Technical Report 2012-8

ADULT PACIFIC LAMPREY PASSAGE: DATA SYNTHESIS AND FISHWAY IMPROVEMENT PRIORITIZATION TOOLS

Prepared by:
Matthew L. Keefer, Tami C. Clabough, Michael A. Jepson, Eric L. Johnson, Charles T. Boggs & Christopher C. Caudill

Department of Fish and Wildlife Sciences
College of Natural Resources, University of Idaho

Prepared for:
U.S. Army Corps of Engineers
Walla Walla District

FINAL

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Under contract #:
W912EF-08-D-0007

FINAL

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EXECUTIVE SUMMARY

This report contains summary information on adult Pacific lamprey migration behavior and passage at dams in the Federal Columbia River Power System (FCRPS). It provides managers and researchers with data summaries and synthesis from more than a decade of adult lamprey research using tagged fish and experimental results from an artificial fishway at Bonneville Dam. It also includes a set of reference and modeling tools developed to identify lamprey passage problems at fishways and to help prioritize sites for future fishway improvements. Separate deliverables include standardized fishway maps and a 3-D interactive fishway mapping tool. The report is organized as follows:

Section 1 provides an introduction to the specific review, data synthesis, prioritization modeling, and fishway mapping objectives.

Section 2 is a review of adult Pacific lamprey swim performance literature. It includes summaries of basic lamprey behaviors such as burst and sustained swim speeds, oral disc attachment, nocturnal activity, and climbing behaviors. It also provides details of known structural and hydraulic challenges adult Pacific lamprey encounter at Columbia and Snake River fishways, plus synopses of reported passage problems in the most common fishway sections (i.e., entrances, collection channels, junction pools, transition pools, count stations, and overflow and serpentine weirs). Section 2 concludes with a compilation of operational criteria for FCRPS fishways (in development) and a summary of information gaps related to lamprey performance at dams.

Section 3 is a collaborative work in progress that may eventually provide standardized terminology for fishway features at FCRPS projects. This section was intended to be developed with U.S. Army Corps of Engineers (USACE) personnel at a workshop held on 30 October 2012; this objective was subsequently given lower priority.

Section 4 provides methodological details for the radiotelemetry and half-duplex (HD) PIT tag studies of adult Pacific lamprey conducted from 1997-2002 and 2005-2011. These include information on lamprey collection and tagging efforts, monitoring arrays, and definitions of entrance, fishway, fishway segment, dam, reservoir passage, and reach passage efficiency and escapement metrics.

Section 5 is a comprehensive summary of the radiotelemetry results from 1997-2002 and 2007-2010. It includes sub-sections for nine Columbia and Snake river dams and provides a review of a full range of behavioral and passage efficiency metrics at Bonneville, The Dalles, John Day, McNary, and Ice Harbor dams. Each of these sub-sections concludes with a ranking of potential lamprey passage bottlenecks and recommendations for potential prioritization.

Section 6 compares lamprey entrance efficiency, fishway passage efficiency, and dam passage efficiency estimates across dams. The side-by-side comparisons will help identify the least and most efficient sites and routes and can be used in prioritization and planning decisions.

Sections 7 and 8 summarize information on reservoir passage efficiency, dam-to-dam escapement, and multi-dam escapement for radio- and HD-PIT tagged lamprey. This information is useful for understanding patterns in lamprey distribution in the Columbia River basin.

Section 9 includes results from a series of passage improvement prioritization models. These models were parameterized using data from the radiotelemetry and HD PIT studies. The first group of models evaluates potential benefits of reducing passage bottlenecks at specific fishway segments at Bonneville, The Dalles, John Day, and McNary dams. They are intended to help managers identify priority sites for fishway improvements at individual projects. The second set of models evaluates how improvements to dam-wide passage efficiency increase lamprey escapement to upriver sites. These models can be used to identify which dams should be prioritized for lamprey passage improvements.

1.0 INTRODUCTION

1.1 OBJECTIVES

The overarching objective of this synthesis is to compile and interpret information related to adult Pacific lamprey passage at dams and through reservoirs in the Federal Columbia River Power System (FCRPS). The document and associated modeling and fishway mapping tools are intended to facilitate deliberation on adult lamprey passage planning, as described in the Pacific Lamprey Passage Improvements Implementation Plan 2008-2018 (USACE 2009). More specifically, the current document will:

1) identify information gaps related to adult lamprey passage performance at FCRPS dams;

2) standardize FCRPS fishway terminology for passage assessments;

3) summarize results from radiotelemetry and HD-PIT tag studies of adult lamprey conducted from 1997-2011;

4) help managers prioritize sites for fishway improvements for adult lamprey using benefits models developed using existing passage data;

5) produce simplified drawings of FCRPS dam fishways;

6) develop reference / mapping tools for USACE staff and regional managers to summarize known adult lamprey passage problems, diagnose potential causes, identify potential solutions, and track passage improvements and evaluations.

1.1.1 LITERATURE REVIEW OF LAMPREY SWIM PERFORMANCE

To put the data synthesis in perspective, we conducted a review of the scientific literature on adult Pacific lamprey swim performance. This was intended to help identify critical information gaps and evaluate potential mechanisms of observed adult lamprey passage problems at FCRPS dams. Our emphasis was on lamprey swim speeds and other migration behaviors (i.e., oral disc attachment, nocturnal activity, predator avoidance) and how they relate to water velocity, turbulence, and structural features of fishways. Information from the literature was evaluated with respect to specific operational criteria for fishways at FCRPS dams.

Literature for the review was initially collected by searching in a peer-reviewed database (Web of Science) and by searching for grey literature (i.e., reports) using Google Scholar. We used the citation lists in the most relevant papers and reports to identify additional relevant material.

1.1.2 FISHWAY TERMINOLOGY STANDARDIZATION

A variety of terms have been used by different agencies and research groups to describe fishway features at FCRPS dams. This has created some confusion. This review was originally to include recommended terminology for various fishway segments (e.g., entrances, collection channels, junction pools, transition pools, etc.) that are structurally accurate and meaningful with respect to existing passage data. The standardization was discussed with USACE and other stakeholders at the 30 October 2012 Workshop. However, a plan to finalize terminology was not prioritized at that time.

1.1.3 REFERENCE MAPS AND TOOLS

As part of the synthesis project, a series of mapping tools are being developed in coordination with USACE staff as separate deliverables. These include:

1) Simplified drawings of each fishway, showing entrances, collection channels, transition and junction pools, weir sections, count stations, AWS channels, diffuser pools, lamprey passage systems (LPS), and other relevant features.

2) A three-dimensional, interactive reference map of the Bonneville Washington-shore fishway that can be annotated and updated as new information becomes available (e.g., Box 1). This tool will be used to graphically present lamprey passage information from the data synthesis, identify known passage problems and their potential mechanisms, display lamprey use patterns, and systematically track passage improvement implementation and evaluations.

Box 1. Example of interactive, 3-D model of a fishway section

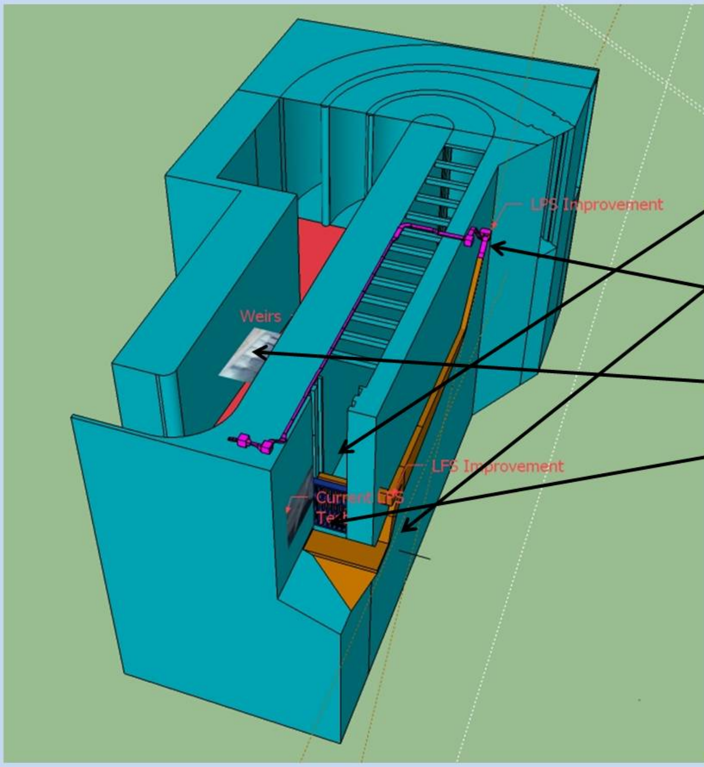

Image from the map in development for the Washington-shore fishway at Bonneville Dam

- North downstream entrance
- Planned lamprey flume structure (LFS)
- Lamprey passage structure (LPS)
- Link to photos
- Link to entrance efficiency data

1.1.4 DATA INVENTORY (1997-2011)

The Portland and Walla Walla districts of the USACE have funded adult Pacific lamprey research and monitoring in the lower Columbia River and/or lower Snake River since 1997 (see Tables 1 and 2 for a list of annual reports and other project-related publications). The data synthesis Sections in this report summarize research conducted jointly by the University of Idaho (UI) and National Marine Fisheries Service (NMFS). Tagging studies using lamprey collected at Bonneville Dam include radiotelemetry (1997-2002 and 2007-2010), half-duplex (HD) PIT tag (2005-2011), and acoustic telemetry (JSATS) (2010-2011) projects. Upriver tagging studies included radiotelemetry of lamprey collected at McNary Dam (2005-2010) and HD-PIT of lamprey collected at John Day Dam (2009).

The Bonneville tagging studies occurred in conjunction with observations of lamprey behavior in an experimental fishway at Bonneville Dam (1999, 2000, 2002, 2004-2006, 2008). Additional observation-based projects included using underwater video inside Bonneville fishways (2001) and at Bonneville and The Dalles count stations (2007-2008), and the use of dual frequency identification sonar (DIDSON) inside Bonneville fishways (2011). The data synthesis portion of this report focuses on data collected in the radiotelemetry and HD-PIT tag studies. JSATS and observational data are used to supplement interpretation of behaviors by radio- and HD PIT-tagged fish.

Section 5.0 summarizes a variety of fishway use and passage efficiency metrics (i.e., fishway entrance efficiency, fishway passage efficiency, fishway segment passage efficiency, dam passage efficiency, etc.) at individual dams. The dam-specific summaries identify known lamprey passage problems and potential mechanisms affecting passage failure and can be used to prioritize fishway improvement or additional research and monitoring at the dam-specific scale. Section 6.0 compares efficiency metrics across multiple dams. This section can be used to help identify lamprey passage priorities across projects. Section 7.0 summarizes reservoir passage data.

1.1.5 PASSAGE IMPROVEMENT PRIORITIZATION MODELS

The adult lamprey radiotelemetry and HD-PIT tag databases on lamprey behavior, passage efficiency, and upriver escapement can be used to test hypotheses related to prioritizing future investments in lamprey passage improvements. We developed a set of models to assess:

1) potential benefits of passage improvements at single sites within fishways (i.e., bottleneck relief); and

2) potential benefits to upriver escapement of increased dam-wide passage efficiency at a single dam or combination of dams.

The spreadsheet-based bottleneck models allow users to manipulate passage efficiency rates through individual fishway segments at individual dams and then assess effects on dam-wide passage efficiency. The base models are parameterized using the 1997-2002 and 2007-2010 radiotelemetry data. The upriver escapement models are simulations that rely on random sampling from existing data distributions and are constrained by user-selected criteria regarding lamprey passage efficiency improvements at dams. The escapement models were built in SAS.

Introduction

Table 1. Summary of peer-reviewed publication derived from USACE-funded studies of adult Pacific lamprey by UI-NMFS. Study types: RT = radiotelemetry, PIT = HD-PIT tag, JSATs = acoustic telemetry, Exp/Obs = experimental fishway, other laboratory experiments, or observational.

Author	Year	Title	Journal	Study type			
				RT	PIT	JSATs	Exp/Obs
Moser et al.	2002a	Passage efficiency of adult Pacific lampreys at hydropower dams on the lower Columbia River, USA	TAFS 131:956-965	X			
Moser et al.	2002b	Use of an extensive radio receiver network to document Pacific lamprey (*Lampetra tridentata*) entrance efficiency at fishways in the lower Columbia River, USA	Hydrobiologia 483:45-53	X			
Moser et al.	2003	Assessing Pacific lamprey status in the Columbia River basin	NW Science 77:116-125	X			
Moser et al.	2007a	Effects of surgically implanted transmitters on anguilliform fishes: lessons from lamprey	JFB 71:1847-1852	X			
Moser et al.	2007b	Capture and collection of lampreys: the state of the science	RFBF 17:45-56				
Reinhardt et al.	2008	Pacific lamprey climbing behavior	CJZ 86:1264-1272				X
Moser et al.	2008	Grating size needed to protect adult Pacific lampreys in the Columbia River basin	NAJFM 28:557-562				X
Keefer et al.	2009a	Effects of body size and river environment on the upstream migration of adult Pacific lampreys	NAJFM 29:1214-1224		X		
Keefer et al.	2009b.	Variability in migration timing of adult Pacific lamprey (*Lampetra tridentata*) in the Columbia River, U.S.A.	EBF 85:253-264		X		
Keefer et al.	2010	Testing adult Pacific lamprey performance at structural challenges in fishways	NAJFM 30:376-385				X
Keefer et al.	2011	Behaviour of adult Pacific lamprey in near-field flow and fishway design experiments	FME 18:177-189				X
Moser et al.	2011	Development of Pacific lamprey fishways at a hydropower dam	FME 18:190-200		X		X
Johnson et al.	2012	Movement of radio-tagged adult Pacific lampreys during a large-scale fishway velocity experiment	TAFS 141:571-579	X			
Keefer et al.	2013	Factors affecting dam passage and upstream distribution of adult Pacific lamprey in the interior Columbia River basin	EFF 22:1-10	X			
Keefer et al.	2013	Context-dependent diel behavior of upstream-migrating anadromous fishes	EBF 96:691-700	X	X	X	
Keefer et al.	*In press*	Fishway passage bottleneck identification and prioritization: a case study of Pacific lamprey at Bonneville Dam	CJFAS	X			

Table 2. Summary of technical and letter reports derived from USACE-funded studies of adult Pacific lamprey. Study types: RT = radiotelemetry, PIT = HD-PIT tag, JSATs = acoustic telemetry, Exp/Obs = experimental fishway, other laboratory experiments, or observational.

Author	Year	Title	Report #	Study type RT	PIT	JSATs	Exp/Obs
Vella et al.	1999	Migration patterns of Pacific lamprey (*Lampetra tridentata*) in the lower Columbia River, 1997	NMFS	X			
Ocker et al.	2001	Monitoring adult Pacific lamprey (*Lampetra tridentata*) migration behavior in the lower Columbia River using radiotelemetry, 1998-99	NMFS	X			
Moser et al.	2002	Radiotelemetry investigations of adult Pacific lamprey migration behavior: evaluation of modifications to improve passage at Bonneville Dam, 2000	NMFS				
Moser et al.	2003	Migration behavior of adult Pacific lamprey in the lower Columbia River and evaluation of Bonneville Dam modifications to improve passage, 2001	NMFS	X			
Moser et al.	2005	Migration behavior of adult Pacific lamprey in the lower Columbia River and evaluation of Bonneville Dam modifications to improve passage, 2002	NMFS	X			X
Daigle et al.	2005	Evaluation of adult Pacific lamprey passage and behavior in an experimental fishway at Bonneville Dam	UI 2005-1				X
Moser et al.	2006	Development and evaluation of a lamprey passage structure in the Bradford Island auxiliary water supply channel, Bonneville Dam, 2004	NMFS				X
Clabough et al.	2008a	Evaluating adult Pacific lamprey dam passage counting methodology at Bonneville and The Dalles dams – 2007 – a preliminary letter report for Bradford Island fishway	UI Letter 28 February				X
Clabough et al.	2008b	Evaluating adult Pacific lamprey dam passage counting methodology at Bonneville and The Dalles dams – 2007 – a preliminary letter report for Washington shore fishway	UI Letter 3 June				X
Johnson et al.	2008	Experimental evaluation of fishway modifications on the passage behavior of adult Pacific lamprey at Bonneville Dam	UI Letter 14 August				X
Cummings et al.	2008	Direct and indirect effects of barriers to migration – Pacific lamprey at McNary and Ice Harbor dams in the Columbia River basin	UI 2008-7	X			
Boggs et al.	2008	Evaluation of adult Pacific lamprey migration and behavior at McNary and Ice Harbor dams, 2007	UI 2008-9	X			

Keefer et al.	2008a	Adult Pacific lamprey bypass structure development: tests in an experimental fishway, 2004-2006	UI 2008-10				X
Daigle et al.	2008	Evaluation of adult Pacific lamprey passage rates and survival through the lower Columbia River hydrosystem: 2005-2006 PIT-tag studies	UI 2008-12		X		
Moser et al.	2008	Development of passage structures for adult Pacific lamprey at Bonneville Dam, 2005	NMFS				X
Keefer et al.	2009	Adult Pacific lamprey migration in the lower Columbia River: 2007 radiotelemetry and half-duplex PIT tag studies	UI 2009-1	X	X		
Johnson et al.	2009	Effects of lowered nighttime velocities on fishway entrance success by adult Pacific lamprey at Bonneville Dam and fishway use summaries for lamprey at Bonneville and The Dalles dams, 2007	UI 2009-2	X			
Boggs et al.	2009	Evaluation of adult Pacific lamprey migration and behavior at McNary and Ice Harbor dams, 2008	UI 2009-5	X			
Keefer et al.	2009a	Adult Pacific lamprey migration in the lower Columbia River: 2008 radiotelemetry and half-duplex PIT tag studies	UI 2009-8	X	X		
Keefer et al.	2009b	Preliminary evaluation of radiotelemetry and half-duplex PIT tag data for Pacific lamprey at Bonneville Dam in 2009	UI Letter 25 Sept.	X	X		
Clabough et al.	2009	Use of night video to quantify adult lamprey passage at Bonneville and The Dalles dams in 2007-2008	UI 2009-9				X
Johnson et al.	2009	Effects of lowered fishway water velocity on fishway entrance success by adult Pacific lamprey at Bonneville Dam and fishway use summaries for lamprey at Bonneville and The Dalles dams, 2008	UI 2009-10	X			
Moser et al.	2009	Development of passage structures for adult Pacific lamprey at Bonneville Dam, 2006					X
Clabough et al.	2010	Evaluation of adult Pacific lamprey passage at the Cascades Island fishway after entrance modifications, 2009	UI 2010-2	X	X		
Keefer et al.	2010a	Adult Pacific lamprey migration in the lower Columbia River: 2009 radiotelemetry and half-duplex PIT tag studies	UI 2010-3	X	X		
Keefer et al.	2010b	Evaluation of adult lamprey behavior in the upper Washington-shore fish ladder and auxiliary water supply channel in 2009	UI Letter 25 March				
Keefer & Caudill	2010	Adult Chinook salmon and Pacific lamprey behavior in Bonneville's UMT channel	UI Letter 10 March	X			
Johnson et al.	2010	Effects of lowered fishway water velocity on fishway entrance	UI 2010-4	X			

		success by adult Pacific lamprey at Bonneville Dam, 2007-2009						
Clabough et al.	2010	General passage and fishway use summaries for adult Pacific lamprey at Bonneville, The Dalles and John Day dams, 2009	UI 2010-5	X				
Boggs et al.	2010	Evaluation of adult Pacific lamprey migration and behavior at McNary Dam with effects of night-time fishway flow reduction, 2009 – AND – Detection and behavior of transported adult Pacific lamprey	UI 2010-6	X	X			
Moser et al.	2010	Development of passage structures for adult Pacific lamprey at Bonneville Dam, 2007-2008						
Keefer et al.	2011	Adult Pacific lamprey migration in the lower Columbia River: 2010 radiotelemetry and half-duplex PIT tag studies	UI 2011-4	X	X			
Clabough et al.	2011a	Evaluation of adult Pacific lamprey passage at the Cascades Island fishway after entrance modifications, 2010	UI 2011-3	X	X			
Clabough et al.	2011b	General passage and fishway use summaries for adult Pacific lamprey at Bonneville, The Dalles and John Day dams, 2010	UI 2011-5	X				
Naughton et al.	2011	Evaluation of the juvenile salmon acoustic telemetry system (JSATS) for monitoring adult Pacific lamprey in the Bonneville reservoir and at Bonneville Dam, 2010	UI 2011-6			X		
Keefer et al.	2011a	Adult Pacific lamprey migration and behavior at McNary Dam 2005-2010	UI 2011-9	X				
Keefer et al.	2011b	Use of floating orifice gate fishway entrances by adult Chinook salmon, steelhead, sockeye salmon and Pacific lamprey at Bonneville Dam	UI Letter 5 July	X				
Keefer et al.	2011c	Evaluation of adult Pacific lamprey use of the John Day Dam north-shore fishway in 1997-1998 and 2000-2002	UI Letter 24 October	X				
Keefer et al.	2012	Adult Pacific lamprey migration in the lower Columbia River: 2011 half-duplex PIT tag studies	2012-3		X			
Noyes et al.	2012	Adult Pacific lamprey migration behavior and escapement in the Bonneville reservoir and lower Columbia River monitored using the juvenile salmonid acoustic telemetry system (JSATS), 2011	UI 2012-4-DRAFT			X		
Johnson et al.	2012	Evaluation of dual frequency identification sonar (DIDSON) for monitoring Pacific lamprey passage behavior at fishways of Bonneville Dam, 2011	UI 2012-5-DRAFT				X	

2.0 LITERATURE REVIEW OF LAMPREY SWIM PERFORMANCE

2.1 ADULT LAMPREY SWIM SPEEDS

Few studies have directly measured adult Pacific lamprey swimming performance, but an understanding of their swimming capability is important for the design and effective operation of fishways and other passage structures. A general conception is that adult Pacific lamprey are relatively poor swimmers compared to salmonids (*Oncorhynchus* spp) and American shad (*Alosa sapidissima*) and that is why lamprey underperform these species at dam fishways designed for these species. However, this is a simplification of the swimming differences between lamprey and other anadromous species in the Columbia River system. The long narrow bodies of Pacific lamprey and their undulating swim behaviors produce less powerful swimming (e.g., lower thrust, lower burst speeds) compared to salmonids, but these 'anguilliform' swimming traits can be energetically efficient (Borazjani and Sotiropoulos 2009). Recent neuromechanical models suggest lamprey may adjust body stiffness to optimize acceleration, maximum swimming speed and efficient steady swimming speeds (Tytell et al. 2010). In suitable environments (i.e., low velocity, low turbulence), lamprey can migrate long distance and may be more energetically efficient than salmonids. Lampreys are also capable of ascending vertical surfaces such as waterfalls that are impassable by salmonids.

One thing is clear: many adult Pacific lamprey have difficulty passing fishways at FCRPS dams and this likely results in mismatches between swimming behavior and design rather than "weak" or "poor" swimming capacity of lamprey. It is likely that the low burst swim speeds and relatively lower power of lamprey, relative to salmonids and shad, is a contributing factor. Water velocities at fishway openings and inside FCRPS fishways > ~1.5-2.0 m/s appear to be one of the contributing factors to poor lamprey passage efficiency, likely because these velocities (and associated turbulence) are a deterrent or partial barrier to upstream lamprey passage.

2.1.1 SUSTAINED SWIM SPEED

Sustained swim speeds are a commonly measured fish performance metric. Sustained speeds are typically estimated over relatively long time periods (e.g., > 1 h) and are an estimate of maximize ground speed within the aerobic scope of the fish and at speeds that are relatively energetically efficient.

Pacific lamprey: Sustained swim speeds of Pacific lamprey have not been well studied in controlled experiments. However, there is a relatively large literature on Pacific lamprey migration rates which provide some insight into sustained swim speeds. In the Columbia River radiotelemetry studies described in this synthesis, adult lamprey passed through reservoirs at rates that often exceeded 30 km/d. This translates to approximately 0.30 m/s of sustained swimming in relatively low velocity habitat. Migration rates in the John Day River radiotelemetry study by Robinson and Bayer (2005) were estimated at 11 km/d (~0.1 m/s) on median and 21 km/d (~0.24 m/s) at maximum. Minimum migration rate estimates in the Willamette River radiotelemetry study by Clemens et al. (2012) were 4.8-7.3 km/d (< 0.10 m/s). We note that all the migration rate data mentioned included likely rest periods with no swimming and were estimated during upstream migration into some opposing current; therefore, adult sustained swim speeds through non-flowing water rather are certainly higher than the ground speed estimates presented here.

Other species: Beamish (1974) found sustained swim speeds of adult sea lamprey (*Petromyzon marinus*) at approximately 0.35 m/s at 15°C and 0.23 m/s at 2°C. Swim speeds of sea lamprey in a river in lower flow areas averaged ~0.70 m/s and in high flow areas movements alternated between short activity periods and rest periods (Quintella et al. 2009). Kemp et al. (2011) also found river lamprey (*Lampetra fluviatilis*) approached weirs less and attached to structures more often under high flows and passage rate was low when velocities at the weir exceeded 1.5 m/s.

2.1.2 BURST SWIM SPEED

Burst swim speed is the highest speed attained by fish and is typically maintained for only seconds. Burst swimming is inefficient and anaerobic. It is used by fish primarily to pass through high velocity areas or to avoid predation or other hazards.

Pacific lamprey: There have been few – if any – direct evaluations of adult Pacific lamprey burst swim speeds. Tests in the experimental fishway at Bonneville Dam suggest that adult Pacific lamprey can burst swim through velocity barriers up to approximately 2.5-3.0 m/s (Keefer et al. 2010a). The climbing experiments by Reinhardt et al. (2008) and Kemp et al. (2009) also showed that adults burst swim up steep to vertical surfaces, often moving only centimeters between oral disc attachments. The relationship between burst swim speed and climbing has not been established, however. DIDSON observations at Bonneville Dam showed adult lamprey entering through the middle of fishway entrances (Johnson et al. 2012), suggesting that some adult lamprey can move upstream short distances through water velocities intended for adult salmonids.

Other species: Hanson (1980) measured swim speeds of adult sea lamprey in a flume with a velocity range of 1.5 to 4 m/s. At velocities of 1.5 and 2.7 m/s some lampreys were able to swim for approximately 4-6 s without attaching their oral discs, suggesting burst speeds for this species are likely near this range of velocities. Consistent with this result, Bell (1990) found that adult sea lamprey could obtain burst speeds up to 2.1 m/s when swimming in a flume with steady flow. It was not clear, however, whether or not lamprey were allowed to attach to the substrate and rest during these trials.

2.1.3 CRITICAL SWIM SPEED

Critical swim speed is a commonly estimated metric used to assess prolonged swimming performance in fishes. Critical swim speed tests measure the maximum swimming velocity that can be sustained for some set time period, typically by incrementally increasing water velocity in a test structure until the fish is forced downstream.

Pacific lamprey: Mesa et al. (2003) reported critical swim speeds of adult Pacific lamprey of 0.86 m/s (untagged lamprey), 0.82 m/s (radio-tagged lamprey), 0.80 m/s (males), and 0.85 m/s (females) at 15° C. Tagged males had significantly lower mean swim speeds than untagged males; there were no differences between female groups. Test velocities in this study were increased my 0.10 m/s every 30 minutes. Physiological changes in exercised lamprey were significantly different than resting controls and returned to resting levels 1-4 hours after fatigue.

Other species: Almeida et al. (2007) found the critical swim speed of adult sea lamprey to be 1.0 m/s. Though they did not directly evaluate critical swim speed, Kemp et al. (2011) and Russon and Kemp (2011) reported that river lamprey (*Lampetra fluviatilis*) were able to pass upstream through water velocities between 1.5 and 2.1 m/s.

2.2 ATTACHMENT WITH ORAL DISCS

Pacific lamprey: Adult Pacific lampreys have been observed attaching to surfaces and then releasing and burst swimming upstream in both field and experimental settings (Reinhardt et al. 2008; Moser and Mesa 2009; Keefer et al. 2010a, 2011). Lamprey use their oral disc to attach to substrate and they appear to preferentially select smooth surfaces for attachment sites. Attachment presumably allows lamprey to rest following periods of aerobic activity, and the behavior has been observed at high velocity and high turbulence areas at fishway openings, inside fishways near orifices, and at count stations (Johnson et al. 2011; Clabough et al. 2012). The attachment behavior is also associated with nest building in spawning streams, where adults use their oral discs to attach and move gravel and cobble (McIlraith 2011).

Other species: Adams and Reinhardt (2008) found grooved (i.e., non-smooth) surfaces prevented sea lamprey from continual attachment and concluded that smooth hard surfaces were most effective for lamprey attachment. Kemp et al. (2011) reported that the amount of time river lamprey attached to flume and weir substrate was positively related to discharge. These findings are consistent with those for Pacific lamprey, in that attachment behavior increases as water velocity and/or turbulence increase.

2.3 CLIMBING BEHAVIORS

Pacific lamprey: Pacific lamprey can climb steep and even vertical surfaces while passing barriers, behaviors that likely evolved in response to passage at natural barriers such as waterfalls (Clemens et al. 2010). When challenged to climb smooth wetted metal ramps, Reinhardt et al. (2008) reported that Pacific lamprey advanced themselves by attaching and incrementally moving forward in “burst swimming” movements of centimeters per movement. Passage performance in these experiments was greater on 18° ramps than on 45° ramps, regardless of flow. In a related study, Kemp et al. (2009) challenged Pacific lampreys to climb a 1.4 m vertical wall. The majority of climbing attempts were characterized by intermittent bouts of climbing along with oral disc attachment. Success and time to ascend was based on lamprey experience, with faster times achieved by lamprey that had previously climbed the wall. Long periods of climbing activity were accompanied by long periods of recovery and fatigue was noted.

In the experimental fishway studies at Bonneville Dam, Pacific lamprey readily ascended fishway bypass ramps of various types and inclines (Keefer et al. 2011). Most lamprey in the experiments were willing to climb ramps, especially when no other upstream passage routes were available. The climbing results were used in the design of the lamprey passage structures currently used at Bonneville Dam (Moser et al. 2011) and at Three Mile Dam on the Umatilla River. Additional LPS's that exploit the willingness of Pacific lamprey to climb are planned, including installations at John Day North fishway and as part of the Bonneville Powerhouse 2 North Lamprey Flume System, both to be installed winter 2012-2013.

Other species: Compared to Pacific lamprey, anadromous and landlocked sea lamprey appear to be less capable climbers (Clemens et al. 2010).

2.4 NOCTURNAL ACTIVITY

Adult Pacific lamprey tend to be more nocturnal than diurnal during upstream migration, and their degree of nocturnality is higher near and inside fishways than at sites with lower hydraulic and environmental complexity (i.e., reservoirs and unimpounded rivers; Keefer et al. 2013). We have hypothesized that lamprey are more active at night at dams to avoid potential predators (e.g., sea lions, white sturgeon) and/or as part of their ectoparasitic life history stage in marine environments. It is also possible that they rely more on their primary orientation methods at dams. More specifically, they may be more likely to use tactile, rheotactic and olfactory cues in complex environments like fishways. Regardless of underlying mechanism, lamprey activity levels decreased during daylight hours at all fishways in the Columbia River tagging studies. Some lamprey held position inside fishways, largely at unknown locations, while others retreated downstream. The onset of daylight may have an important effect on passage efficiency, especially at the longer and more complex fishways where lampreys take more than a night to pass. Such diel effects on fishway and dam passage efficiency have not been thoroughly evaluated.

2.5 PACIFIC LAMPREY PASSAGE CHALLENGES IN FISHWAYS

2.5.1 HYDRAULIC CHALLENGES

Observations in the experimental fishway at Bonneville Dam consistently indicated that adult lamprey orient to rheotactic cues and are attracted to both bulk flow and high velocity plumes or jets (such as at fishways and spillways) (Keefer et al. 2010a, 2011). They most typically oriented into the flow and tended to be near the fishway floor or walls in most experimental configurations. When confronted with high velocity challenges, such as at vertical-slot and submerged-orifice weirs, many lamprey attached to substrate and many did not continue upstream movements. Lampreys used low-velocity refuge areas when they were provided.

The experimental results have been supplemented with more recent observations of lamprey inside the Bonneville and John Day fishways using DIDSON. In these much larger field settings, most of the observed fish were free swimming in mid-channel. Free swimming was especially common in the low-velocity Bonneville junction pool, but also was observed at four monitored fishway entrances at Bonneville's Powerhouse 2 fishway. Lamprey did attach to walls at fishway entrances (fishway floors were not observed), and attachment behaviors were more frequent when fishway velocity was higher (Johnson et al. 2012a). These results were consistent with the experimental fishway studies.

Velocity: Lamprey in the experimental fishway preferentially selected low-velocity routes when they were available and used velocity refuges when provided (Keefer et al. 2011). Velocities in the 2.5-3.0 m/s range substantially inhibited upstream movement and/or prompted lamprey to select other less demanding routes. Lamprey more readily moved through sections where water velocity was ≤ 1.2 m/s, below the estimated burst swim speed for adults.

Distance: The relationship between velocity and distance is unknown, but we hypothesize that passage success decreases with increasing distance for a given velocity, particularly at velocities approaching and exceeding critical swim speeds. We expect that velocities near 2.0-3.0 m/s may be a complete barrier for some lamprey in fishway configurations where they must move long distances with either limited attachment surfaces or no velocity refuge.

Shear flow: We are unaware of any studies that have quantitatively evaluated the effects of shear flow or other strong gradients in water velocity on lamprey behavior. Shear flows most often occur inside fishways at sites where water is moving quickly past a structure adjacent to an area of low velocity. Such sites include weir orifices, sites with elevated or recessed steps, some fishway corners, and serpentine weirs. We have observed in the experimental fishway and in both DIDSON and optical video studies that lamprey that move into shear flows are often swept downstream. This appears to occur because lampreys do not have the momentum to stem the higher velocity in the shear or because they are positioned perpendicular to the shear flow with no opportunity for oral disc attachment.

Turbulence: Turbulence, shear flows and high water velocity often spatially coincide inside fishways. As with shear flow, however, there has been limited directed study of how turbulence affects lamprey passage behavior or passage efficiency through fishways, despite the importance of this hydraulic feature for fish passage (e.g., Haro and Kynard 1997; Mallen-Cooper and Brand 2007; Russon et al. 2010). Sites with elevated turbulence at FCRPS fishways include serpentine weir sections, fishway corners and turnpools, some submerged orifices, fishway entrances (especially adjacent to spillways), and diffuser areas. Recent design improvements for lampreys have included the installation of structural elements (bollards) on the bottom of fishway entrances intended to reduce near-bottom water velocities. However, these structures do increase turbulence.

2.5.2 STRUCTURAL CHALLENGES

FCRPS dams and dams in many other rivers were designed for adult salmonids or shad. These fishways have a variety of structural features that can be challenging for adult Pacific lamprey.

Vertical steps: In the experimental fishway at Bonneville Dam and in underwater video inside Bonneville Dam fishways, lamprey had difficulty passing through orifices at weirs when there were small (a few centimeters) vertical steps in front of the orifices (Keefer et al. 2010a). The sharp-cornered steps impeded attachment with the oral disc and many lamprey that attempted to move over the step into the orifice were swept downstream when they encountered shearing flows or turbulence. Similar behaviors have been observed at the overflow sections of weirs.

Sharp corners: As in the vertical step experiments, lamprey had difficulty passing experimental bulkheads with 90° corners compared to bulkheads with rounded corners (Keefer et al. 2010a). This pattern was also evident in the field, where radio-tagged lamprey entrance efficiency was lower at square bulkheads than at rounded bulkheads at the entrances adjacent to the Bonneville spillway. Sharp corners do not appear to negatively affect behavior in low velocity or low turbulence environments, where lamprey can free swim without oral disc attachment. For instance, the vast majority of adults passing through count windows were observed free swimming in the water column, where target water velocity is ~0.50 m/s (Clabough et al. 2009).

Diffuser grating: Collection channels, overflow weir sections of the fish ladders, and AWS channels all have diffuser grating through which additional water is pumped into fishways. Tests in the Bonneville experimental fishway indicate that lamprey have difficulty passing diffuser grating when adjacent water velocity or turbulence is high (Keefer et al. 2010a). The primary challenge at grating was the lack of adequate attachment surfaces. Diffusers do not appear to be problematic in low velocity environments. For example, almost all of the lamprey that were observed using the DIDSON camera at the Washington-shore junction pool at Bonneville Dam were free-swimming over the extensive diffuser grating in that fishway section and demonstrated no discernible response to the transition from solid floor to grating (Johnson et al. 2012a).

Picket leads: Adult lamprey can pass through picket leads at several locations at FCRPS dams. This behavior has been most studied at the picket leads near count stations at Bonneville Dam, using radio-tagged fish. Historically, lamprey could not move upstream and pass the dam to the forebay after passing through pickets and into AWS channels, and downstream movements through the pickets were necessary. More recently, lamprey passage structures (LPSs)were installed in the AWS channels upstream from the Bonneville picket leads to facilitate upstream passage (Moser et al. 2011) and pickets were raised slightly to allow lamprey greater access to the AWS channels. Most adults that enter the AWS pass readily through LPSs and exit into the forebay. However, the picket leads / AWS channels may continue to contribute to passage delays for lamprey, in part because body size may limit easy passage through pickets at some sites and because orientation cues may be confusing in these areas.

Cul de sacs and dead ends: Adult lamprey have been observed inside or salvaged from a variety of fishway features that have no upstream outlets. These include obsolete fishway segments (e.g., the flow control section at the Bonneville Cascades Island fishway), juvenile salmonid passage structures (e.g., at McNary Dam), and flow control features (e.g., diffusers, AWS channels). These sites vary in how frequently they are used by upstream migrants. Sites that provide attraction flow appear to be used most often, and these sites contribute to passage delays and some fishway passage failure. Others may be used as daylight refuges. For instance, most HD PIT-tagged lamprey that were detected entering the juvenile salmonid passage structures at McNary Dam South Fishway were later detected exiting the fishway.

2.5.3 FISHWAY ENTRANCES

As described in greater detail in the data synthesis sections, some adult Pacific lamprey have difficulty entering fishway openings at FCRPS dams, likely due to high water velocity and turbulence (Moser et al. 2002b; Clabough et al. 2010a, 2010b). At all of the fishways where radio-tagged adult lamprey have been monitored, some portion of the tagged fish approach fishway openings but fail to enter. The standard performance metric at the openings – fishway entrance efficiency – varies among fishway entrances, among dams, and in response to environmental conditions in the tailrace.

A large-scale experimental velocity reduction at the Bonneville Washington-shore fishway entrances at night significantly improved lamprey entrance efficiency, presumably by allowing weaker swimmers to traverse velocity barriers more easily (Johnson et al. 2012b). A similar experiment at McNary Dam proved inconclusive, at least in part because only small numbers of radio-tagged lamprey were collected and monitored during the treatment period (Boggs et al. 2010). Structural modifications (rounded edges) to entrance bulkheads have also improved lamprey entrance efficiency, presumably by reducing shear flows and increasing attachment opportunities (Moser et al. 2002a).

