179	60	27	9	158
Entered (n)	0.79 (141)	0.97 (58)	1.00 (27)	1.00 (9)	0.81 (128)
Passed (n)	0.47 (85)	0.68 (41)	0.41 (11)	0.67 (6)	0.65 (102)

*Years: 2005-2010; Keefer et al. 2013a

Fallback Ratio

Similar to our observations in 2014, fallback rates observed in 2015 were highest at Ice Harbor Dam and Little Goose Dam, with 28% (24 out of 85) and 18% (2 out of 11), respectively (Figure 22). A "fallback" was defined as a fish that passed a dam, but was later detected back downstream with no further successful attempts to pass. Only 2% (1 out of 41) of fish fell back below Lower Monumental Dam and none of the fish (0 out of 6) that passed Lower Granite Dam descended back into the lower Snake River hydropower system. Not surprisingly, HDX PIT tag data from fish released into the lower Snake River in 2015 also indicated that Ice Harbor Dam had the highest fallback rate (6%, 3 out of 53) and Lower Granite Dam had the lowest fallback rate (0 out of 5). However, we note that HDX PIT detections underestimate true fallback rates, as adults must reenter a fishway in close proximity to an HDX receiver in order to be detected post-fallback. Therefore, while the general pattern was consistent for the two monitoring methods, radio telemetry results provide more precise fallback estimates for each dam.

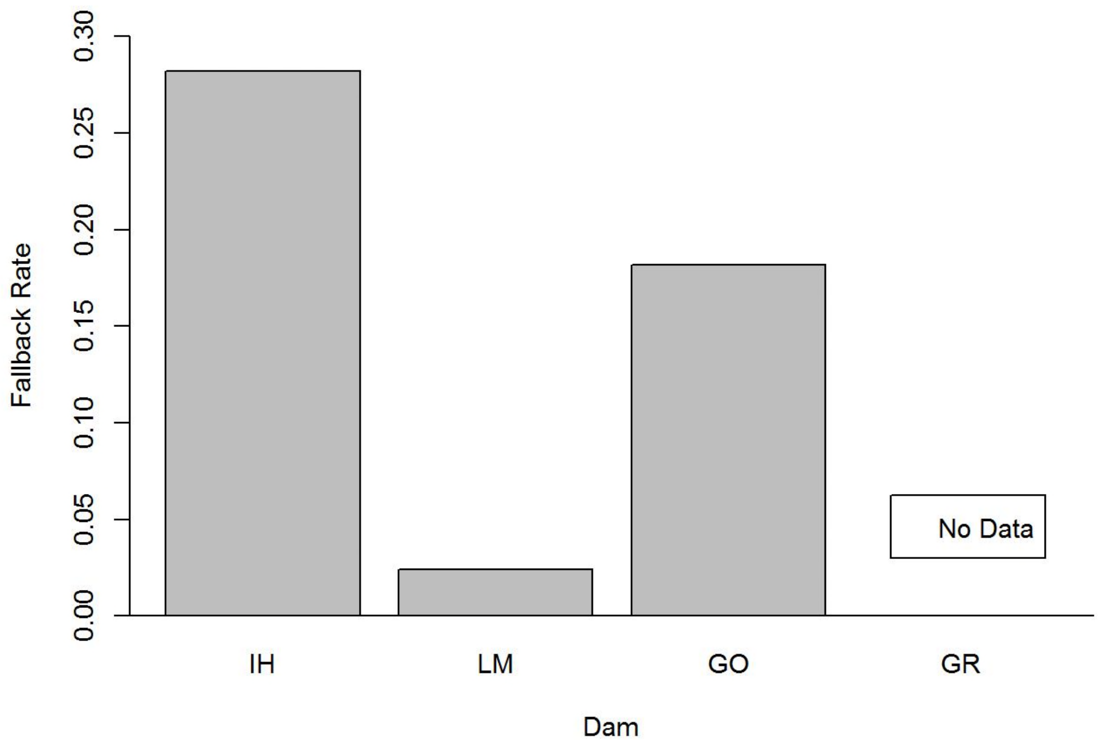

Figure 22. Fallback ratios (# unique fallbacks / # unique passages) at lower Snake River dams calculated using radio-telemetry data, 2015. IH=Ice Harbor, LM=Lower Monumental, GO=Little Goose, GR=Lower Granite.

Dam Passage Distributions & Entrance & Passage Time Analysis

The distribution of passage dates at Ice Harbor Dam peaked in mid-August in 2015, concurrent with the maximum number of fish released and available for passage in the system (Figure 23). Passage at Lower Monumental Dam had a unimodal distribution in 2015 with a peak in mid-August. Detections at Little Goose Dam and Lower Granite Dam revealed passage peaking in late-August, but our ability to describe passage distribution patterns was limited by small sample sizes for these two dams. Passage time distribution for translocated fish at Ice Harbor Dam reasonably approximated peak passage times from ladder counts (see Figure 3). However, due to temperature restrictions, releases and passage distributions captured primarily the latter half of the natural run at Ice Harbor Dam in 2015.

Telemetry detections included a time stamp, which made it possible to calculate the amount of time elapsed between fish release, dam entrance, and dam passage events. Median times-to-event at Ice Harbor Dam were 0.05 and 0.89 days from first approach to first entrance and first entrance to first passage, respectively, in 2015. Similar rates calculated for Lower Monumental Dam revealed longer times-to-event (2015: Enter – 0.02, Pass – 1.20). At Little Goose Dam, median times-to-event were 0.09 ad 2.2 days for entrance and passage, respectively, in 2015. At

Lower Granite Dam, median times-to-event were 0.08 and 0.94 days for entrance and passage, respectively. Times-to-event were relatively short in all cases (Figure 24 and Figure 25) compared to previous results (Keefer et al. 2013) and did not differ significantly between study years except for passage time at Ice Harbor Dam (Tables 11 and 12; Stevens et al. 2015).

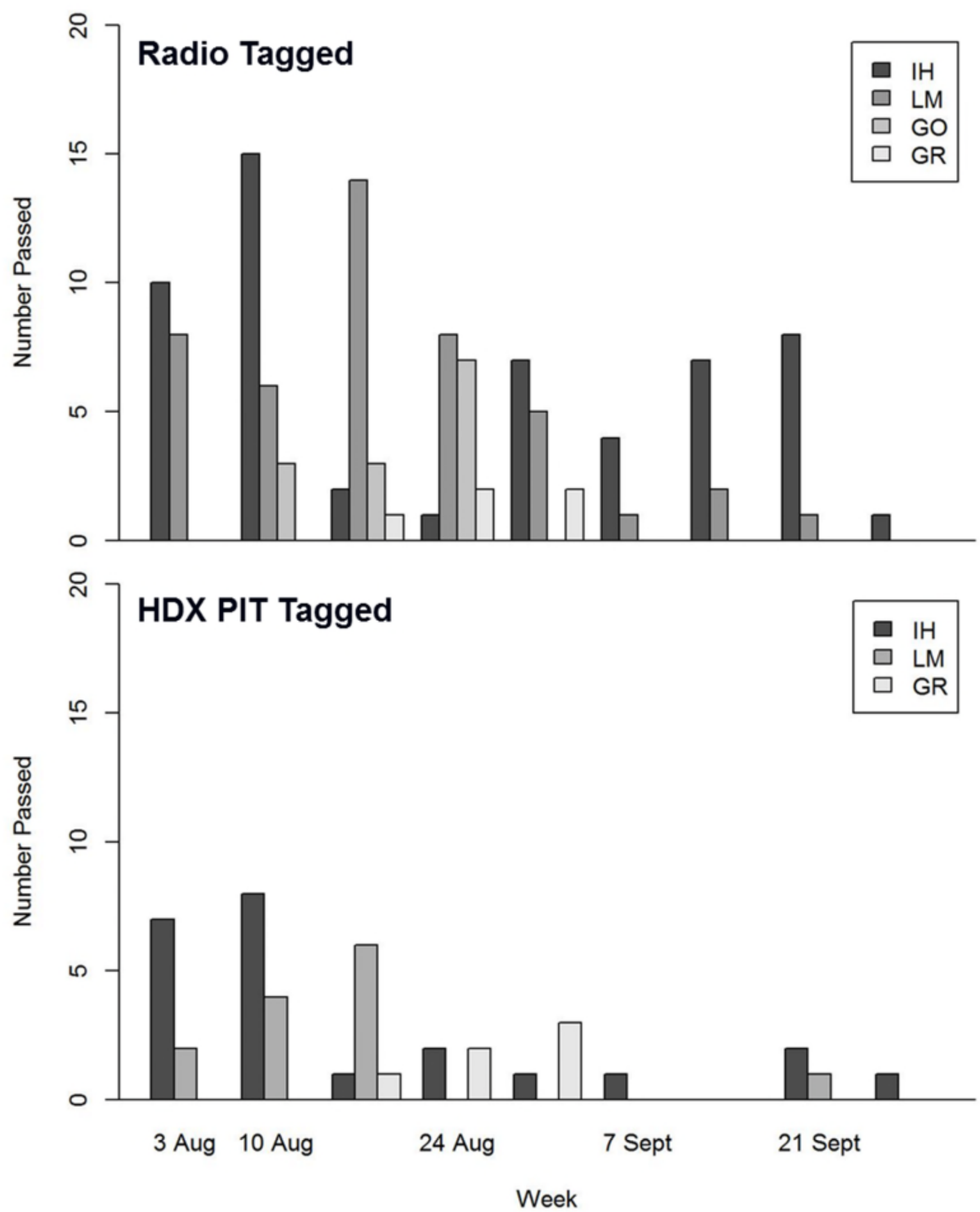

Figure 23. Passage of translocated radio and HDX PIT-tagged adult Pacific lamprey by week at lower Snake River dams between 8 August and 19 October 2015.