When extrapolated to the total adult run, the entrance efficiency results from radio-tagged lamprey at Bonneville Dam (11-18% fail to enter; see synthesis) suggest that thousands of lampreys that approach Bonneville Dam may never enter fishways in some years. The downstream distribution and fate of these fish is unknown. Importantly, it remains unknown whether such apparent passage abandonment is followed by reproductive failure or if it is relatively natural behavior used by lampreys at passage obstructions where failed passage is followed by entry and spawning at downstream sites. Failure-to-enter rates appear to be lower at upstream dams (especially The Dalles and McNary dams), and it is possible that these fishway openings are more suitable for lampreys. Alternately, the fish that reach these sites tend to be larger (Keefer et al. 2009) and have more experience using fishways, traits that may contribute to their relatively better performance at fishway entrances.

2.5.4 COLLECTION CHANNELS

Fishway collection channels are located along the base of powerhouses at the FCRPS dams and inside some fishway openings. Collection channels are characterized by relatively non-turbulent flow, although some powerhouse channels have multiple diffusers where water is pumped from the tailrace into the fishway. It is not clear how this upwelling water affects lamprey behavior, but the diffusers do limit lamprey attachment sites. Additionally, adult white sturgeon (*Acipenser transmontanus*) congregate inside the collection channels at some dams – especially at Bonneville Dam – and these predators may be a deterrent to lamprey passage.

Generally, lamprey can move through the lower-velocity powerhouse collection channels relatively quickly (Clabough et al. 2010b), although many do exit from the channels back into the tailrace via open sluice and orifice gates (see synthesis results for specific fishways). There has been limited monitoring in the main powerhouse collection channels and the mechanisms that affect lamprey fallout into the tailrace from these sites are poorly understood.

Fishway collection channels at non-powerhouse entrances (e.g., the north fishways at The Dalles, John Day, and McNary dams) often have higher water velocity than the powerhouse collection channels, and many lamprey turn around in these segments and exit back to the tailrace. In some cases, the entrance collection channels terminate at the first submerged weirs inside fishways, a transition that is hypothesized to negatively affect upstream passage. (Note: we recommend clarifying the appropriate term(s) and spatial endpoints for entrance and powerhouse collection channels in the fishway terminology workshop.)

2.5.5 TRANSITION POOLS / JUNCTION POOLS

Junction pools are fishway segments where two or more fishway components join together. Examples include the three collection channels that join at the north-shore junction pool at Bonneville Dam, the junction of the A- and B-branch fishways at the Bradford Island fishway at Bonneville Dam, and the three collection channels that join at the east junction pool at The Dalles Dam (see Figures 1, 2, and 13). 'Transition pool' is the term that has been used to describe the fishway sections where submerged weirs transition to overflow weirs. These areas have features of both fish ladders (weirs, orifices) and junction pools (reduced velocity, greater depth, etc.). The spatial extent of the transition areas can vary with fluctuations in tailwater elevations.

Some junction pools and transition pools appear to present a significant passage challenge to adult lampreys (Boggs et al. 2010; Clabough et al. 2012). Many of the lamprey turn-around events at the four lower Columbia River dams, for example, have been associated with these pools (see synthesis results for specific fishways), but specific mechanisms of passage failure remain poorly understood. In part, this is because lamprey activity in the pools is difficult to monitor at the scale needed to resolve behavioral responses to specific challenges. It is possible that there are sites in junction and transition pools that have low or confusing attraction flows, velocity barriers, structural challenges, or other passage impediments. These sites can have diffuser grating, vertical steps inside submerged orifices, recessed floor segments, and high sturgeon density. Additionally, the hydraulics in junction and transition pools differ considerably with changing tailrace elevation and operations at many locations, and it is likely these changes affect lamprey behavior and passage efficiency.

Notably, many lamprey that successfully pass through transition pools do so without long passage delays. It is possible that these fish used different routes (i.e., along walls versus along the fishway floor versus over overflow weirs) than those that turned around in the pools, that they approached during favorable tailwater or operational conditions, or periods of lower predator density.

2.5.6 OVERFLOW / ORIFICE WEIRS

Long sections of the fishways at most FCRPS have overflow weirs with submerged orifices. These fishway segments can have relatively high localized velocity and turbulence, but their design also intentionally provides low-velocity rest areas between each pair of weirs. In our direct observations at Bonneville and McNary dams, more lamprey pass through submerged orifices than over overflow sections. However, both behaviors have been observed, and many lamprey reportedly pass via overflow routes at Public Utility District (PUD) dams (S. Juhnke, USACE, *personal communication*). Many lamprey efficiently pass through the relatively high-velocity submerged orifices using attach-and-burst behaviors; the length of the velocity barrier at these sites (~1-2 feet) may be short enough to limit failure rates. A subset of the submerged orifice weirs has vertical steps in front of each orifice, and these sites have proven somewhat more difficult for lamprey to pass (Keefer et al. 2010a).

The radiotelemetry results suggest that small proportions of the total turn-around events by adult lamprey at the FCRPS dams occur in the overflow weir sections of ladders (see synthesis). An important caveat, however, is that these sections have been relatively lightly monitored and turn-around behaviors have likely been underestimated. It is also unclear how many attempts lamprey make to pass individual weirs and whether there are notable differences in passage performance under different operational criteria (e.g., during shad operations at Bonneville Dam).

2.5.7 COUNT STATIONS

The fish counting staff at the Bonneville count stations reported many adult lamprey moving downstream in front of the count windows during the day and these sites or locations upstream were therefore identified as potential lamprey passage impediments. The night video study by Clabough et al. (2012) showed that many lampreys also moved downstream past the Bonneville count windows at night. The behavior was much less common at count stations at The Dalles Dam. Monitoring of radio-tagged fish indirectly indicated that multiple upstream and downstream movements by individual fish were common. Notably, the tagged fish data also indicated that many turned around upstream from the count stations in the serpentine weir sections of the Bonneville fishways, suggesting that the count stations were not the primary passage problem. The radiotelemetry results also indicated that some lampreys entered the AWS channels, moved upstream past the count station, re-entered the fishway near the serpentine weirs by unknown routes, and then moved downstream past the count window. Recent improvements of raising the picket lead gate in the AWS at both Bonneville Dam fishways may have improved access to the LPS's and allowed more lamprey to circumvent the serpentine weir sections.

Radiotelemetry monitoring at count stations at other dams has been limited and is not well suited to evaluations at meter scales. There is little evidence, however, that count stations at dams other than Bonneville present major passage impediments to lamprey. Some fish do pass behind count station crowders at other sites, further suggesting the downstream movements at Bonneville Dam are related to passage conditions upstream of the count station.

2.5.8 SERPENTINE WEIRS

Serpentine weir sections in the upper Washington-shore and Bradford Island fishways at Bonneville Dam are among the most difficult fishway sections for adult lamprey (see synthesis results). These weirs are characterized by squared edges, grated sections, and some squared vertical slots recessed into fishway walls. Each of these structural features makes it more difficult for lamprey to find suitable attachment substrate in the high velocity sections. Turbulence through the weirs is also high. Additionally, relatively long distances through high velocity slots (up to 0.75 m) between serpentine weirs may test the limit of how far lamprey are willing or able to use the burst-and-attach behaviors observed at other high velocity sites. As noted above, many radio-tagged fish attempted to pass through the serpentine weir sections multiple times before retreating downstream. The vast majority of lamprey that failed to pass the serpentine weir sections moved into the Bonneville tailrace and were not observed to reattempt passage.

Bonneville's serpentine weir sections have been associated with many lamprey passage failures (see data synthesis section 5.1), with ~25-30% of adults reaching the count stations failing to pass the dam after attempting to pass the serpentine weir section in some years (Clabough et al. 2009; Keefer et al. 2010b). The bottleneck appears to be at least partially associated with forebay elevation because lamprey passage failure can substantially increase as forebay elevation decreases. It is possible that operational conditions associated with low forebay elevation create a difficult lamprey passage environment in the lower serpentine weir section or in the turnpool upstream from the count windows. Among potential mechanisms are: 1) changes in water velocity, 2) lamprey attachment problems on the grated slots where water moves between the serpentine weirs and AWS, 3) increased turbulence in the serpentine weirs as water enters from the AWS , or 4) confusing or misleading lamprey attraction cues (such as lower attraction flows in the upper ladder). Lamprey passage structures installed in the AWS channels at Bonneville Dam have allowed some lampreys to circumvent serpentine weir sections. The annual proportion of lamprey using LPSs at the dam has increased in each year since installation (Moser et al. 2011).

2.6 EFFECTS OF TAGGING

A persistent issue in adult lamprey monitoring projects is the potential for negative effects associated with fish handling and tagging to bias observation of behavior and passage success. While tagging undoubtedly affects lamprey physiology and behavior, it remains difficult to assess to what degree if any tagged adults behave and migrate differently than untagged adults because adequate controls are unavailable. In our research, dam passage efficiency and migration distance of adult Pacific lamprey have been lower in radio-tagged versus HD PIT-tagged samples (e.g., Keefer et al. 2011). It is likely that the additional tag burden of the larger radio transmitters and the external trailing antenna on transmitters have negative effects on fish performance. The longer anesthesia time required for transmitter insertion (~10 minutes) relative to HD PIT insertion (~3 minutes) and presence of an external antenna also may play a role.

In experiments, Close et al. (2003) measured effects of surgically implanted transmitters on adult Pacific lamprey swimming performance. The authors found no differences in swimming performance, ventilation rate or glucose levels after 1-3 d recovery. Survival rate in all tagged fish was 100%. In other experiments, Mesa et al. (2003) reported slightly lower lamprey swim speeds for radio-tagged versus untagged fish, and suggested that sutures at transmitter insertion sites may increase the risk of infection and reduce survival. There is also evidence that radio transmitter size, relative to lamprey size, affects performance. Moser et al. (2007) showed that lamprey with larger transmitter burdens were associated with lower dam passage success. The distribution of adults to upstream sites as estimated with dam counts and HD PIT tagged adults are generally similar suggesting HD PIT tagging does not have strong impacts on migration distance. In summary, definitive studies of tag effects are logistically challenging, and evidence to date suggests measurable tag effects for larger tag sizes (e.g., larger radio-tags) whereas smaller tags may have little or no measurable effects on behavior.

2.7 OPERATIONAL CRITERIA AT FCRPS FISHWAYS

There has been little systematic documentation of the hydraulic conditions inside FCRPS fishways at the spatial scale needed to assess the relationship between hydraulics and adult Pacific lamprey passage behaviors and passage efficiency. As part of this review, we searched for specific FCRPS fishway passage criteria in the following documents:

NMFS. 2008. Anadromous salmonid passage facility design. National Marine Fisheries Service, Northwest Region, Portland, OR. 135 p.

USACE 2011. Annual Fish Passage Report.

USACE. 2012. Army Corps of Engineers Fish Passage Plan.

Relatively few spatially-explicit velocity or other hydraulic criteria were found in these documents. Identifying additional sources for such data will be a part of the 30 October 2012 Workshop. Objectives will be to identify measured velocity and/or turbulence data sources and target criteria for: individual fishway entrances, entrance collection channels, powerhouse collection channels, junction pools, transition pools, overflow weir and serpentine weir ladder sections, count stations, and AWS channels.

2.8 PERFORMANCE INFORMATION GAPS

The experimental fishway studies and direct observations inside fishways (video, DIDSON) have greatly improved our understanding of adult Pacific lamprey behavior and performance at fishways. However, as noted in the previous sections, there are many information gaps remaining. The critical gaps are mostly related to the specific mechanisms of passage failure at fine spatial scales inside fishways. The sites with the highest failure rates have largely been identified (see data synthesis) but our understanding of which hydraulic and/or structural factors negatively affect behavior at these sites is relatively limited. To date, direct video observations have been limited to count stations (Clabough et al. 2012) and a handful of overflow and submerged orifice weirs (Keefer et al. 2010a). DIDSON observations have been limited to four openings to the Bonneville Washington-shore fishway and junction pool, but only using existing I-beams that did not allow direct observation of critical sites (Johnson et al. 2012a). The 2012 DIDSON study at John Day Dam north fishway will provide some of the first observational data of lamprey behavior inside an entrance collection channel, at the first submerged weir that lamprey encounter, and in a transition pool. Similarly, 2012 underwater video and DIDSON studies at McNary Dam will provide detailed behavioral data at the south-shore fishway entrance.

General information gaps include:

- site-specific information on the mechanisms of lamprey passage failure, and specifically whether hydraulic, structural, or other features like predator presence affect turn-around behavior at individual fishway passage bottlenecks;

- identification of water velocity thresholds where lamprey performance is restricted, especially at fishway openings, in serpentine weirs, and at other sites where velocity is routinely > ~1.5 m/s;

- identification of sites where water turbulence rather than simply velocity negatively effects lamprey behavior;

- the role of poor attraction flow inside low-velocity fishway segments such as junction pools and transition pools;

- the role white sturgeon on lamprey passage efficiency through lower fishway segments (i.e., collection channels, junction pools, transition pools);

- identification of additional sites where structures (including steps and corners), diffusers, and dead-end features deter lamprey passage;

- identification of sites where high water velocity and/or turbulence coincide with limited opportunities for lamprey attachment.

2.9 LITERATURE REVIEW REFERENCES

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3.0 FISHWAY TERMINOLOGY STANDARDIZATION

This objective was discussed but ultimately was determined to be low priority after the 30 October 2012 Workshop.

4.0 DATA SYNTHESIS: METHODS

4.1 RADIOTELEMETRY STUDIES

4.1.1 LAMPREY COLLECTED AT BONNEVILLE DAM

A total of 3,350 adult Pacific lamprey were collected and radio-tagged at Bonneville Dam over ten years (1997-2002 and 2007-2010, Table 3). Details of fish collection, anesthetization, surgery, and details of radio transmitter type and insertion methods were summarized by Moser et al. (2002a, 2002b) and Johnson et al. (2012). Briefly, most lamprey were trapped at night in the Washington-shore fishway starting in mid-May or early June and ending in August or early September. Additional traps were deployed in some years. Anesthesia included tricaine methanesulfanate (MS-222) or eugenol (i.e., clove oil). Lamprey were released ~10 km downstream from Bonneville Dam in 1997 and ~3 km downstream in all subsequent years; an additional 50 lamprey were released in the Bonneville forebay in 1997 and in The Dalles reservoir in 2000 (Table 3).

Differences in lamprey tagging among years were largely a function of variability in run timing and run size, some temperature-related handling restrictions, and restrictions related to transmitter size. Across years, lamprey body length ranged from 49-86 cm (*grand mean* = 68.2 cm, SD = 4.6 cm). Annual mean lengths ranged from 69.7-72.1 cm in 1997-2002 and from 65.8-67.0 cm in 2007-2010 (Table 3). Among-year differences in body length were due to less restrictive lamprey selection criteria starting in 2007 when transmitters were considerably smaller than those available in 1997-2002.

4.1.2 LAMPREY COLLECTED AT MCNARY DAM

A total of 276 adult Pacific lamprey were collected and radio-tagged at McNary Dam over six years (2005-2010, Table 4). Details of fish collection were summarized by Keefer et al. (2012). Surgical methods were the same as in the Bonneville-tagged studies. Briefly, most lamprey were trapped at night in the Oregon-shore fishway starting in July and ending in late August or early September. McNary-tagged lamprey were released ~1 km downstream from McNary Dam in all years; an additional 20 lamprey were released downstream from Ice Harbor Dam in both 2005 and 2006 (Table 2). Across years, lamprey body length for the McNary-released group ranged from 54-76 cm (*grand mean* = 66.0 cm, SD = 4.1 cm). Annual mean lengths ranged from 65.2-66.6 cm. The Ice Harbor-released groups were similar.

4.1.3 RADIOTELEMETRY MONITORING ARRAYS

Section 5.0 includes descriptions of the radiotelemetry monitoring effort at each individual dam, including year-to-year changes in arrays and maps showing approximate antenna locations. Additional details are provided in Appendix A.

4.2 HALF DUPLEX (HD) PIT TAG STUDIES

4.2.1 LAMPREY COLLECTED AT BONNEVILLE DAM

A total of 5,386 adult Pacific lamprey were collected and HD PIT-tagged at Bonneville Dam over seven years (2005-2011, Table 5). Details of fish collection, anesthetization, surgery, and PIT tag insertion were summarized by Keefer et al. (2009). Lamprey were trapped as described above for radio-tagged fish. Lamprey were released directly into the Bradford Island fishway in 2005 and ~3 km downstream from the dam in 2006-2011; an additional 109 lamprey were released into the Bonneville forebay in 2011 (Table 5).

Differences in lamprey tagging among years were largely a function of variability in run timing and run size and some temperature-related handling restrictions. Very small run size precluded most of the proposed sampling in 2010. Across years, lamprey body length ranged from 38-83 cm. Annual mean lengths ranged from 62.4-67.9 cm (Table 5).

4.2.2 LAMPREY COLLECTED AT JOHN DAY DAM

In 2009, 79 lamprey were collected behind the picket leads at the John Day north fishway. These fish were HD PIT-tagged and either released upstream from John Day Dam (n = 36) or transported and released into the McNary Dam tailrace (n = 43).

4.2.3 HD PIT MONITORING ARRAYS

HD PIT antennas were installed inside dam fishway and lamprey passage systems (LPS) starting in 2005. The largest effort was at Bonneville Dam, with 8-10 locations monitored in most years from 2007-2011. Top-of-ladder antennas were installed at The Dalles and John Day dams, with one addition ladder antenna in The Dalles east fishway. McNary and Ice Harbor dams had 4-6 monitoring locations in all years, though top-of-ladder sites provided most of the data used in analyses. Only ladder sites were monitored at Priest Rapids (2008-2011). Lower Monumental (2011) and Lower Granite (2011) dams had ladder sites near the base and exits of fish ladders. Appendix A has details and maps of HD PIT antenna locations.

4.3 FISHWAY USE METRICS: RADIOTELEMETRY

Three fishway use metrics were calculated using data from radio-tagged lamprey. These metrics describe the distributions of lamprey activity at fishway openings. Data tables are presented in Appendix B.

- **Fishway approach –** where radio-tagged lamprey approached fishway openings. Two metrics were summarized:

  1) the distribution of first approach sites for individual lamprey, and

  2) the distribution of all approach events.

- **Fishway entry –** where radio-tagged lamprey entered fishway openings. Two metrics were summarized:

  1) the distribution of first entry sites for individual lamprey, and

  2) the distribution of all entry events.

- **Fishway exit –** where radio-tagged lamprey exited fishway openings back to the dam tailrace. Two metrics were summarized:

  1) the distribution of first exit sites for individual lamprey, and

  2) the distribution of all exit events.

It was possible at all dams for radio-tagged lamprey to approach, enter, and exit fishways at unmonitored fishway openings. These events were categorized as unknown unless the location could be confidently inferred from other telemetry records.

4.4 DAM PASSAGE EFFICIENCY METRICS: RADIOTELEMETRY

A variety of passage efficiency metrics were calculated using data from radio-tagged lamprey at dams (Box 2). These metrics have been used to evaluate lamprey 'passage success' at dams, at fishway openings, and through specific fishway segments at multiple spatial scales. Some metrics are calculated on a per-fish basis and typically evaluate passage success regardless of route or number of attempts while others are calculated on a per-site basis using all events recorded at a location and evaluate levels of milling, etc. Efficiency metrics have been one of the primary tools used to identify problem passage areas for lamprey. An implicit assumption is that detections at approach antennas represent directed attempts at upstream passage on the part of the lamprey. Data tables in Appendices C-H.

- **Dam-wide fishway entrance efficiency –** estimate of lamprey passage success at fishway openings. One metric was calculated at each dam:

  1) the number of unique lamprey that entered a fishway / number of unique lamprey that approached a fishway. All fishway openings were combined at a dam.

- **Dam-wide fishway passage efficiency –** estimate of lamprey passage success through entire fishways, from fishway entry to exit from the top of a ladder. Does not include behavior in the tailrace. One metric was calculated at each dam:

  1) the number of unique lamprey that passed dam / number of unique lamprey that entered a fishway. All fishways were combined at a dam.

Data synthesis methods

- **Dam-wide dam passage efficiency** – estimate of lamprey passage success for entire dam from fishway approach to exit from the top of a ladder. One metric was calculated at each dam:

  1) the number of unique lamprey that passed dam / number of unique lamprey that approached a fishway. All fishway openings were combined at a dam.

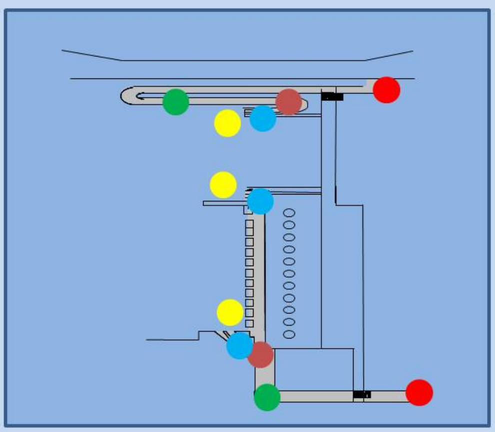
Box 2. Passage efficiency metrics: radiotelemetry

$$\text{Fishway entrance efficiency} = \frac{\text{Entered fishway}}{\text{Approached fishway}}$$

$$\text{Fishway passage efficiency} = \frac{\text{Passed dam}}{\text{Entered fishway}}$$

$$\text{Dam passage efficiency} = \frac{\text{Passed dam}}{\text{Approached fishway}}$$

$$\text{Fishway segment passage efficiency} = \frac{\text{Detected > segment}}{\text{Detected in segment}}$$



- Dam-wide metrics include all sites

- Site-specific and route-specific metrics use spatially separated subsets of the data

- Many metrics can be estimated for both unique lamprey and total events

- **Site-specific fishway entrance efficiency** – estimate of lamprey passage success at individual fishway openings. Two metrics were calculated at each opening:

  1) **unique lamprey** = the number of unique lamprey that entered at a site / number of unique lamprey that approached the same site; and

  2) **total attempts** = the total number of fishway entry events at a site / total number of fishway approaches at the same site.

- **Route-specific fishway passage efficiency** – estimate of lamprey passage success through individual fishways from entry to top-of-ladder exit. Routes were separated by fishway entry location, so that multiple routes were possible for some fishways. Two metrics were calculated for each route:

1) **unique lamprey** = the number of unique lamprey that passed dam / number of unique lamprey that entered at a site; and

2) **total attempts** = the number of lamprey that passed dam / total number of fishway entries at a site.

- **Fishway segment passage efficiency** – estimates of lamprey passage success through individual fishway segments. Segments were defined by the locations of monitoring antennas. One metric was calculated for each segment:

1) the number of unique lamprey that passed a segment / number of unique lamprey detected in the segment. Note that this metric potentially differed by which route lamprey used to enter the segment (i.e., in junction pool segments).

- **Fishway turn-arounds –** estimate of where radio-tagged lamprey turned around inside fishways prior to exiting to dam tailraces. One metric was estimated:

1) the distribution of fishway turn-around sites for all fishway passage attempts that resulted in lamprey exit to the tailrace.

- **Passage bottleneck metrics –** estimates of the relative contribution of different fishway segments to lamprey passage failure. Three metrics were calculated:

1) **turn-around rate** = total number of turn-arounds in a fishway segment / number of unique lamprey recorded in the segment. This is a measure of how frequently lamprey turned around in each fishway segment;

2) **additional passage attempts** = number of lamprey that attempted to pass a fishway after exit to the tailrace / number of turn-around events in a fishway segment. This is a measure of how likely a lamprey was to attempt to pass a dam after turning around in a specific fishway segment and exiting to the tailrace; and

3) **failure rate** = number of unsuccessful final fishway entries / number of unique lamprey at a site. This is related to the 'additional passage attempts' metric, except it is a measure of which fishway segments were associated with dam passage failure (i.e., exit to tailrace was not followed by additional passage attempts).

4.5 RESERVOIR PASSAGE EFFICIENCY: RADIOTELEMETRY

Reservoir conversion rates – or reservoir passage efficiency – were estimated for radio-tagged lamprey through the three lower Columbia River reservoirs. Reservoir passage efficiency should not be compared across sites because varying proportions of the lamprey that enter each reservoir subsequently enter tributaries or other spawning areas and because the starting population of lampreys entering upstream reaches is a non-random subsample that are (on average) larger and with earlier run-timing of those entering lower reaches. The estimates do provide information on the distribution of lamprey and year-to-year differences in the proportion that pass through individual reservoirs.

- **Reservoir passage efficiency** – estimate of lamprey passage from the exit of one dam to the tailrace of the next upstream dam. One metric was calculated at each dam:

  1) the number of unique lamprey detected at upstream dam / number of unique lamprey that passed downstream dam.

4.6 REACH ESCAPEMENT: RADIOTELEMETRY & HD PIT

Reach-specific conversion rates – or escapement rates – were estimated for radio-tagged and HD PIT-tagged lamprey through eleven reaches of varying length. As with reservoir passage efficiency estimates, reach escapement estimates provide information on the distribution of lamprey and year-to-year differences in the proportion that pass through individual reaches.

- **Reach-specific escapement** – estimate of lamprey passage from the release site or the fishway exit at a dam to the fishway exit at an upstream dam. One metric was calculated:

  1) the number of unique lamprey detected passing upstream dam / number of unique lamprey that were released or that passed a downstream dam.

Table 3. Numbers of Pacific lamprey that were collected and radio-tagged and at **Bonneville Dam** in 1997-2002 and 2007-2010 and released below the dam (top), in the Bonneville forebay, or in The Dalles reservoir. Morphometric data includes mean and range of lamprey length, weight, and girth. Source documents: Moser et al. (2002, 2003, 2004, 2005) and Clabough et al. (2011).

	1997	**1998**	**1999**	**[2]2000**	**2001**	**2002**	**2007**	**2008**	**2009**	**2010**
Released (*n*)	147	205	199	299	298	201	398	595	596	312
Mean length (cm)	69.7	69.9	71.1	70.4	71.2	72.1	65.8	66.2	66.8	67.0
Range	60-80	59-79	65-78	62-80	62-82	60-80	53-86	49-79	56-79	55-77
Mean weight (g)	-	545	571	570	588	612	466	464	471	482
Range	> 450	420-830	475-755	405-825	380-880	440-790	256-810	284-706	276-860	272-722
Mean girth (cm)	-	-	12.0	11.9	12.3	12.7	11.0	10.9	11.0	11.2
Range	-	-	11.3-13.2	10.2-13.8	10.7-14.5	11.5-14.8	9.0-13.4	9.0-13.0	9.0-14.4	9.0-13.0
Released (*n*)	[1]50	-	-	[2]50	-	-	-	-	-	-
Mean length (cm)	68.6	-	-	70.4	-	-	-	-	-	-
Range	62-75	-	-	65-77	-	-	-	-	-	-
Mean weight (g)	-	-	-	580	-	-	-	-	-	-
Range	>450	-	-	460-700	-	-	-	-	-	-
Mean girth (cm)	-	-	-	12.0	-	-	-	-	-	-
Range	-	-	-	11.2-13.4	-	-	-	-	-	-

[1] Released in Bonneville Dam forebay, ~ 5 km upstream from Bonneville Dam
[2] Released ~15 km upstream from The Dalles Dam

Table 4. Numbers of Pacific lamprey that were collected and radio-tagged at **McNary Dam** and then released downstream from **McNary Dam** or **Ice Harbor Dam** in 2005-2010 plus mean and range of lamprey length, weight, and girth.

	2005	**2006**	**2007**	**2008**	**2009**	**2010**
Released (*n*)	40	40	60	34	84	18
Mean length (cm)	66.6	66.4	64.7	65.2	66.4	65.8
Range	62-73	54-75	54-78	56-74	56-76	56-72
Mean weight (g)	439	452[1]	431	425	447	440
Range	370-566	356-562[1]	312-680	302-636	290-626	294-566
Mean girth (cm)	10.7	10.7	10.5	10.5	10.8	10.6
Range	10.0-11.9	9.2-12.4	9.4-12.5	9.5-12.2	9.2-12.5	9.5-11.8
Released (*n*)	20[2]	20[2]	-	-	-	-
Mean length (cm)	67.5	66.6	-	-	-	-
Range	61-73	60-73	-	-	-	-
Mean weight (g)	455	430[1]	-	-	-	-
Range	376-594	292-556[1]	-	-	-	-
Mean girth (cm)	10.9	10.6	-	-	-	-
Range	10.0-12.2	9.0-12.4	-	-	-	-

[1] Incomplete data
[2] Released downstream from Ice Harbor Dam

Table 5. Numbers of Pacific lamprey that were HD PIT-tagged and released downstream from **Bonneville Dam** or in the Bonneville forebay in 2005-2011 plus mean and range of lamprey length, weight, and girth. Note exception in 2005 on release locations.

	2005	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
Released (*n*)	841[1]	2000	757	607	368	13	800
Mean length (cm)	67.9	67.0	64.8	64.7	65.3	62.4	64.8
Range	53-82	52-83	38-81	31-78	40-76	51-69	53-80
Mean weight (g)	500	482	445	434	443	403	437
Range	282-835	238-886	124-798	74-712	120-728	260-552	234-774
Mean girth (cm)	11.5	11.2	10.9	10.6	10.8	10.7	10.8
Range	7.3-14.1	8.2-14.3	7.5-13.5	6.1-13.3	7.7-13.4	9.3-11.9	8.3-14.8
Released (*n*)							109
Mean length (cm)							64.8
Range							53-74
Mean weight (g)							431
Range							224-614
Mean girth (cm)							10.7

[1] released in Bradford Island fishway

5.0 DATA SYNTHESIS: SINGLE-DAM SUMMARIES

5.1 BONNEVILLE DAM

5.1.1 NUMBERS OF RADIO-TAGGED LAMPREY

A total of 3,350 adult Pacific lamprey were radio-tagged at Bonneville Dam over ten years (1997-2002, 2007-2010) (Table 1). Almost all (n = 3,250; 97%) were released at sites 1-10 km downstream from Bonneville Dam from both sides of the Columbia River. The remainder was released in the Bonneville Dam forebay in 1997 (n = 50; ~1%) or in The Dalles reservoir in 2000 (n = 50; ~1%).

5.1.2 MONITORING EFFORT

The adult fishways at Bonneville Dam (Figures 1 & 2) were intensively monitored in all years (Table A1). However, there were important year-to-year changes in radio antenna and receiver configurations that included:

- sluice gate fishway openings at Powerhouse 1 (PH1) were monitored in 1997-2002 only
- floating orifice gate openings at Powerhouse 2 (PH2) were monitored in 1997-1999 only
- monitoring in the upper fishways (count station to top-of-ladder exits) was limited to exit antennas in 1997-1999; additional antenna sites were added in 2000-2002 and 2007-2010 near both count stations and inside auxiliary water supply (AWS) channels to address study objectives that differed among years

5.1.3 FISHWAY APPROACH SUMMARY

A total of 2,684 unique radio-tagged lamprey (80% of those released downstream) approached monitored fishway openings a total of 26,772 times at Bonneville Dam for a combined total of 10.0 fishway approaches/lamprey. In years when Powerhouse priority was at PH1 (1997-2000) the distribution of first fishway approach sites averaged 43% at PH1, 18% at the spillway, and 39% at PH2 (Figure 3). In years when priority was at PH2 (2001-2002, 2007-2010) mean first approach sites were 37% at PH1, 17% at the spillway, and 56% at PH2.

The most-approached openings at the Bradford Island fishway were the sluice-gate openings in the years that they were monitored (1997-2002). Lamprey also frequently approached the south-shore opening at PH1 and the south-spillway (B-Branch) opening.

The most-approached openings at the Washington-shore fishway were at the south and north ends of the PH2 collection channel and the orifice gates were frequently approached in years they were monitored (1997-1999).

Single-dam summaries

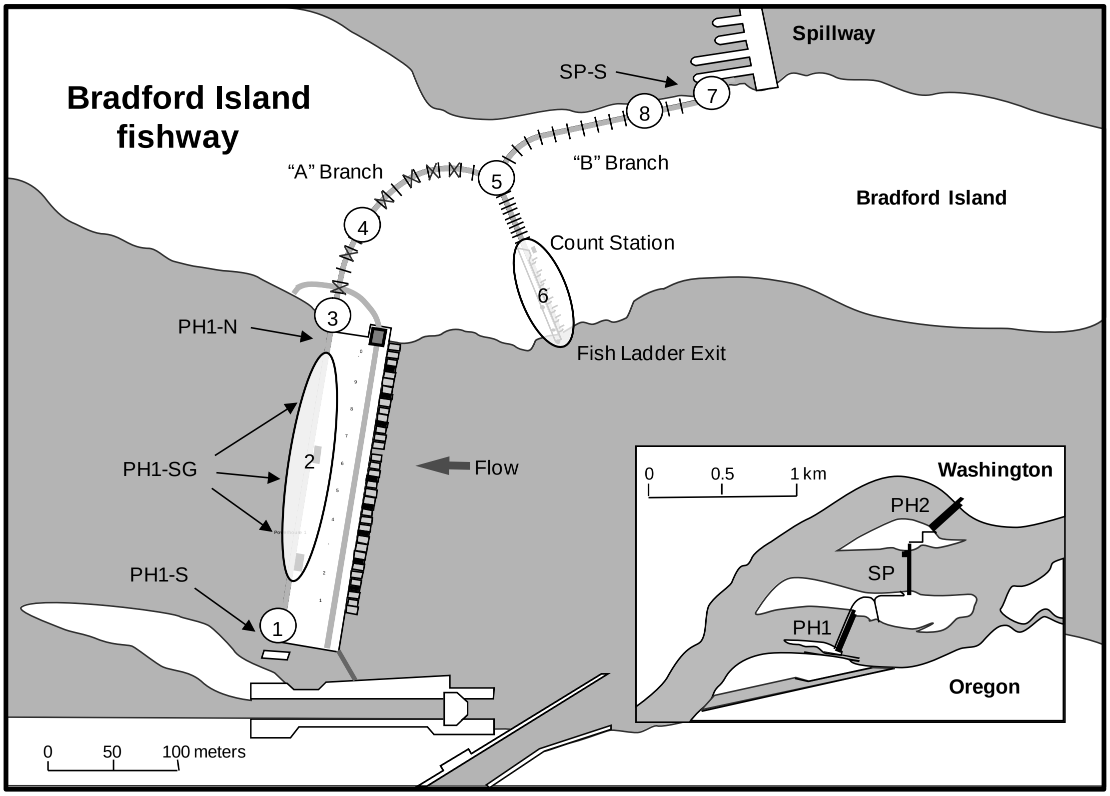


Figure 1. Map of Bradford Island fishway at Bonneville Dam. Numbers indicate fishway segments monitored with radiotelemetry.

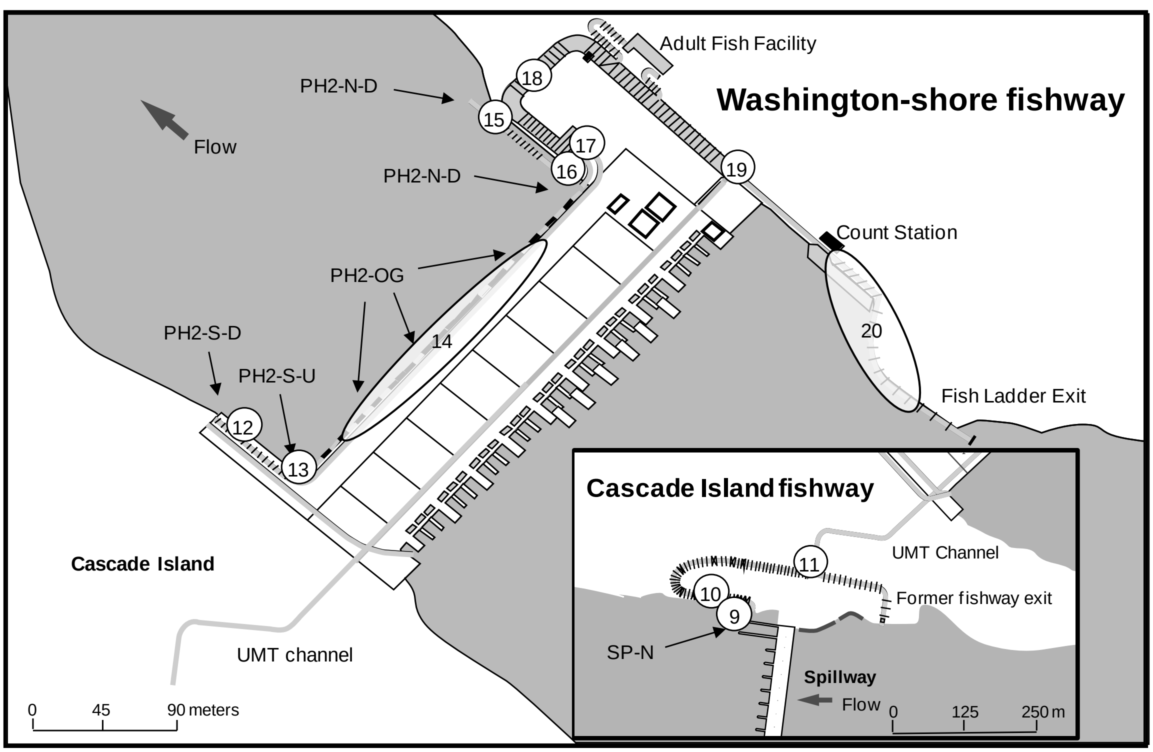


Figure 2. Map of Washington-shore fishway at Bonneville Dam. Numbers indicate fishway segments monitored with radiotelemetry.

CAVEAT: fishway approaches at Bonneville Dam were somewhat affected by release location, particularly in years when releases sites were closer to the dam. Fish were somewhat more likely to approach fishways located on the same side of the river as they were released from.

CAVEAT: unmonitored fishway openings (sluice gates and orifice gates) resulted in underestimation of fishway approaches and potential biases in their relative distribution among sites.

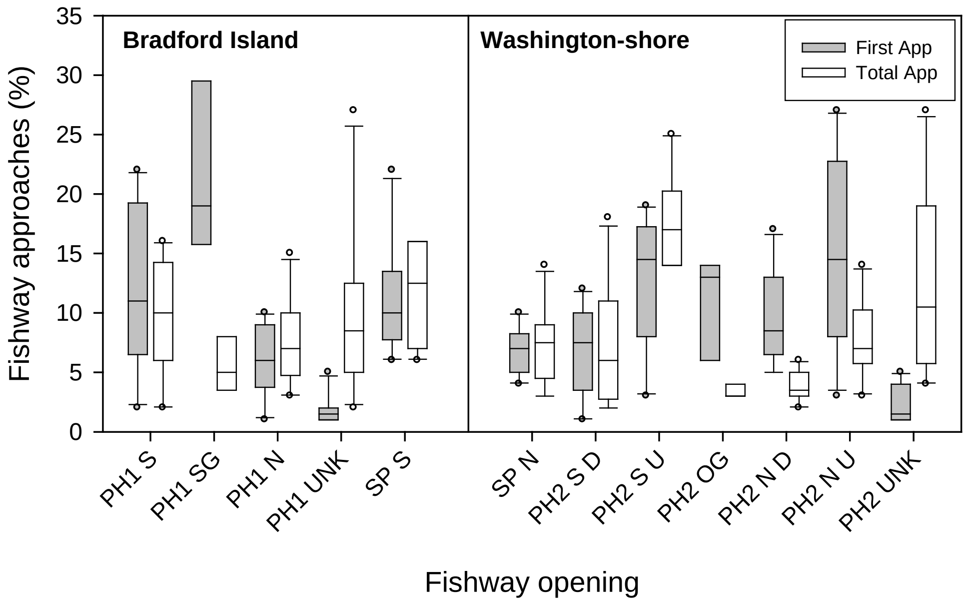


Figure 3. Distributions of annual estimates of radio-tagged Pacific lamprey fishway approach locations at Bonneville Dam. See Figures 1 & 2 for fishway sites. Note: lamprey could approach undetected at unmonitored sluice gate openings (2007-2010) and orifice gate openings (2000-2002, 2007-2010). Box plots percentiles are: 25th, 50th, and 75th (boxes), 10th and 90th (whiskers) and 5th and 95th (circles).

5.1.4 FISHWAY ENTRY SUMMARY

A total of 2,179 unique radio-tagged lamprey entered monitored fishway openings a total of 5,305 times at Bonneville Dam for a combined total of 2.4 fishway entries/lamprey. In years when Powerhouse priority was at PH1 (1997-2000) the distribution of first fishway entry sites averaged 39% at PH1, 17% at the spillway, and 43% at PH2 (Figure 4). In years when priority was at PH2 (2001-2002, 2007-2010) mean first entry sites were 25% at PH1, 21% at the spillway, and 55% at PH2.

The most-entered openings at the Bradford Island fishway were the south-shore opening at PH1 and the south-spillway opening. Lamprey entered sluice-gate openings relatively infrequently in the years that they were monitored (1997-2002).

The most-entered openings at the Washington-shore fishway were at the south end of the PH2 collection channel. Entries at orifice gates were underestimated due to limited monitoring.

CAVEAT: unmonitored sluice gates and orifice gates resulted in underestimation of fishway entries (and exits) and potential biases in their distribution among sites. More specifically, some entries at unmonitored sites may have inadvertently been assigned to adjacent monitored openings.

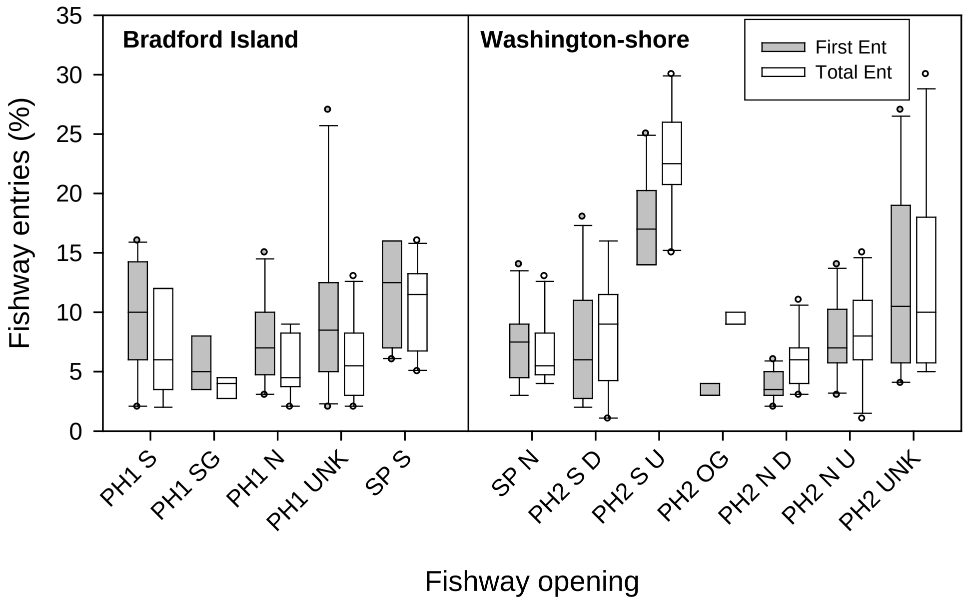


Figure 4. Distributions of annual estimates of radio-tagged Pacific lamprey fishway entry locations at Bonneville Dam. See Figures 1 & 2 for fishway sites. Note: lamprey could enter undetected at unmonitored sluice gate openings (2007-2010) and orifice gate openings (2000-2002, 2007-2010). Box plots percentiles are: 25^{th}, 50^{th}, and 75^{th} (boxes), 10^{th} and 90^{th} (whiskers) and 5^{th} and 95^{th} (circles).

5.1.5 FISHWAY EXIT SUMMARY

A total of 1,580 unique radio-tagged lamprey exited monitored fishway openings into the tailrace a total of 4,164 times at Bonneville Dam for a combined total of 2.6 fishway exits/lamprey. In years when Powerhouse priority was at PH1 (1997-2000) the distribution of first fishway entry sites averaged 16% at PH1, 20% at the spillway, and 65% at PH2 (Figure 5). In years when priority was at PH2 (2001-2002, 2007-2010) mean first approach sites were 13% at PH1, 18% at the spillway, and 68% at PH2.

The most-exited opening at the Bradford Island fishway was the south-spillway (B-Branch) opening.

The most-exited openings at the Washington-shore fishway were at the south end of the PH2 collection channel and at the downstream south-shore opening. A relatively large number of exits were at unknown locations, but many of these were presumably from unmonitored orifice gates.

CAVEAT: unmonitored sluice and orifice gates resulted in slight underestimation of fishway exits and potential biases in their distribution among sites. More specifically, some exits at unmonitored sites may have inadvertently been assigned to adjacent monitored openings.

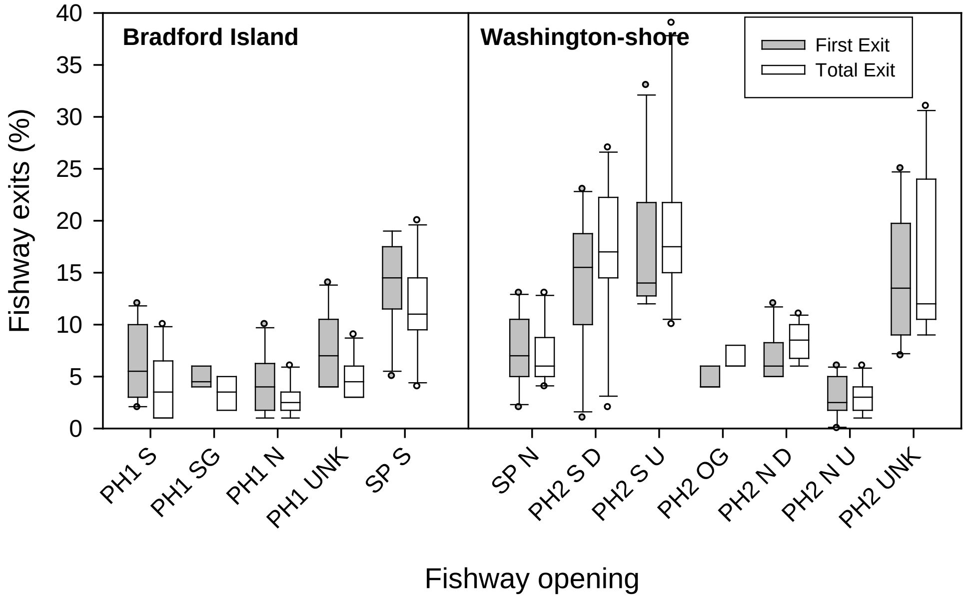


Figure 5. Distributions of annual estimates of radio-tagged Pacific lamprey fishway exit locations at Bonneville Dam. See Figures 1 & 2 for fishway sites. Note: lamprey could exit undetected at unmonitored sluice gate openings (2007-2010) and orifice gate openings (2000-2002, 2007-2010). Box plots percentiles are: 25^{th}, 50^{th}, and 75^{th} (boxes), 10^{th} and 90^{th} (whiskers) and 5^{th} and 95^{th} (circles).

5.1.6 DAM-WIDE PASSAGE EFFICIENCY METRICS

Fishway entrance efficiency (unique fish that entered / unique fish that approached): dam-wide fishway entrance efficiency ranged from 0.72 to 0.89 (*median* = **0.84**, n = 10 years, Figure 6). Median estimates for the three monitoring eras were **0.89** in 1997-1999 (all fishway openings monitored), **0.87** in 2000-2002 (orifice gates unmonitored), and **0.78** (orifice and sluice gates unmonitored). Across years, larger radio-tagged lamprey were more likely than smaller lamprey to enter fishways at Bonneville Dam (r^2 = 0.54, Figure 7).

Fishway passage efficiency (unique fish that passed / unique fish that entered): dam-wide fishway passage efficiency ranged from 0.41 to 0.58 (*median* = **0.52**, n = 10 years). Median estimates for the three monitoring eras were **0.48** (1997-1999), **0.54** (2000-2002), and **0.51** (2007-2010). Larger lamprey were more likely than smaller lamprey to pass Bonneville Dam after entering fishways (r^2 = 0.24).

Dam passage efficiency (unique fish that passed / unique fish that approached): dam-wide dam passage efficiency ranged from 0.31 to 0.48 (*median* = **0.44**, n = 10 years). Median estimates for the three monitoring eras were **0.40** (1997-1999), **0.47** (2000-2002), and **0.39** (2007-2010). Larger lamprey were more likely than smaller lamprey to pass Bonneville Dam after approaching fishways (r^2 = 0.49).

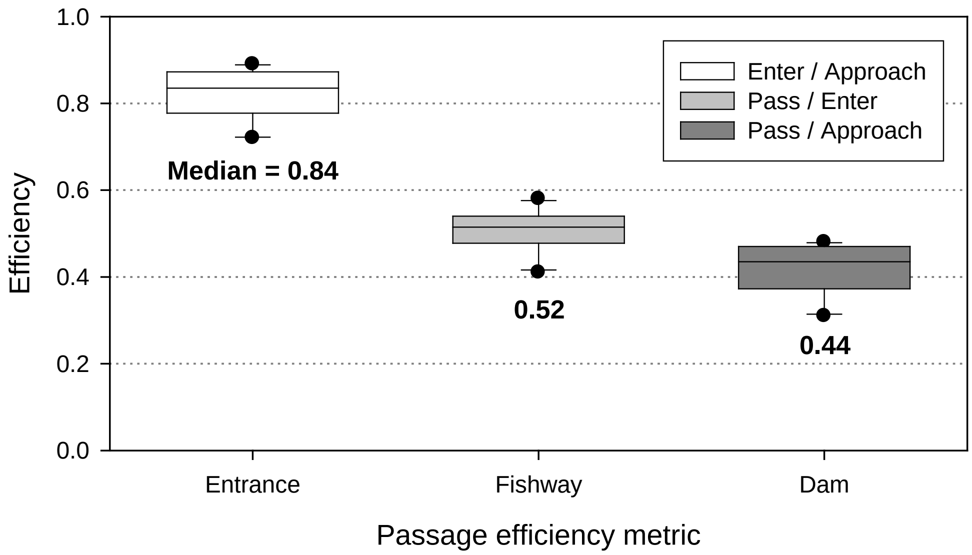


Figure 6. Distributions of annual dam-wide passage efficiency metrics estimated for radio-tagged Pacific lamprey at Bonneville Dam. Box plots percentiles are: 25th, 50th, and 75th (boxes), 10th and 90th (whiskers) and 5th and 95th (circles).

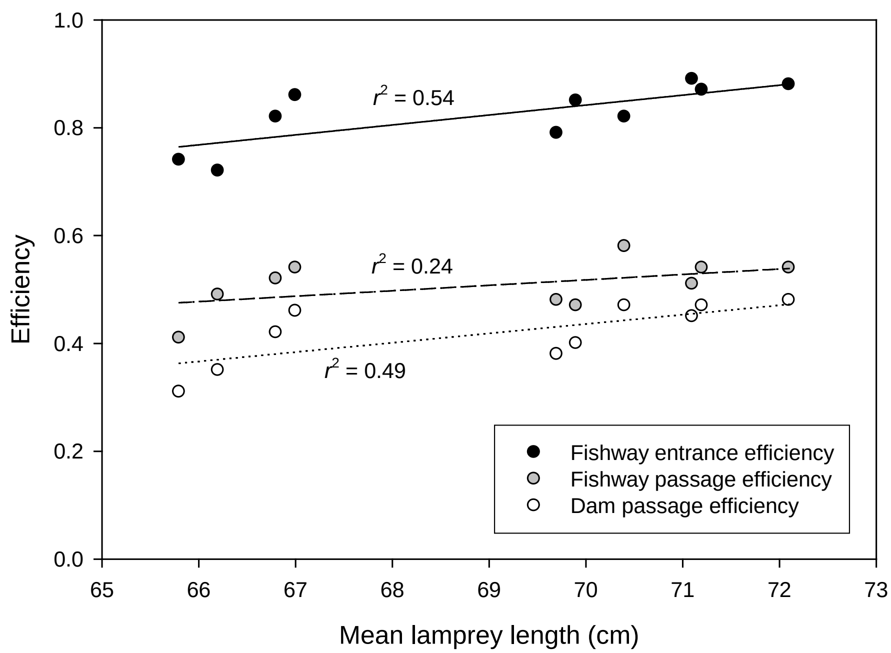


Figure 7. Scatterplots showing the linear relationship between mean Pacific lamprey length (cm) and annual dam-wide passage efficiency metrics at Bonneville Dam.

5.1.7 SITE-SPECIFIC FISHWAY ENTRANCE EFFICIENCY

Unique lamprey: unique lamprey entrance efficiency varied widely among the ten fishway openings monitored at Bonneville Dam (Figure 8). Efficiency was lowest at the PH2 north downstream opening (*median* = **0.27**, *n* = 10 years) and at PH1 sluice gates (*median* = **0.29**, *n* = 6). Median estimates were highest at the north spillway (i.e., Cascades Island, **0.53**, *n* = 10), PH1 north (**0.53**, *n* = 10) and PH2 north upstream (**0.56**, *n* = 10) openings.

Total attempts: entrance efficiency estimates based on total approach and entry events was lowest at PH2 orifice gates (*median* = **0.04**, *n* = 3 years) and PH1 sluice gates (**0.09**, *n* = 6). Median estimates were highest at the north spillway (**0.37**, *n* = 10), south spillway (**0.38**, *n* = 10) and PH1 north (**0.38**, *n* = 10) openings.

CAVEAT: many fishway approaches and entries were excluded because sluice gates and orifice gates were unmonitored in some years.

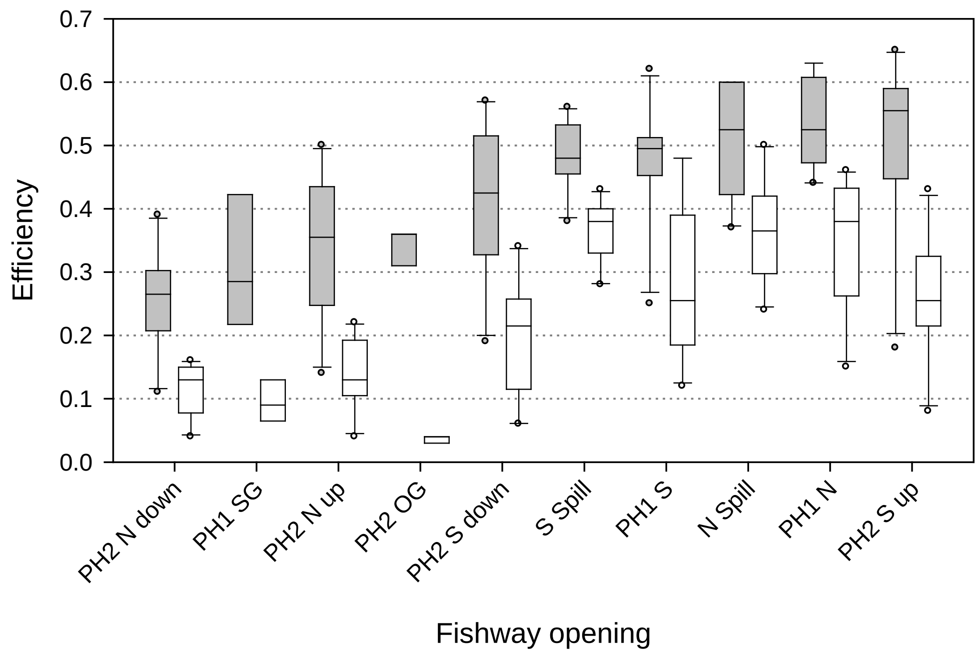


Figure 8. Annual **site-specific fishway entrance efficiency** estimates for unique fish (unique fish that entered fishway / unique fish that approached at each monitored fishway opening; gray boxes) and total events (total number of fishway entries / total number of fishway approaches; white boxes) at Bonneville Dam. Estimates are ordered from lowest to highest median unique fish values. Box plots percentiles are: 25^{th}, 50^{th}, and 75^{th} (boxes), 10^{th} and 90^{th} (whiskers) and 5^{th} and 95^{th} (circles).

5.1.8 ROUTE-SPECIFIC FISHWAY PASSAGE EFFICIENCY

Unique lamprey: unique-lamprey fishway passage efficiency varied widely among the twelve routes identified at Bonneville Dam (Figure 8). Efficiency was lowest for lamprey that entered at the PH2 south upstream (*median* = **0.04**, *n* = 10 years) and PH2 south downstream (**0.05**, *n* = 10) openings. Median estimates were highest for those that entered at PH1 north (**0.57**, *n* = 10), PH1 south (**0.46**, *n* = 10), and at unknown PH1 (**0.46**, *n* = 10) openings. The unknown category mostly included fish that entered via unmonitored sluice gates.

Total attempts: fishway passage efficiency estimates based on total entry events was also lowest at the PH2 south upstream (*median* = **0.02**, *n* = 10 years) and PH2 south downstream (**0.03**, *n* = 10) openings. Median estimates were highest at PH1 north (**0.49**, *n* = 10), PH1 unknown (**0.40**, *n* = 10), PH1 south (**0.36**, *n* = 10) and PH2 north upstream (**0.36**, *n* = 10) openings.

Importantly, route-specific passage efficiency estimates were highly variable within year (Box 3). Efficiency at many routes, particularly at the Bradford Island fishway, increased within season as water temperature increased and tailwater elevation decreased. Efficiency was varied in response to the time of day that lamprey entered each route, with lower efficiency for events that were during daylight hours (Box 3).

CAVEAT: across years, 1,057 fishway entries were at unknown sites; most were presumably via unmonitored sluice gates and orifice gates. Fishway passage efficiency for this group of unknown events was likely overestimated slightly because some fish may have entered and exited fishways undetected.

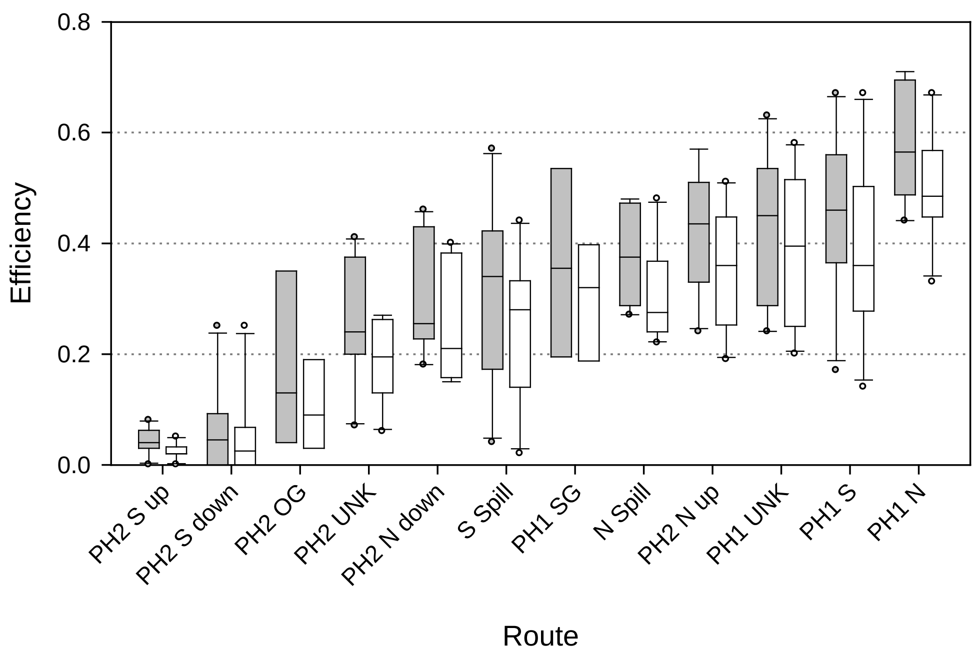
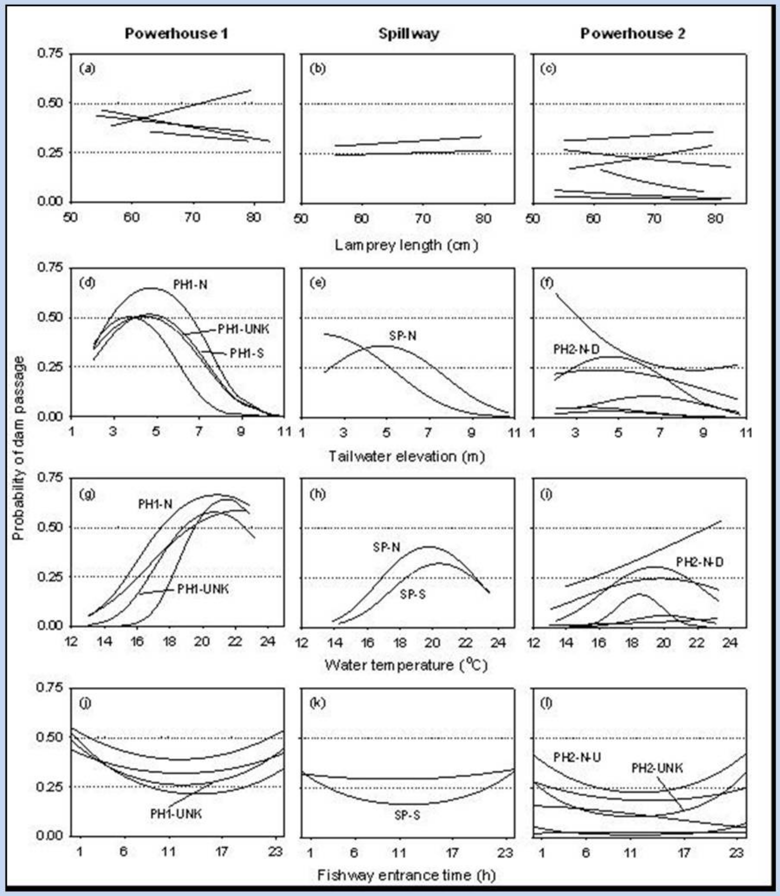


Figure 9. Annual **route-specific fishway passage efficiency** estimates for unique fish (unique fish that passed dam / unique fish that entered at each monitored fishway opening; gray boxes) and total events (total number of dam passages / total number of fishway entries; white boxes) at Bonneville Dam. Estimates are ordered from lowest to highest median unique fish values. PH1 UNK and PH2 UNK include fishway entries where the specific opening used was unknown; these were most likely via unmonitored sluice gates and orifice gates. Box plots percentiles are: 25th, 50th, and 75th (boxes) of annual estimates, 10th and 90th (whiskers) and 5th and 95th (circles).

Box 3. Examples of effects on route-specific fishway Passage efficiency at Bonneville Dam

- Modest lamprey size effects
- Higher efficiency at low tailwater elevation
- Increasing efficiency as temperature increases
- Higher efficiency at night than during the day
- Effects differ among routes



5.1.9 FISHWAY SEGMENT PASSAGE EFFICIENCY

Unique lamprey passage efficiency was estimated for 20 fishway segments at Bonneville Dam (Figure 10; see Figures 1 & 2 for site locations). The five lowest passage efficiency estimates were in the main PH2 collection channel (segment 14, *median* = **0.29**, *n* = 3), the entry channel at the south spillway (segment 7, B-Branch, **0.59**, *n* =10), the south end of the PH2 collection channel (segment 13, **0.60**, *n* = 3), the Washington-shore fishway transition pool (segment 17, **0.73**, *n* = 10) and the north spillway (i.e., Cascades Island) transition pool (segment 10, **0.74**, *n* =10).

In the second quartile were: the upper Washington-shore fishway between the count station and the top-of-ladder exit (segment 20, *median* = **0.76**, *n* = 6), the south spillway (B-Branch) transition pool (segment 8, **0.77**, *n* = 10), the north spillway entry channel (segment 9, **0.79**, *n* = 10), the PH1 collection channel (segment 2, **0.80**, *n* = 6), and the south end of the PH1 fishway (segment 1, **0.80**, *n* = 10).

In the third quartile were: the PH2 north downstream collection channel (segment 15, *median* = **0.83**, *n* = 10), the upper Bradford Island fishway between the count station and top-of-ladder exit (segment 6, **0.87**, *n* = 10), the PH1 transition pool (segment 4, **0.91**, *n* = 10), the PH2 north upstream collection channel (segment 16, **0.91**, *n* = 10), and the north end of the PH1 fishway (segment 3, **0.92**, *n* = 10).

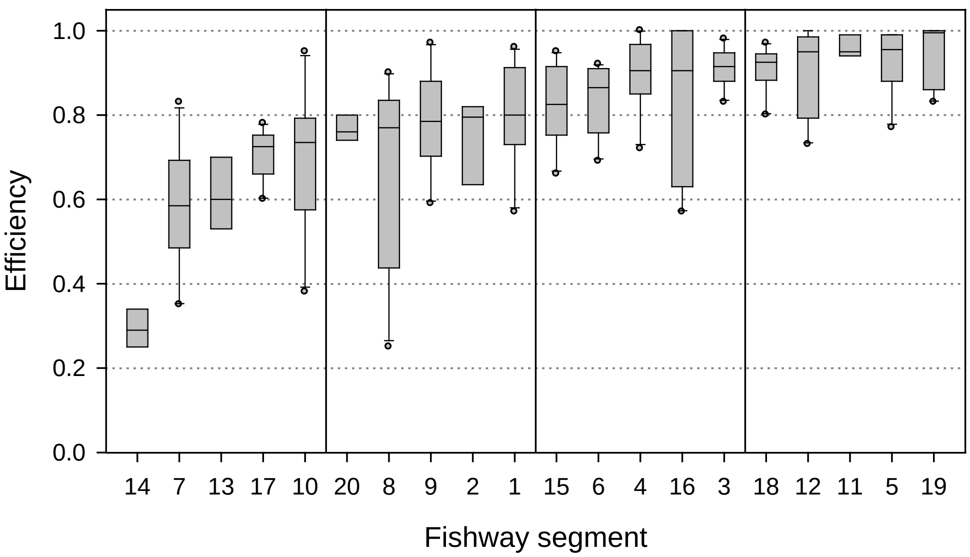


Figure 10. Annual **segment-specific fishway passage efficiency** estimates for unique fish (number of unique lamprey that passed a segment/number of unique lamprey detected in the segment) at Bonneville Dam. Estimates are ordered from lowest to highest median unique fish values. Box plots percentiles are: 25th, 50th, and 75th (boxes), 10th and 90th (whiskers) and 5th and 95th (circles). Vertical lines are quartiles. See Figures 1 & 2 for site locations.

Segment efficiency estimates were highest in: the lower Washington-shore ladder (segment 18, *median* = **0.93**, *n* = 10), the PH2 south downstream collection channel (segment 12, **0.95**, *n* = 10), the junction area in the Cascades Island fishway near the former exit channel (segment 11, **0.95**, *n* = 4), the Bradford Island junction pool (i.e., the junction of the A- and B-Branch fishways, segment 5, **0.96**, *n* = 10), and the UMT junction in the Washington-shore fishway (segment 19, **1.00**, *n* = 10).

CAVEAT: limited monitoring in the main PH2 collection channel, including orifice gates, made it challenging to estimate segment efficiency from the south end of the channel to the transition pool.
CAVEAT: segment passage efficiencies were estimated using fish that entered via different routes

CAVEAT: there was only top-of-ladder exit monitoring at the Washington-shore fishway in 1997-1999, with no sites near the count station or serpentine weirs.

CAVEAT: passage efficiency at the UMT junction was likely underestimated in 1997-1999 (*median* = **0.86**) because it was not possible to determine whether fish turned around near the UMT junction or upstream near the unmonitored count station or serpentine weirs.

5.1.10 FISHWAY TURN-AROUND LOCATIONS

Across years a total of 4,127 fishway entry events resulted in exit to the Bonneville Dam tailrace, also termed ‘fishway fallout’ (Table 4). Across years, 956 (23%) fallouts were from the Bradford Island fishway and 3,171 (77%) were from the Washington-shore fishway. Some lamprey turned around in each of the 20 monitored fishway segments, but turn-arounds were most likely in the first or second fishway segment encountered after fishway entry (Figure 11). This behavior was consistent across entry sites and years. Smaller numbers of lamprey turned around in fishway segments upstream from transition areas.

Table 4. Numbers of fishway entry events recorded for radio-tagged Pacific lamprey and estimated turn-around locations inside fishways for those events that did not result in Bonneville Dam passage, all years combined. See Figures 1 & 2 for fishway locations. 956 = number of turn-arounds in Bradford Island fishway; 3,171 = number of turn-arounds in Washington-shore fishway; 4,127 = total turn-arounds.

	Entry	Turn-around location in Bradford Island fishway							
	n	1	[1]2	3	4	5	[2]6	7	8
PH1-S	361	111	19	22	24	10	35		
PH1-SG	114		36	20	9	6	5		
PH1-N	264			61	32	16	27		
PH1-UNK	255	11	51	44	20	11	21		
SP-S	541					4	39	263	59
Total	**1535**	**122**	**106**	**147**	**85**	**47**	**127**	**263**	**59**
% of 956		**13%**	**11%**	**15%**	**9%**	**5%**	**13%**	**28%**	**6%**
% of 4127		**3%**	**3%**	**4%**	**2%**	**1%**	**3%**	**6%**	**1%**

		Turn-around location in Washington-shore fishway											
		9	10	[3]11	12	13	[4]14	15	16	17	18	19	[5]20
SP-N	355	111	74	6								3	50
PH2-S-D	438				61	289	51			11	3		6
PH2-S-U	1242					1084	93			27	4		5
PH2-OG	134					3	103			9	3	3	
PH2-N-D	303							82	52	67	16	4	10
PH2-N-U	418									210	32	9	24
PH2-UNK	802				24	282	39	8	7	171	32	1	69
Total	**3692**	**111**	**74**	**6**	**85**	**1658**	**286**	**100**	**59**	**495**	**90**	**20**	**164**
% of 3171		**4%**	**2%**	**<1%**	**3%**	**52%**	**9%**	**3%**	**2%**	**16%**	**3%**	**1%**	**5%**
% of 4127		**3%**	**2%**	**<1%**	**2%**	**40%**	**7%**	**2%**	**1%**	**12%**	**2%**	**<1%**	**4%**

[1] main PH1 collection channel not monitored in 2007-2010
[2] limited monitoring near count station, AWS, serpentine weirs in Bradford Island fishway in 1997-1999
[3] no monitoring of former Cascades Island exit area in 1997-2002
[4] no monitoring of main PH2 collection channel in 2000-2002 or 2007-2010
[5] limited monitoring near count station, AWS, serpentine weirs in Washington-shore fishway in 1997-1999

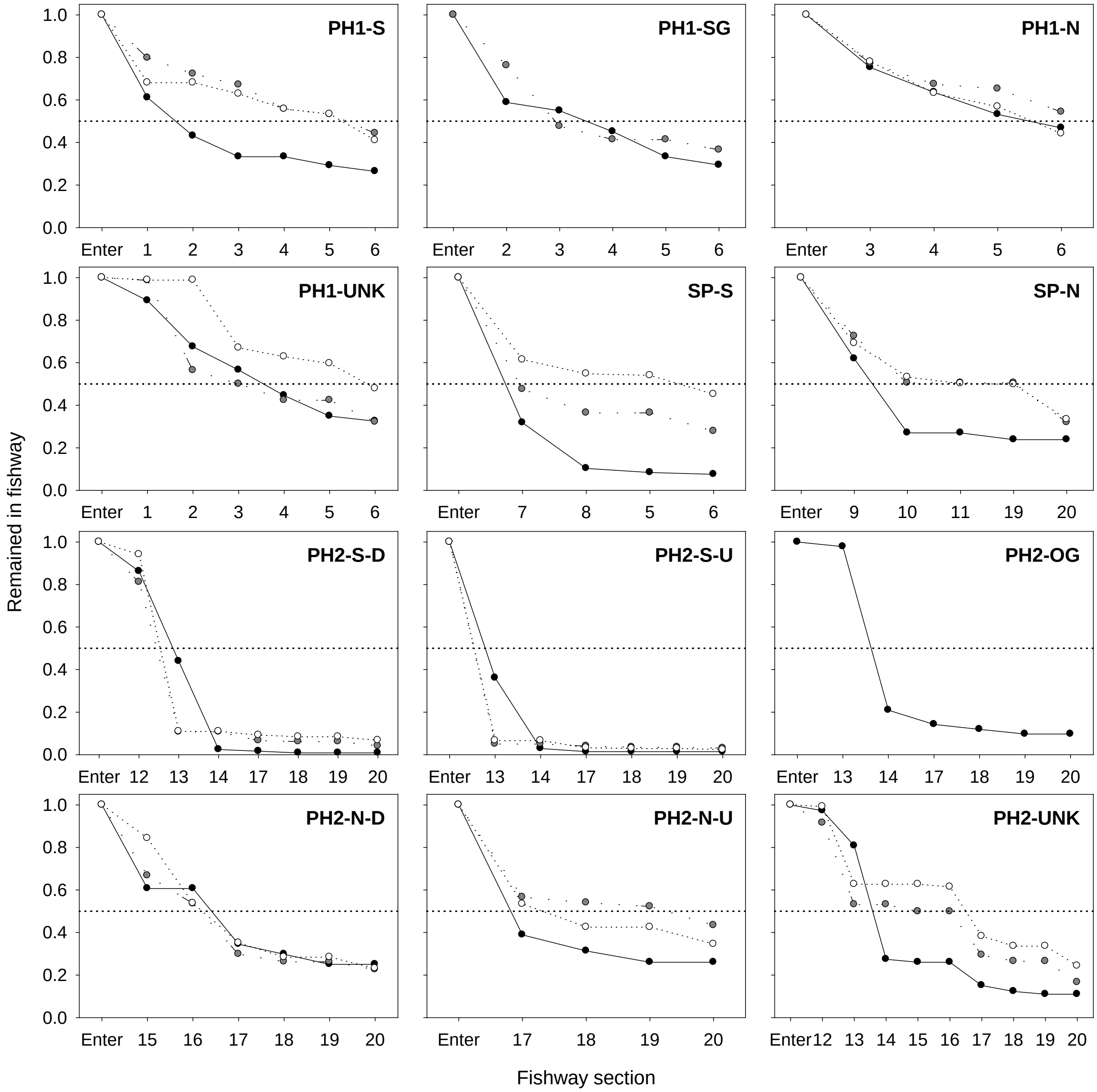


Figure 11. Route-specific relationships between fishway entrance location, fishway monitoring segment, and the proportion of radio-tagged adult Pacific lamprey that remained inside Bonneville Dam fishways. Symbols represent study years with different antenna arrays: (●) = 1997-1999; (●) = 2000-2002; (○) = 2007-2010. Panels represent the 12 fishway entrance routes. See Figures 1 and 2 for entrance locations and Table 4 for total sample sizes.

Dam-wide, four fishway segments accounted for 65% of all turn-around events across years. These were the southern end of the PH2 collection channel (segment 13, *n* =**1,658** turn-arounds), the PH2 junction pool (segment 17, *n* = **496**), the main PH2 collection channel (segment 14, *n* = **296**), and the south spillway entrance collection channel (segment 7, *n* = **263**). See CAVEAT below. Segments with relatively few turn-arounds included: the area near the former Cascades Island exit (segment 11, *n* = **6** turn-arounds), the junction of the main Washington-shore fishway and the UMT channel (segment 19, *n* = **20**), and the Bradford Island junction pool (segment 5, *n* = **47**).

CAVEAT: the main collection channel at PH2 was not monitored after 1999 and therefore the total number of turn-arounds in that area was substantially underestimated; many turn arounds were instead attributed to the south end of the channel starting in 2000. In 1997-1999, when all lower fishway sites were monitored, a median of 27% of all (dam-wide) turn-around events were along the main PH2 collection channel and another 22% were near the south end of the PH2 collection channel. In 2000-2002 and 2007-2010, a median of 46% of all turn-around events were assigned to the combined south end and main PH2 collection channel.

CAVEAT: upper fishway monitoring was limited in 1997-1999 and total turn-arounds were likely underestimated at both sites.

CAVEAT: monitoring near the former Cascades Island fishway exit did not occur in 1997-2002 and total turn-arounds were likely underestimated; note that this number was likely very small.

5.1.11 BOTTLENECK ASSESSMENT

Several metrics were used to assess the relative impact of specific lamprey passage bottlenecks on lamprey passage at Bonneville Dam. As much as possible, these metrics were standardized to take into account the differences in monitoring effort among years. In combination, the bottleneck metrics can be used to help prioritize sites for mitigation, such as structural or operational changes to improve passage. The metrics can also help identify priority sites for additional targeted monitoring to identify specific mechanisms of lamprey passage failure.

Turn-around rate (number of turn-arounds at site / number of unique lamprey at site): lamprey turn-around rates were highest at the south end of the PH2 collection channel (segment 13, *rate* = **1.98** turn-arounds per unique fish), the main PH2 collection channel (segment 14, **1.11**), the south spillway entrance collection channel (segment 7, **0.65**), and the Washington-shore junction pool / transition pool (segment 17, **0.57**) (Figure 12a).

Four additional segments had turn-around rates ≥ 0.30: the north spillway (Cascades Island) transition pool (segment 10, **0.33**), the PH2 north downstream collection channel (segment 15, **0.37**), the south end of the PH1 collection channel (segment 1, **0.38**), and the north spillway (Cascades Island) collection channel (segment 9, **0.39**).

Turn-around rates were lowest (< 0.10) in mid-elevation fishway segments that included the Bradford Island junction pool (segment 5, **0.07**), the area near the former Cascades Island fishway exit (segment 11, **0.04**), and the UMT junction area in the Washington-shore fishway (segment 19, **0.03**).