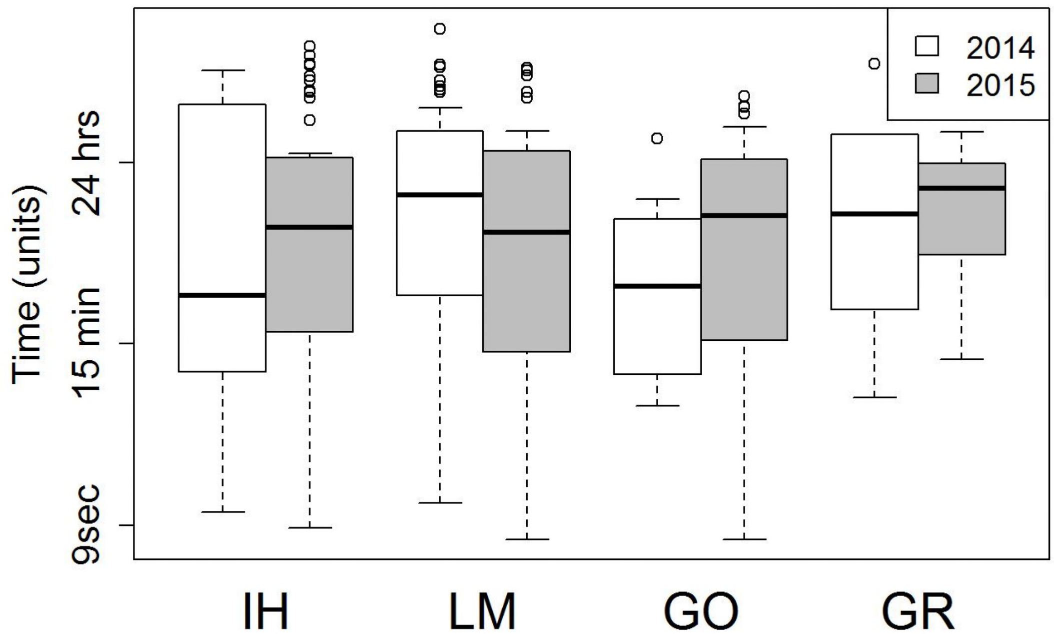

Figure 24. Median entrance times in days for translocated lamprey at lower Snake River dams calculated using radio-telemetry data. Note the log scale for time values on the y-axis.

Table 11. Wilcoxon Rank-Sum Test for median lamprey entrance time by dam between years for lower Snake River Dams, 2014-2015.

Dam	Test Statistic (W – value)	p-value
Ice Harbor Dam	748	0.44
Lower Monumental Dam	932	0.12
Little Goose Dam	165	0.14
Lower Granite Dam	14	0.93

* Significant at the $\alpha = 0.05$ level

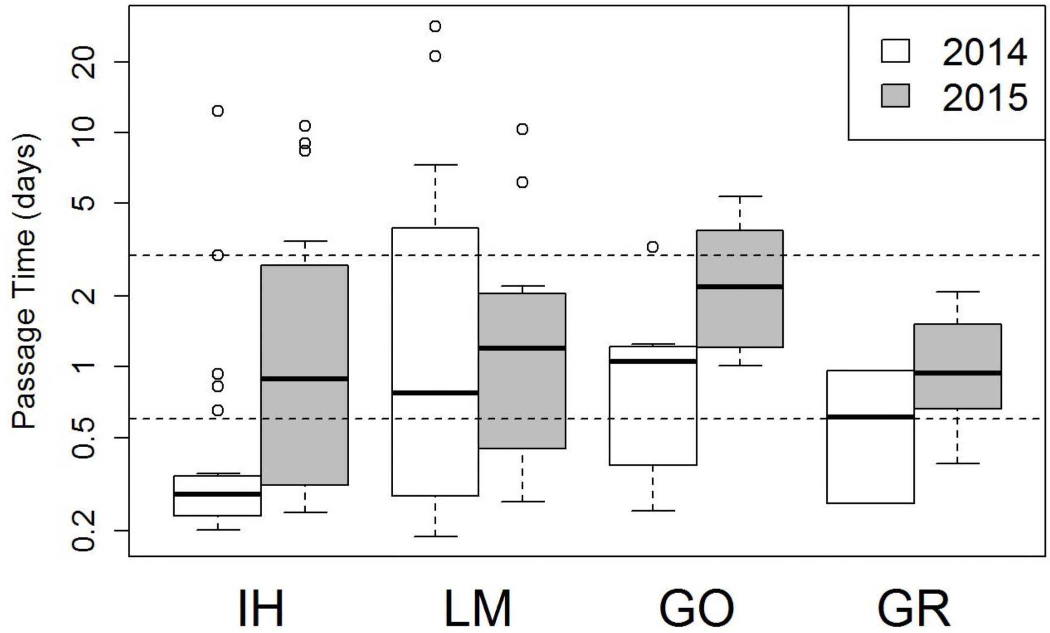

Figure 25. Median passage times in days for translocated lamprey at lower Snake River dams calculated using radio-telemetry data. Horizontal dashed lines at 0.6 and 3.0 days represent the median passage time for McNary Dam from 2005 – 2010 (Keefer et al. 2013) for reference. Note the log scale for time values on the y-axis.

Table 12. Wilcoxon Rank-Sum Test for median lamprey passage time by dam between years for lower Snake River Dams, 2014 – 2015.

Dam	Test Statistic (W – value)	p-value
Ice Harbor Dam	139	0.004*
Lower Monumental Dam	173	0.67
Little Goose Dam	10	0.07
Lower Granite Dam	2	0.80

* Significant at the $\alpha = 0.05$ level

Release Group and Release Site Comparisons

Fish were released at four different locations in 2014 and 2015 (Figure 26 and Figure 27). Approach, entrance and passage ratios did not vary substantially between release groups at Ice Harbor Dam (IHN, IHM and IHS; Figure 26 – left column and Figure 27 – left column). Thus, there does not appear to be any release location effect.

Passage rates at Lower Monumental Dam were higher among adults that successfully passed Ice Harbor Dam than for fish released in the Ice Harbor Dam forebay (IHT Pass vs. IHF; Figure 26 – right column and Figure 27 – right column). Differences in passage rates for these two groups of fish at Lower Monumental Dam likely reflects the combined effects of: 1) larger body size of the subsample passing Ice Harbor Dam and 2) tagging/handling effects in the forebay release group. Similar passage rates for fish released downstream (IHN, IHM, IHS in Figures 26 and 27) and upstream of Ice Harbor Dam (IHF in Figure 26 and Figure 27) at Ice Harbor Dam or Lower Monumental Dam, respectively, suggest that tagging effects and/or size selection were similar in total magnitude at both dams. Moreover, the additional migration distance for fish traveling through Ice Harbor Dam forebay did not appear to bias Lower Monumental Dam passage rates relative to rates observed at Ice Harbor Dam, suggesting that future evaluations of lamprey passage in the lower Snake River do not need to rely on fish releases proximate to each dam if such releases are logistically difficult.

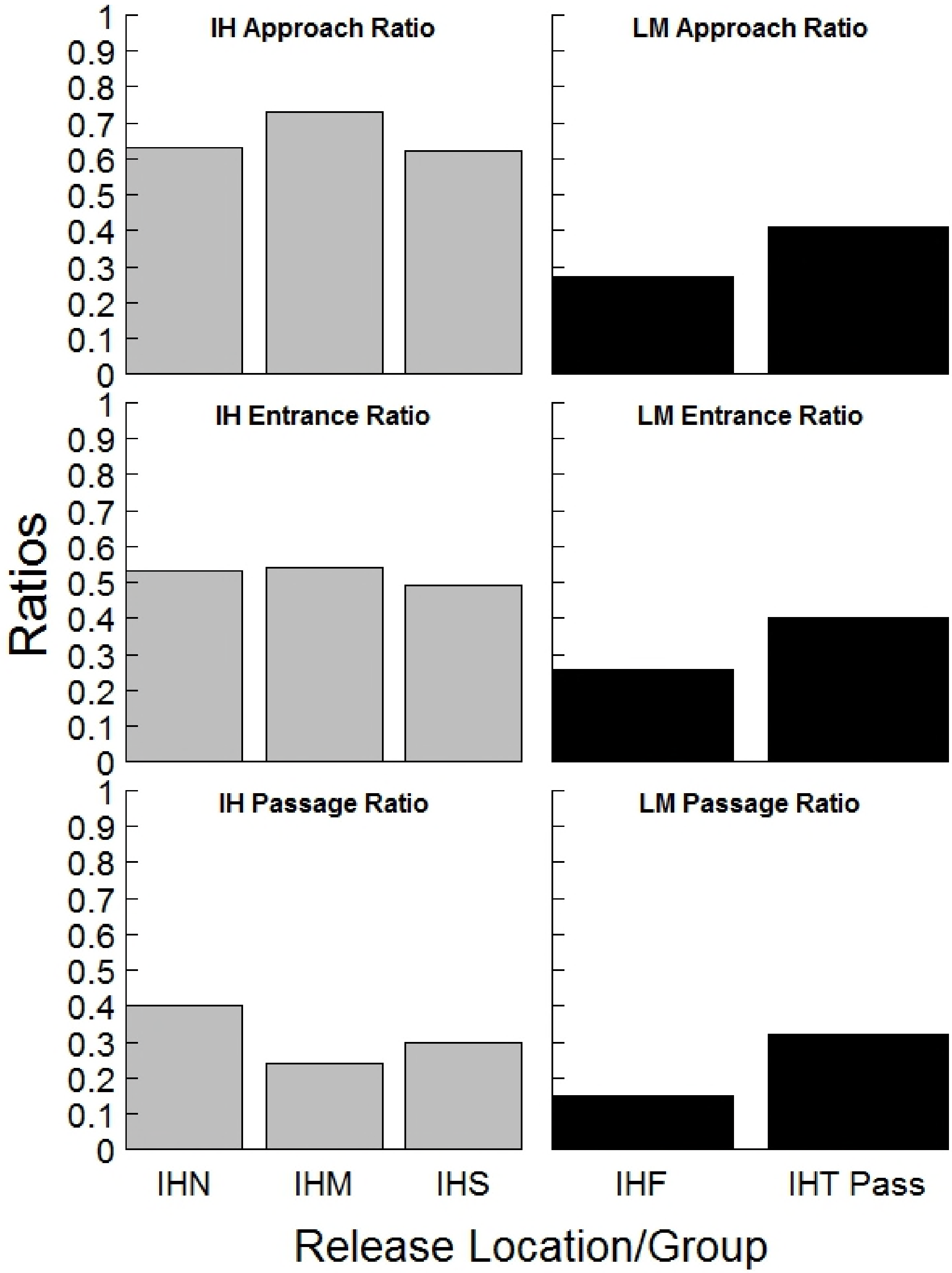

Figure 26. Approach, entry, and passage ratios (# unique approaches, entrances or passages / # released below Ice Harbor [left column] or Lower Monumental Dam [right column], respectively) at Ice Harbor and Lower Monumental Dams for translocated lamprey released along the northshore (IHN), southshore (IHS) and center-channel (IHM) of Ice Harbor Dam tailrace, fish released in Ice Harbor Dam forebay, and fish that successfully passed Ice Harbor Dam. Ratios calculated using radio-telemetry data, 2015. IHN=north shore tailrace, IHM=mid-channel tailrace, IHS=south shore tailrace, IHF=forebay, IHT Pass = rates at Lower Monumental for all Ice Harbor Tailrace release groups which volitionally pass Ice Harbor Dam to the Ice Harbor Forebay combined.