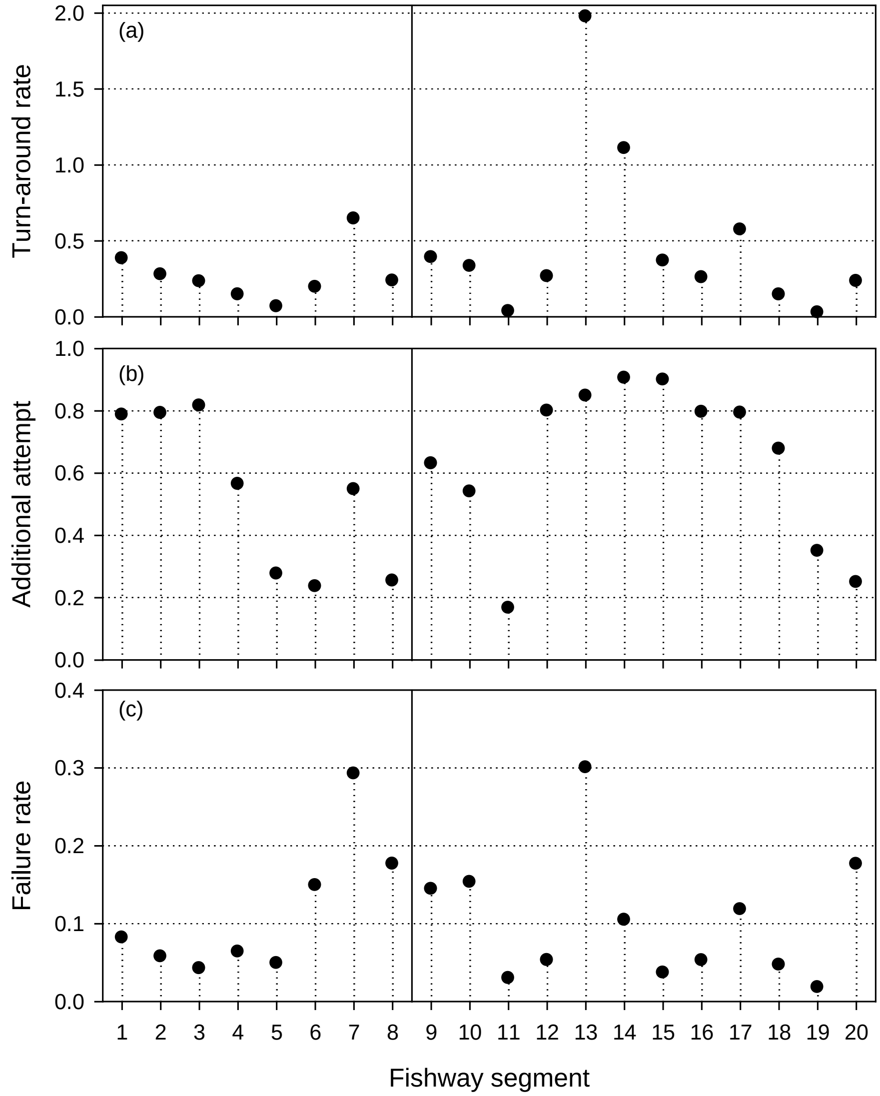


Figure 12. Fishway bottleneck metrics estimated for radio-tagged adult Pacific lamprey at 20 fishway segments at Bonneville Dam. Metrics include: (a) proportion of unique lamprey recorded at each segment that turned around and exited to the tailrace (number of turn-arounds / number of unique lamprey at site); (b) proportion of turn-around events that were followed by an additional dam passage attempt (additional attempt / turn-around event); and (c) proportion of unique lamprey that failed to make an additional dam passage attempt (number of unsuccessful final entries / number of unique lamprey at site). See Figures 1 and 2 for fishway segments.

Additional passage attempts (additional passage attempt / turn-around event): in general, lamprey that turned around in upper fishway segments were least likely to make additional dam passage attempts (Figure 12b). The lowest estimates were for turn-arounds near the former Cascades Island fishway exit (segment 11, **0.17** followed by additional dam passage attempts), the upper Bradford Island fishway (segment 6, **0.24**), the upper Washington-shore fishway (segment 20, **0.25**), the north spillway (B-Branch) transition pool (segment 8, **0.25**), and the Bradford Island junction pool (segment 5**, 0.28**).

The six segments with the highest estimates were all near fishway openings: the PH2 north upstream collection channel (segment 16, **0.80**), the PH2 south downstream collection channel (segment 12, **0.80**), the PH1 north collection channel (segment 3, **0.82**), the PH2 south upstream collection channel (segment 13, **0.85**), the PH2 north downstream collection channel (segment 15, **0.90**), and the PH2 orifice gates (segment 14, **0.91**).

Failure rate (number of unsuccessful final entries / number of unique lamprey at site): failure rates were highest for lamprey that turned around in the south end of the PH2 collection channel (segment 13, **0.30** made no additional passage attempt), the south spillway (B-Branch) collection channel (segment 7, **0.29**) and transition pool (segment 8, **0.18**), the upper Washington-shore fishway (segment 20, **0.18**), and the north spillway (Cascades Island) transition pool (segment 10, **0.15**) (Figure 12c).

Five additional sites had failure rates from 0.10-0.15: the main PH2 collection channel (segment 14, **0.10**), the PH2 transition pool (segment 17, **0.12**), the north spillway (i.e., Cascades Island) collection channel (segment 9, **0.14**), the upper Bradford Island fishway (segment 6, **0.15**), and the north spillway (i.e., Cascades Island) transition pool (segment 10, **0.15**).

5.1.12 PRIORITIZATION CONSIDERATIONS

The radiotelemetry data synthesis results for Bonneville Dam identify many potential sites where adult lamprey passage could be improved.

Fishway openings: Lamprey have many potential routes into the Bonneville fishways and there are large differences in the effectiveness among sites. The least effective, as estimated using the unique fish and total entrance efficiency metrics were the north and south downstream openings at Powerhouse 2, the floating orifice gates at Powerhouse 2, and the sluice gates at Powerhouse 1. We have hypothesized that lamprey move along the face of both Bonneville powerhouses, passing in front of the sluice and orifice gates without attempting to enter. This may result in some efficiency deflation at these sites and it is not clear that improving movement into these openings would greatly improve fishway or dam passage given the high turn-around rates in the collection channels and junction / transition pools.

The experimental reductions in fishway velocity at the Washington-shore fishway in 2007-2009 did indicate that lowered fishway entrance velocity improved entrance efficiency. The benefits were much larger at the north-shore than at the south-shore openings (floating orifices were not monitored). The experimental results suggested that reducing night-time velocity may be an effective treatment for improving efficiency at openings, but these benefits did not necessarily translate to more fish past the dam, perhaps in part because of the very poor efficiency for lamprey that entered at the southern entrance at Powerhouse 2 or because of bottlenecks upstream of entrances in the fishway (e.g., the Washington-shore fish ladder transition pool).

Fishway routes: Poor efficiencies at entrance collection channels and the powerhouse collection channel in the Washington-shore fishway suggest that improvements in these areas should be prioritized. The sections from the south-shore entrances through the Powerhouse 2 collection channel, in particular, had the greatest scope for improvement dam-wide. Another relatively inefficient route was via the south spillway (B-Branch) opening, which had relatively high lamprey use, but poor passage success. Turn-arounds were very common in the entrance collection channel and transition pool segments of the B-Branch.

Bottlenecks: In addition to the Powerhouse 2 segments described above, the Washington-shore junction pool and the top-of-ladder segments in both Bonneville fishways are important bottlenecks at the dam. Because many routes pass through threes fishway segments, any passage improvements at these segments potentially affect large numbers of lamprey. Within the top-of-ladder segments, the serpentine weir sections appear to be the most difficult for lamprey to pass. In addition, lamprey that turn around in the serpentine weirs and retreat to the tailrace are among the least likely to make additional dam passage attempts. See Section 9.1.1 for prioritization models for bottleneck reductions at Bonneville Dam.

5.2 THE DALLES DAM

5.2.1 NUMBERS OF RADIO-TAGGED LAMPREY

A total of 665 radio-tagged Pacific lamprey were detected at The Dalles Dam or in The Dalles tailrace over ten years (1997-2002, 2007-2010). Annual sample sizes ranged from 38 to 112 (*median* = 82).

5.2.2 MONITORING EFFORT

The adult fishways at The Dalles Dam (Figures 13 & 14) were monitored in all years except 1999, when only top-of-ladder exits were monitored. Radiotelemetry monitoring at The Dalles Dam focused on fishway openings (east, west, spillway, north), transition pools, and top-of-ladder sites. Sites that were *not* monitored included:

- count stations
- overflow weir sections of fish ladders between transition pools and ladder tops
- orifice gates along the Powerhouse, in years that they were open
- the Powerhouse collection channels

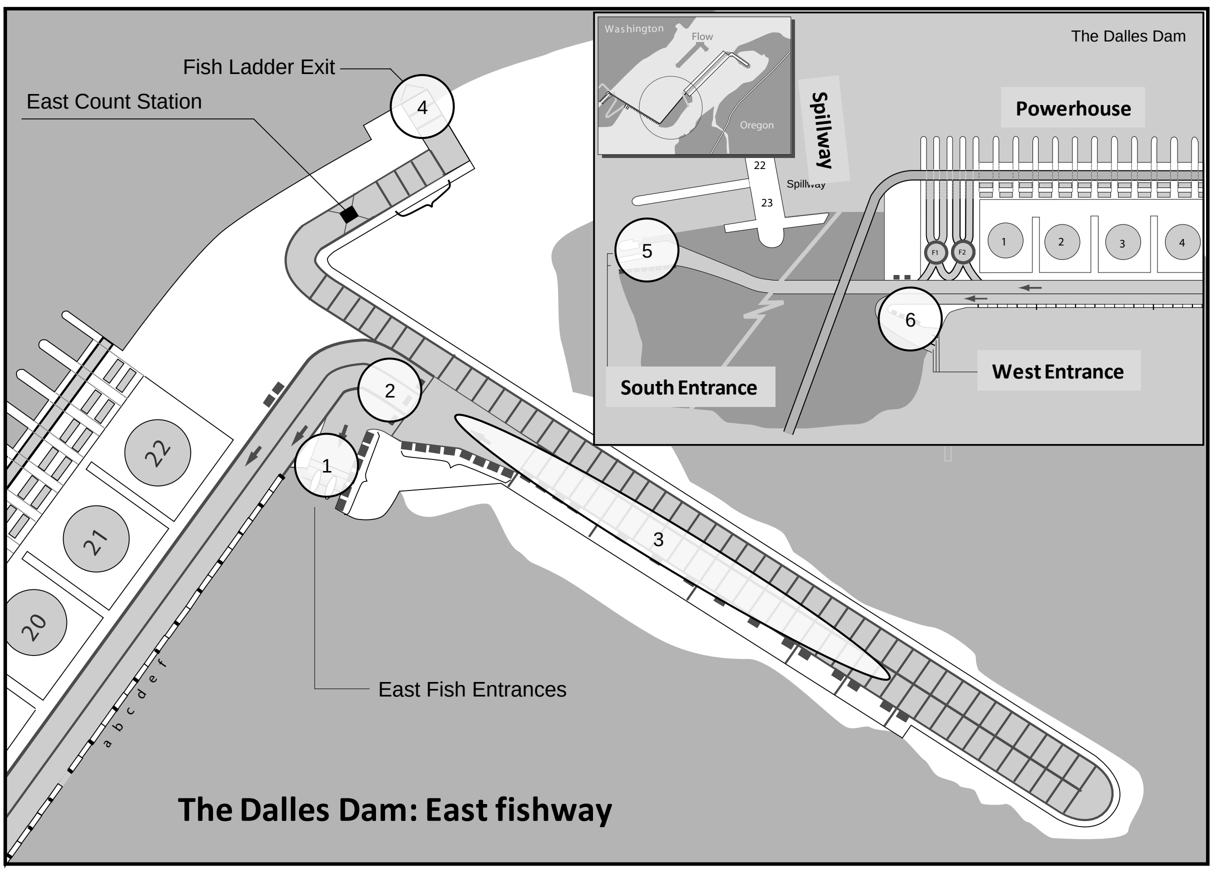


Figure 13. Map of the east fishway at The Dalles Dam. Numbers indicate fishway segments monitored with radiotelemetry.

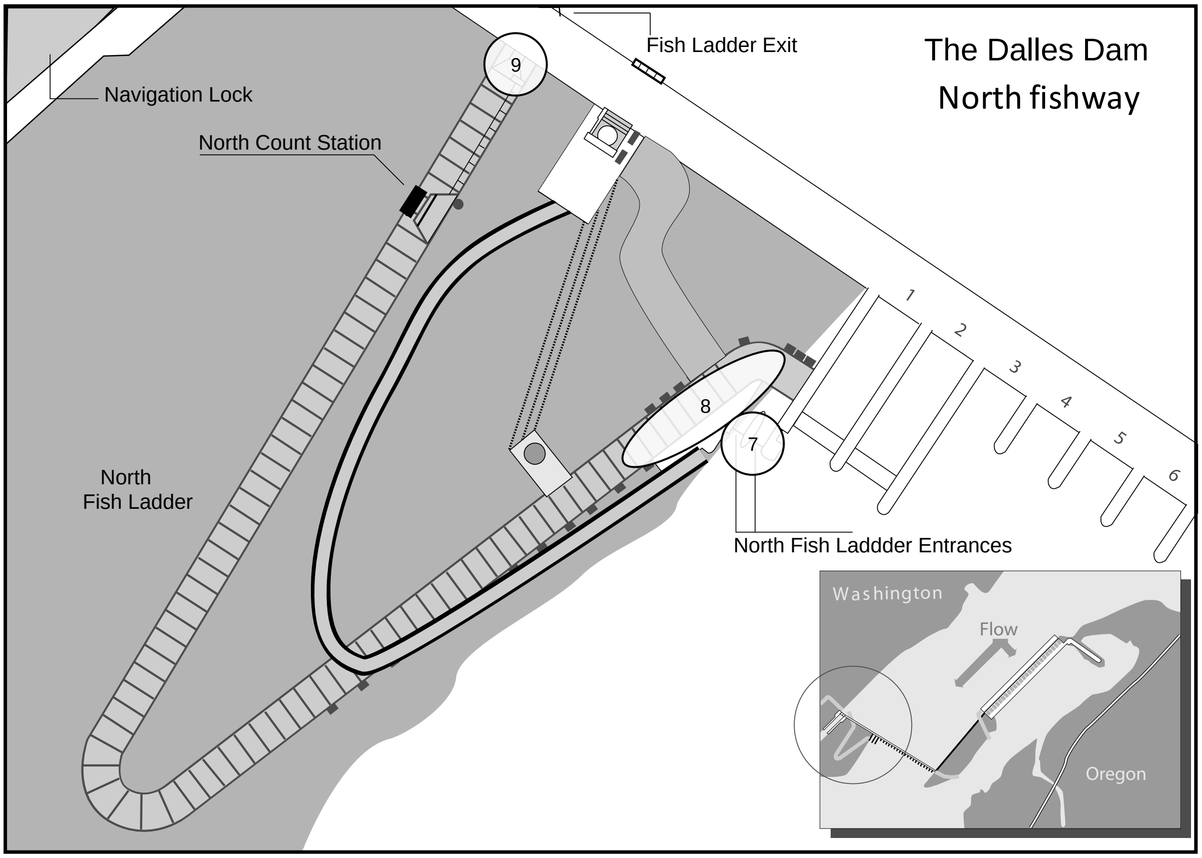


Figure 14. Map of the north fishway at The Dalles Dam. Numbers indicate fishway segments monitored with radiotelemetry.

5.2.3 FISHWAY APPROACH SUMMARY

A total 652 unique radio-tagged lamprey approached monitored fishway openings a total of 2,096 times at The Dalles Dam for a combined total of 3.2 fishway approaches/lamprey. The distribution of first fishway approach sites averaged 28% at the east opening, 21% at the west opening, 10% at the south spillway opening, and 36% at the north opening (Figure 15); another 5% were at the east fishway, but exact locations were unknown. Distributions of total approach events were very similar to first approaches.

CAVEAT: orifice gates were open and unmonitored in 1997-1999; they were closed in 2000.

5.2.4 FISHWAY ENTRY SUMMARY

A total of 597 unique radio-tagged lamprey entered monitored fishway openings a total of 1,123 times at The Dalles Dam for a combined total of 1.9 fishway entries/lamprey. The distribution of first fishway entry sites averaged 28% at the east opening, 14% at the west opening, 8% at the south spillway opening, and 36% at the north opening (Fig. 15); another 14% were at the east fishway, but exact locations were unknown. Distributions of total entry events were very similar to first entries.

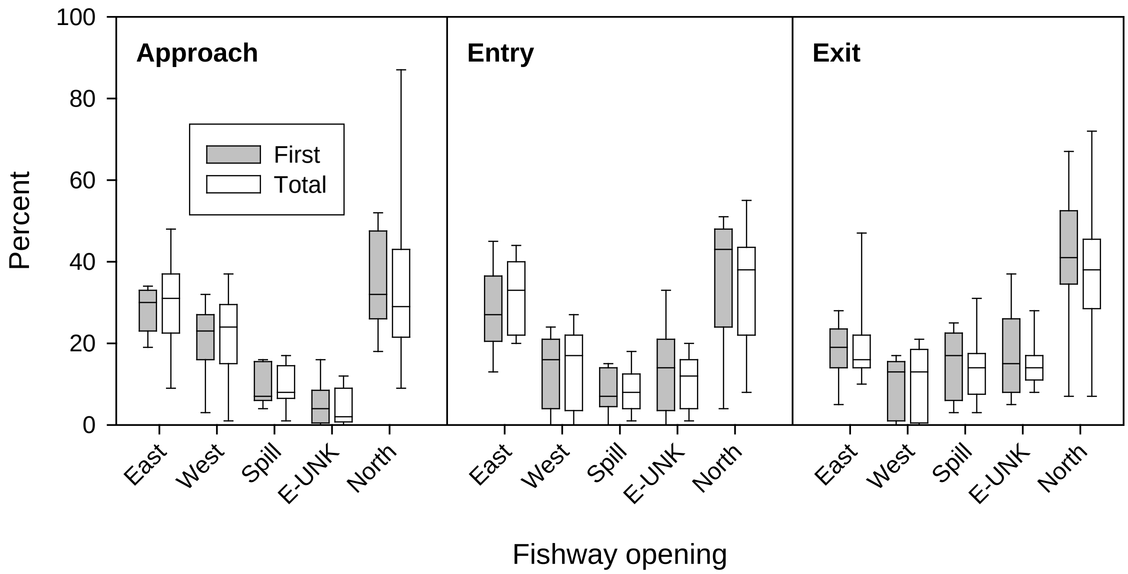


Figure 15. Distributions of annual estimates of radio-tagged Pacific lamprey fishway approach, entry, and exit locations at The Dalles Dam. See Figures 13 & 14 for fishway sites. E-UNK indicates that event occurred at the East fishway, but the exact location was unknown or ambiguous. Box plots percentiles are: 25th, 50th, and 75th (boxes), and 10th and 90th (whiskers).

5.2.5 FISHWAY EXIT SUMMARY

A total of 304 unique radio-tagged lamprey exited monitored fishway openings into the tailrace a total of 634 times at The Dalles Dam for a combined total of 2.1 fishway exits/lamprey. The distribution of first fishway entry sites averaged 18% at the east opening, 10% at the west opening, 14% at the south spillway opening, and 41% at the north opening (Figure 15); another 17% were at the east fishway, but exact locations were unknown. Distributions of total exit events were very similar to first exits.

5.2.6 DAM-WIDE PASSAGE EFFICIENCY METRICS

Fishway entrance efficiency (unique fish that entered / unique fish that approached): dam-wide fishway entrance efficiency ranged from 0.75 to 0.96 (*median* = **0.87**, *n* = 9 years, Figure 16). Median estimates for the three monitoring eras were **0.81** (1997-1999), **0.87** (2000-2002), and **0.91** (2007-2010).

Fishway passage efficiency (unique fish that passed / unique fish that entered): dam-wide fishway passage efficiency ranged from 0.72 to 0.88 (*median* = **0.75**, *n* = 9 years). Median estimates for the three monitoring eras were **0.73** (1997-1999), **0.82** (2000-2002), and **0.77** (2007-2010).

Dam passage efficiency (unique fish that passed / unique fish that approached): dam-wide dam passage efficiency ranged from 0.55 to 0.79 (*median* = **0.68**, *n* = 10 years). Median estimates for the three monitoring eras were **0.59** (1997-1999), **0.74** (2000-2002), and **0.69** (2007-2010).

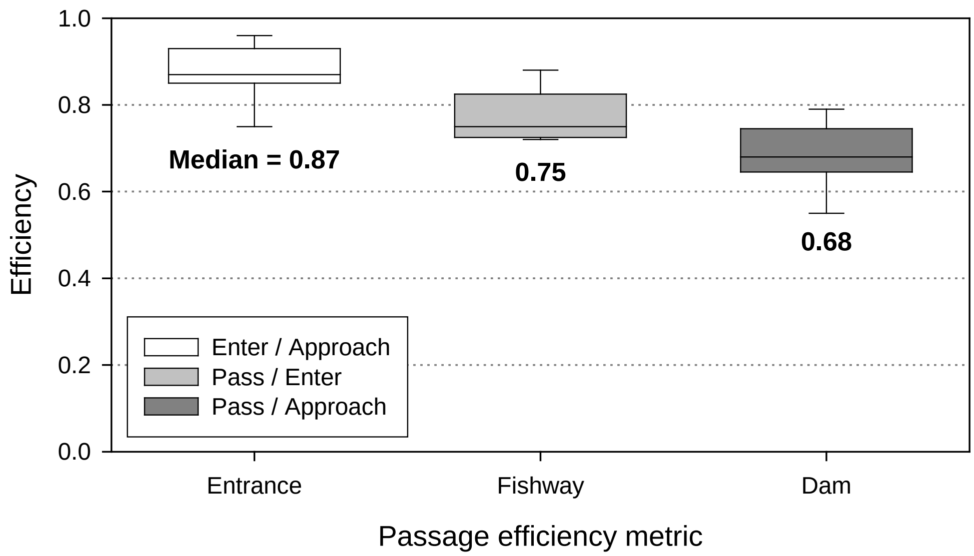


Figure 16. Distributions of annual dam-wide passage efficiency metrics estimated for radio-tagged Pacific lamprey at The Dalles Dam. Box plots percentiles are: 25th, 50th, and 75th (boxes), and 10th and 90th (whiskers).

5.2.7 SITE-SPECIFIC FISHWAY ENTRANCE EFFICIENCY

Unique lamprey: unique lamprey entrance efficiency varied widely among the four fishway openings monitored at The Dalles Dam, and among years at each opening (Figure 17). Efficiency was lowest at the west opening (*median* = **0.47**, *n* = 9 years) and at the spillway opening (**0.64**, *n* = 9). Median estimates were highest at the east (**0.76**, *n* = 9) and north (**0.89**, *n* = 9) openings.

Total attempts: entrance efficiency estimates based on total approach and entry events was also lowest at the west opening (*median* = **0.42**, *n* = 9 years). Median estimates were higher at the east (**0.52**, *n* = 9), spillway (**0.53**, *n* = 9), and north (**0.77**, *n* = 9) openings.

CAVEAT: many fishway approaches and entries were excluded because the specific sites used were ambiguous.

5.2.8 ROUTE-SPECIFIC FISHWAY PASSAGE EFFICIENCY

Unique lamprey: unique-lamprey fishway passage efficiency varied among the five routes identified at The Dalles Dam and varied among years at each route (Figure 18). Efficiency was lowest for lamprey that entered at the spillway opening (*median* = **0.43**, *n* = 9 years), west opening (**0.48**, *n* = 9), and at unknown east fishway sites openings (**0.50**, *n* = 9). Median estimates were higher for those that entered at north (**0.65**, *n* = 9) and east (**0.71**, *n* = 9) openings.

Single-dam summaries

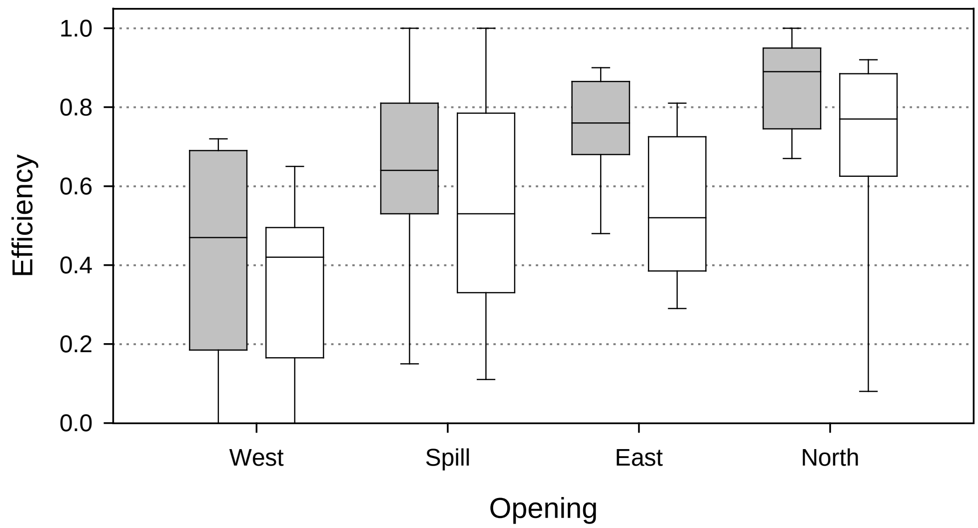


Figure 17. Annual **site-specific fishway entrance efficiency** estimates for unique fish (unique fish that entered fishway / unique fish that approached at each monitored fishway opening; gray boxes) and total events (total number of fishway entries / total number of fishway approaches; white boxes) at The Dalles Dam. Estimates are ordered from lowest to highest median unique fish values. Box plots percentiles are: 25th, 50th, and 75th (boxes), and 10th and 90th (whiskers).

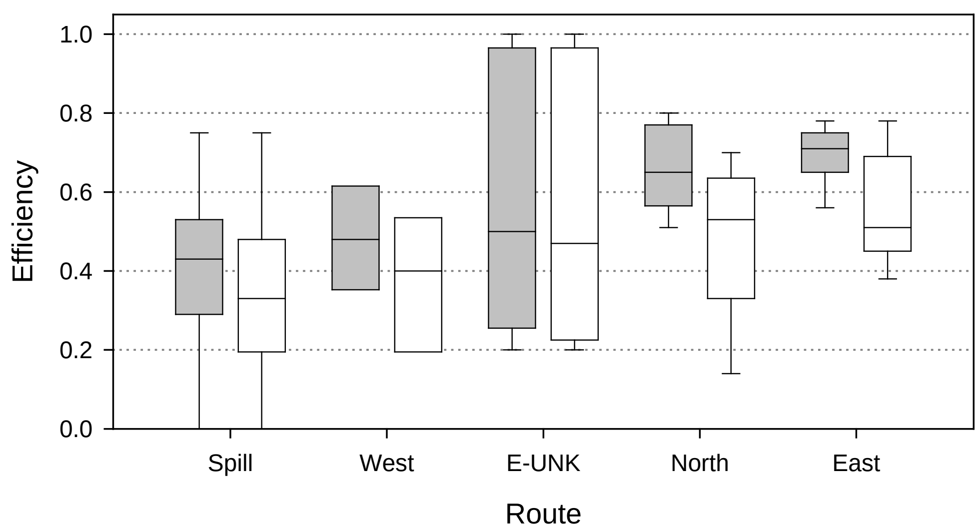


Figure 18. Annual **route-specific fishway passage efficiency** estimates for unique fish (unique fish that passed dam / unique fish that entered at each monitored fishway opening; gray boxes) and total events (total number of dam passages / total number of fishway entries; white boxes) at The Dalles Dam. Estimates are ordered from lowest to highest median unique fish values. E-UNK includes fishway entries where the specific opening used was unknown. Box plots percentiles are: 25th, 50th, and 75th (boxes), and 10th and 90th (whiskers).

Total attempts: fishway passage efficiency estimates based on total entry events was also lowest at the spillway (*median* = **0.33**, *n* = 9 years) and west (**0.40**, *n* = 9) openings. Median estimates were higher for the unknown east fishway route (**0.47**, *n* = 10), east opening (**0.51**, *n* = 9), and north opening (**0.53**, *n* = 9).

CAVEAT: in early study years some lamprey likely approached, entered, and exited orifice gates, resulting in overestimation of route passage efficiency.

5.2.9 FISHWAY SEGMENT PASSAGE EFFICIENCY

Unique lamprey passage efficiency was estimated for 9 fishway segments at The Dalles Dam (Figure 19). The lowest passage efficiency estimates was in the spillway collection channel (*median* = **0.71**, *n* = 9 years) opening. Importantly, efficiency for this segment extended a considerable distance up the collection channel because the next upstream antenna location was in the junction pool. Three additional segments had median efficiency estimates near 0.80: the north fishway transition pool (**0.77**, *n* = 9), the west collection channel (**0.79**, *n* = 9), and the east fishway transition pool (**0.79**, *n* = 10). The remaining five segments had efficiency estimates that were ≥ **0.95**.

CAVEAT: long segments of fishways at The Dalles were unmonitored, including the collection channels between powerhouse fishway openings and the junction pool, and ladders from transition pools to near ladder tops. Therefore, efficiency estimates for transition pools and the spillway and west collection channels were underestimated (i.e., some lamprey likely passed through these areas and turned around upstream).

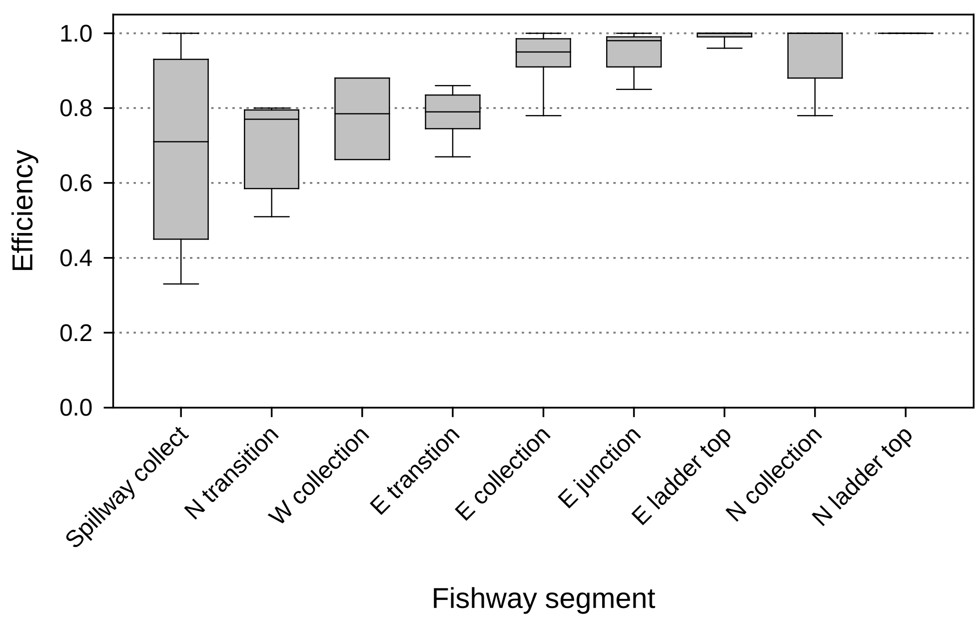


Figure 19. Annual **segment-specific fishway passage efficiency** estimates for unique fish (number of unique lamprey that passed a segment/number of unique lamprey detected in the segment) at The Dalles Dam. Estimates are ordered from lowest to highest median unique fish values. Box plots percentiles are: 25th, 50th, and 75th (boxes), and 10th and 90th (whiskers). Vertical lines are quartiles.

5.2.10 FISHWAY TURN-AROUND LOCATIONS

Across years a total of 645 fishway entry events resulted in exit to The Dalles Dam tailrace, also termed 'fishway fallout' (Table 5). Across years, 377 (58%) fallouts were from the east fishway and 268 (42%) were from the north fishway. Some lamprey turned around in each of the monitored fishway segments except the top of the north fishway (Figure 20). In both the east and north fishways, more turn-around events occurred in the transition pool segments than in the collection channel segments near the openings.

Dam-wide, three fishway segments accounted for 65% of all turn-around events across years. These were the north fishway transition pool (segment 8, *n* =**172** turn-arounds), the east fishway transition pool (segment 3, *n* = **149**), and the east fishway junction pool (segment 2, *n* = **96**).

CAVEAT: some turn-arounds assigned to the spillway collection channel (segment 5) and the west collection channel (segment 6) almost certainly occurred inside the main collection channels along the powerhouse. These longer channels were not monitored.

CAVEAT: some turn-arounds assigned to the transition pools (segments 3 & 8) almost certainly occurred in the main ladders further upstream. These ladders were not monitored.

Table 5. Numbers of fishway entry events (*n* = 1,114) recorded for radio-tagged Pacific lamprey and estimated turn-around locations inside fishways for those events that did not result in The Dalles Dam passage (*n* = 645), all years combined. See Figures 13 & 14 for fishway locations.

		Turn-around location									
	Entry	East fishway							North fishway		
	n	1	2	3	4	5	6		7	8	9
East	269	29	17	69	2						
West	173		12	31			79				
Spillway	101		5	15		47					
East-UNK	122	[1]21	15	34	1						
North	449								96	172	-
Total	**1114**	**50**	**49**	**149**	**3**	**47**	**79**		**96**	**172**	**-**
% of 645 (all)		**8%**	**8%**	**23%**	**<1%**	**7%**	**12%**		**15%**	**27%**	**-**
% of 377 (E)		**13%**	**13%**	**40%**	**1%**	**12%**	**21%**				
% of 268 (N)									**36%**	**64%**	**-**

[1] specific entry channel unknown

5.2.11 BOTTLENECK ASSESSMENT

Turn-around rate (number of turn-arounds at site / number of unique lamprey at site): lamprey turn-around rates were highest at west collection channel (segment 6, *rate* = **0.69** turn-arounds per unique fish), the north transition pool (segment 8, **0.67**), the spillway collection channel (segment 5, **0.56**), and the east transition pool (segment 3, **0.41**) (Fig 21a). Turn-around rates were intermediate at the east transition pool (segment 3, **0.41**), north collection channel (segment 7, **0.36**), east collection channel (segment 1, **0.23**), and east junction pool (segment 2, **0.13**). Turn-around rates were near zero at top-of-ladder segments.

Single-dam summaries

Additional passage attempts (additional passage attempt / turn-around event): lamprey that turned around at the top of the east fishway in the east transition pool were least likely to make additional dam passage attempts (Figure 21b). Rates were **0.00** for the three fish that turned near the top of the east fishway and **0.62** for those that turned in the east transition pool. All other sites had estimates between **0.82** and **0.94**.

Failure rate (number of unsuccessful final entries / number of unique lamprey at site): failure rates were highest for lamprey that turned around in the east transition pool (segment 3, **0.16** made no additional passage attempt), the north transition pool (segment 8, **0.12**), the west collection channel (segment 6, **0.11**), and spillway collection channel (segment 5, **0.08**) (Figure 21c). Failure rates were < **0.04** at the five other segments.

CAVEAT: the aforementioned monitoring gaps in powerhouse collection channels and ladders affect interpretation of all bottleneck metrics because turn-around locations were relatively imprecise (i.e., compared to Bonneville Dam).

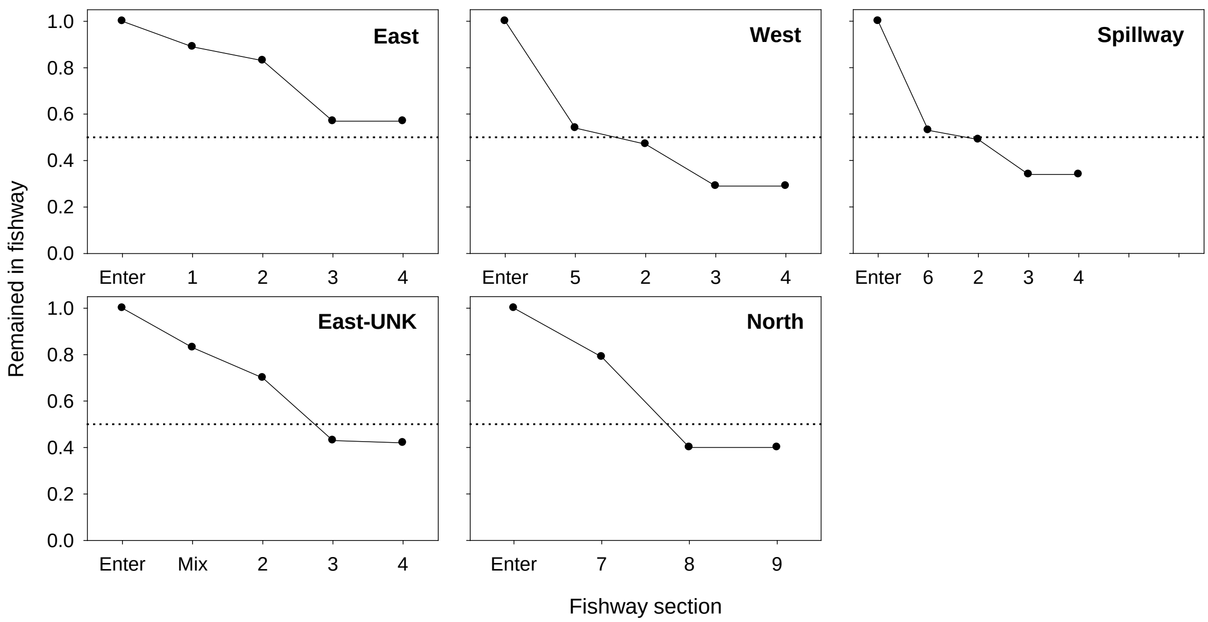


Figure 20. Route-specific relationships between fishway entrance location, fishway monitoring segment, and the proportion of radio-tagged adult Pacific lamprey that remained inside The Dalles Dam fishways. Panels represent the 5 fishway entrance routes. See Figures 13 and 14 for entrance locations and Table 5 for total sample sizes.

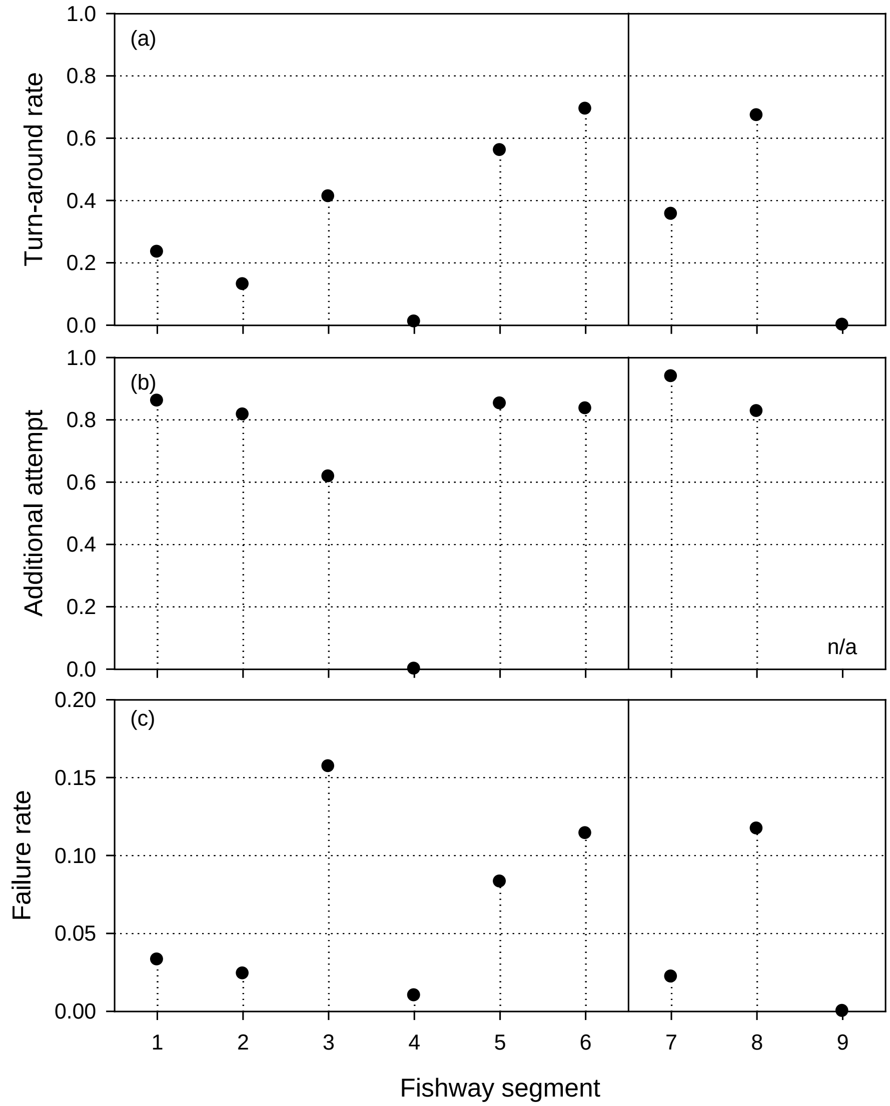


Figure 21. Fishway bottleneck metrics estimated for radio-tagged adult Pacific lamprey at 9 fishway segments at The Dalles Dam. Metrics include: (a) proportion of unique lamprey recorded at each segment that turned around and exited to the tailrace (number of turn-arounds / number of unique lamprey at site); (b) proportion of turn-around events that were followed by an additional dam passage attempt (additional attempt / turn-around event); and (c) proportion of unique lamprey that failed to make an additional dam passage attempt (number of unsuccessful final entries / number of unique lamprey at site). See Figures 13 & 14 for fishway segments.

5.2.12 PRIORITIZATION CONSIDERATIONS

The radiotelemetry data synthesis results for The Dalles Dam help identify potential sites where adult lamprey passage could be improved.

Fishway openings: Poor entrance efficiency was observed at the west powerhouse and spillway openings at The Dalles Dam. It is possible that some approach events at these sites are recorded when lamprey swim past the spillway or the powerhouse (i.e., the fish are not attempting to enter the fishways), but this behavior is difficult to differentiate from actual entrance attempts. Some 'swim-by' behavior may also occur at the main east fishway opening, and efficiency at this large opening was generally lower than at the north fishway, suggesting that there is room for improvement at this frequently approached site.

Fishway routes: Poor entrance efficiency at the west powerhouse and spillway openings appear to carry over to poor route-specific fishway passage efficiency for lamprey that enter the east fishway via these openings. Very little is known about where lamprey turn around inside the powerhouse collection channels at The Dalles Dam, as these routes were not monitored in any year.

Bottlenecks: Turn-arounds in the powerhouse collection channels were frequent, but a larger proportion of lamprey had difficulty passing the transition areas in both fishways and the entrance collection channel at the north fishway. Bottlenecks at these fishway segments may be of highest priority at The Dalles Dam. See Section 9.1.2 for prioritization models for bottleneck reductions at The Dalles Dam.

5.3 JOHN DAY DAM

5.3.1 NUMBERS OF RADIO-TAGGED LAMPREY

A total of 319 radio-tagged Pacific lamprey were detected at John Day Dam or in the John Day tailrace over ten years (1997-2002, 2007-2010). Annual sample sizes ranged from 1 to 74 (*median* = 37).

5.3.2 MONITORING EFFORT

Radiotelemetry monitoring occurred at John Day Dam (Figure 21) in all years, but the number of sites varied and overall effort was limited compared to Bonneville and The Dalles dams. Only top-of-ladder sites at John Day Dam were monitored in all years. The main fishway openings (north, south, north powerhouse) and both transition pools were monitored in 1997-1998 and 2000-2002, but not in 2007-2010. Other monitoring notes:

- the count stations were monitored in 1997 only, but only one lamprey was detected
- overflow weir sections of fish ladders from transition pools to ladder tops were not monitored
- orifice gates along the Powerhouse and powerhouse collection channel were not monitored

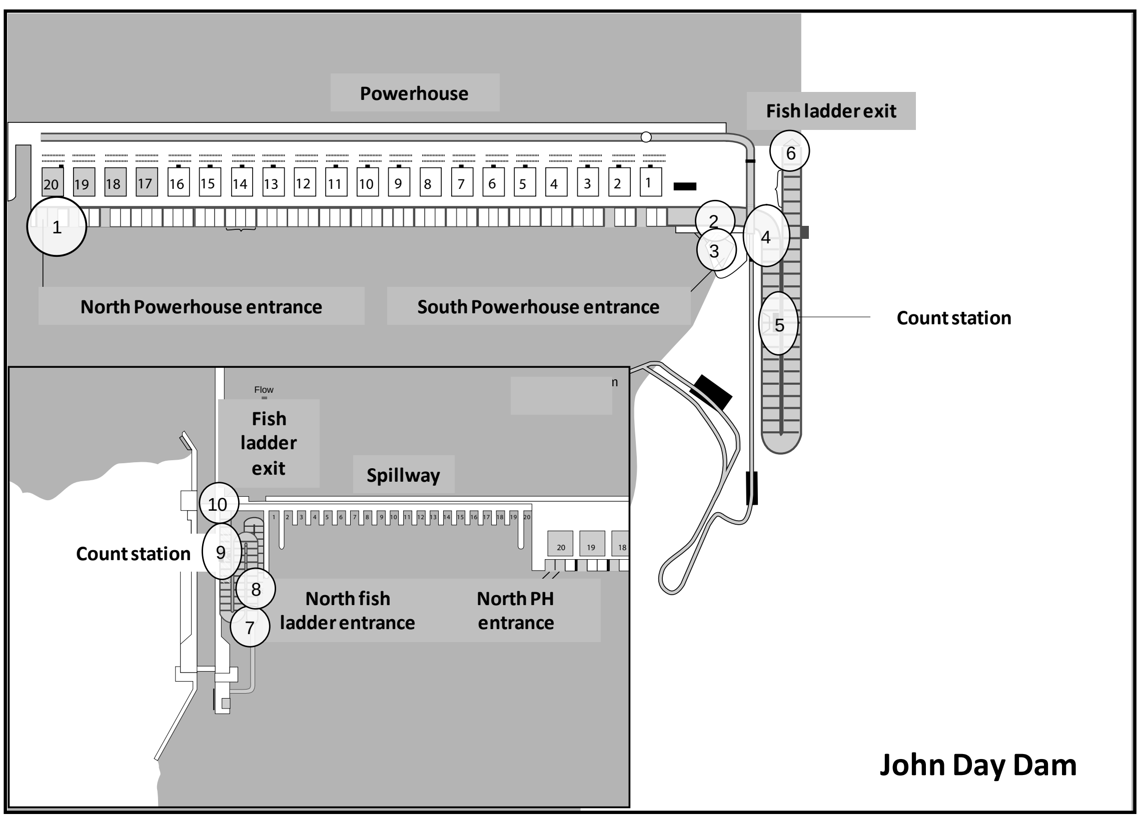


Figure 22. Map of the fishways at John Day Dam. Numbers indicate fishway segments monitored with radiotelemetry.

5.3.3 FISHWAY APPROACH SUMMARY

A total 204 unique radio-tagged lamprey approached monitored fishway openings a total of 889 times at John Day Dam for a combined total of 4.4 fishway approaches/lamprey. In years when multiple openings were monitored (1997-1998, 2000-2002), the distribution of first fishway approach sites averaged 70% at the main south opening, 10% at the north powerhouse opening, and 11% at the north opening (Figure 23); another 9% were at the south fishway, but exact locations were unknown. Distributions of total approach events were somewhat more evenly distributed among sites, though the main south opening was most approached.

CAVEAT: lamprey could approach orifice gates undetected in all years, resulting in underestimation of events and potential bias in their distribution.

CAVEAT: only the main south opening was monitored in 2009 and no openings were monitored in 1999, 2007-2008, and 2010.

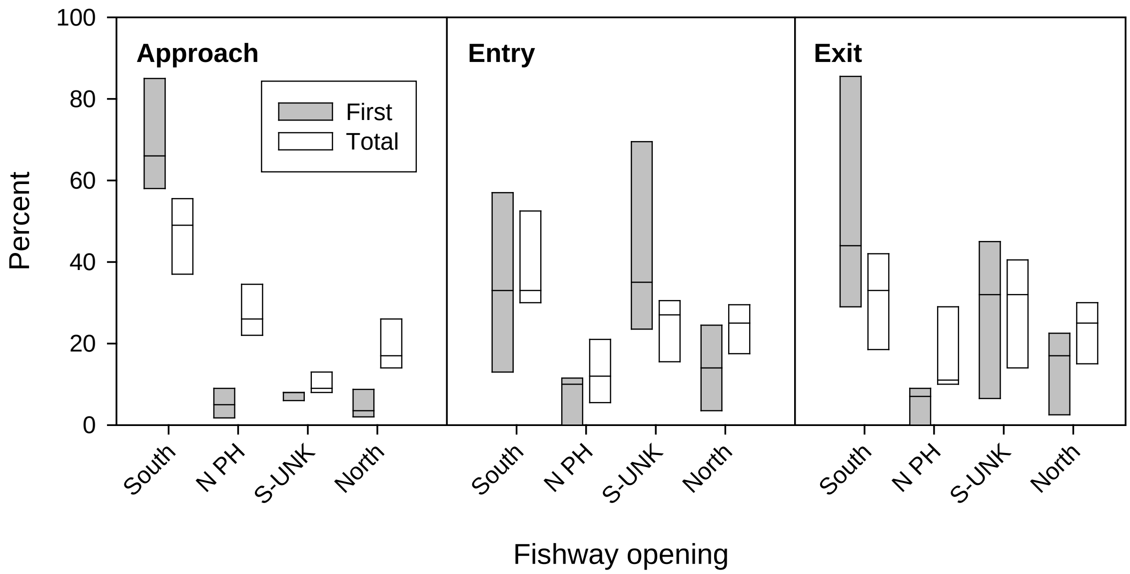


Figure 23. Distributions of annual estimates of radio-tagged Pacific lamprey fishway approach, entry, and exit locations at John Day Dam. See Fig, 22 for fishway sites. S-UNK indicates that event occurred at the south fishway, but the exact location was unknown or ambiguous. Box plots percentiles are: 25th, 50th, and 75th (boxes).

5.3.4 FISHWAY ENTRY SUMMARY

A total of 187 unique radio-tagged lamprey entered monitored fishway openings a total of 498 times at John Day Dam for a combined total of 2.7 fishway entries/lamprey. The distribution of first fishway entry sites averaged 35% at the south opening, 7% at the north powerhouse opening, and 14% at the north opening (Figure 23); another 4% were at the south fishway, but exact locations were unknown. Distributions of total entry events were broadly similar to first entries, though proportionally fewer were unassigned.

CAVEAT: lamprey could enter orifice gates undetected in all years.

CAVEAT: only the main south opening was monitored in 2009 and no openings were monitored in 1999, 2007-2008, and 2010.

5.3.5 FISHWAY EXIT SUMMARY

A total of 144 unique radio-tagged lamprey exited monitored fishway openings into the tailrace a total of 387 times at John Day Dam for a combined total of 2.7 fishway exits/lamprey. The distributions of first and total fishway exit sites were similar to those for fishway entries (Figure 23).

CAVEAT: as with fishway approaches and entries, there was considerable uncertainty regarding fishway exit locations due to limited monitoring at the south fishway.

5.3.6 DAM-WIDE PASSAGE EFFICIENCY METRICS

Fishway entrance efficiency (unique fish that entered / unique fish that approached): dam-wide fishway entrance efficiency ranged from 0.70 to 1.00 (*median* = **0.90**, *n* = 6 years, Figure 24). Median estimates for the three monitoring eras were **0.85** (1997-1998), **0.87** (2000-2002), and **0.90** (2009).

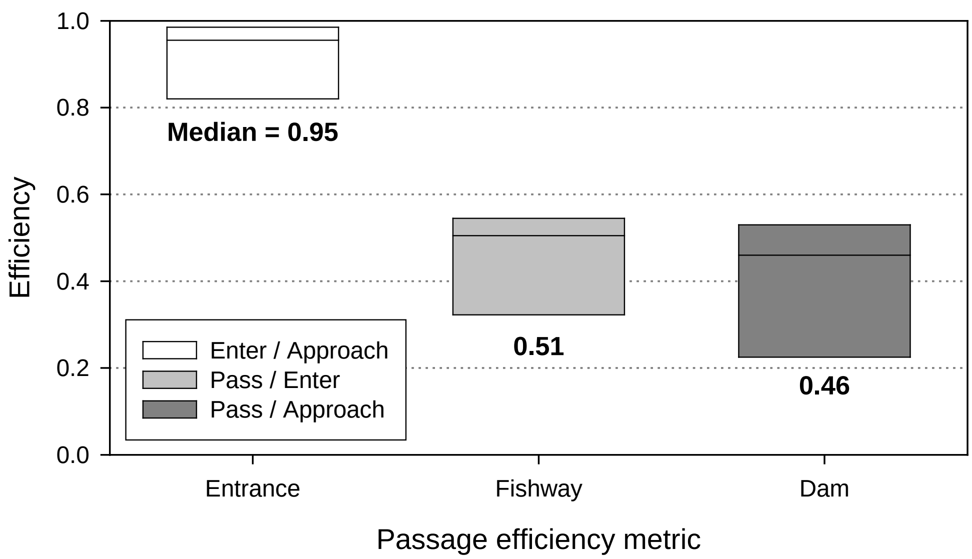


Figure 24. Distributions of annual dam-wide passage efficiency metrics estimated for radio-tagged Pacific lamprey at John Day Dam. Box plots percentiles are: 25th, 50th, and 75th (boxes).

Fishway passage efficiency (unique fish that passed / unique fish that entered): dam-wide fishway passage efficiency ranged from 0.00 to 0.56 (*median* = **0.51**, *n* = 6 years). Median estimates for the three monitoring eras were **0.22** (1997-1998), **0.52** (2000-2002), and **0.56** (2009).

Dam passage efficiency (unique fish that passed / unique fish that approached): dam-wide dam passage efficiency ranged from 0.00 to 0.53 (*median* = **0.46**, *n* = 6 years). Median estimates for the three monitoring eras were **0.15** (1997-1998), **0.49** (2000-2002), and **0.52** (2009).

CAVEAT: total sample sizes were ≤ 10 fish in 1997 and 1998.

CAVEAT: only the main south opening was monitored in 2009.

5.3.7 SITE-SPECIFIC FISHWAY ENTRANCE EFFICIENCY

Unique lamprey: unique lamprey entrance efficiency estimates at the three fishway openings monitored at John Day Dam were lowest at the north powerhouse opening (*median* = **0.50**, *n* = 5 years) and were higher at main south opening (**0.75**, *n* = 6) and north opening (**0.75**, *n* = 5) (Figure 25).

Total attempts: entrance efficiency estimates based on total approach and entry events was also lowest at the north powerhouse opening (*median* = **0.09**, *n* = 5 years). Median estimates were higher at the south (**0.58**, *n* = 6) and north (**0.60**, *n* = 5) openings.

CAVEAT: sample sizes were ≤ 10 in 1997 and 1998.

CAVEAT: only the main south opening was monitored in 2009.

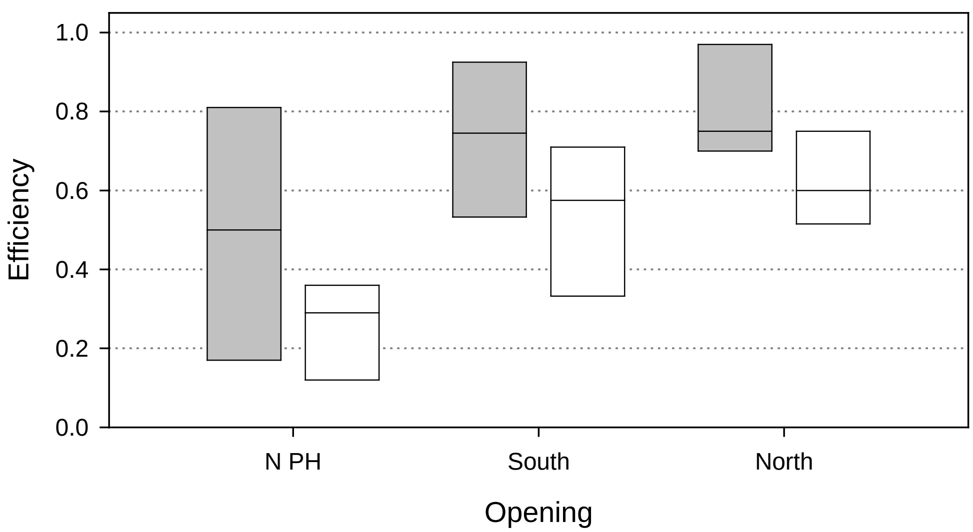


Figure 25. Annual **site-specific fishway entrance efficiency** estimates for unique fish (unique fish that entered fishway / unique fish that approached at each monitored fishway opening; gray boxes) and total events (total number of fishway entries / total number of fishway approaches; white boxes) at John Day Dam. Estimates are ordered from lowest to highest median unique fish values. Box plots percentiles are: 25th, 50th, and 75th (boxes).

5.3.8 ROUTE-SPECIFIC FISHWAY PASSAGE EFFICIENCY

Unique lamprey: unique-lamprey fishway passage efficiency varied among the four routes identified at John Day Dam and varied among years at each route (Figure 26). Efficiency was lowest for lamprey that entered at the north fishway opening (*median* = **0.19**, *n* = 4 years). Estimates were slightly higher at the north powerhouse opening (**0.33**, *n* = 9), the main south openings (**0.34**, *n* = 4), and for those that entered via unknown south fishway routes (**0.35**, *n* = 3).

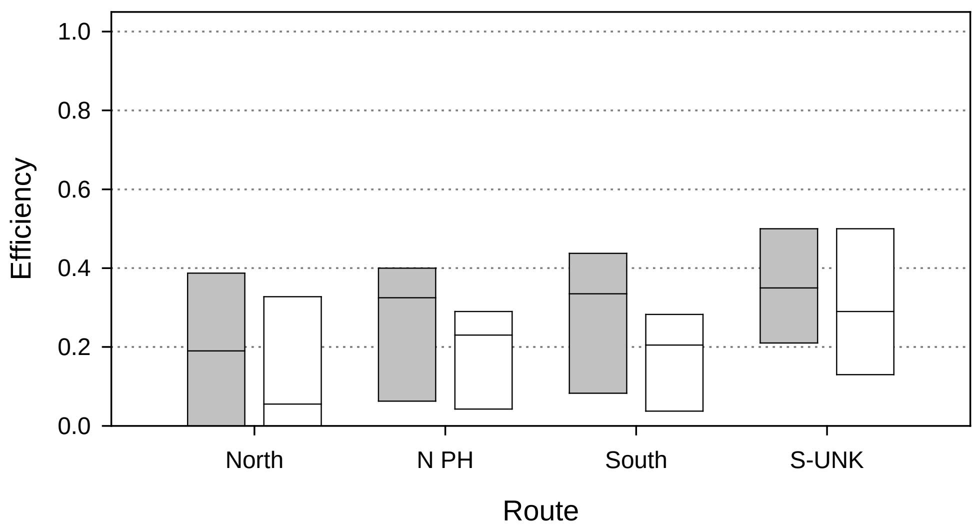


Figure 26. Annual **route-specific fishway passage efficiency** estimates for unique fish (unique fish that passed dam / unique fish that entered at each monitored fishway opening; gray boxes) and total events (total number of dam passages / total number of fishway entries; white boxes) at John Day Dam. Estimates are ordered from lowest to highest median unique fish values. S-UNK includes fishway entries where the specific opening used was unknown. Box plots percentiles are: 25th, 50th, and 75th (boxes).

Total attempts: fishway passage efficiency estimates based on total entry events was also lowest at the north fishway (*median* = **0.06**, *n* = 4 years), followed by the main south opening (**0.21**, *n* = 4), the north powerhouse opening (**0.23**, *n* = 4), and unknown south fishway (**0.29**, *n* = 3).

CAVEAT: in all years, some lamprey likely approached, entered, and exited orifice gates, resulting in overestimation of route passage efficiency.

CAVEAT: in 2009, north powerhouse and north fishway openings were not monitored.

5.3.9 FISHWAY SEGMENT PASSAGE EFFICIENCY

Unique lamprey passage efficiency was estimated for 8 fishway segments at John Day Dam (Figure 27). The lowest passage efficiency estimates were in the north fishway transition pool (*median* = **0.45**, *n* = 4 years) and the south transition pool (**0.50**, *n* = 5). Importantly, efficiency for these segments extended up the overflow-sections of the fish ladders, although individual antenna sites suggested that most fish turned in the transition pool. Segment efficiency estimates were similar in the main south powerhouse collection channel (**0.87**, n = 4) and north powerhouse collection channel (**0.94**, n = 4). Median values were **1.00** at both top-of-ladder segments. The median estimate was also **1.00** at the south end of the main collection channel, but estimating efficiency at this site was somewhat ambiguous. The count stations were monitored in 1997-1998 only, with very small samples ($n \leq 4$ fish per site).

CAVEAT: long segments of fishways at John Day Dam were unmonitored, including the collection channels between powerhouse fishway openings, and ladders from transition pools to near ladder tops. Therefore, efficiency estimates for transition pools and the powerhouse collection channel were underestimated (i.e., some lamprey likely passed through these areas and turned around upstream).

CAVEAT: estimates for the south end of the main collection channel were difficult to conclusively estimate.

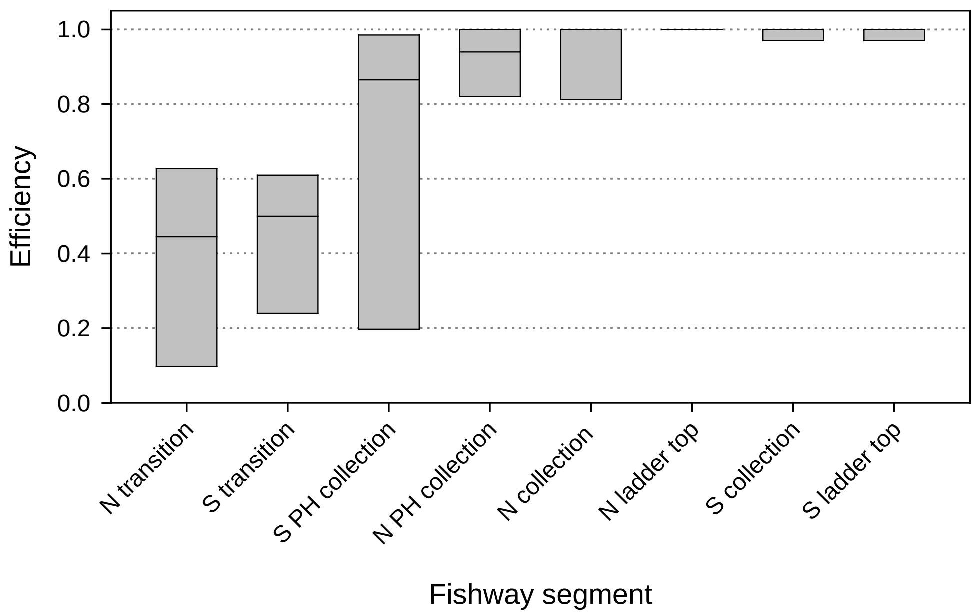


Figure 27. Annual **segment-specific fishway passage efficiency** estimates for unique fish (number of unique lamprey that passed a segment/number of unique lamprey detected in the segment) at John Day Dam. Estimates are ordered from lowest to highest median unique fish values. Box plots percentiles are: 25th, 50th, and 75th (boxes).

5.3.10 FISHWAY TURN-AROUND LOCATIONS

Across years a total of 315 fishway entry events resulted in exit to John Day Dam tailrace, also termed ‘fishway fallout’ (Table 6). Across years, 271 (86%) fallouts were from the south fishway and 44 (14%) were from the north fishway; note, however, that only the main south opening was monitored in 2009. Some lamprey turned around in each of the monitored fishway segments, including count station segments in the two years they were monitored (Figure 28). In both the south and north fishways, more turn-around events occurred in the transition pool segments than in the collection channel segments near the openings.

Dam-wide, three fishway segments accounted for 82% of all turn-around events across years. These were the south fishway transition pool (segment 4, *n* =**172** turn-arounds), the south end of the powerhouse collection channel (segment 3, *n* = **57**), and the north fishway transition pool (segment 8, *n* = **28**).

CAVEAT: some turn-arounds assigned to the north powerhouse collection channel (segment 1) almost certainly occurred inside the unmonitored main collection channel along the powerhouse.

CAVEAT: some turn-arounds assigned to the transition pools (segments 4 & 8) almost certainly occurred in the main ladders further upstream. Except for top-of-ladder sites and count stations (1997-1998), these ladders were not monitored.

Table 6. Numbers of fishway entry events (*n* = 417) recorded for radio-tagged Pacific lamprey and estimated turn-around locations inside fishways for those events that did not result in John Day Dam passage (*n* = 315 total, 271 south fishway, 44 north fishway), all years combined. See Figure 22 for fishway locations.

	Entry	Turn-around location									
		South fishway						North fishway			
	n	1	2	3	4	[1]5	6	7	8	[1]9	10
South	191		4	57	88		1				
N PH	49	11	6		21	1					
South-UNK	122		20		63						
North	55							13	28	2	1
Total	**417**	**11**	**30**	**57**	**172**	**1**	**1**	**13**	**28**	**2**	1
% of 315 (all)		**3%**	**10%**	**18%**	**55%**	**<1%**	**<1%**	**4%**	**9%**	**1%**	<1%
% of 271 (S)		**4%**	**11%**	**21%**	**63%**	**<1%**	**<1%**				
% of 44 (N)								**30%**	**64%**	**5%**	**2%**

[1] count stations monitored in 1997-1998 only

5.3.11 BOTTLENECK ASSESSMENT

Turn-around rate (number of turn-arounds at site / number of unique lamprey at site): lamprey turn-around rates were highest at the south fishway transition pool (segment 4, *rate* = **1.35** turn-arounds per unique fish), the north transition pool (segment 8, **1.00**), and the south end of the main powerhouse collection channel (segment 2, **0.63**) (Fig 28a). Turn-around rates were intermediate at the north fishway collection channel (segment 7, **0.43**) and the north end of the powerhouse collection channel (segment 1, **0.37**). Some lamprey turned around near count stations (limited monitoring effort) and top-of-ladder segments (*rates* ≤ **0.17**).

Additional passage attempts (additional passage attempt / turn-around event): in general, lamprey that turned around in collection channels were more likely to make additional dam passage attempts than those that turned around in transition pools or at sites further up the fishways (Figure 28b). Rates were **0.64-0.74** for fish that turned near in transition pools and were ≥ **0.84** for those that turned around at lower elevation sites.

Single-dam summaries

Failure rate (number of unsuccessful final entries / number of unique lamprey at site): failure rates were highest for lamprey that turned around in the north transition pool (segment 8, **0.36** made no additional passage attempt) and the south transition pool (segment 4, **0.35** (Figure 28c). Failure rates were < **0.10** at the eight other segments.

CAVEAT: the aforementioned monitoring gaps in the powerhouse collection channel and ladders affect interpretation of all bottleneck metrics because turn-around locations were relatively imprecise (i.e., compared to Bonneville Dam).

CAVEAT: estimates for the south end of the main collection channel were difficult to conclusively estimate.

CAVEAT: some turn-arounds occurred near count stations when they were monitored (1997-1998 only); lack of monitoring in subsequent years suggests bottleneck metrics may have been underestimated for these segments.

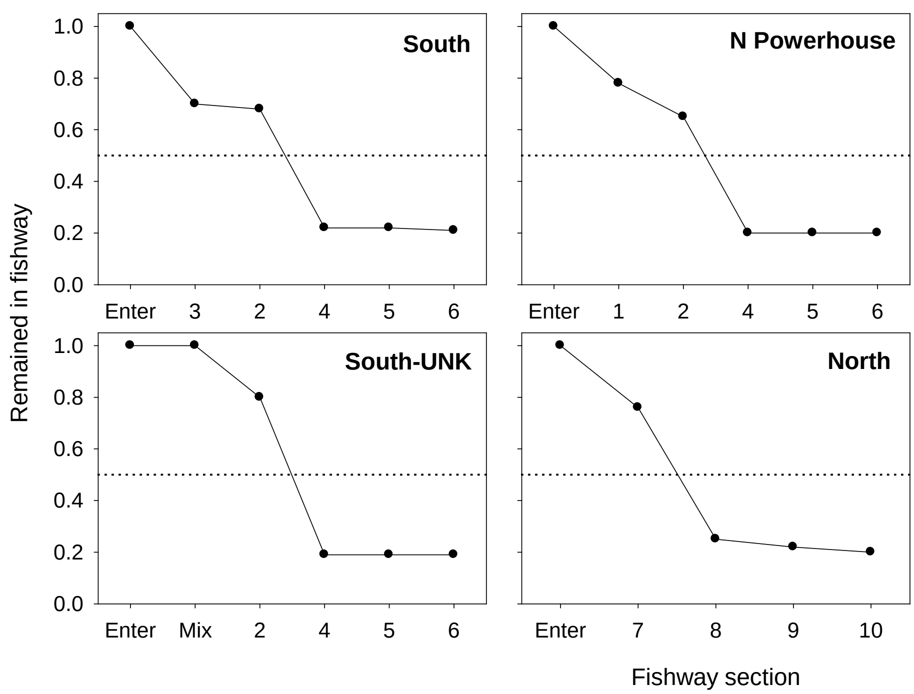


Figure 28. Route-specific relationships between fishway entrance location, fishway monitoring segment, and the proportion of radio-tagged adult Pacific lamprey that remained inside the John Day Dam fishways. Panels represent the 4 fishway entrance routes. See Figure 22 for entrance locations and Table 6 for total sample sizes.

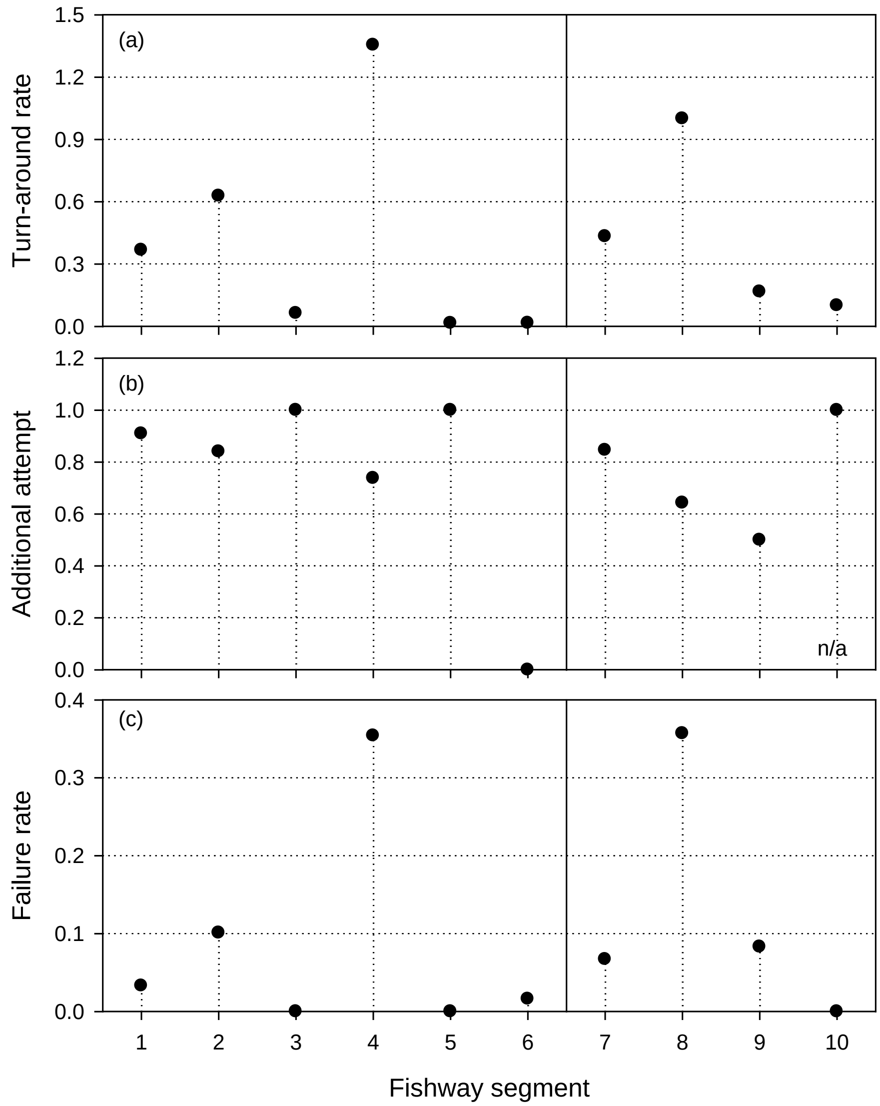


Figure 29. Fishway bottleneck metrics estimated for radio-tagged adult Pacific lamprey at 9 fishway segments at John Day Dam. Metrics include: (a) proportion of unique lamprey recorded at each segment that turned around and exited to the tailrace (number of turn-arounds / number of unique lamprey at site); (b) proportion of turn-around events that were followed by an additional dam passage attempt (additional attempt / turn-around event); and (c) proportion of unique lamprey that failed to make an additional dam passage attempt (number of unsuccessful final entries / number of unique lamprey at site). See Figure 22 for fishway segments.

5.3.12 PRIORITIZATION CONSIDERATIONS

Lamprey passage efficiency metrics at John Day Dam were among the lowest recorded at the study dams. They were most similar to results at Bonneville Dam, although lamprey encountered more favorable passage conditions – in terms of discharge and water temperature – at John Day Dam. Monitoring effort was relatively low at John Day Dam, and sample sizes were small. Nonetheless, the radiotelemetry data synthesis results do help identify potential sites where adult lamprey passage could be improved.

Fishway openings: The lowest entrance efficiency at John Day Dam was estimated at the north powerhouse opening. It is possible that some approach events at this site were recorded when lamprey swam past the powerhouse. It is unknown whether lamprey use the orifice gate openings to enter the fishway.

Fishway routes: Lamprey that entered the north fishway and those that entered via the north powerhouse had low fishway passage success. The very low route efficiency via the north fishway was somewhat surprising given the much higher efficiency at the similarly-configured north fishway at The Dalles Dam. As objective of the 2012 DIDSON monitoring in the north entrance collection channel and transition area is to identify mechanisms of lamprey passage failure in these segments.

As at The Dalles Dam, very little is known about where lamprey turn around inside the powerhouse collection channel at John Day Dam, but mechanisms may be similar at both sites.

Bottlenecks: Far more lamprey use the south fishway than the north fishway at John Day Dam. Consequently, bottlenecks in the south fishway affect more fish and may warrant higher priority. Passage segment efficiency and turn-around metrics were highest in the south transition pool area; lamprey performance was also poor in the north transition area. Importantly, there was very limited monitoring in the overflow weir sections at John Day Dam and it is possible that there are unidentified ladder sections that are challenging for lamprey. See Section 9.1.3 for prioritization models for bottleneck reductions at John Day Dam.

5.4 MCNARY DAM

5.4.1 NUMBERS OF RADIO-TAGGED LAMPREY

Bonneville sample: A total of 56 Pacific lamprey tagged at Bonneville Dam were detected at McNary Dam or in the McNary tailrace in six of the ten Bonneville study years (2000-2002, 2008-2010). Annual sample sizes ranged from 5 to 13 (*median* = 10). None of the lamprey tagged at Bonneville Dam in 1997-1999 or 2007 were detected at McNary Dam.

McNary sample: A total of 276 adult Pacific lamprey were collected and radio-tagged at McNary Dam and were released downstream from both sides of the river over six years (2005-2010) (Table 2).

5.4.2 MONITORING EFFORT

Radiotelemetry monitoring occurred at McNary Dam and the sites were relatively consistent across years (Figure 30). Year-to-year monitoring differences included:

- orifice gate openings were monitored in 1997-1999, but no lamprey were present
- overflow weir sections of fish ladders from transition pools to ladder tops were not monitored
- antenna configurations near the top of the south fishway changed slightly among years, with antennas added above the count station in later study years

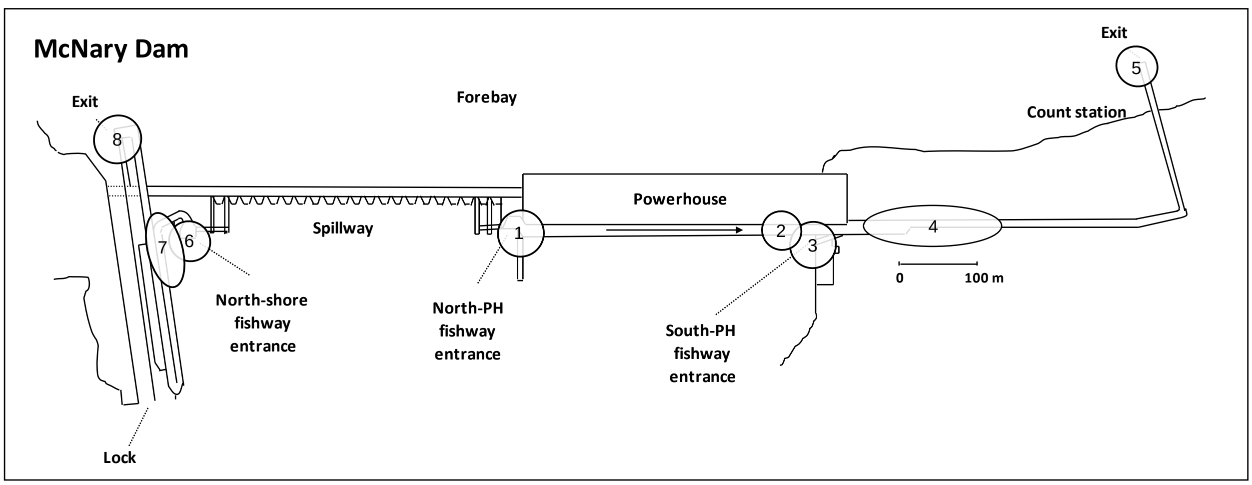


Figure 30. Map of the fishways at McNary Dam. .Numbers indicate fishway segments monitored with radiotelemetry.