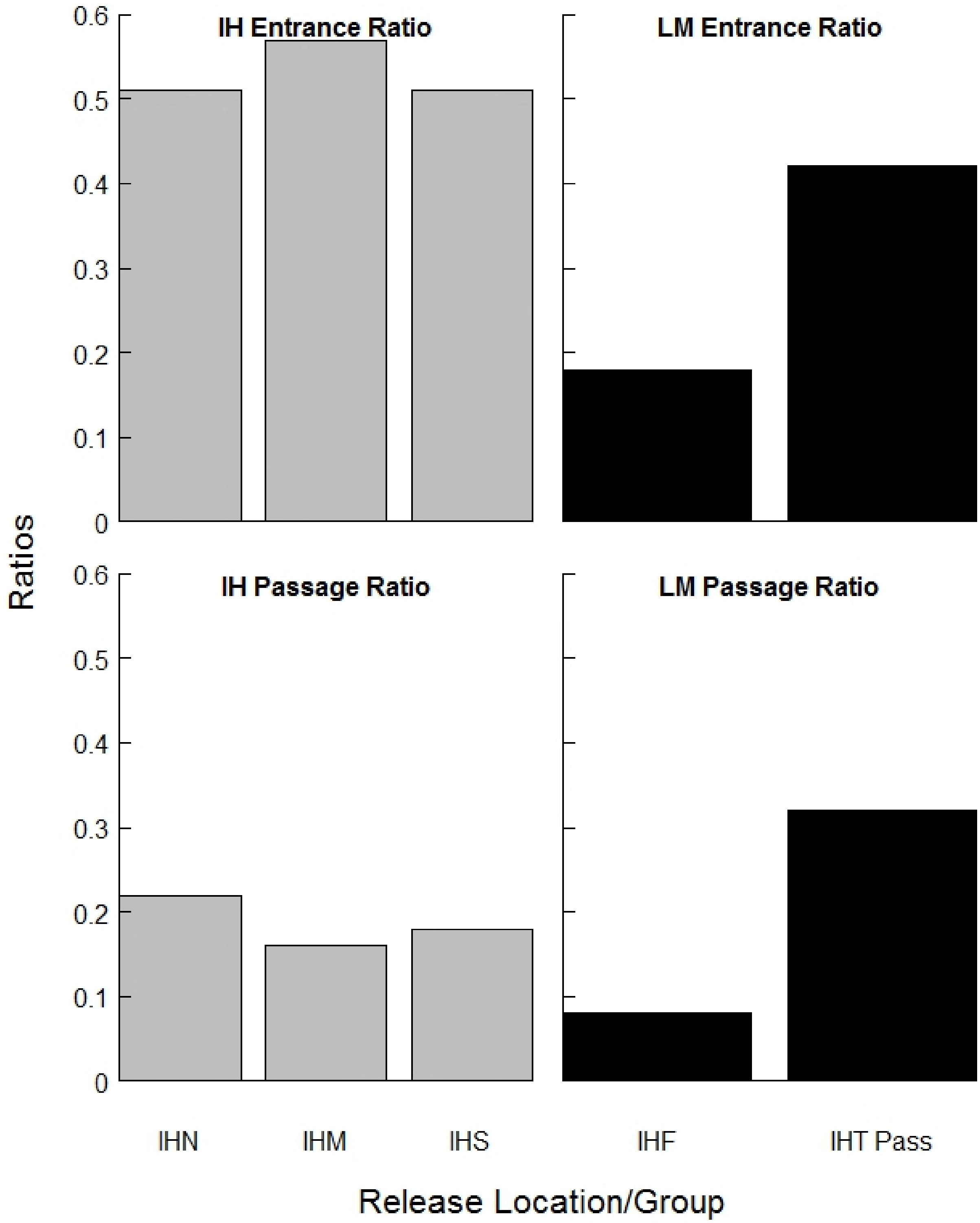

Figure 27. Entry and fishway passage ratios (# unique approaches, entrances or passages / # released below Ice Harbor [left column] or Lower Monumental Dam [right column], respectively) for tailrace passage of translocated lamprey by release location/group at Ice Harbor Dam for tailrace release groups IHN, IHM, and IHS and at Lower Monumental Dam for passage of IHF release group calculated using HDX PIT data, 2015. IHN=north shore tailrace, IHM=mid-channel tailrace, IHS=south shore tailrace, IHF=forebay, IHT Pass = rates at Lower Monumental for all Ice Harbor Tailrace release groups combined.

Translocation Effects

Fish released below Lower Monumental Dam approached, entered and passed at higher rates than fish released below Ice Harbor (Figure 28; Table 13). This trend was consistent across both study years. Keefer et al. (2013a) reported that approach, entrance and passage efficiencies were 57%, 46% and 37% respectively for radio-tagged lamprey released below McNary Dam (Figure 28; Table 13). Similar metrics for Ice Harbor and Lower Monumental Dam appear to bracket observations at McNary Dam. This suggests that translocation of lamprey to the Snake River did not produce greater bias in lamprey passage metrics than would be expected from studies elsewhere in the Columbia Basin. In fact, the proportion of radio-tagged fish passing each of the Snake River dams was similar for all four dams, and the proportion of fish that entered passage facilities at the dams increased with distance from the release sites (see Figure 21), indicating that fish that chose to ascend a dam had a higher probability of ascending the next upstream dam. This was further corroborated by similarity between lamprey passage metrics at lower Snake River dams and McNary Dam, including those calculated with the number of fish "approached" (Table 10) and metrics calculated with the number of fish "released" at each dam (Table 13). This result suggests that translocation or tagging effects were reduced with each successive dam ascension, but these effects could not be partitioned from other factors, such as fish body size. Associations between migration distance and genetics reported by Hess et al. (2014) also confound interpretations of the causal mechanisms influencing our observed passage success rates.

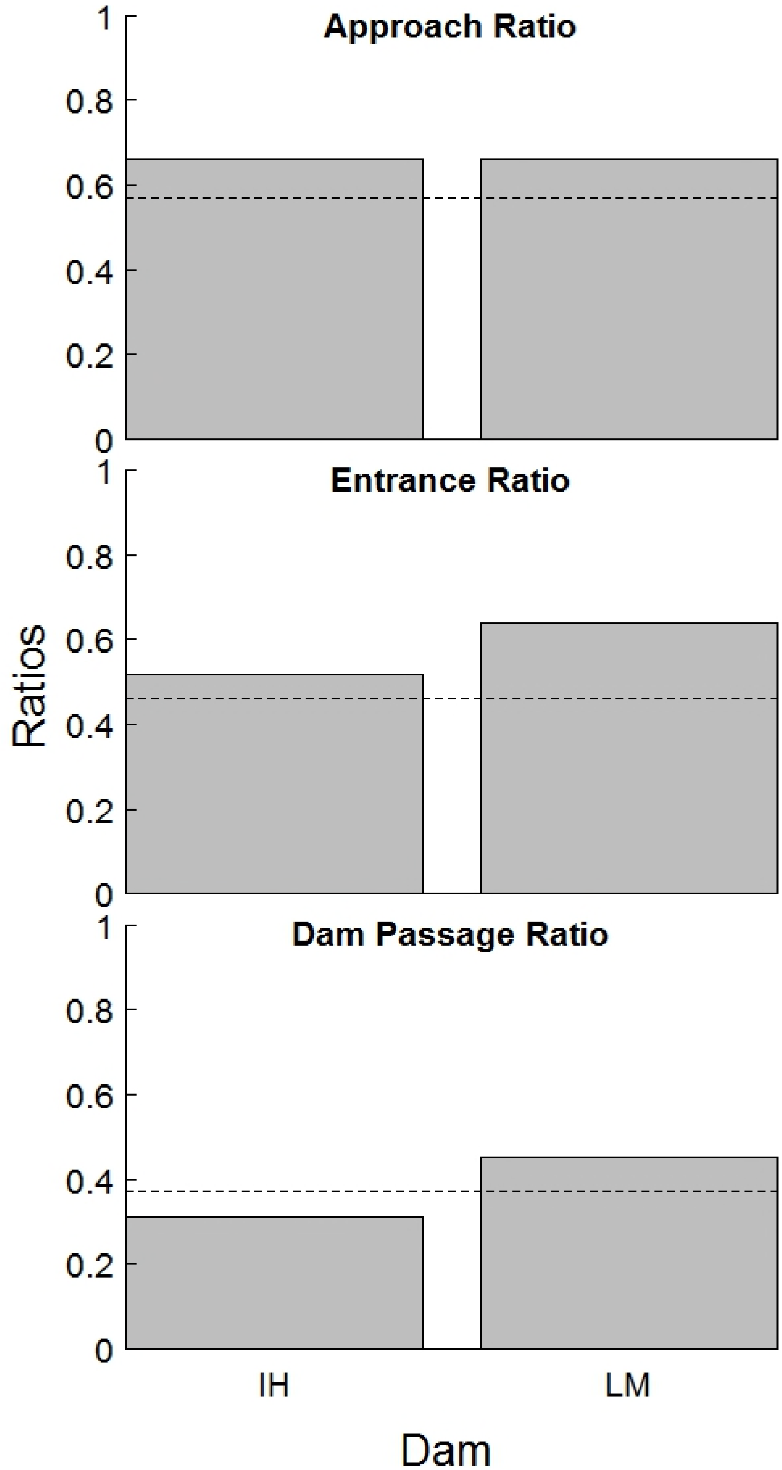

Figure 28. Release group passage metrics (# unique approaches, entrances or passages / # released below Ice Harbor or Lower Monumental Dams, respectively) at two lower Snake River dams using fish translocated from John Day Dam, 2015 compared to observations at McNary Dam from 2005 to 2010 using fish captured at McNary Dam (Keefer et al. 2013a) All metrics were calculated using radio-telemetry data. Horizontal dashed lines at 0.57, 0.46 and 0.37 are the approach, entrance and passage ratios, respectively, for McNary Dam from 2005 – 2010 (Keefer et al. 2013) for reference.