5.4.3 FISHWAY APPROACH SUMMARY

Bonneville sample: A total of 53 unique Bonneville-tagged lamprey approached monitored fishway openings a total of 111 times at McNary Dam for a combined total of 2.1 fishway approaches/lamprey. The distribution of first fishway approach sites averaged 42% at the main south opening, 29% at the north powerhouse opening, and 11% at the north opening (Figure

31a); another 18% were at the south fishway, but exact locations were unknown. Distributions of total approach events were similar.

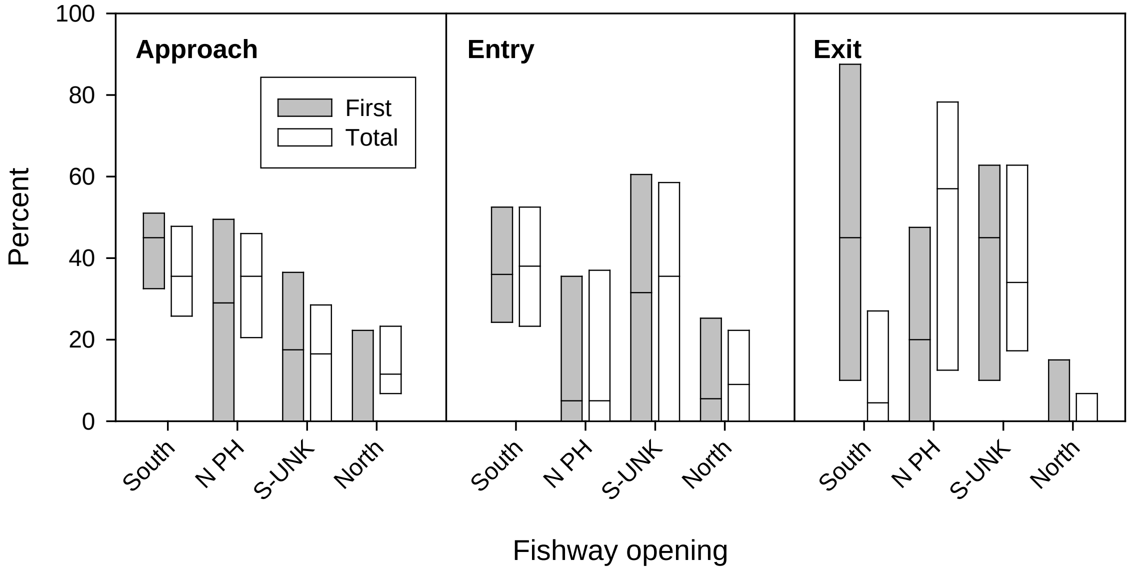


Figure 31a. Distributions of annual estimates of radio-tagged Pacific lamprey fishway approach, entry, and exit locations at McNary Dam. See Figure 30 for fishway sites. S-UNK indicates that event occurred at the south fishway, but the exact location was unknown or ambiguous. Box plots percentiles are: 25th, 50th, and 75th (boxes). Note: fish tagged at Bonneville Dam.

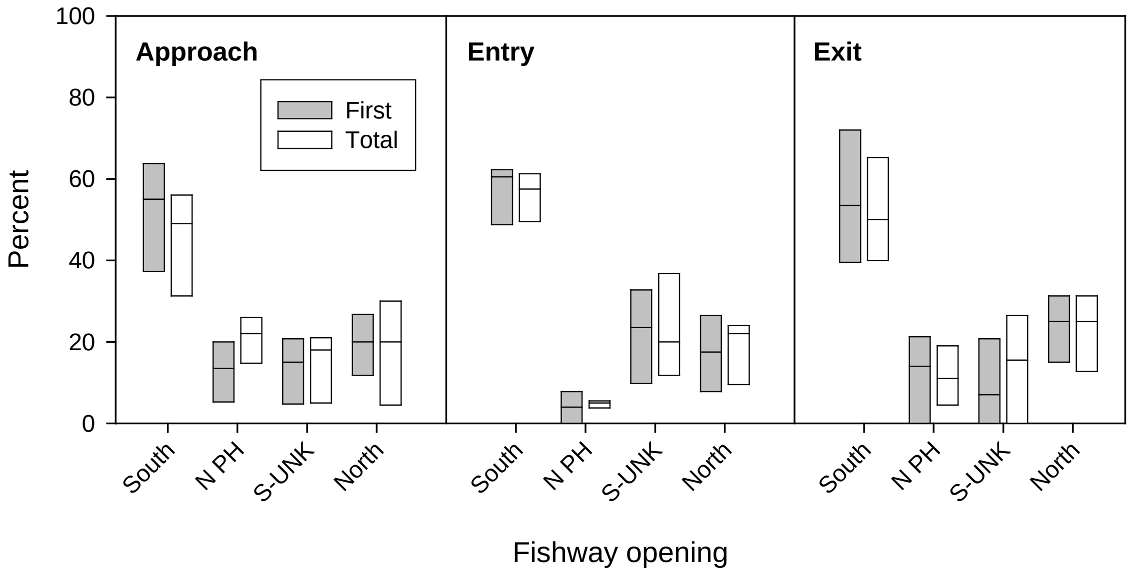


Figure 31b. Distributions of annual estimates of radio-tagged Pacific lamprey fishway approach, entry, and exit locations at McNary Dam. See Figure 30 for fishway sites. S-UNK indicates that event occurred at the south fishway, but the exact location was unknown or ambiguous. Box plots percentiles are: 25th, 50th, and 75th (boxes). Note: fish tagged at McNary Dam.

McNary sample: A total of 128 unique McNary-tagged lamprey approached monitored fishway openings a total of 165 times at McNary Dam for a combined total of 1.3 fishway approaches/lamprey. The distribution of first fishway approach sites averaged 56% at the main south opening, 4% at the north powerhouse opening, and 17% at the north opening (Figure 31b); another 22% were at the south fishway, but exact locations were unknown. Distributions of total approach events were similar.

CAVEAT: lamprey could approach orifice gates undetected in all years, resulting in underestimation of events and potential bias in their distribution.

CAVEAT: samples sizes were small for Bonneville-tagged lamprey in most years.

CAVEAT: release sites for McNary-tagged lamprey were ~1 km downstream from the dam, which may have affected the distribution of lamprey fishway approaches, entries, and exits.

5.4.4 FISHWAY ENTRY SUMMARY

Bonneville sample: A total of 47 unique Bonneville-tagged lamprey entered monitored fishway openings a total of 62 times at McNary Dam for a combined total of 1.3 fishway entries/lamprey. The distribution of first fishway entry sites averaged 38% at the south opening, 17% at the north powerhouse opening, and 13% at the north opening (Figure 31a); another 32% were at the south fishway, but exact locations were unknown. Distributions of total entry events were very similar to first entries.

McNary sample: A total of 128 unique McNary-tagged lamprey entered monitored fishway openings a total of 165 times at McNary Dam for a combined total of 1.3 fishway entries/lamprey. Compared to the Bonneville-tagged group, more McNary-tagged lamprey entered the south opening, with a mean of 55-56% of first and total fishway entries (Figure 31b).

CAVEAT: lamprey could enter orifice gates undetected in all years and many of the unknown entries presumably were through these openings.

CAVEAT: samples sizes were small for Bonneville-tagged lamprey in most years.

5.4.5 FISHWAY EXIT SUMMARY

Bonneville sample: A total of 13 unique Bonneville-tagged lamprey exited monitored fishway openings into the tailrace a total of 22 times at McNary Dam for a combined total of 1.7 fishway exits/lamprey. The distributions of first and total fishway exit sites were quite variable among years, reflecting the small sample sizes (Figure 31a).

McNary sample: A total of 40 unique McNary-tagged lamprey exited monitored fishway openings into the tailrace a total of 54 times at McNary Dam for a combined total of 1.4 fishway exits/lamprey. The distributions of first and total fishway exit sites were similar to those for fishway entries (Figure 31b).

5.4.6 DAM-WIDE PASSAGE EFFICIENCY METRICS

Fishway entrance efficiency (unique fish that entered / unique fish that approached)

Bonneville sample: dam-wide fishway entrance efficiency ranged from 0.64 to 1.00 (*median* = **0.96**, *n* = 6 years, Figure 32).

McNary sample: dam-wide fishway entrance efficiency ranged from 0.71 to 1.00 (*median* = **0.80**, *n* = 6 years, Figure 32).

CAVEAT: Bonneville sample sizes were ≤ 13 in all years.

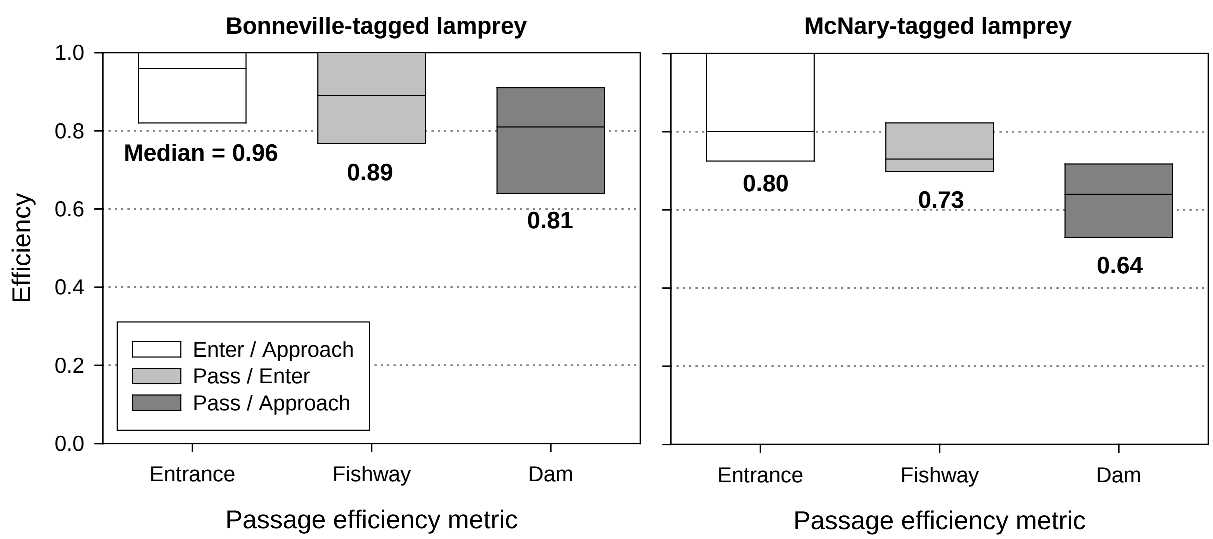


Figure 32. Distributions of annual dam-wide passage efficiency metrics estimated for radio-tagged Pacific lamprey at McNary Dam. Box plots percentiles are: 25th, 50th, and 75th (boxes). Two panels are for lamprey tagged at Bonneville Dam or McNary Dam.

Fishway passage efficiency (unique fish that passed / unique fish that entered)

Bonneville sample: dam-wide fishway passage efficiency ranged from 0.67 to 1.00 (*median* = **0.89**, *n* = 6 years).

Dam passage efficiency (unique fish that passed / unique fish that approached): dam-wide dam passage efficiency ranged from 0.69 to 0.89 (*median* = **0.73**, *n* = 6 years).

CAVEAT: Bonneville sample sizes were ≤ 12 in all years.

Dam passage efficiency (unique fish that passed / unique fish that approached)

Bonneville sample: dam-wide dam passage efficiency ranged from 0.55 to 1.00 (*median* = **0.81**, *n* = 6 years).

McNary sample: dam-wide dam passage efficiency ranged from 0.54 to 0.80 (*median* = **0.64**, *n* = 6 years).

CAVEAT: Bonneville sample sizes were ≤ 13 in all years.

5.4.7 SITE-SPECIFIC FISHWAY ENTRANCE EFFICIENCY

Bonneville sample:

Unique lamprey: unique lamprey entrance efficiency estimates at the three fishway openings monitored at McNary Dam were lowest at the north powerhouse opening (*median* = **0.13**, *n* = 6 years) and were higher at north fishway opening (**0.59**, *n* = 6) and south fishway opening (**0.75**, *n* = 6) (Figure 33).

Total attempts: entrance efficiency estimates based on total approach and entry events were also lowest at the north powerhouse opening (*median* = **0.13**, *n* = 6 years). Median estimates were higher at the south (**0.25**, *n* = 6) and north (**0.50**, *n* = 6) openings.

McNary sample:

Unique lamprey: unique lamprey entrance efficiency estimates at the three fishway openings monitored at McNary Dam were lowest at the north powerhouse opening (*median* = **0.15**, *n* = 6 years) and were higher at the north fishway opening (**0.57**, *n* = 6) and south opening (**0.76**, *n* = 6) (Figure 33).

Total attempts: entrance efficiency estimates based on total approach and entry events was also lowest at the north powerhouse opening (*median* = **0.10**, *n* = 6 years). Median estimates were higher at the north (**0.42**, *n* = 6) and south (**0.58**, *n* = 6) openings.

CAVEAT: Bonneville sample sizes were ≤ 9 unique fish and ≤ 20 approach events per opening in all years.

CAVEAT: orifice gate openings were unmonitored in all years.

5.4.8 ROUTE-SPECIFIC FISHWAY PASSAGE EFFICIENCY

Bonneville sample:

Unique lamprey: unique-lamprey fishway passage efficiency varied among the four routes identified at McNary Dam and varied among years at each route (Figure 34). Efficiency was lowest for lamprey that entered at the north powerhouse opening (*median* = **0.33**, *n* = 3 years). Estimates were higher at the north fishway opening (**0.75**, *n* = 4), the main south fishway opening (**1.00**, *n* = 6), and for those that entered via unknown south fishway routes (**0.84**, *n* = 4).

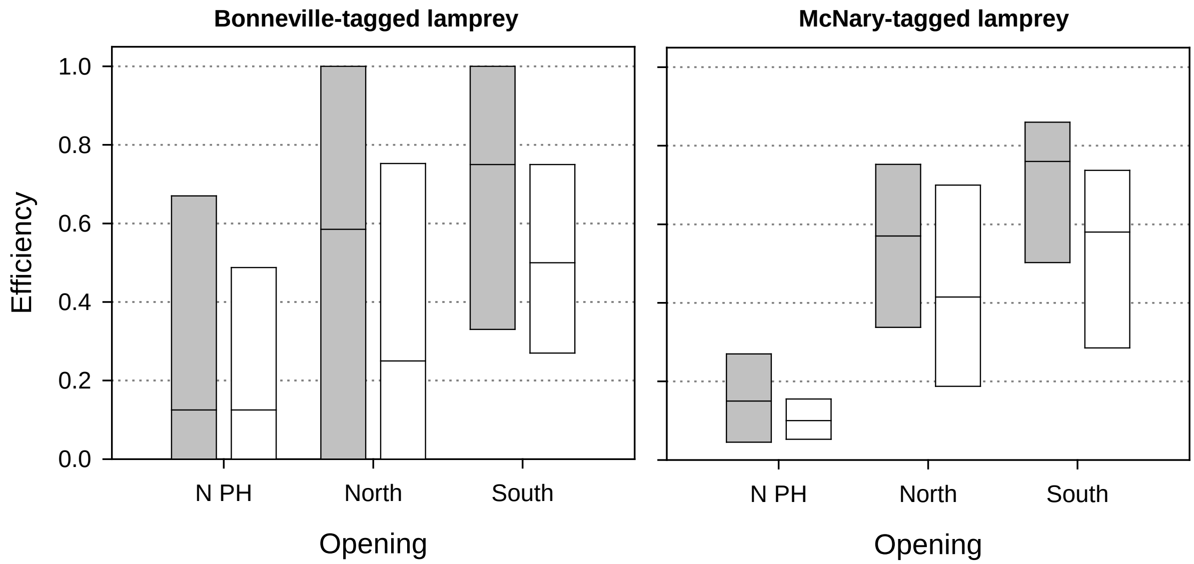


Figure 33. Annual **site-specific fishway entrance efficiency** estimates for unique fish (unique fish that entered fishway / unique fish that approached at each monitored fishway opening; gray boxes) and total events (total number of fishway entries / total number of fishway approaches; white boxes) at McNary Dam. Estimates are ordered from lowest to highest median unique fish values. Box plots percentiles are: 25th, 50th, and 75th (boxes). Two panels are for lamprey tagged at Bonneville Dam or McNary Dam.

Total attempts: fishway passage efficiency estimates based on total entry events was also lowest for the north powerhouse route (*median* = **0.18**, *n* = 3 years), followed by the north fishway route (**0.25**, *n* = 4), unknown south fishway (**0.64**, *n* = 4), and the main south fishway opening (**1.00**, *n* = 6).

McNary sample:

Unique lamprey: unique-lamprey fishway passage efficiency varied among the four routes identified at McNary Dam and varied among years at each route (Figure 34). Efficiency was lowest for lamprey that entered at the north powerhouse opening (*median* = **0.00**, *n* = 5 years). Estimates were considerably higher at the north fishway opening (**0.66**, *n* = 6), for those that entered via unknown south fishway routes (**0.71**, *n* = 6), and for those that entered the main south opening (**0.74**, *n* = 6).

Total attempts: fishway passage efficiency estimates based on total entry events was also lowest for those that entered the north powerhouse opening (*median* = **0.00**, *n* = 5 years). Estimates were **0.64**-**0.68** for the other three routes (all *n* = 6).

CAVEAT: Bonneville sample sizes were ≤ 6 unique fish and ≤ 11 fishway entry events per route in all years.

CAVEAT: in all years, some lamprey likely approached, entered, and exited orifice gates, resulting in overestimation of route passage efficiency.

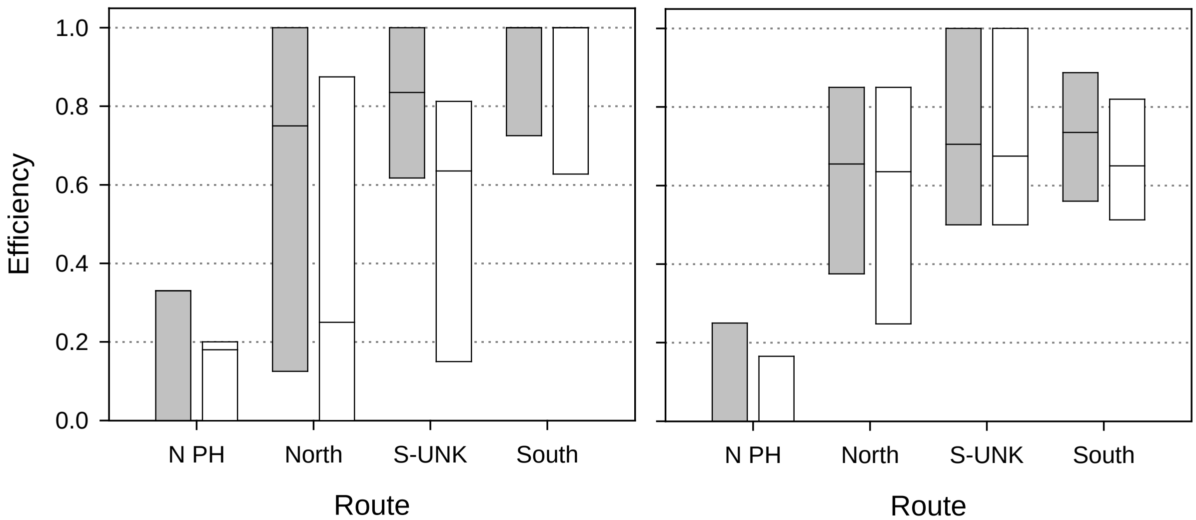


Figure 34. Annual **route-specific fishway passage efficiency** estimates for unique fish (unique fish that passed dam / unique fish that entered at each monitored fishway opening; gray boxes) and total events (total number of dam passages / total number of fishway entries; white boxes) at McNary Dam. Estimates are ordered from lowest to highest median unique fish values. S-UNK includes fishway entries where the specific opening used was unknown. Box plots percentiles are: 25th, 50th, and 75th (boxes). Two panels are for lamprey tagged at Bonneville Dam or McNary Dam.

5.4.9 FISHWAY SEGMENT PASSAGE EFFICIENCY

Bonneville sample: Unique lamprey passage efficiency was estimated for 8 fishway segments at McNary Dam (Figure 35). Annual variability was quite high and samples of Bonneville-tagged lamprey were very small (Figure 35). The lowest passage efficiency estimates were in the north powerhouse collection channel (segment 1, *median* = **0.46**, *n* = 4 years) and the south transition pool (segment 4, **0.95**, *n* = 6). Importantly, efficiency for these segments extended up the main powerhouse collection channel and the overflow-sections of the south fish ladder. Median segment efficiency estimates were **1.00** in all other fishway segments.

McNary sample: The lowest segment passage efficiency estimates for McNary-tagged fish were in the north powerhouse collection channel (segment 1, *median* = **0.34**, *n* = 6 years) and the entry collection channel of the north fishway (segment 6, **0.74**, *n* = 6). Segment efficiency estimates were **0.87**-**0.94** in the entry collection channel of the south powerhouse (segment 3), the south transition pool (segment 4), and the south top-of-ladder segment (segment 5). Median segment efficiency estimates were **1.00** in all other fishway segments.

CAVEAT: long segments of fishways at McNary Dam were unmonitored, including the main powerhouse collection channel and ladders from transition pools to near ladder tops. Therefore, efficiency estimates for transition pools and the powerhouse collection channel were underestimated.

CAVEAT: Bonneville sample sizes were ≤ 10 unique fish per segment in all years.

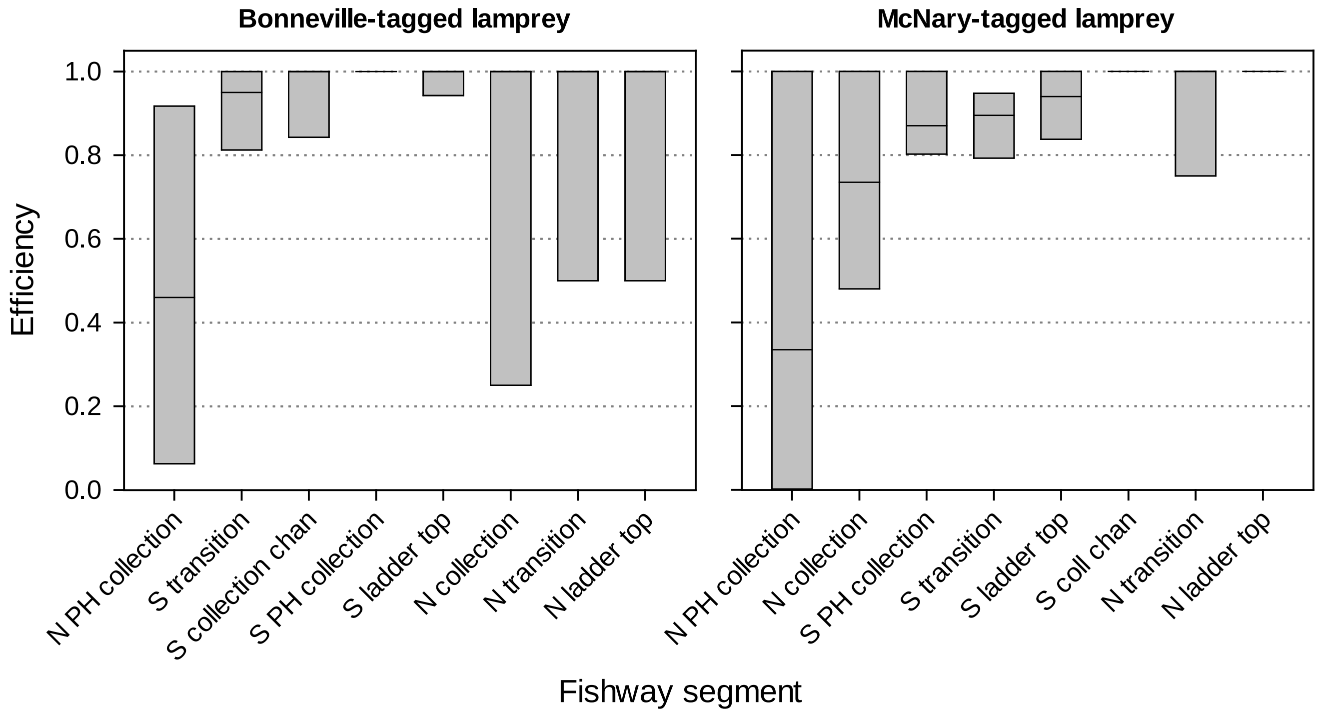


Figure 35. Annual **segment-specific fishway passage efficiency** estimates for unique fish (number of unique lamprey that passed a segment/number of unique lamprey detected in the segment) at McNary Dam. Estimates are ordered from lowest to highest median unique fish values. Box plots percentiles are: 25th, 50th, and 75th (boxes). Two panels are for lamprey tagged at Bonneville Dam or McNary Dam.

5.4.10 FISHWAY TURN-AROUND LOCATIONS

Bonneville sample:

Across years a total of 23 fishway entry events by Bonneville-tagged lamprey resulted in exit to the McNary Dam tailrace (Table 7a). Across years, 21 (91%) fallouts were from the south fishway and 2 (9%) were from the north fishway. Dam-wide, 65% of all turn-around events were assigned to the north powerhouse collection channel segment (which likely included turn-arounds in the main powerhouse collection channel), 13% were in the south transition pool, and 9% were in the upper south ladder.

McNary sample:

Across years a total of 58 fishway entry events by McNary-tagged lamprey resulted in exit to the McNary Dam tailrace (Table 7b). Across years, 45 (78%) fallouts were from the south fishway and 13 (22%) were from the north fishway. In both the south and north fishways, most turn-around events occurred in the entry collection channel and transition pool segments (Figure 36).

Single-dam summaries

Dam-wide, three fishway segments accounted for 81% of all turn-around events across years. These were the south fishway transition pool (segment 4, *n* =**19** turn-arounds), the entry channel at the south end of the powerhouse (segment 3, *n* = **17**), and the entry channel at the north fishway (segment 6, *n* = **11**).

CAVEAT: some turn-arounds assigned to the north powerhouse collection channel (segment 1) almost certainly occurred inside the unmonitored main collection channel along the powerhouse.

CAVEAT: some turn-arounds assigned to the south transition pool (segment 4) almost certainly occurred in the main ladder further upstream.

Table 7a. Numbers of fishway entry events (*n* = 62) recorded for Bonneville-tagged Pacific lamprey and estimated turn-around locations inside fishways for those events that did not result in McNary Dam passage (*n* = 23 total, 21 south fishway, 2 north fishway), all years combined. See Figure 30 for fishway locations.

		Turn-around location							
	Entry	South fishway					North fishway		
	n	1	2	3	4	5	6	7	8
South	21			1	1	1			
N PH	17	13			1				
South-UNK	19	2			1	1			
North	5						1	1	
Total	**62**	**15**	**-**	**1**	**3**	**2**	**1**	**1**	**-**
% of 23 (all)		**65%**	**-**	**4%**	**13%**	**9%**	**4%**	**4%**	
% of 21(S)		**71%**	**-**	**5%**	**14%**	**10%**			
% of 2 (N)							**50%**	**50%**	

Table 7b. Numbers of fishway entry events (*n* = 164) recorded for McNary-tagged Pacific lamprey and estimated turn-around locations inside fishways for those events that did not result in McNary Dam passage (*n* = 58 total, 45 south fishway, 13 north fishway), all years combined. See Figure 30 for fishway locations.

		Turn-around location							
	Entry	South fishway					North fishway		
	n	1	2	3	4	5	6	7	8
South	81			14	12	2			
N PH	7	2			4				
South-UNK	44	4		3	3	1			
North	32						11	2	-
Total	**164**	**6**	**-**	**17**	**19**	**3**	**11**	**2**	**-**
% of 58 (all)		**10%**	**-**	**29%**	**33%**	**5%**	**19%**	**3%**	
% of 45 (S)		**13%**	**-**	**38%**	**42%**	**7%**			
% of 13 (N)							**85%**	**15%**	

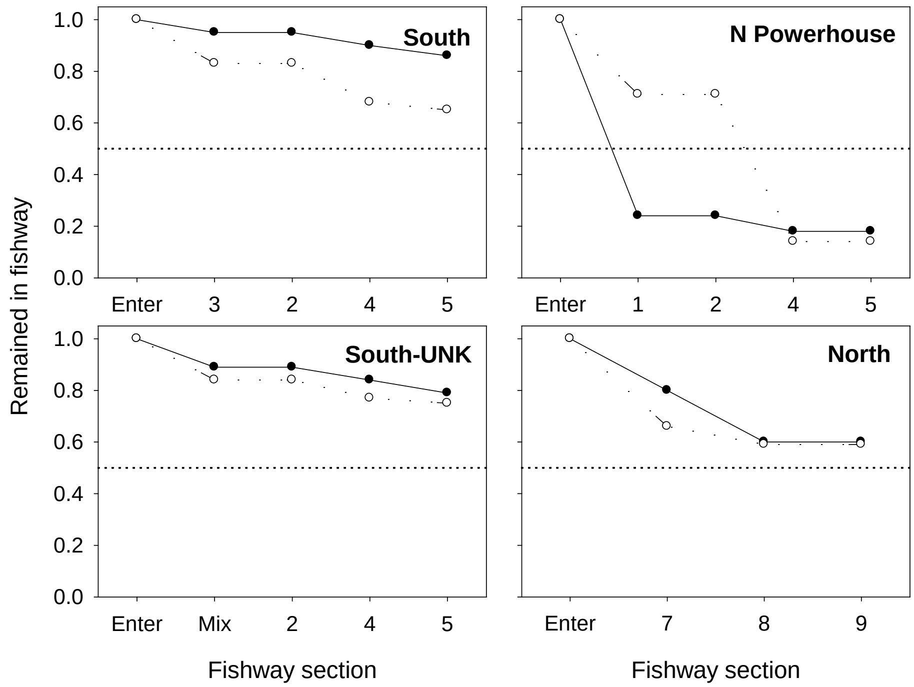


Figure 36. Route-specific relationships between fishway entrance location, fishway monitoring segment, and the proportion of radio-tagged adult Pacific lamprey that remained inside the McNary Dam fishways. Symbols represent different lamprey samples: (●) = Bonneville-tagged lamprey; (○) = McNary-tagged lamprey. Panels represent the 4 fishway entrance routes. See Figure 30 for entrance locations and Tables 7a and 7b for total sample sizes.

5.4.11 BOTTLENECK ASSESSMENT

Bonneville sample:

Turn-around rate (number of turn-arounds at site / number of unique lamprey at site): lamprey turn-around rates were highest at the north powerhouse collection area (segment 1, *rate* = **1.25** turn-arounds per unique fish), the north transition pool (segment 7, **0.25**), and the north fishway collection area (segment 6, **0.20**) (Fig 37a). Turn-around rates were ≤ **0.07** at all other sites.

Additional passage attempts (additional passage attempt / turn-around event): in general, lamprey that turned around in collection channels were more likely to make additional dam passage attempts than those that turned around in transition pools or at sites further up the fishways (Figure 37b). Rates were **0.87-1.00** for lamprey that turned in the entry areas of the north and south powerhouse collection channels and were ≤ **0.33** at all other sites.

Failure rate (number of unsuccessful final entries / number of unique lamprey at site): failure rates were highest for lamprey that turned around in the north transition pool (segment 7, **0.25** made no additional passage attempt), the north fishway collection channel (segment 6, **0.20**), and the entry area of the north powerhouse (segment 1, **0.17**) (Figure 37c). Failure rates were < **0.05** at the other segments.

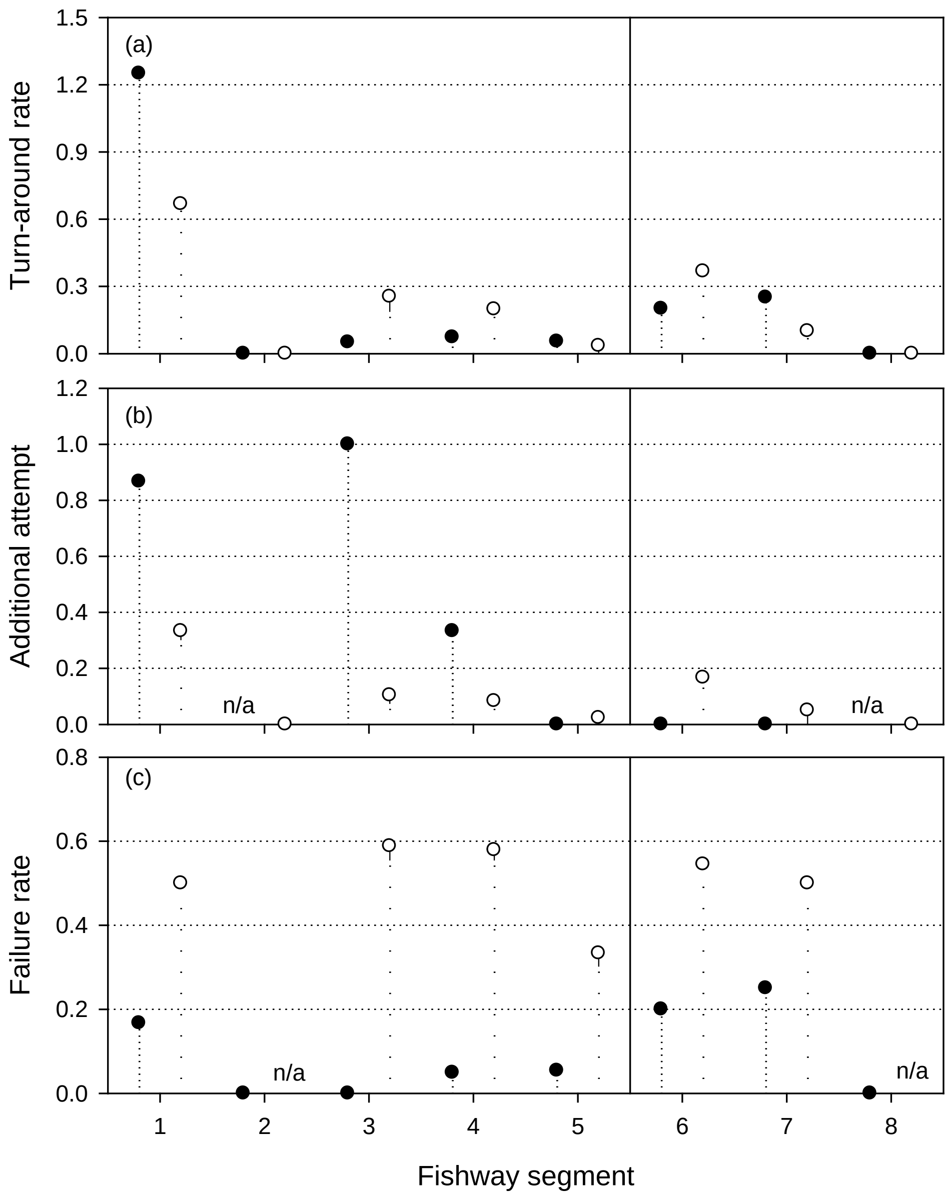


Figure 37. Fishway bottleneck metrics estimated for radio-tagged adult Pacific lamprey at 8 fishway segments at McNary Dam. Metrics include: (a) proportion of unique lamprey recorded at each segment that turned around and exited to the tailrace (number of turn-arounds / number of unique lamprey at site); (b) proportion of turn-around events that were followed by an additional dam passage attempt (additional attempt / turn-around event); and (c) proportion of unique lamprey that failed to make an additional dam passage attempt (number of unsuccessful final entries / number of unique lamprey at site). Symbols represent different lamprey samples: (●) = Bonneville-tagged lamprey; (○) = McNary-tagged lamprey. See Figure 30 for fishway segments.

Single-dam summaries

McNary sample:

Turn-around rate (number of turn-arounds at site / number of unique lamprey at site): lamprey turn-around rates were highest at the entry area of the north powerhouse collection channel (segment 1, *rate* = **0.67** turn-arounds per unique fish), the entry area of the north fishway collection channel (segment 6, **0.37**), the main south fishway entry channel (segment 3, **0.25**), and the south transition pool (segment 4, **0.20**) (Fig 37a). Turn-around rates were intermediate ≤ **0.10** at all other sites.

Additional passage attempts (additional passage attempt / turn-around event): lamprey that turned around near the top of the south fishway (*n* =3) were the least likely to make additional dam passage attempts (*rate* = **0.33**). Rates were **0.50-0.59** for fish that turned in other segments.

Failure rate (number of unsuccessful final entries / number of unique lamprey at site): failure rates were highest for lamprey that turned around in the north powerhouse collection channel area (segment 1, **0.33** made no additional passage attempt) and the north fishway entry collection channel (segment 4, **0.17**) (Figure 37c). Failure rates were < **0.10** at the other segments.

CAVEAT: the aforementioned monitoring gaps in the powerhouse collection channel and ladders affect interpretation of all bottleneck metrics because turn-around locations were relatively imprecise (i.e., compared to Bonneville Dam).

CAVEAT: estimates for the south end of the main collection channel were difficult to conclusively estimate.

5.4.12 PRIORITIZATION CONSIDERATIONS

The two samples monitored at McNary Dam (Bonneville- and McNary-tagged groups) provided qualitatively similar results and the two combined provided useful information on which sites may benefit lamprey passage.

Fishway openings: The three main monitored openings (north, north powerhouse, south) had very different efficiency estimates. The north powerhouse was the least efficient site and shares features of the powerhouse and spillway openings at The Dalles and John Day dams. The north fishway, though similar to the north fishways at The Dalles and John Day dams, had lower entrance efficiency than at those sites. Mechanisms for the relatively lower efficiency at this site are unknown.

Fishway routes: Once inside the north fishway and the south fishway opening, lamprey route efficiency estimates were relatively high at McNary Dam. In contrast, route passage efficiency was very low for the small number of lamprey that entered at the north powerhouse opening. This pattern is consistent with results at powerhouse collections channels at the downstream dams.

Bottlenecks: The north powerhouse, north entrance collection channel, and north transition area all had relatively low passage metrics, indicating the largest scope for improvement at these sites.

However, the largest proportion of lamprey were detected at the south entrance and south transition pool. Therefore, improvements at these sites may have the greatest potential for increasing the total number of lamprey passing at McNary Dam. See Section 9.1.4 for prioritization models for bottleneck reductions at McNary Dam.

5.5 ICE HARBOR DAM

5.5.1 NUMBERS OF RADIO-TAGGED LAMPREY

A total of 12 Pacific lamprey tagged at McNary Dam and released downstream were detected at Ice Harbor Dam or in the Ice Harbor tailrace spread over four of the six study years. This group was combined in the summaries below and is referred to as the 'McNary sample'. Additionally, 40 lamprey tagged at McNary Dam were released downstream from Ice Harbor Dam in 2005-2006. The latter group is referred to as the 'Ice Harbor sample' in summaries below. The handful of lamprey radio-tagged at Bonneville Dam that were detected at Ice Harbor Dam are not included.

5.5.2 MONITORING EFFORT

Radiotelemetry monitoring occurred at Ice Harbor Dam and the sites were relatively consistent across years (Figure 38). Year-to-year monitoring differences included:

- orifice gate openings were unmonitored
- overflow weir sections of fish ladders from transition pools to ladder tops not monitored

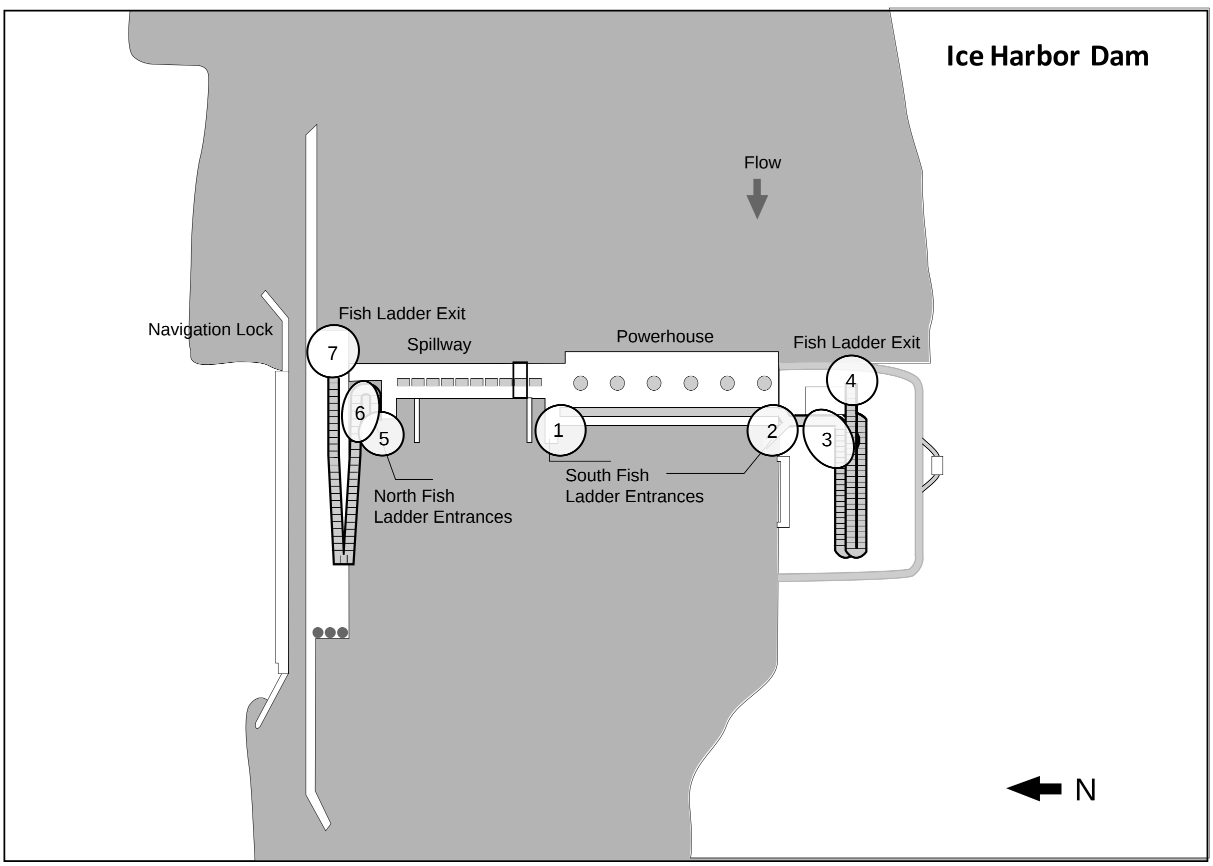


Figure 38. Map of the fishways at Ice Harbor Dam. Numbers indicate fishway segments monitored with radiotelemetry.

5.5.3 FISHWAY APPROACH SUMMARY

McNary sample: A total of 11 unique lamprey from the McNary sample approached monitored fishway openings a total of 50 times at Ice Harbor Dam for a combined total of 4.5 fishway approaches/lamprey. The distribution of first fishway approach sites was 55% at the main south opening and 27% at the north opening; another 18% were at the south fishway, but exact locations were unknown. Distributions of total approach events were similar.

Ice Harbor sample: In 2005-2006, a total of 21 unique lamprey from the Ice Harbor sample approached monitored fishway openings a total of 117 times at John Day Dam for a combined total of 5.6 fishway approaches/lamprey. The distribution of first fishway approach sites was 67% at the main south opening and 19% at the north opening; another 14% were at the south fishway, but exact locations were unknown. Distributions of total approach events were similar.

CAVEAT: lamprey could approach orifice gates undetected in all years, resulting in underestimation of events and potential bias in their distribution.

5.5.4 FISHWAY ENTRY SUMMARY

McNary sample: A total of 10 unique lamprey entered monitored fishway openings a total of 16 times at Ice Harbor Dam for a combined total of 1.6 fishway entries/lamprey. The distribution of first fishway entry sites was 40% at the south opening and 30% at the north opening; another 30% were at the south fishway, but exact locations were unknown. Distributions of total entry events were 44% at the south opening, 6% at the north powerhouse opening, 19% at the north opening, and 31% at unknown south fishway locations.

Ice Harbor sample: In 2005-2006, a total of 19 unique lamprey entered monitored fishway openings a total of 36 times at Ice Harbor Dam for a combined total of 1.9 fishway entries/lamprey. Lamprey first entered at the main south opening (58%), the north opening (16%), and via unknown routes at the south fishway (26%).

CAVEAT: lamprey could enter orifice gates undetected in all years and many of the unknown entries presumably were through these openings.

5.5.5 FISHWAY EXIT SUMMARY

McNary sample: A total of 5 unique lamprey exited monitored fishway openings into the tailrace a total of 6 times at Ice Harbor Dam for a combined total of 1.2 fishway exits/lamprey. Half (50%) of all exits were from the main south fishway opening, 33% were via unknown routes at the south fishway, and 17% were via the north fishway opening.

Ice Harbor sample: In 2005-2006, a total of 10 unique McNary-tagged lamprey exited monitored fishway openings into the tailrace a total of 17 times at Ice Harbor Dam for a combined total of 1.7 fishway exits/lamprey. The distribution total fishway exit sites was 24% via the main south opening and 76% via unknown south fishway routes.

5.5.6 DAM-WIDE PASSAGE EFFICIENCY METRICS

Fishway entrance efficiency (unique fish that entered / unique fish that approached)

McNary sample: with all years combined, 10 McNary-tagged lamprey entered fishways at Ice Harbor Dam, of 12 that approached fishways for a dam-wide fishway entrance efficiency estimate of **0.83**.

Ice Harbor sample: dam-wide fishway entrance efficiency was **0.89** in 2005 (*n* = 9 approached fishways) and was **0.92** in 2006 (*n* = 12).

Fishway passage efficiency (unique fish that passed / unique fish that entered)

McNary sample: with all years combined, 8 McNary-tagged lamprey passed Ice Harbor Dam, of 10 that entered fishways for a dam-wide fishway passage efficiency estimate of **0.80**.

Ice Harbor sample: dam-wide fishway passage efficiency was **0.38** in 2005 (*n* = 8 entered fishways) and was **0.82** in 2006 (*n* = 11).

Dam passage efficiency (unique fish that passed / unique fish that approached)

McNary sample: with all years combined, 8 McNary-tagged lamprey passed Ice Harbor Dam, of 12 that approached fishways for a dam-wide dam passage efficiency estimate of **0.67**.
Ice Harbor sample: dam-wide dam passage efficiency was **0.33** in 2005 (*n* = 9 approached fishways) and was **0.75** in 2006 (*n* = 12).

5.5.7 SITE-SPECIFIC FISHWAY ENTRANCE EFFICIENCY

McNary sample:

Unique lamprey: with all years combined, unique lamprey entrance efficiency estimates at the three fishway openings monitored at Ice Harbor Dam were **0.50** (*n* = 10 fish approached) at the main south-shore opening, **0.00** (*n* = 3) at the north powerhouse opening, and **0.14** (*n* = 7) at the north fishway opening.

Total attempts: with all years combined, entrance efficiency estimates based on total approach and entry events were **0.28** (*n* = 29 total approaches) at the main south-shore opening, **0.00** (*n* = 5) at the north powerhouse opening, and **0.08** (*n* = 12) at the north fishway opening.

Ice Harbor sample:

Unique lamprey: in 2005-2006, unique lamprey entrance efficiency estimates were **0.60-0.71** (*n* = 7-10 approached) at the main south-shore opening, **0.00** (*n* = 3) at the north powerhouse opening, and **0.25-0.57** (*n* = 4-7) at the north fishway opening.

Total attempts: in 2005-2006, entrance efficiency estimates based on total approach and entry events were **0.18-0.38** (*n* = 24-56 total approaches) at the main south-shore opening, **0.00** (*n* = 3) at the north powerhouse opening, and **0.13-0.40** (*n* = 8-15) at the north fishway opening.

CAVEAT: orifice gate openings were unmonitored in all years.

5.5.8 ROUTE-SPECIFIC FISHWAY PASSAGE EFFICIENCY

McNary sample:

Unique lamprey: with all years combined, fishway passage efficiency estimates for unique lamprey were **0.80** (*n* = 5 fish entered) at the main south-shore opening and **0.67** (*n* = 3) at the north fishway opening.

Total attempts: with all years combined, fishway passage efficiency estimates based on total entry events were **0.63** (*n* = 8 entry events) at the main south-shore opening and **0.67** (*n* = 3) at the north fishway opening.

Ice Harbor sample:

Unique lamprey: in 2005-2006, unique-lamprey fishway passage efficiency were **0.40-0.83** (*n* = 5-6 fish entered) at the main south-shore opening and **0.00-1.00** (*n* = 1-5) at the north fishway opening.

Total attempts: in 2005-2006, fishway passage efficiency estimates based on total entry events were **0.22-0.50** (*n* = 9-10 entry events) at the main south-shore opening and **0.00-0.86** (*n* = 1-6) at the north fishway opening.

CAVEAT: in all years, some lamprey likely approached, entered, and exited orifice gates.

5.5.9 FISHWAY SEGMENT PASSAGE EFFICIENCY

Segment efficiencies were not estimated at Ice Harbor Dam because sample sizes were considered too small to be informative.

5.5.10 FISHWAY TURN-AROUND LOCATIONS

McNary sample:

Across years, a total of 8 fishway entry events resulted in exit to the Ice Harbor Dam tailrace (Table 8a). Most (*n* = 7, 88%) fallouts were from the south fishway and 1 (12%) was from the north fishway. A majority of turn-around events were assigned to transition pool segments and none were at top-of-ladder segments.

Single-dam summaries

Ice Harbor sample:

Across years, a total of 22 fishway entry events resulted in exit to the Ice harbor Dam tailrace, with 20 (91%) from the south fishway and 2 (9%) from the north fishway (Table 8b). The largest number of turn-around events were in the south end of the south fishway collection channel and/or the main south entry collection channel. It was difficult to separate these locations given the monitoring array used in 2005-2006. None turned in the upper fishways.

CAVEAT: resolution for turn-arounds was limited, in part because relatively few antennas were included in 2006-2006 (years with the largest samples) in the transition pools.

Table 8a. Numbers of fishway entry events (*n* = 14) recorded for Pacific lamprey and estimated turn-around locations inside fishways for those events that did not result in Ice Harbor Dam passage (*n* = 6 total, 5 south fishway, 1 north fishway). All years combined from McNary sample. See Figure 38 for fishway locations.

		Turn-around location							
	Entry	South fishway					North fishway		
	n	1	2	3	4		5	6	7
South	8			3					
N PH	-								
South-UNK	4	1		1					
North	2							1	
Total	**14**	**1**	**-**	**4**			**-**	**1**	**-**
% of 6 (all)		**17%**	**-**	**67%**	**-**		**-**	**17%**	**-**
% of 5 (S)		**20%**	**-**	**80%**	**-**		**-**	**-**	**-**
% of 1 (N)								**100%**	

Table 8b. Numbers of fishway entry events (*n* = 35) recorded for Pacific lamprey and estimated turn-around locations inside fishways for those events that did not result in Ice Harbor Dam passage (*n* = 22 total, 20 south fishway, 2 north fishway). 2005-2006 data combined for Ice Harbor sample. See Figure 38 for fishway locations.

		Turn-around location							
	Entry	South fishway					North fishway		
	n	1	2	3	4		5	6	7
South	19	1	11						
N PH									
South-UNK	9		7	1					
North	7						2		
Total	**164**	**1**	**18**	**1**			**2**		
% of 22 (all)		**5%**	**82%**	**5%**	**-**		**9%**	**-**	**-**
% of 20 (S)		**5%**	**90%**	**5%**	**-**		**10%**	**-**	**-**
% of 2 (N)							**100%**		

5.5.11 BOTTLENECK ASSESSMENT

Bottleneck metrics were not estimated at Ice Harbor Dam because sample sizes were considered too small to be informative.

5.6 Lower Monumental Dam

A total of 14 radio-tagged lamprey were detected at Lower Monumental Dam across years and samples. These included 3 tagged at Bonneville Dam (1 in 2009, 2 in 2010) and 11 tagged at McNary Dam (1 in 2005, 5 in 2006, 2 in 2009, and 3 in 2010).

In most years, only top-of-ladder exits were monitored. Therefore, fishway use and passage efficiency metrics were not estimated.

5.7 Little Goose Dam

A single radio-tagged lamprey was detected at Little Goose Dam, in 2009. The fish was from the sample collected and tagged at McNary Dam. Only tailrace and top-of-ladder sites were monitored.

5.8 Lower Granite Dam

Two radio-tagged lamprey were detected at Lower Granite Dam, one each from the McNary-tagged sample (2009) and the Bonneville-tagged sample (2010). Only tailrace and top-of-ladder sites were monitored.

5.9 Priest Rapids Dam

A total of 45 radio-tagged lamprey were detected at Priest Rapids Dam, including 15 tagged at Bonneville Dam and 30 tagged at McNary Dam (Table 9). Monitoring was limited to single sites in each fishway in most years.

Table 9. Numbers of radio-tagged lamprey that were detected at Priest Rapids dam in all study years.

Tag site	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Bonneville	-	-	-	-	4	3	-	-	-	2	3	3
McNary	n/a	n/a	n/a	n/a	n/a	n/a	1	-	-	5	23	2

Note: some fish were detected only on HD PIT antennas, primarily in the year following capture

6.0 DATA SYNTHESIS: AMONG-DAM COMPARISONS

Comparing lamprey passage efficiency metrics among projects can help identify which sites have relatively high or low performance measures. This section presents several of the dam-wide, site-specific, and route-specific efficiency metrics from the radiotelemetry studies for all dams in the same graphics. We caution, however, that direct comparisons are fraught with potential problems. These include:

- **Temporal effects**: Lamprey migration timing differs considerably among lower Columbia River projects. The typical lamprey passage peak at Bonneville Dam precedes the peak at McNary Dam, for example, by approximately a month. On average, lamprey encounter warmer water temperatures, lower total discharge, and lower spill at each successive dam upstream. Each of these factors potentially affects the distribution of lamprey among fishway sites, their ability to find and successfully enter fishway openings, and their relative performance.

- **Selection effects**: Lamprey that reach the upriver dams are a non-random subsample of those approaching downstream dams. For instance, upstream populations are often among the largest in the sample detected at Bonneville Dam. These phenotypic differences may mean that those that reach upriver sites have some performance advantages at dams (e.g., their larger size may be the result of greater energy reserves or better swimming capabilities). Higher efficiency metrics at upstream dams may simply reflect the superior capabilities of the subpopulation that reach these sites.

- **Monitoring effects**: The spatial and temporal distribution of monitoring effort differed widely among dams. In the lower river, Bonneville Dam had the most intensive monitoring, followed by McNary, The Dalles, and John Day dams. On average, fewer fishway openings and fishways segments were monitored at the upstream dams. Consequently, more events (e.g., fishway entries, turn-arounds, etc.) were likely undetected at these sites, potentially skewing comparisons with data from sites like Bonneville Dam.

- **Sample size effects**: The absolute numbers of lamprey used to estimate passage efficiencies differed substantially across sites, with the largest numbers for all estimates at Bonneville Dam.

6.1 FISHWAY ENTRANCE EFFICIENCY

Dam-wide: Fishway entrance efficiency estimates for unique radio-tagged lamprey (number entered / number approached) were in a relatively constricted range across dams (Figure 39) compared to other metrics. The lowest median estimates were for McNary-tagged lamprey at McNary Dam (**0.80**) and Bonneville-tagged lamprey at Bonneville Dam (**0.84**). The highest estimates were for Bonneville-tagged lamprey at McNary Dam (**0.96**) and McNary-tagged lamprey released below Ice Harbor Dam (**0.91**). Estimates were intermediate for Bonneville-tagged fish at The Dalles (**0.87**) and John Day (**0.90**) dams and for McNary-tagged fish at Ice Harbor Dam (**0.88**).

Site-specific, unique fish: In contrast with the dam-wide estimates, site-specific fishway entrance efficiencies differed widely across monitored openings (Figure 40). Several fishway openings had unique lamprey entrance efficiency estimates that were **< 0.20**, on median. These included the Ice Harbor north fishway opening, Ice Harbor north powerhouse opening, and the north powerhouse opening at McNary Dam. Note that all of these sites had relatively small numbers of unique fish, and low values may reflect sampling error to some degree. The next-lowest group of estimates included five sites at Bonneville Dam: the Powerhouse 2 north downstream (*median* = **0.27**), Powerhouse 1 sluice gates (**0.29**), Powerhouse 2 orifice gates (**0.36**), Powerhouse 2 north upstream (**0.36**), and Powerhouse 2 south downstream (**0.41**) openings.

Five fishway openings had unique fish entrance efficiency ≥ 0.75 (Figure 40). These included the main south-shore openings at John Day and McNary dams, the main east fishway opening at The Dalles Dam, the north fishway opening at John Day Dam (all **0.75-0.77**), and the north fishway opening at The Dalles Dam (**0.89**). Among-year variance in point estimates differed widely among sites.

Site-specific, total events: Site-specific entrance efficiency estimates were lower at all openings when all fishway approach and entry events were included (Figure 41). The sites with the highest and lowest efficiency estimates were generally similar to those reported above. The least efficient group included north powerhouse openings at McNary and Ice Harbor dams, orifice and sluice gates at Bonneville Dam, and the main openings at Bonneville Powerhouse 2. The most efficient sites were at north fishway openings at The Dalles and John Day dams, as well as the main south-shore openings at John Day and McNary dams.

6.2 FISHWAY PASSAGE EFFICIENCY

Dam-wide: Fishway passage efficiency for unique radio-tagged lamprey (number past dam / number entered fishway) was lowest at John Day (*median* = **0.51**) and Bonneville (**0.52**) dams and was highest at McNary (**0.73**, Bonneville-tagged fish) and Ice Harbor (**0.84**, McNary-tagged fish) dams (Figure 42).

Route-specific, unique fish: There were at total of 35 routes across dams, with route-specific estimates that ranged from < 0.05 to 1.00 (Figure 43). The lowest estimates using unique lamprey were for those that entered the north powerhouse route at McNary Dam (**0.00**), entered via the upstream and downstream openings at the south end of Powerhouse 2 at Bonneville Dam (**0.04-0.05**), via unknown openings at Ice Harbor Dam (**0.13**), via the orifice gates at Bonneville Powerhouse 2 (**0.13**), and via the north fishway opening at John Day Dam (**0.19**). The most efficient (>**0.75**) routes were at McNary and Ice Harbor dams (small samples) and via the main east opening at The Dalles Dam.

Among-dam comparisons

Route-specific, total attempts: Similar to the estimates for unique lamprey, route-specific estimates using total passage attempts varied widely with medians ranging from 0.00 to 1.00 (Figure 44). The least efficient routes were the north powerhouse route at McNary Dam, via the main openings at Bonneville's Powerhouse 2 south and the Powerhouse 2 orifice gates, and the John Day north fishway. The most efficient routes were at McNary and Ice Harbor dams.

6.3 DAM PASSAGE EFFICIENCY

Dam-wide: Total dam passage efficiency (number past dam / number approached fishway) was lowest at Bonneville (*median* = **0.44**) and John Day (**0.46**) dams (Figure 45). In ascending order, the other dam-wide estimates were **0.54** (Ice Harbor, McNary-tagged fish released below Ice Harbor), **0.59** (Ice Harbor, McNary-tagged fish released below McNary), **0.64** (McNary, McNary-tagged fish), **0.68** (The Dalles), and **0.81** (McNary, Bonneville-tagged fish).

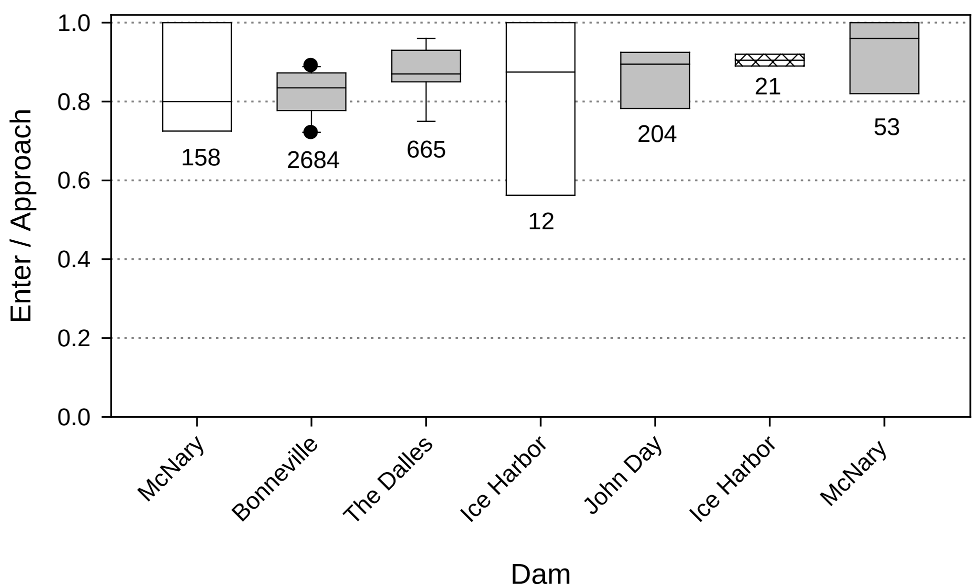


Figure 39. Annual **dam-wide fishway entrance efficiency** estimates for unique fish (unique fish that entered fishway / unique fish that approached dam) for radio-tagged adult Pacific lamprey in 1997-2002 and 2005-2010. Gray boxes are estimates for lamprey tagged at Bonneville Dam, open white boxes are for lamprey tagged at McNary Dam and released downstream, and hashed white boxes are for lamprey tagged at McNary Dam and released below Ice Harbor Dam. Estimates are ordered from lowest to highest median values. Box plots percentiles are: 25th, 50th, and 75th (boxes), 10th and 90th (whiskers) and 5th and 95th (circles). Numbers are the total number of unique lamprey across years.

Among-dam comparisons

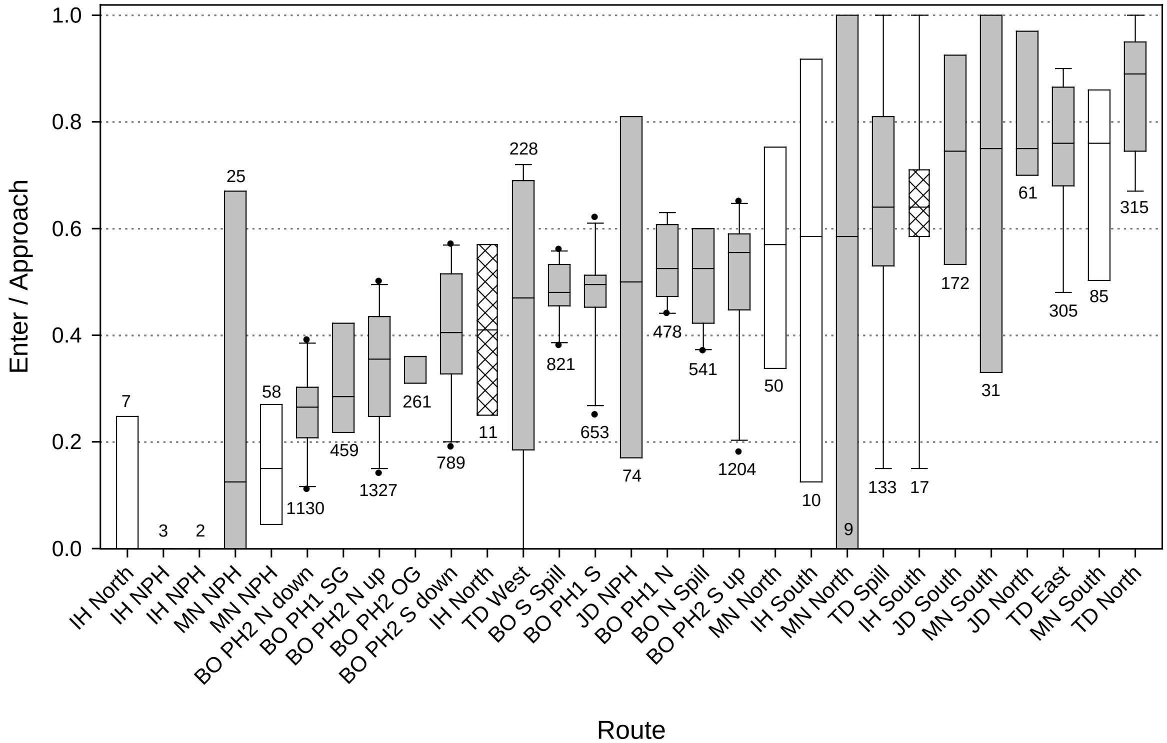


Figure 40. Annual **site-specific fishway entrance efficiency** estimates for unique fish (unique fish that entered fishway / unique fish that approached at each monitored fishway opening) for radio-tagged adult Pacific lamprey in 1997-2002 and 2005-2010. Gray boxes are estimates for lamprey tagged at Bonneville Dam, open white boxes are for lamprey tagged at McNary Dam and released downstream, and hashed white boxes are for lamprey tagged at McNary Dam and released below Ice Harbor Dam. Estimates are ordered from lowest to highest median values. Box plots percentiles are: 25th, 50th, and 75th (boxes), 10th and 90th (whiskers) and 5th and 95th (circles). Numbers are the total number of unique lamprey across years.

Among-dam comparisons

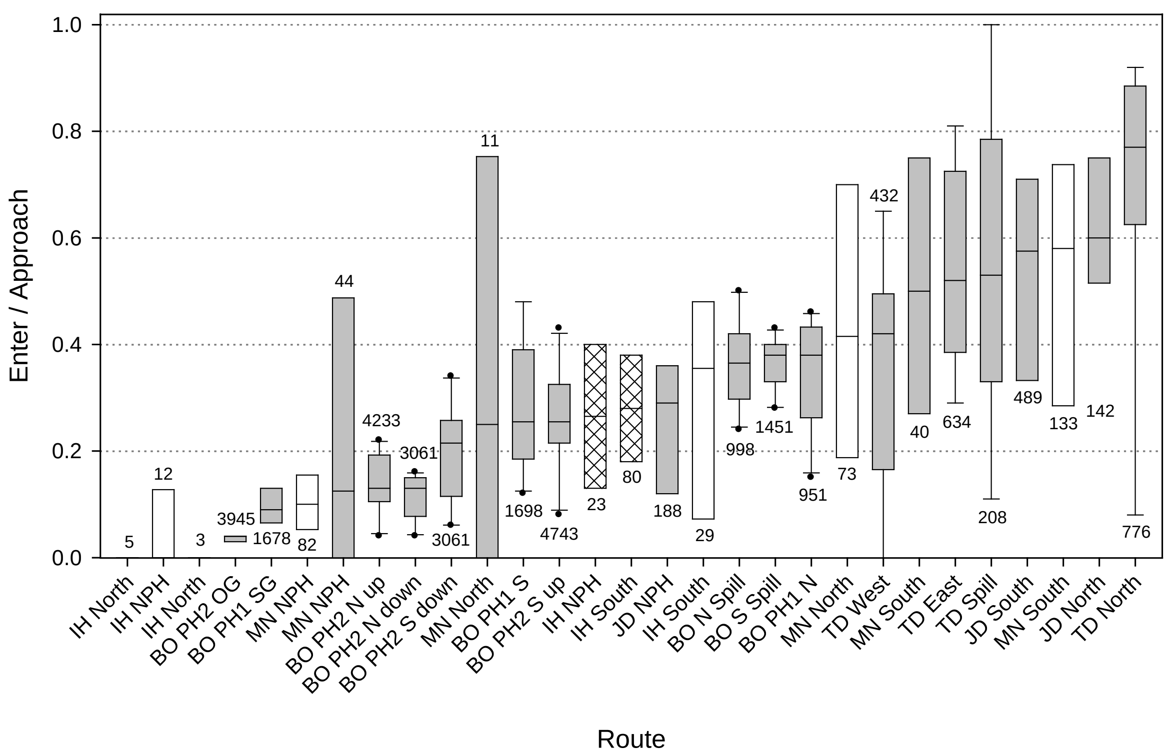


Figure 41. Annual **site-specific fishway entrance efficiency** estimates for total attempts (total number of fishway entries / total number of fishway approaches at each monitored fishway opening) for radio-tagged adult Pacific lamprey in 1997-2002 and 2005-2010. Gray boxes are estimates for lamprey tagged at Bonneville Dam, open white boxes are for lamprey tagged at McNary Dam and released downstream, and hashed white boxes are for lamprey tagged at McNary Dam and released below Ice Harbor Dam. Estimates are ordered from lowest to highest median values. Box plots percentiles are: 25th, 50th, and 75th (boxes), 10th and 90th (whiskers) and 5th and 95th (circles). Numbers are the total number of approach events across years.

Among-dam comparisons

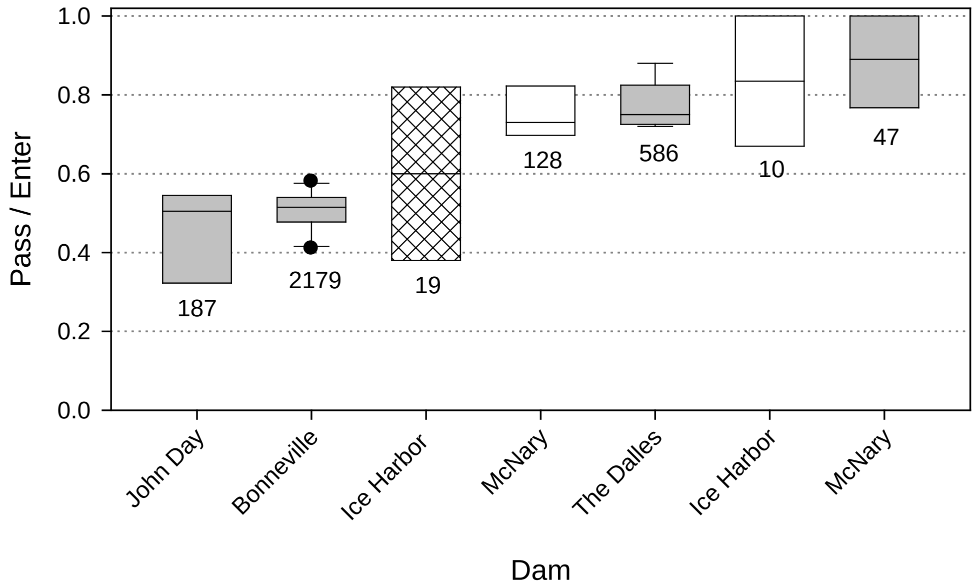


Figure 42. Annual **dam-wide fishway passage efficiency** estimates for unique fish (unique fish that passed dam / unique fish that entered fishways) for radio-tagged adult Pacific lamprey in 1997-2002 and 2005-2010. Gray boxes are estimates for lamprey tagged at Bonneville Dam, open white boxes are for lamprey tagged at McNary Dam and released downstream, and hashed white boxes are for lamprey tagged at McNary Dam and released below Ice Harbor Dam. Estimates are ordered from lowest to highest median values. Box plots percentiles are: 25th, 50th, and 75th (boxes), 10th and 90th (whiskers) and 5th and 95th (circles). Numbers are the total number of unique lamprey across years.

Among-dam comparisons

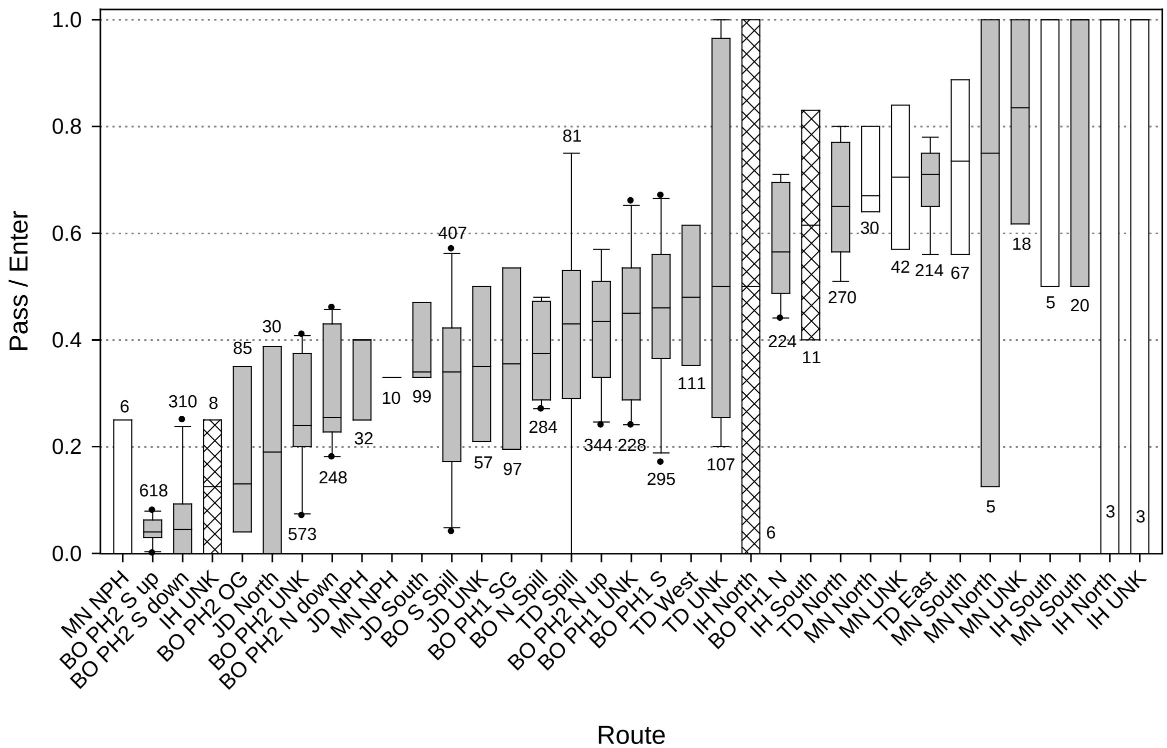


Figure 43. Annual **route-specific fishway passage efficiency estimates** for unique fish (unique fish that passed dam / unique fish that entered each monitored fishway opening) for radio-tagged adult Pacific lamprey in 1997-2002 and 2005-2010. Gray boxes are estimates for lamprey tagged at Bonneville Dam, open white boxes are for lamprey tagged at McNary Dam and released downstream, and hashed white boxes are for lamprey tagged at McNary Dam and released below Ice Harbor Dam. Estimates are ordered from lowest to highest median values. Box plots percentiles are: 25th, 50th, and 75th (boxes), 10th and 90th (whiskers) and 5th and 95th (circles). Numbers are the total number of unique lamprey across years.

Among-dam comparisons

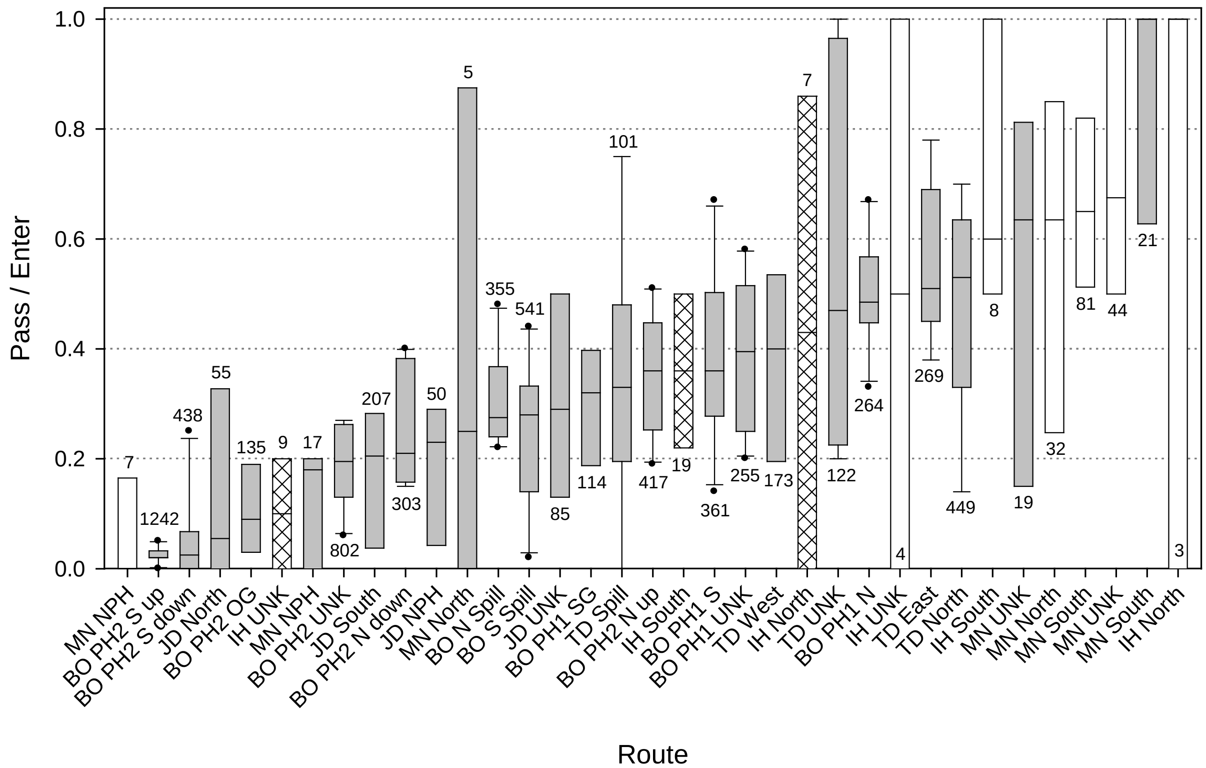


Figure 44. Annual **route-specific fishway passage efficiency** estimates for total passage attempts (fish that passed dam / number of entries at each monitored fishway opening) for radio-tagged adult Pacific lamprey in 1997-2002 and 2005-2010. Gray boxes are estimates for lamprey tagged at Bonneville Dam, open white boxes are for lamprey tagged at McNary Dam and released downstream, and hashed white boxes are for lamprey tagged at McNary Dam and released below Ice Harbor Dam. Estimates are ordered from lowest to highest median values. Box plots percentiles are: 25th, 50th, and 75th (boxes), 10th and 90th (whiskers) and 5th and 95th (circles). Numbers are the total number of passage attempts across years.