Table 13. Release group passage metrics at two lower Snake River dams using fish translocated from John Day Dam, 2015 compared to observations at McNary Dam from 2005 to 2010 using fish captured at McNary Dam (Keefer et al. 2013a) All metrics were calculated using radio-telemetry data. Sample sizes are in parentheses. IH=Ice Harbor, LM=Lower Monumental, MN=McNary.

	Snake River Dams		
	IH	LM	MN*
Released	270	91	276
Approached (n)	0.66 (179)	0.66 (60)	0.57 (158)
Entered (n)	0.52 (141)	0.64 (58)	0.46 (128)
Passed (n)	0.31 (85)	0.45 (41)	0.37 (102)

*Years: 2005-2010; Keefer et al. 2013a

Length-Dependent Passage

Dam Passage was consistently higher at Lower Monumental, Little Goose, and Lower Granite Dams for fish released in Ice Harbor Dam tailrace compared with those released in the forebay (Figure 29), likely because of the larger size of adults passing Ice Harbor Dam (Figure 30). This did provide some evidence to support the hypothesis that lamprey size affects passage at lower Snake River dams, as observed at Columbia River dams (Keefer et al. 2013a). In the cases of Ice Harbor, Lower Monumental, and Little Goose Dams, fish length distributions were also slightly longer for fish that passed the dams compared with those that did not. While the directionality of this trend was consistent with previous studies (i.e. – fish that pass are larger than those that do not pass), the differences were marginally statistically significant for Little Goose Dam only (p = 0.10;Table 14). A synthesis of these data for Lower Granite Dam was not developed due to small sample sizes.

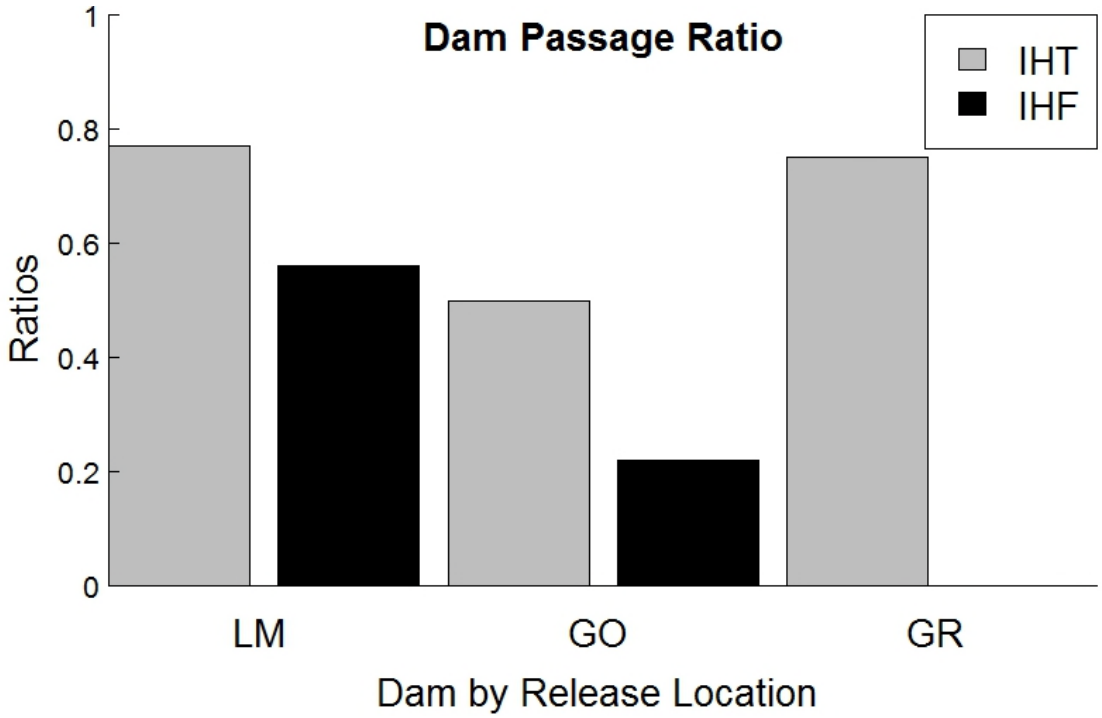

Figure 29. Entrance, fishway passage, and dam passage ratios (# unique entrances, fishway passages or dam passages / # unique approaches) for three lower Snake River dams by release location calculated using radio-telemetry data, 2015. Dams: LM=Lower Monumental, GO=Little Goose, GR=Lower Granite. Release groups: IHT=Ice Harbor tailrace, IHF=Ice Harbor forebay.

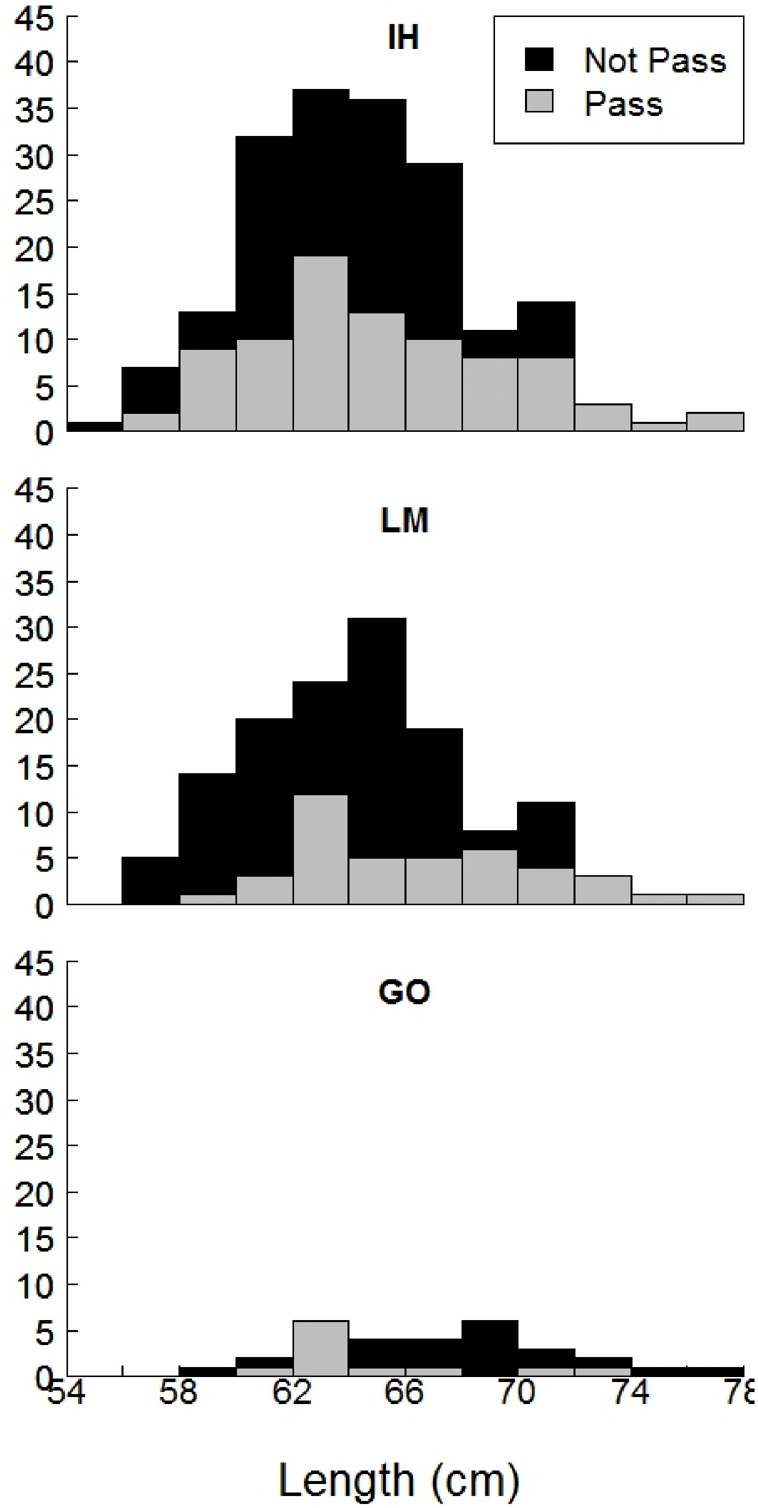

Figure 30. Passage results for translocated lamprey by length for three lower Snake River dams calculated using radio-telemetry data, 2015. IH=Ice Harbor, LM=Lower Monumental, GO=Little Goose.

Table 14. Logistic regressions on passage results by length for Ice Harbor, Lower Monumental, Little Goose and Lower Granite dams on the lower Snake River calculated using radio-telemetry data, 2015.

Snake River Dam	Sample Size (*n*)	Test Statistic (z value)	p-value
Ice Harbor	270	1.401	0.16
Lower Monumental	176	2.930	0.003*
Little Goose	41	-1.156	0.248
Lower Granite	11	0.626	0.53

+Significant at the $\alpha = 0.1$ level

Hydrosystem-wide Comparisons

Conversion Rates

Top-of-dam to top-of-dam conversion rates were similar to those observed in the lower Columbia River. Among the three dams for which conversion rates could be calculated with radio-telemetry data, Lower Monumental Dam exhibited the highest rate during the 2015 study period (Figure 31). Over 60% of fish that passed Ice Harbor Dam also ascended Lower Monumental Dam. This was not unexpected given the proximity of Lower Monumental Dam to Ice Harbor Dam. Moreover, fish would be expected to arrive at these dams relatively early in the migration season allowing them more time to pass, potentially increasing conversion rates. Early migrating lamprey have also been found to be larger on average than later migrating fish though this would have had a less pronounced confounding effect on conversion rate comparisons between dams in 2015 because the majority of tagging occurred during the latter half of the run.

Lower Granite Dam appeared to have a higher conversion rate relative to Little Goose Dam, though small sample sizes at Lower Granite Dam (9 fish) precluded a clear comparison. One might surmise that conversion rates would steadily decline with increasing distance traveled and the number of dams passed, but this was not the case. Additional years of data would be useful for determining whether this observation was an anomaly. However, it is worth noting that lamprey at Little Goose Dam were smaller than those at Lower Granite Dam (65.7 cm and 67.0 cm, respectively; Figure 30). Larger average size, a strong correlate to higher passage rates, may allow fish to convert at higher rates as they move upstream through the hydropower system.

Conversion rates using HDX PIT tag data could only be calculated for Lower Monumental and Lower Granite Dams because Little Goose Dam is not currently outfitted with HDX PIT tag antennas. Lower Granite Dam's HDX PIT tag conversion rate (50%) was the same as that calculated using radio-telemetry data. This result is not surprising given that lamprey in this study received both a radio tag and HDX pit tag, so the metrics were calculated from the same sample of fish and any discrepancy between these metrics would represent a difference in detection rates between the two tracking technologies. For example, Lower Monumental Dam's

HDX PIT tag conversion rate was less than half (30%) of that calculated using radio-telemetry data. However, this did not come as a surprise either given the fact that the south fishway had its top-of-ladder HDX receiver shutdown for the duration of 2015. The north ladder HDX PIT tag conversion rate was more comparable to that obtained from for radio-telemetry data (48%).

Passage estimates and conversion rates should also be regarded as biased low due to uncertainties about the final fates of migrating fish. While we were able to account for spring 2015 migration movements for some fish released during the 2014 evaluation, any spring migration movement by fish released in 2015 will remain unknown. This could affect passage metrics, particularly conversion rates, which do not account for fish holding in the main stem Snake River and those failing to successfully navigate a reservoir and ascend a dam.

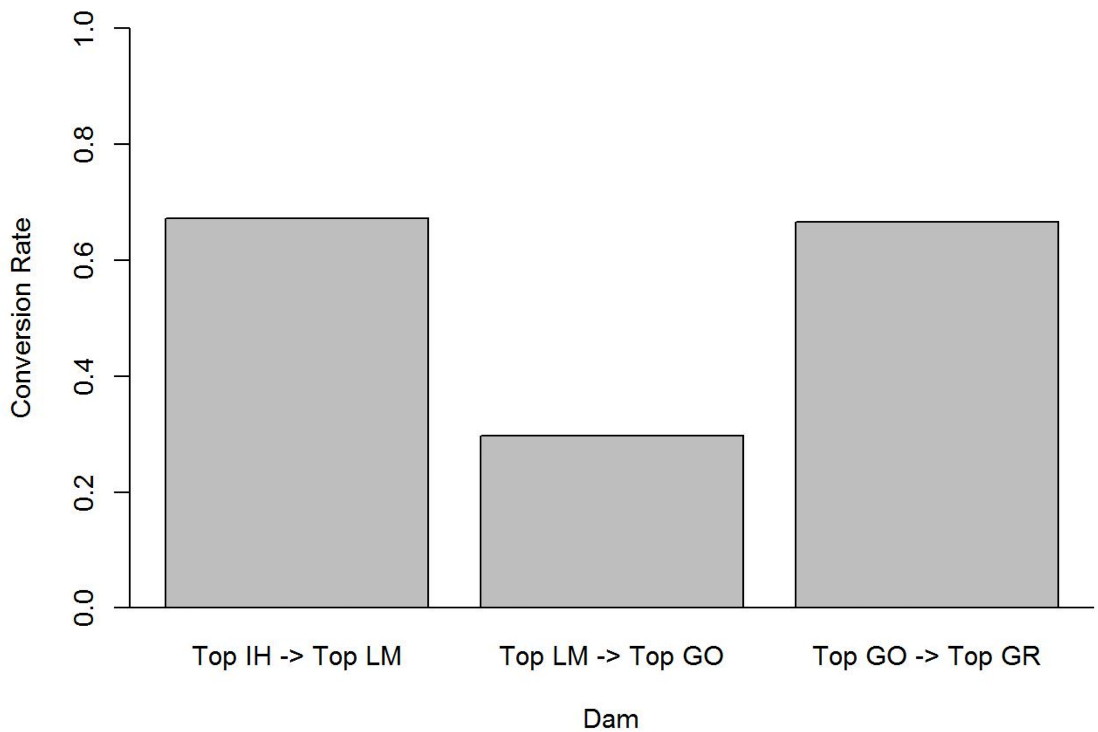

Figure 31. Conversion rates (Unique # passages current dam / [Unique # passages previous dam – [Unique # fallbacks + Unique # Tributary diversions]]) of translocated lamprey at three Snake River dams calculated using radio-telemetry data, 2015.

Dispersal Curves

There was an exponential decrease in the proportion of fish dispersing up or downstream from the Ice Harbor Dam release sites in both 2014 and 2015 (Figure 32). This is likely because a major selection event occurs at Ice Harbor Dam with the majority of fish ceasing upstream or downstream dispersal beyond that point. Selection events of lesser magnitude appear to take place at all subsequent dams.

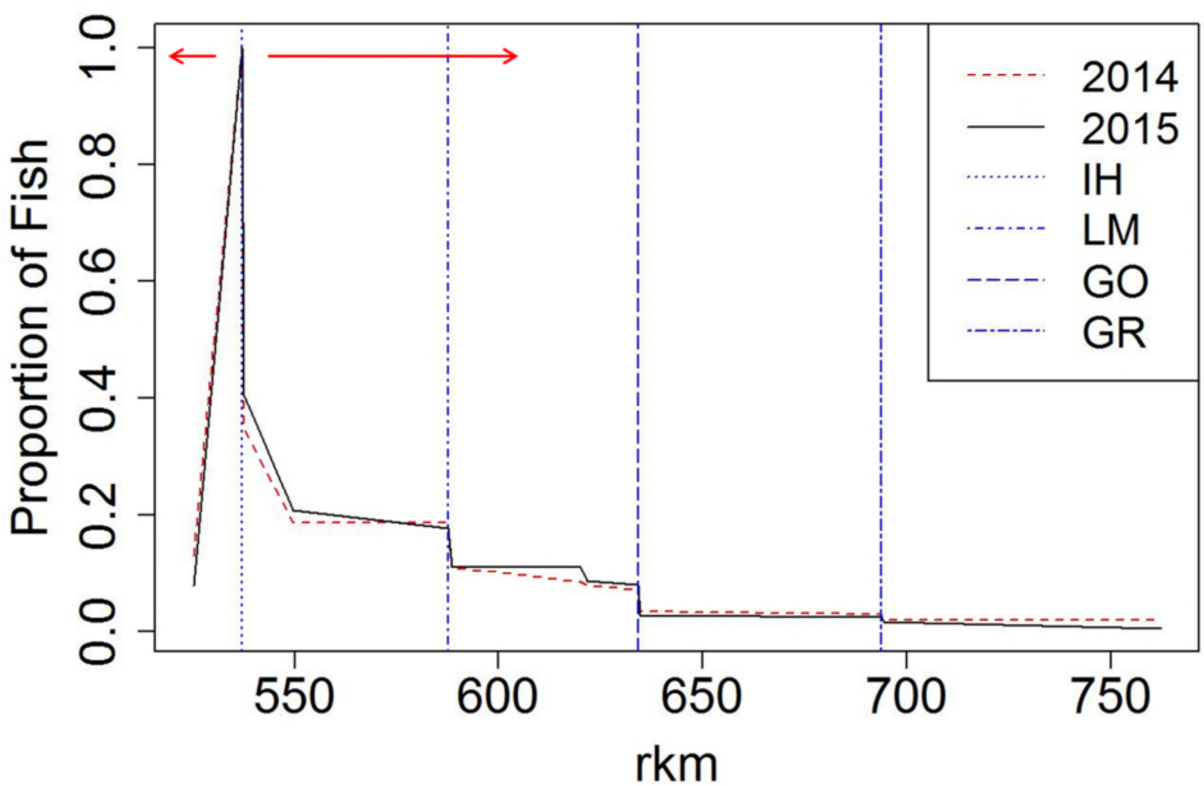

Figure 32. Dispersal curves for translocated lamprey in the lower Snake River calculated using radio and HDX PIT telemetry data, 2015.

Final Fates

As of December 28, 2015, more than half of the fish released in both years were last detected downstream of Ice Harbor Dam (2014 - 65.7%; 2015 – 72%), including 7.8% in 2014 and 2015, respectively, in the Columbia River (Table 15; Figure 33; Figure 34). Thereafter, fish were last detected in progressively smaller proportions with increasing distance upstream from the release site. A significant portion of the fish were occupying areas in the main stem Snake River within the hydropower system (2014 - 20.3%; 2015 – 26.6%), and the remaining fish were distributed between tributaries to the Snake River (2014 – 2.0%; 2015 – 0.8%) and the Snake River main stem upstream of Lower Granite Dam (2014 - 2.0%; 2015 – 0.6%). This means 82.5% and 90% of fish in 2014 and 2015, respectively, were still at large within the lower Snake River hydrosystem at the conclusion of our study.

Table 15. Final distribution of radio-tagged adult Pacific lamprey at their last detection by radio-telemetry and/or HDX PIT tag on, or prior to 29 January 2015. Zeros (0) indicate no detections. "No Data" indicates no data collected.

rkm	Site	Number of Fish	% of Released
	2014		
638.9 +	At or Above Priest Rapids (Col. R.)	2	1.0
522	Columbia River	24	12.0
537.2	Ice Harbor Tailrace (Released but never detected)	12	6.0
	Ice Harbor Tailrace (Released and detected)	82	41.2
537.7	Ice Harbor Forebay (Released but never detected)	11	5.5
	Ice Harbor Forebay (Released and detected)	15	7.5
587.6	Lower Monumental Tailrace	23	11.6
588.6	Lower Monumental Forebay	8	4.0
620.2	Palouse River	1	0.5
621.7	Tucannon River	3	1.5
634.3	Little Goose Tailrace	9	4.5
634.8	Little Goose Forebay	1	0.5
693.8	Lower Granite Tailrace	3	1.5
694.6	Lower Granite Forebay	0	0
753.3	Clearwater River	3	1.5
762.3	Main stem Snake	2	1.0
	2015		
638.9 +	At or Above Priest Rapids (Col. R.)	3	0.8
522	Columbia River	28	7.8
537.2	Ice Harbor Tailrace (Released but never detected)	36	10.0
	Ice Harbor Tailrace (Released and detected)	151	41.8
537.7	Ice Harbor Forebay (Released but never detected)	42	11.6
	Ice Harbor Forebay (Released and detected)	37	10.3
587.6	Lower Monumental Tailrace	24	6.7
588.6	Lower Monumental Forebay	9	2.5
620.2	Palouse River	0	0
621.7	Tucannon River	3	0.8
634.3	Little Goose Tailrace	16	4.4
634.8	Little Goose Forebay	3	0.8
693.8	Lower Granite Tailrace	3	0.8
694.6	Lower Granite Forebay	4	1.1
753.3	Clearwater River	0	0
762.3	Main stem Snake	2	0.6

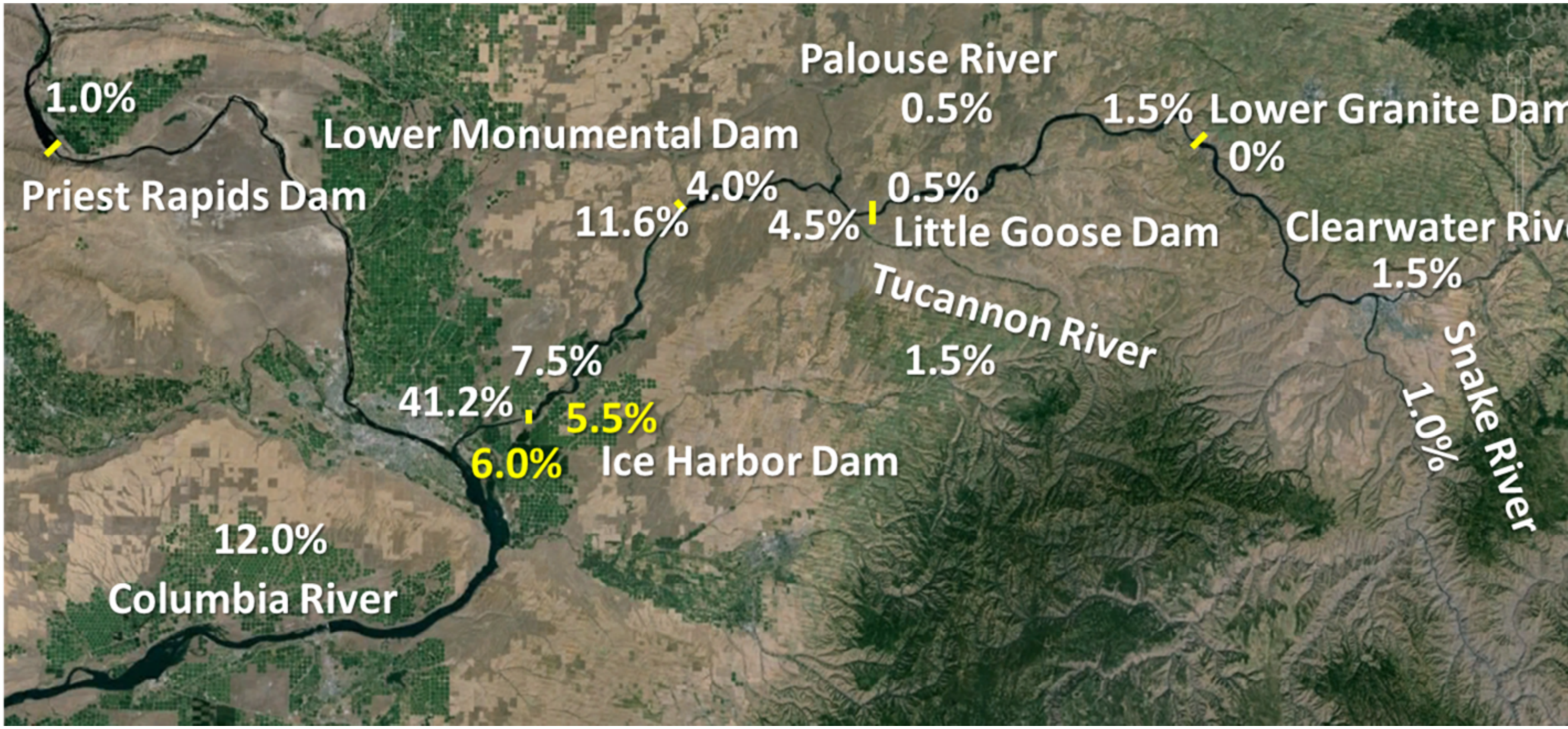

Figure 33. Final distribution of radio-tagged adult Pacific lamprey from 2014 at their last detection by radio-telemetry and/or HDX PIT tag on, or prior to 29 January 2015. Yellow text indicates fish that were released in the Ice Harbor tailrace or forebay and were never subsequently detected anywhere else.

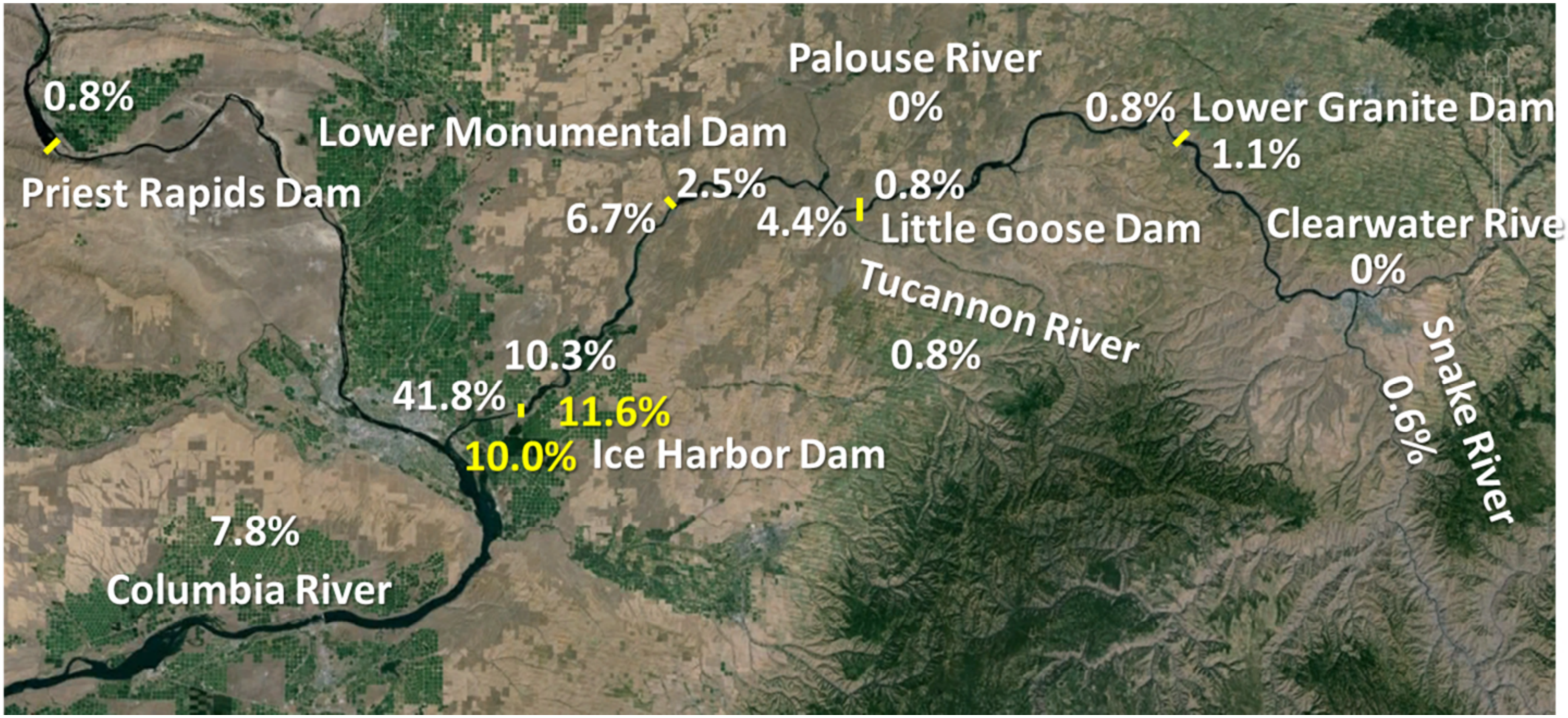

Figure 34. Final distribution of radio-tagged adult Pacific lamprey from 2015 at their last detection by radio-telemetry and/or HDX PIT tag on, or prior to 29 January 2016. Yellow text indicates fish that were released in the Ice Harbor tailrace or forebay and were never subsequently detected anywhere else.

SUMMARY & CONCLUSIONS

The primary objective of our research effort was to evaluate passage conditions and quantify lamprey passage success at the four lower Snake River dams to provide baseline data on lamprey passage and movement within the lower Snake River. It was apparent that passage conditions inside the fishways are similar among dams. However, lamprey exhibited substantial differences in approach, entrance and passage ratios at entrances within and among dams (Objective 1). This indicates that an understanding of conditions related to successful entries and passage is an important area of further research. The influence of fishway entrance conditions on lamprey passage success is highlighted by our observation that the location of a fish's initial approach was not a reliable indicator of which fishway would be entered and ultimately used for passage. That is, lamprey appeared to explore multiple potential passage routes before selecting a suitable route. It was also not uncommon for our study fish to enter and exit a fishway multiple times before ascending the dam, with only 14% to 51% of fish passing on their first entry. In general terms, lamprey do not often enter the fishway to which they were initially attracted, and often did not pass the fishway they first entered (turning around most often in the transition pool areas) on their first attempt. Thus, current conditions at fishway entrances and transition pools appear to be the primary bottlenecks limiting successful lamprey passage at Snake River Dams.

The baseline passage metrics (Objective 2) reported in this study indicate that lamprey in the Snake River appear to approach, enter and pass dams at rates comparable to those observed for similar studies in the Columbia River (Keefer et al. 2013a) and that these rates remain consistent across our two study years despite substantial climatic differences between the two years. These results provide a useful baseline of lamprey movement and passage data on the Lower Snake River but suggest that further targeted studies may be necessary to elucidate specific dam passage challenges. The need for additional fine scale lamprey movement data precludes development of specific recommendations for fishway alterations that might improve lamprey passage conditions in the lower Snake River. However, the similarity between Columbia River mainstem passage metrics and lower Snake River passage metrics suggest similar mechanisms may be at work and that insights and passage improvements may be directly transferrable between systems.

Subtle differences in the calculation of the suite of lamprey passage metrics reported here (Objective 2) and for similar studies previously completed in the Columbia River combined with highly similar, if not identical, nomenclature has led to confusion and understandable but erroneous questions of redundancy. For example, the subtle difference between passage ratios where the denominator can be either total fish released below the dam (e.g. Figure 28), the number of fish approaching the dam (e.g. Figure 19), or the number of fish that entered a fishway (e.g. Figure 20) is difficult to follow. These difficulties are exacerbated when the same terminology is used to describe each metric and correct interpretation is dependent on the reader's understanding of how each metric is calculated. Subtle differences in calculations result in metrics and figures that may appear redundant at first glance, but are distinct in that they are each intended to evaluate a different component of the fish passage process in a comprehensive manner. We acknowledge that, a clearer nomenclature for passage metrics and more advanced metrics developed with greater statistical rigor, though outside the scope of this project, is desirable and should be incorporated into future efforts to study lamprey passage in the lower Snake River.

Conversion rates (Objective 3) varied across years but generally decreased in an upstream direction through the hydrosystem. This variation and trend is likely explained by the interaction of a variety of factors including passage conditions at each dam, size-selective passage success and/or behavioral factors, such as a lamprey’s choice to actively migrate upstream, remain near the release site, or migrate downstream to the Columbia River. Fish within our study population exhibited all of these behaviors and the results of this study likely represent a combination of all three factors. Therefore, while conversion rates are extremely useful for salmon studies, where final destinations are often known and reservoir effects are of interest, these metrics are more confounded for lamprey, which may choose not to pass a dam for numerous reasons. The site specific factors underlying each conversion rate are beyond the scope of the present study but would merit further, targeted examination.

While radio telemetry and HDX PIT tag technology, coupled with fish translocation, have been successful elsewhere in the Columbia Basin, their effectiveness in the lower Snake River was uncertain due to the need to translocate large numbers of lamprey from trapping locations at mainstem Columbia River dams for release downstream of lower Snake River dams. If not for translocation, many of our study fish may have migrated up other Columbia River tributaries. It was expected that some radio-tagged fish would migrate upstream following release below Ice Harbor Dam (Peery et al. 2013), but whether the number of upstream migrants would be sufficient to monitor passage rates was unknown. Fortunately, our results indicated that translocated lamprey in the Snake River migrate upstream and pass dams at rates comparable to those observed for similar studies in the Columbia River (Keefer et al. 2013a), validating our study design.

While translocation was an effective strategy for increasing the number of tagged fish in our study population, we were not able to quantify the effect of translocation relative to other biotic and abiotic determinants of passage success. Therefore, the dam passage metrics reported here should be regarded as minimum estimates. Quantifying the effect of translocation would permit the development of passage metrics representative of adult lamprey that volitionally enter the Snake River, but doing so is not trivial. Quantification of effects of translocation on lamprey migration behavior is complex and has proven challenging elsewhere in the Columbia Basin. While relative metrics of passage success are useful for identifying potential lamprey migration impediments, quantifying an unbiased passage success rate is necessary to understand the impact of dam passage on lamprey population abundance in the Snake River Basin. Future studies should consider approaches that quantify translocation effects by including upstream release groups and employing study designs that can support and take advantage of more complex data analyses.

A substantial percentage of our study animals were still at large within the Snake River hydrosystem at the conclusion of our monitoring efforts in 2015. These fish will have one of five final fates: 1) move up an unmonitored tributary in the spring, 2) perish within the hydrosystem, 3) elect to spawn in the tailrace of the nearest upstream dam, 4) dropout of the lower Snake River and continue their migration up the Columbia River, or 5) ascend upstream to suitable spawning habitat. Similar studies conducted in the Columbia River have found that fish commonly move up tributaries in the spring from the reservoirs or tailraces in which they overwintered. However, there are relatively few suitable tributaries within the lower Snake River and past studies indicate that few fish undertake significant upstream migrations in the spring following overwintering. Indeed, HDX PIT tag data from fish released in the lower Snake River in 2014 also indicated that lamprey were unlikely to proceed up the Snake River after overwintering. We expect most of our at-large fish will either attempt to spawn in the lower Snake River or drop back into the Columbia River in search of a suitable spawning tributary.

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APPENDIX A: DAM SCHEMATICS

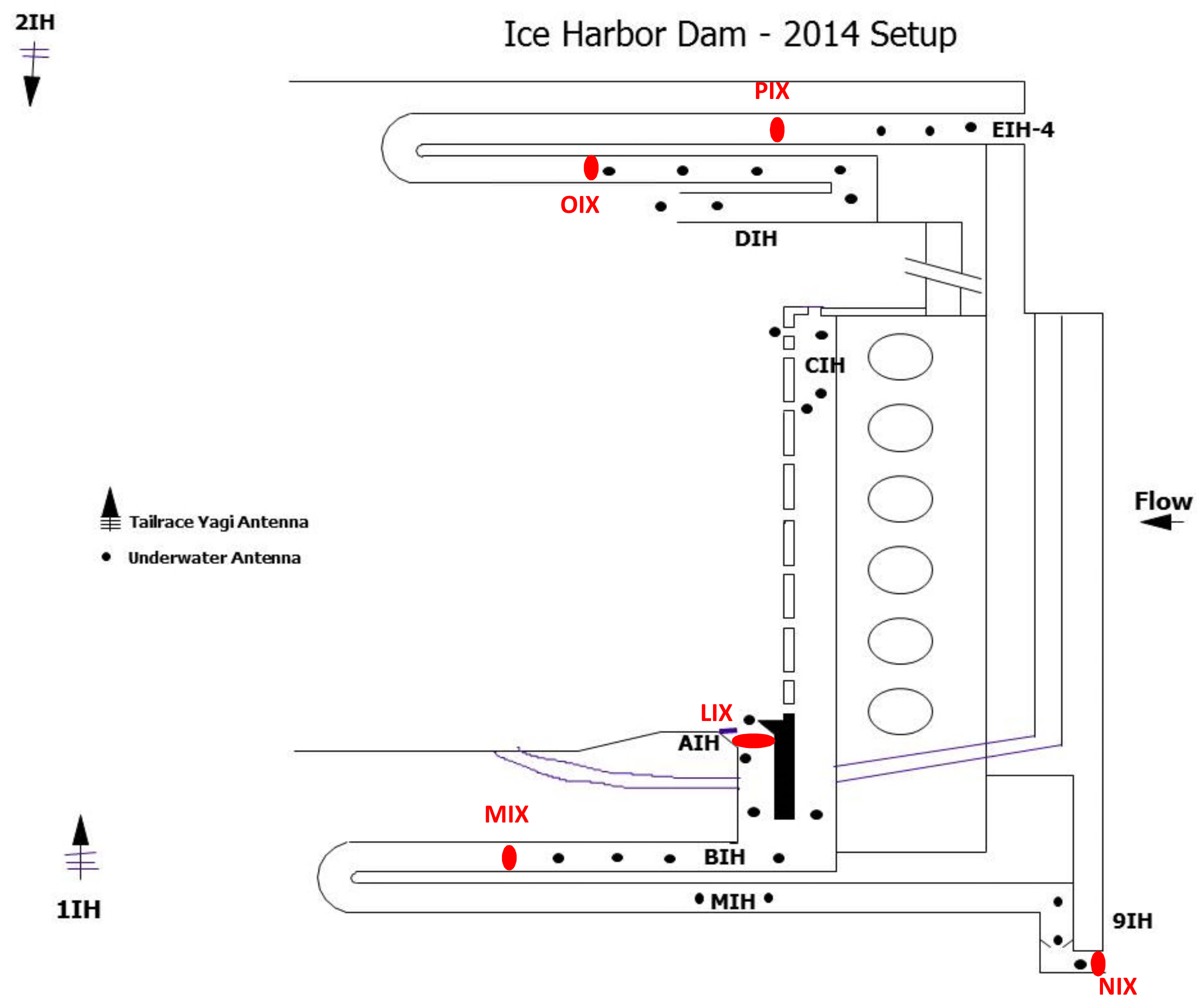

Figure A - 1. Radio-telemetry (black circles and text) and HD PIT (red ovals and text) tag antenna locations used in 2014 - 2015 studies at Ice Harbor Dam.

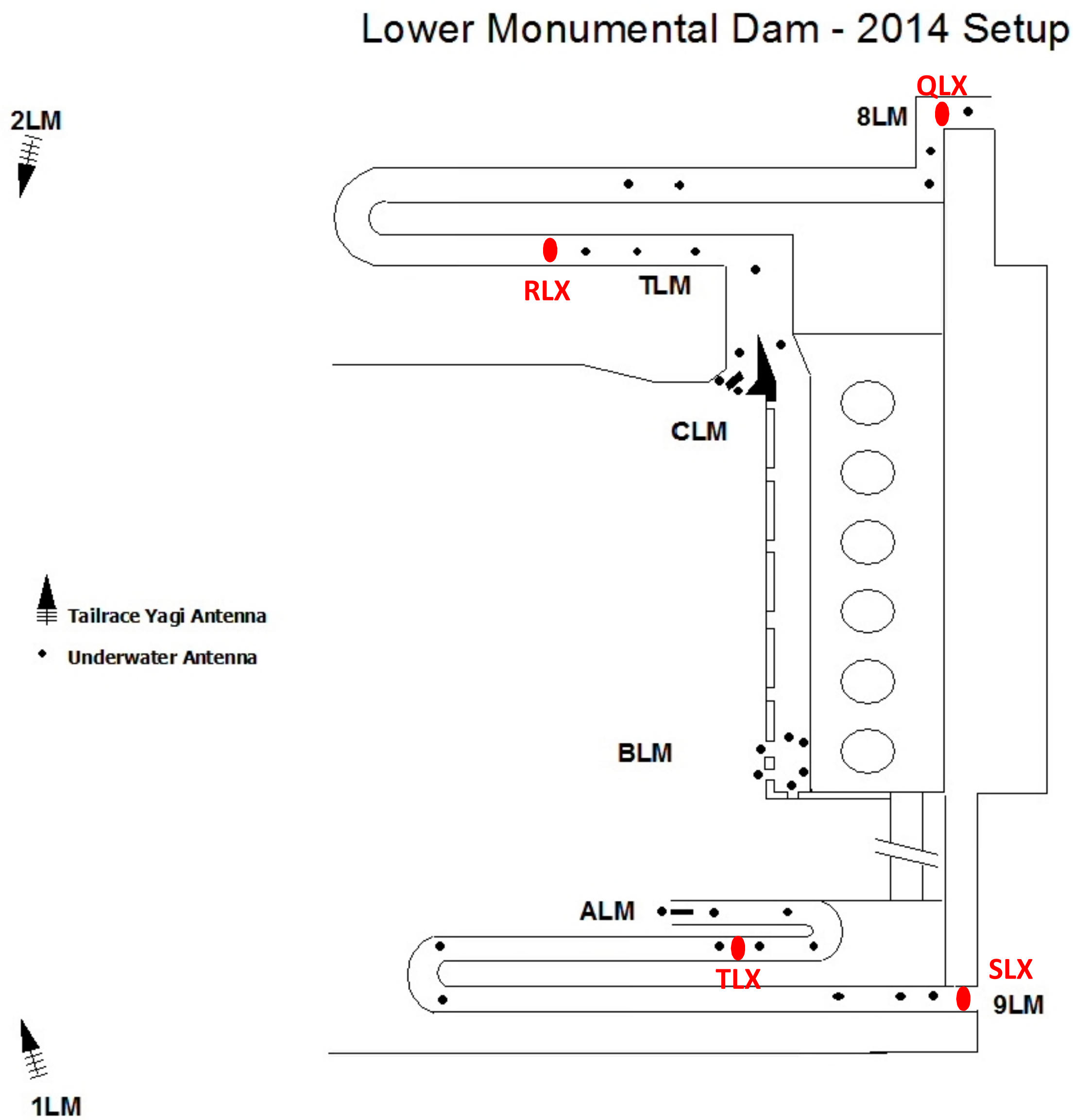

Figure A -2. Radio-telemetry (black circles and text) and HD PIT (red ovals and text) tag antenna locations used in 2014 - 2015 studies at Lower Monumental Dam.

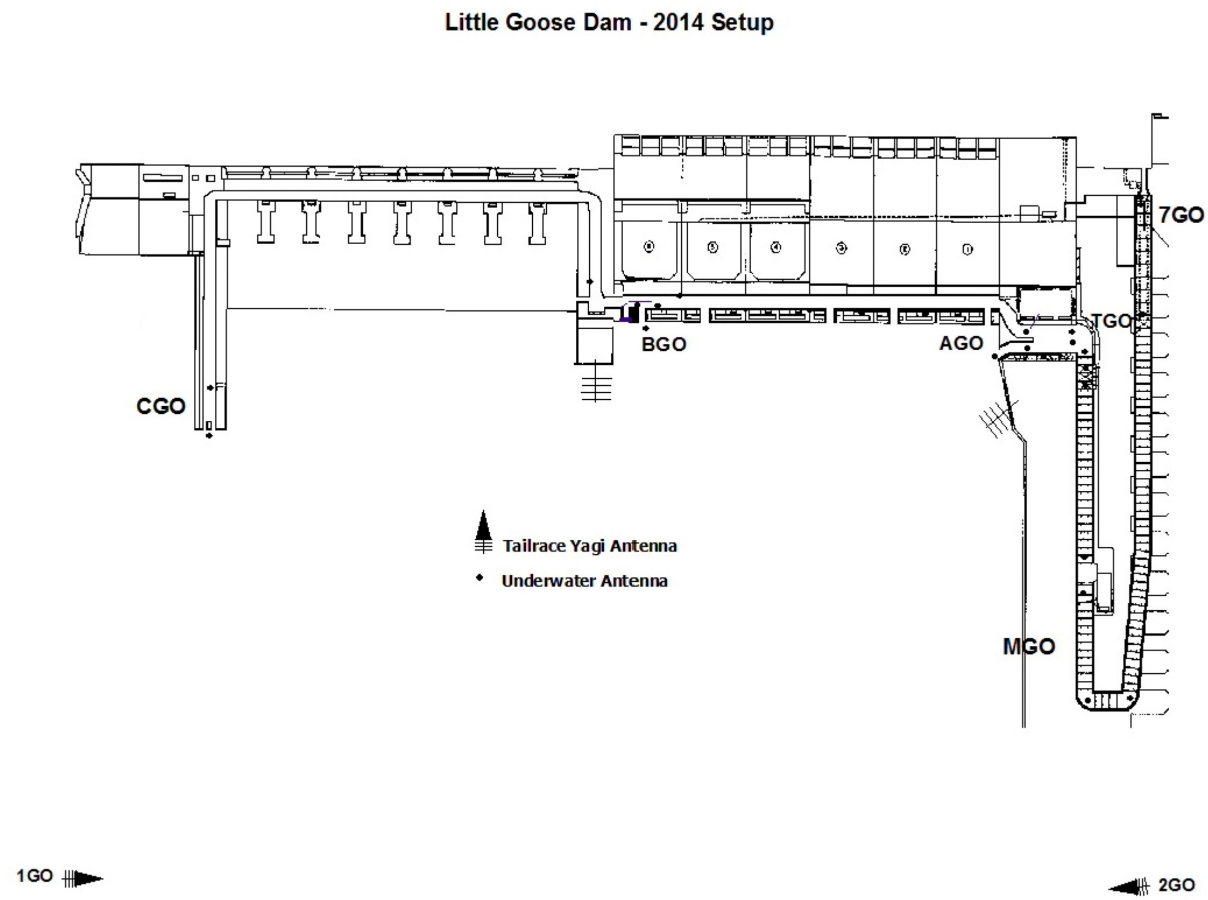

Figure A - 3. Radio-telemetry (black circles and text) tag antenna locations used in 2014 - 2015 at Little Goose Dam. HD PIT tag antenna system has not been installed at Little Goose Dam.

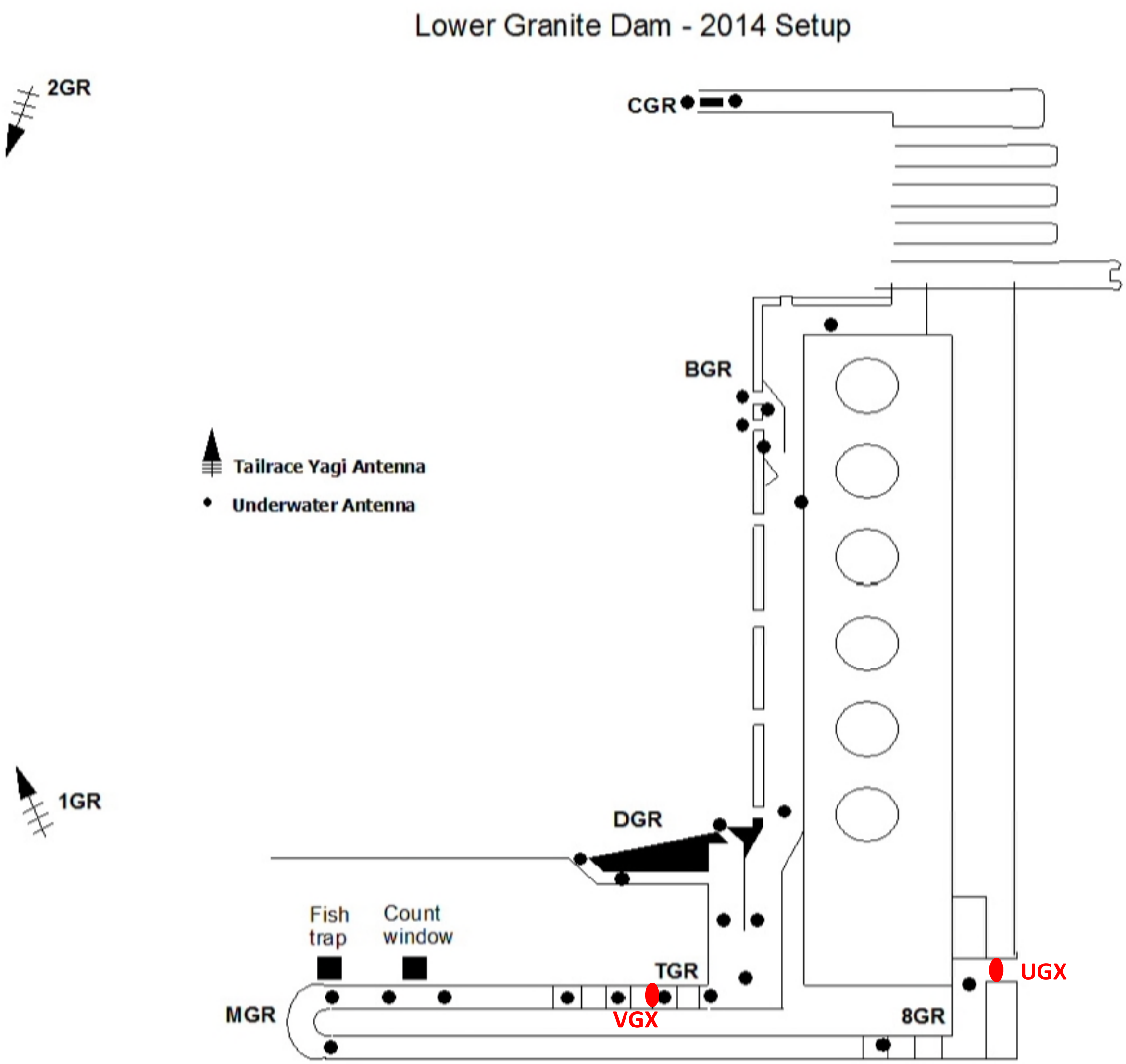

Figure A - 4. Radio-telemetry (black circles and text) and HD PIT (red ovals and text) tag antenna locations used in 2014 - 2015 studies at Lower Granite Dam.