Among-dam comparisons

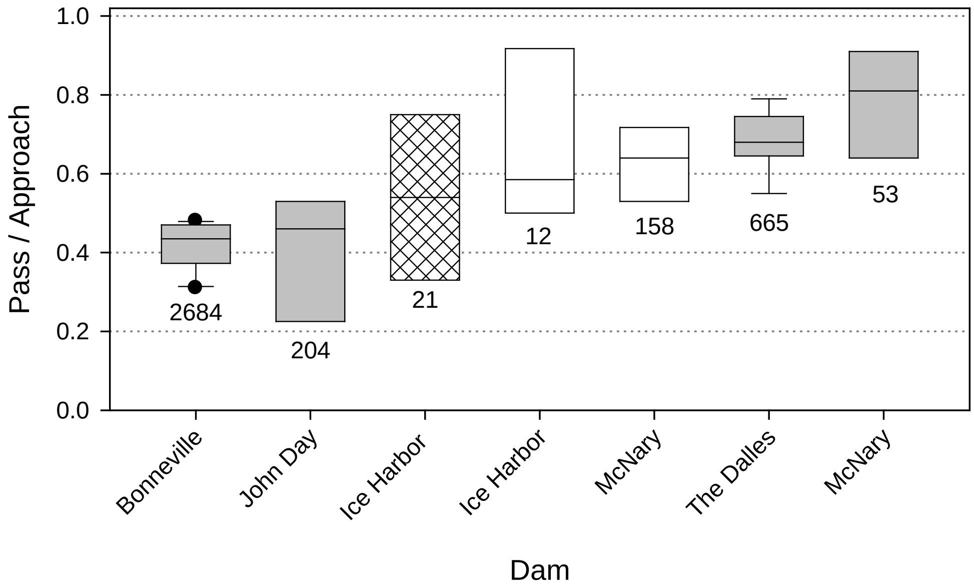


Figure 45. Annual **dam-wide dam passage efficiency** estimates for unique fish (unique fish that passed dam / unique fish that approached dam) for radio-tagged adult Pacific lamprey in 1997-2002 and 2005-2010. Gray boxes are estimates for lamprey tagged at Bonneville Dam, open white boxes are for lamprey tagged at McNary Dam and released downstream, and hashed white boxes are for lamprey tagged at McNary Dam and released below Ice Harbor Dam. Estimates are ordered from lowest to highest median values. Box plots percentiles are: 25th, 50th, and 75th (boxes), 10th and 90th (whiskers) and 5th and 95th (circles). Numbers are the total number of unique lamprey across years.

7.0 DATA SYNTHESIS: RESERVOIR PASSAGE EFFICIENCY

Reservoir passage efficiency estimates were calculated for radio-tagged lamprey only because no HD-PIT monitoring occurred in tailraces. Reservoir reaches were from the top-of-ladder exits at downstream dams (Bonneville, The Dalles, John Day) to detection in the tailrace or at fishways at the upstream dam (The Dalles, John Day, McNary, respectively). No estimates were made for the McNary reservoir (very limited monitoring in the Hanford Reach) or in Snake River reservoirs (very small sample sizes).

In the lower river, median reservoir passage efficiency estimates were **0.61** (*range* = 0.46-0.81) through the Bonneville reservoir, **0.61** (0.42-0.75) through The Dalles reservoir, and **0.34** (0.29-0.46) through the John Day reservoir (Figure 46). The lower rate for the John Day reservoir was associated with its greater length.

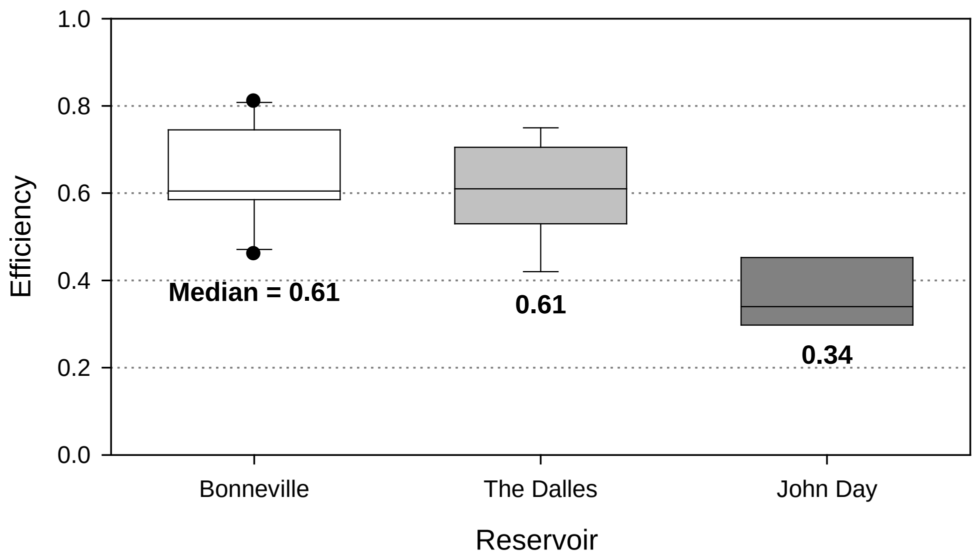


Figure 46. Distributions of annual reservoir passage efficiency estimates for radio-tagged Pacific lamprey through the Bonneville, The Dalles, and John Day reservoirs. Box plots percentiles are: 25th, 50th, and 75th (boxes), 10th and 90th (whiskers) and 5th and 95th (circles).

8.0 DATA SYNTHESIS: REACH ESCAPEMENT

8.1 RADIOTELEMETRY

Median reach escapement estimates for radio-tagged lamprey from release below Bonneville Dam were **0.39** (*range* = 0.21-0.46) past Bonneville Dam, **0.13** (0.05-0.23) past The Dalles Dam, **0.05** (0.01-0.11) past John Day Dam, **0.02** (0.01-0.03) past McNary Dam, and **<0.01** past Ice Harbor and Priest Rapids dams (Figure 47). Dam-to-Dam escapement estimates (between top-of-ladder sites) were **0.37** (0.25-0.57) from Bonneville – The Dalles, **0.35** (0.12-0.49) from The Dalles – John Day, **0.24** (0.12-0.43) from John Day – McNary, **0.23** (0.13-0.33) from McNary – Ice Harbor, and **0.50** (0.38-0.50) from McNary – Priest Rapids.

8.2 HD PIT

Median reach escapement estimates for HD PIT-tagged lamprey from release below Bonneville Dam were **0.52** (*range* = 0.41-0.62) past Bonneville Dam, **0.28** (0.23-0.32) past The Dalles Dam, **0.18** (0.14-0.24) past John Day Dam, **0.05** (0.02-0.08) past McNary Dam, and **~0.01** past Ice Harbor and Priest Rapids dams (Figure 48). Dam-to-Dam escapement estimates (between top-of-ladder sites) were **0.52** (0.38-0.68) from Bonneville – The Dalles, **0.67** (0.52-0.80) from The Dalles – John Day, **0.26** (0.16-0.34) from John Day – McNary, **0.14** (0.05-0.23) from McNary – Ice Harbor, and **0.50** (0.11-0.55) from McNary – Priest Rapids.

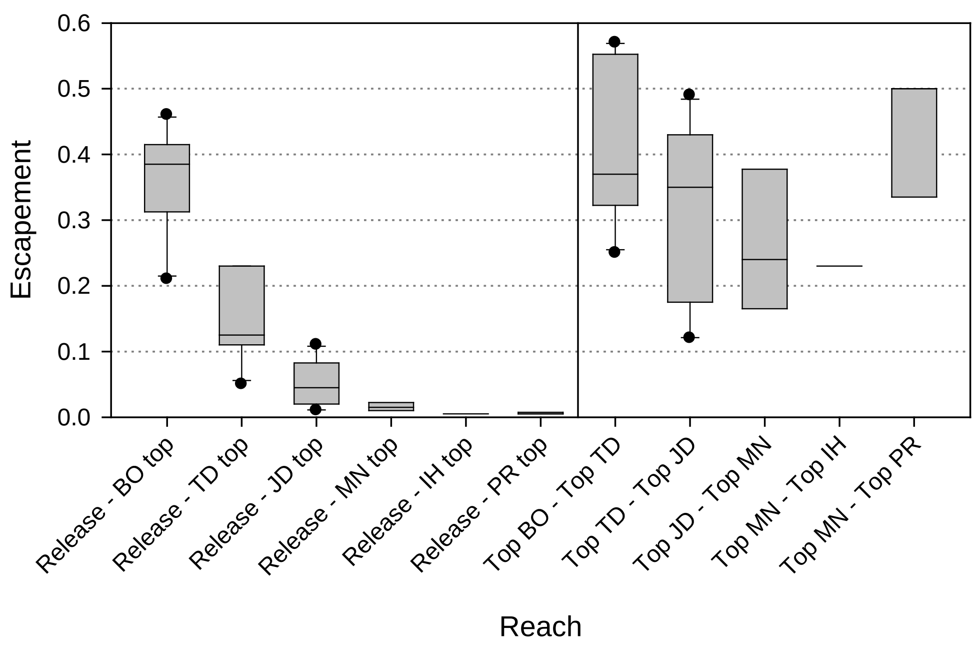


Figure 47. Annual **reach escapement** estimates for radio-tagged lamprey, 1997-2002 and 2007-2010. Box plots percentiles are: 25th, 50th, and 75th (boxes), and 10th and 90th (whiskers). Left panel is escapement from the release site downstream from Bonneville Dam. Right panel is dam-to-dam escapement.

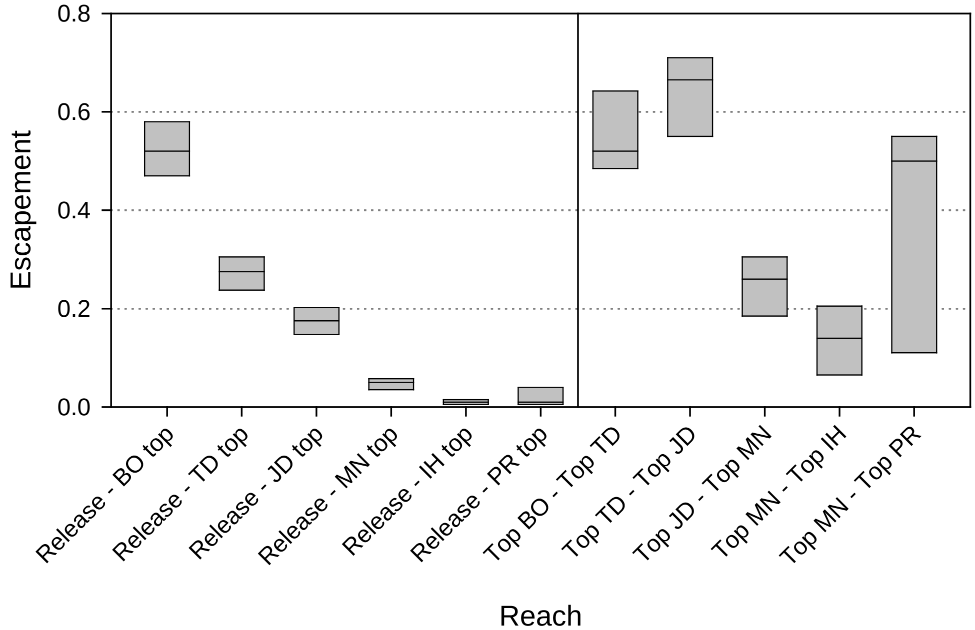


Figure 48. Annual **reach escapement** estimates for HD PIT-tagged lamprey, 2005-2011. Box plots percentiles are: 25th, 50th, and 75th (boxes). Left panel is escapement from the release site downstream from Bonneville Dam. Right panel is dam-to-dam escapement.

8.3 FACTORS AFFECTING REACH ESCAPEMENT

Tag type was systematically associated with reach escapement where values for HD-PIT samples were consistently and relatively evenly higher than for radio-tagged samples. In addition, both the radiotelemetry and HD PIT studies, upriver escapement has been strongly size dependent, with the largest lampreys being two to four times more likely to pass upstream than the smallest fish. Lamprey size appears to affect escapement at multiple scales, from individual fishway passage success to the likelihood of passage past multiple projects. In our multi-year escapement summary for HD PIT-tagged fish, lamprey size was more strongly associated with upriver passage than were river discharge, water temperature, or migration timing variables in most river reaches. Similarly, annual Bonneville Dam passage efficiency was strongly positively correlated with mean size of the radio-tagged fish (see Figure 7) and size was a strong predictor of McNary Dam passage in the McNary studies. Several hypotheses may explain the higher escapement for larger lamprey:

1) larger lamprey may be stronger swimmers, with greater sustained and burst swim speeds, making them more able to pass fishways than smaller fish;

2) larger lamprey may have greater energetic reserves, allowing for longer upstream migration distances before they seek spawning areas or initiate overwintering behaviors;

3) larger lamprey may be disproportionately from upriver populations, though this would be at odds with a general consensus that anadromous lampreys lack geographic stock structure;

4) negative handling and tagging effects may be reduced in larger fish, though we note that the size-migration distance relationship has been observed for all tag types and is of similar nature (e.g., there is no evidence of a sizeXtag type interaction).

Compared to the size effect, broad-scale environmental effects on upriver lamprey escapement have been mixed across study years and study types. In some years, we have detected a seasonal effect where escapement is higher for fish tagged and released early in the run. The opposite has also been observed, with higher upriver escapement later in the summer when water temperatures were relatively higher and discharge was relatively lower. Very high water temperatures have been associated substantially reduced upstream escapement, particularly in the John Day reservoir, but also in lower river reaches. Across years, the window of favorable migration conditions (i.e., moderate discharge and temperature) for adult lamprey may vary by several weeks and these differences almost certainly contribute to both the among-year variability in run timing and upriver escapement estimates.

The combination of very high discharge and low water temperature has been linked to slow migration speeds and lower dam passage success, particularly at Bonneville Dam. The effect may be related to the ability of lamprey to locate fishway entrances and to pass through lower fishway segments. Poor fishway passage efficiencies have been noted during the high tailwater elevations associated with high flow, which inundates larger portions of the lower fishways. Turn-around rates in lower fishway segments are often very high at Bonneville Dam under these conditions.

Separating broad-scale environmental effects from proximate conditions encountered by tagged lamprey has proven challenging. This is largely because there is limited available data – especially water velocity data – at fine spatial scales. For example, we think it is very likely that water velocity and turbulence near fishway openings and inside fishways have a greater effect on upriver escapement than total Columbia River discharge. Fine-scale conditions at the fishways fluctuate in response to overall river conditions, particularly tailwater and forebay elevation, but these relationships are not well described at spatially relevant scales. Similarly, operational criteria at individual fishways may have important effects on escapement that are largely unexamined. Alternatively, the relatively weak associations may be related in part to the protracted and flexible migration timing of adult lamprey compared to some salmonids which move upstream through relatively narrow temporal windows.

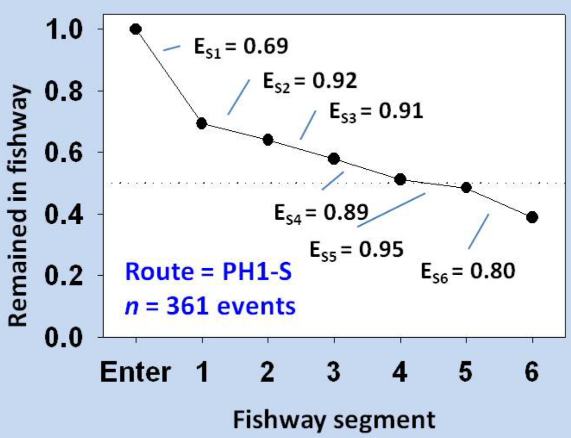
9.0 PASSAGE IMPROVEMENT PRIORITIZATION MODELS

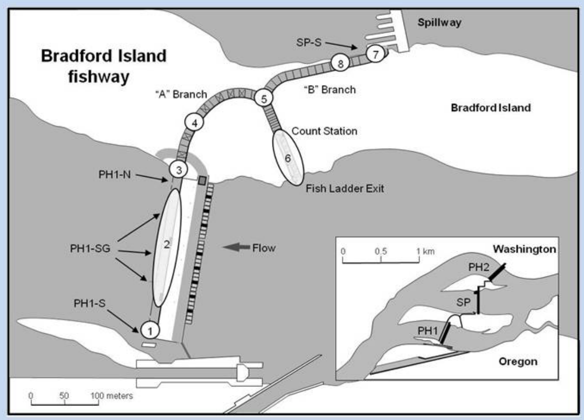
9.1 REDUCED BOTTLENECKS IN FISHWAY SEGMENTS

The first set of prioritization models address the question: what are the potential benefits of improved lamprey passage efficiency through individual fishway segments on dam-wide fishway passage efficiency? This can be rephrased as: what are the benefits of reducing passage bottlenecks in specific fishway segments at a single dam?

The intended use of these bottleneck reduction models is to compare the relative benefits of improving lamprey passage efficiency in different fishway segments by some set amount (e.g., 5%, 10%, etc.). This tool should help managers assess which sites should be prioritized for fishway improvements at a single dam or single fishway.

Box 4. Reduced bottleneck model





Dam passage estimates by route

Baseline dam passage = Number of events × Segment efficiencies for each passage route

For example, for PH1-S route: Dam Passage = $(N_{events} \times E_{S1} \times E_{S2} \times E_{S3} \times E_{S4} \times E_{S5} \times E_{S6})$

Bottleneck reduction model

1) **Increase Efficiency (E) for fishway segment**

   Example: $E_{S6} \times 1.10$ = 10% increase In efficiency in segment 6

2) **Recalculate Passage for all routes**
3) **Calculate increase in dam-wide passage**

   = (New – Baseline) / Baseline

We constructed bottleneck reduction models for the four lower Columbia River dams. Models were parameterized using the fishway segment passage efficiency data from radio-tagged lamprey shown in Figures 11 (Bonneville), 20 (The Dalles), 28 (John Day), and 36 (McNary). Rather than using segment efficiency estimates from individual years, when sample sizes were sometimes limiting, we aggregated the data across all study years for each dam. The aggregated data should reduce the potential influence of year-to-year variability and provide reasonable data for evaluating ‘relative’ benefits.

Box 4 provides an overview of the general approach for the bottleneck reduction models. The example in the upper left graph shows the fishway segment passage efficiency data for all lamprey entry events at the south-shore entrance of the Bradford Island fishway. The ‘baseline’ number of lamprey that passed the dam via this route was:

361 entry events × 0.69 × 0.92 × 0.91 × 0.89 ×0.95 × 0.80 = 141 past the dam.

Similar data were included for all 12 routes at Bonneville Dam to create the baseline model.

The lower left panel in Box 4 demonstrates the basic method for assessing the effect of a bottleneck reduction in a single fishway segment. In this case, the test is an increase in passage efficiency through fishway Segment 6 (top of Bradford Island ladder) of 10% (i.e., $E_{S6} \times 1.10 = 0.80 \times 1.10 = 0.88$). The new estimate of dam passages for the route would be:

361 entries × 0.69 × (0.92 × 1.1) × 0.91 × 0.89 ×0.95 × 0.80 = 155 past the dam.

The benefit from a 10% increase in Segment 6 to total lamprey passage for adults using this route would be:

(155-141) / 141 = + 9.9%.

In linear fishways with single openings (such as The Dalles north fishway), a constant improvement at any segment produces an identical improvement in passage (e.g., an increase of 10% at Segment 2 in the example above also results in 155 lampreys past the dam and a +9.9% increase in passage). Importantly, few fishways have simple linear structures but rather have multiple routes in lower sections leading to each exit. Consequently, the number entering each route, segment efficiencies below the junctions among routes, as well as segment efficiencies in shared upstream reaches. For example, a larger number of lamprey enter the Bradford Island B-branch entrance and segment efficiencies below the A- and B-branch ladders differ between routes. Hence a 10% improvement in segment 7 or 8 in Box 4 will have a greater impact than A-branch segments.

Scope for improvement: An important feature of the bottleneck models is that not all fishway segments have the same ‘scope for improvement’. For example, a segment with passage efficiency of 0.95 cannot have a 10% improvement (i.e., 0.95 × 1.10 = 1.045, which is > 100% efficiency). Furthermore, the absolute increase in passage efficiency in a segment depends on the baseline efficiency. For example, 10% improvements in segments with efficiency of 0.10 or 0.50 produce new efficiency estimates of 0.11 (0.10 × 1.10 = 0.11) and 0.55 (0.50 × 1.10 = 0.55), respectively. Put another way, the maximum scope for improvement for segments with baseline efficiency of 0.10, 0.50, and 0.90 is 1000% (0.10 × 10.0 = 1), 200% (0.50 × 2.0 = 1), and 11.1% (0.9 ×1.111 = 1), respectively.

Limitations: The segment efficiency estimates in the models shown below were calculated using total passage attempts, not unique lamprey, because total attempts incorporate information about all of the activity by tagged fish (i.e., some lamprey attempt to pass dams multiple times or by multiple routes). Using all attempts means that model runs that include very large increases in fishway segment passage efficiency or increases at multiple segments simultaneously will produce biased benefit estimates. This is because there were more passage attempts than unique lamprey (i.e., at Bonneville Dam, lamprey entered fishways 2.4 times per fish, on average) and the simple numerical models currently do not attempt to adjust for reduced attempts per fish. Differences in relative benefits should be realistic, however, using modest (< 25%) increases in segment efficiency at single sites.

9.1.1 BONNEVILLE DAM

We calculated the increase in dam-wide fishway passage efficiency at Bonneville Dam in response to improved segment passage efficiency through 20 monitored fishway segments (Figure 49). Each model run tested an improvement at a single segment so that relative benefits could be assessed. Tested increases in segment passage efficiency were +5%, +10%, and +20%.

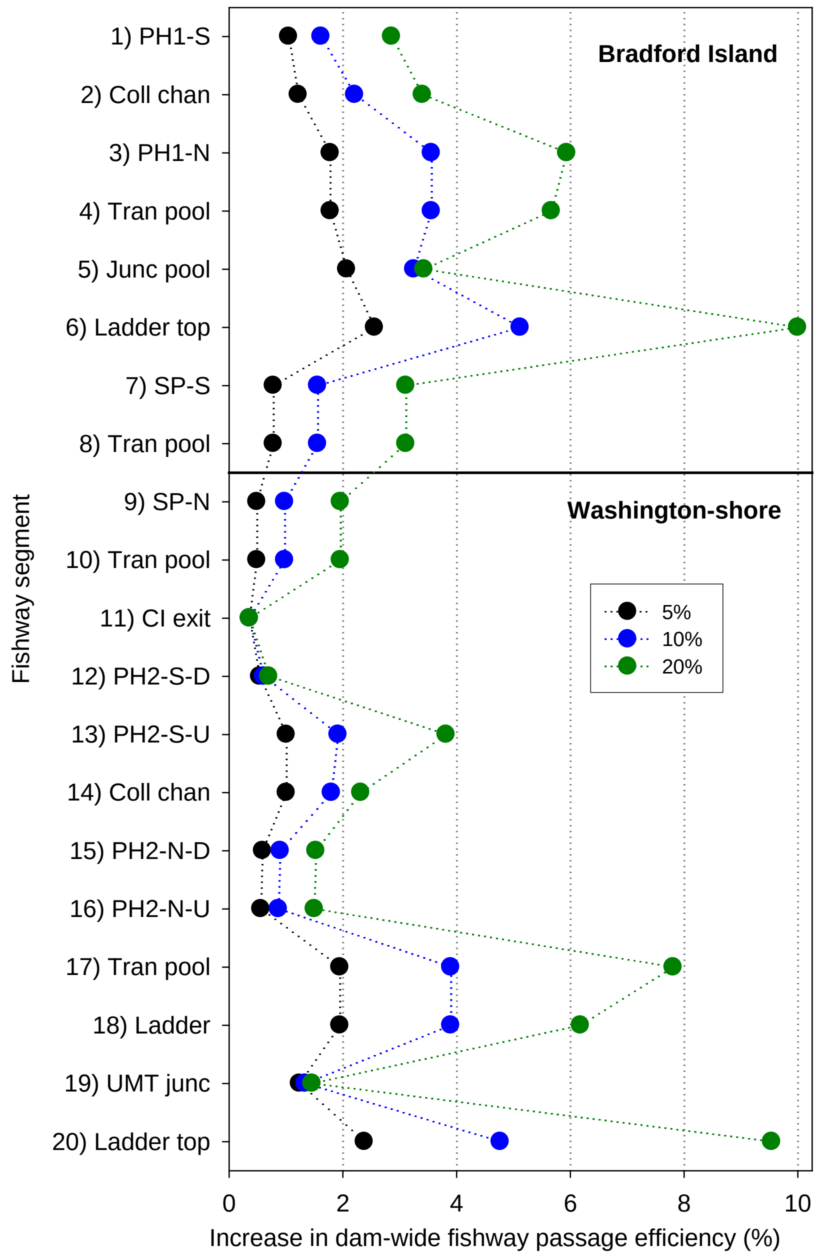


Figure 49. Modeled benefit in dam-wide fishway passage efficiency of 5%, 10%, and 20% reductions in passage bottlenecks in individual fishway segments at Bonneville Dam. Note that some segments had limited scope for improvement (see text). Maps in Figures 1 and 2 show fishway segment locations.

+5% models: the largest dam-wide benefits were for increased segment passage efficiency at the top of the Bradford Island fishway (segment 6, *benefit* = **+2.56%**) and the top of the Washington-shore fishway (segment 20, **+2.38%**). Benefits were also relatively high for the Bradford Island junction pool (segment 5, **+2.07%**), the Washington-shore junction pool (segment 17, **+1.95%**), and the Washington-shore lower ladder (segment 18, **+1.95%**).

Dam-wide benefits were lowest for improvements near the former Cascades Island ladder exit (segment 11, **+0.36%**), the Cascades Island collection channel (segment 9, **+0.49%**), the Cascades Island transition pool (segment 10, **+1.95%**), and the north entrance channels at Powerhouse 2 (segment 16, **+0.56%**; segment 15, **+0.59%**). Although the scope for improvement at these sites was quite high, relatively small numbers of lamprey passed through these segments compared to other fishway segments.

+10% models: results for the 10% models paralleled those for the 5% models (Figure 49). The largest dam-wide benefits were for top-of-ladder sites (segment 6, *benefit* = **+5.12%**; segment 20, **+4.77%**). The next best benefits were for the Washington-shore junction pool (segment 17, **+3.90%**) and transition pool / lower ladder (segment 18, **+3.90%**), the north end of the Powerhouse 1collection channel (segment 3, **+3.56%**), the Powerhouse 1 transition pool (segment 4, **+3.56%**), and the Bradford Island junction pool (segment 5, **+3.25%**).

+20% models: general patterns were similar to those described above, with top-of-ladder, the Washington-shore junction pool and transition area, and the north end of Powerhouse 1 collection channel and transition pool providing the largest benefits. Notably, benefits at several sites were limited by their scope for improvement; sites with baseline segment passage efficiency of ~0.84 reach 100% efficiency with a 20% increase.

CAVEAT: limited monitoring in some years may have resulted in underestimates of benefits of improvements at top-of-ladder segments (turn-arounds were assigned to lower fishway segments) and overestimates of benefits at sites like the Bradford Island junction pool (turn-arounds occurred upstream but were assigned to this segment).

CAVEAT: benefits were calculated using all data from 1997-2002 and 2007-2010, and therefore represent an ‘average’ value. Changes in powerhouse priority, entrance efficiency, or other factors that affect the distribution of lamprey entering each route could change results.

9.1.2 THE DALLES DAM

We calculated the increase in dam-wide fishway passage efficiency at The Dalles Dam in response to improved segment passage efficiency through 9 monitored fishway segments (Figure 50).

+5% models: the largest dam-wide benefits were for increased segment passage efficiency at the junction pool (segment 2, *benefit* = **+3.05%**) and transition pool of the east fishway (segment 3, **+3.05%**) and at the collection channel (segment 7, **+1.95%**) and transition pool of the north fishway (segments 8, **+1.95%**). These estimates at these two pairs of sites were the same because they shared the same sample size. Benefits were lowest for the west powerhouse entrance (segment 6, **+0.30%**) and the spillway entrance (segment 5, **+0.55%**); fewer lamprey passed through these segments.

+10% and +20% models: patterns were generally similar to those in the 5% models, with the greatest benefits realized in the junction pool and transition pool segments in the east fishway and the entrance collection channel and transition pool of the north fishway (Figure 50). The scope for improvement was limiting in the east junction pool and both top-of-ladder segments.

CAVEAT: many lamprey entered the east fishway via unknown routes and estimating segment efficiency for the entrance and collection channel segments was therefore imprecise.

CAVEAT: fish ladders were only monitored in the transition pool and top-of-ladder segments, potentially resulting in underestimates of segment passage efficiency in the transition pools.

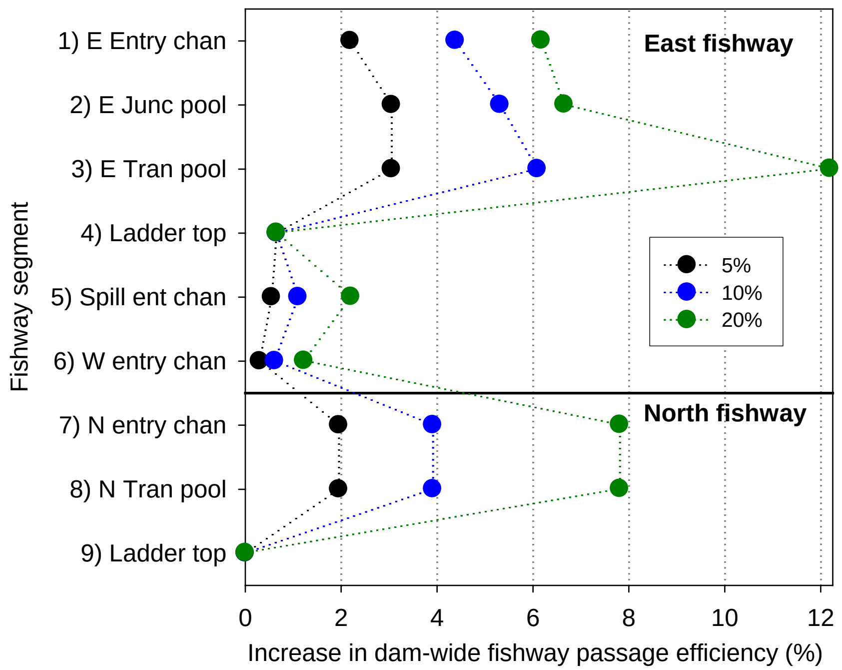


Figure 50. Modeled benefit in dam-wide fishway passage efficiency of 5%, 10%, and 20% reductions in passage bottlenecks in individual fishway segments at The Dalles Dam. Note that top-of-ladder segments had limited scope for improvement (see text). Maps in Figures 14 and 15 show fishway segment locations.

9.1.3 JOHN DAY DAM

We calculated the increase in dam-wide fishway passage efficiency at John Day Dam in response to improved segment passage efficiency through 10 monitored fishway segments (Figure 51).

+5% models: the largest dam-wide benefits were for increased segment passage efficiency at the south transition pool (segment 4, *benefit* = **+4.32%**), the south end of the powerhouse collection channel (segment 2, **+3.35%**), and the main south fishway entrance (segment 3, **+2.53%**). Benefits were lowest for the north powerhouse entrance (segment 1, **+0.62%**). The benefit was **+0.68%** for the four north fishway segments (estimates were the same for these segments as there was only a single route).

+10% and +20% models: patterns were generally similar to those in the 5% models, with the greatest benefits realized in the south transition pool segments and lower segments of the south fishway where the most lamprey were present (Figure 51).

CAVEAT: many lamprey entered the south fishway via unknown routes and estimating segment efficiency for the entrance and collection channel segments was therefore imprecise.

CAVEAT: very limited monitoring occurred at John Day count stations and the ladders were only monitored in the transition pool and top-of-ladder segments, potentially resulting in poor estimates of efficiency at count stations and underestimates of segment passage efficiency in the transition pools.

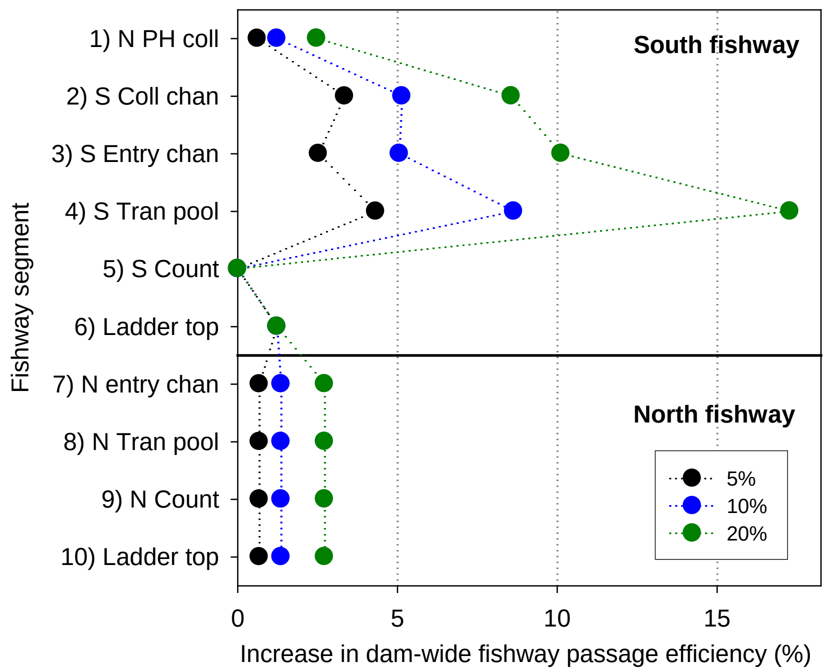


Figure 51. Modeled benefit in dam-wide fishway passage efficiency of 5%, 10%, and 20% reductions in passage bottlenecks in individual fishway segments at John Day Dam. Maps in Figure 22 show fishway segment locations.

9.1.4 MCNARY DAM

We calculated the increase in dam-wide fishway passage efficiency at John Day Dam in response to improved segment passage efficiency through 8 monitored fishway segments (Figure 52). Models were run for Bonneville- and McNary-tagged lamprey separately.

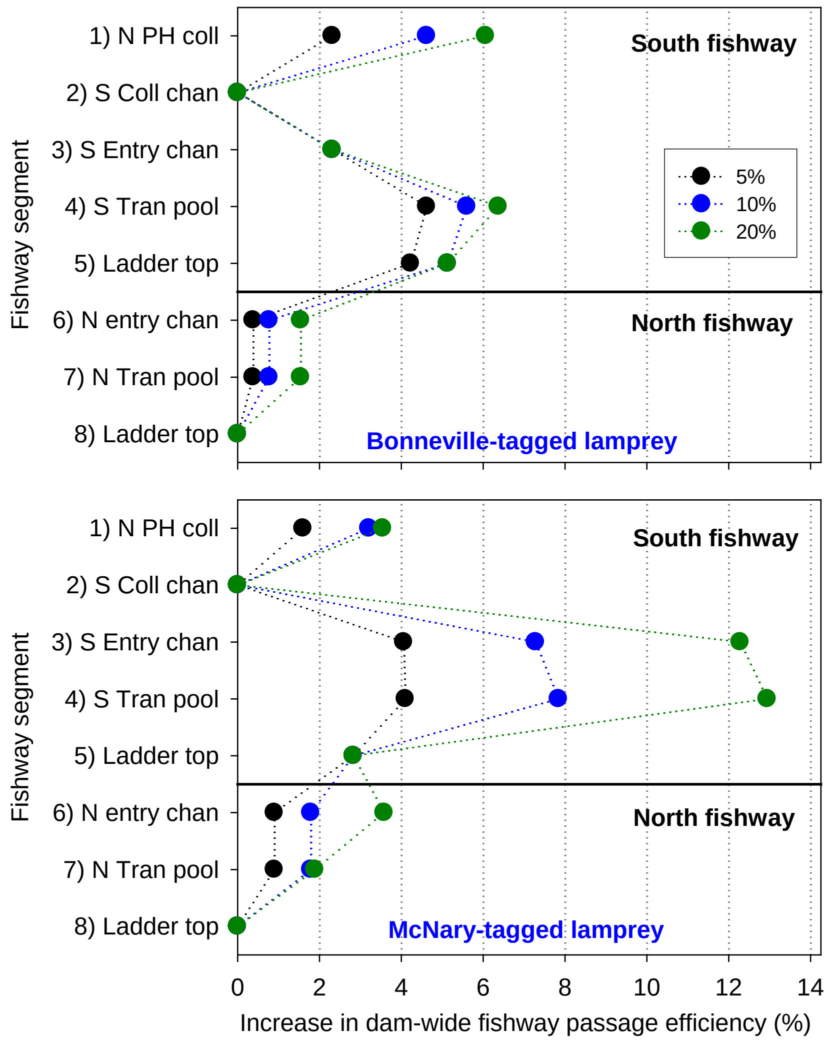


Figure 52. Modeled benefit in dam-wide fishway passage efficiency of 5%, 10%, and 20% reductions in passage bottlenecks in individual fishway segments at McNary Dam. Map in Figure 30 shows fishway segment locations. Top panel: Bonneville-tagged lamprey. Bottom panel: McNary-tagged lamprey.

+5% models: the largest dam-wide benefits were for increased segment passage efficiency at the south transition pool (segment 4, *benefit* = **+4.62%** for Bonneville fish and **+4.10%** for McNary fish). The benefit was also relatively high for the south top-of-ladder (segment 5, **+4.23%**) for Bonneville fish and for the main south entry collection channel (segment 3, **+4.06%**) for the McNary fish. Benefits were modest for all other segments, either because the scope for improvement was limited or sample sizes were small (i.e, the north fishway).

+10% and +20% models: patterns were generally similar to those in the 5% models, with the greatest benefits realized in the south transition pool and south collection channel segments.

CAVEAT: many lamprey entered the south fishway via unknown routes and estimating segment efficiency for the entrance and collection channel segments was therefore imprecise.

CAVEAT: the ladders were only monitored in the transition pool and top-of-ladder segments, potentially resulting in underestimates of segment passage efficiency in the transition pools.

CAVEAT: sample sizes were very small in the Bonneville-tagged estimates.

9.2 INCREASED DAM PASSAGE EFFICIENCY: UPRIVER BENEFITS

The second set of prioritization models ask the question: what are the potential benefits of improved dam-wide dam passage efficiency on upriver lamprey escapement? The intended use of the upriver escapement models is to compare the relative benefits of improving lamprey dam passage efficiency at a single dam by some set amount (e.g., 5%, 10%, etc.) compared to similar improvements at another dam. These tools should help managers assess which dams should be prioritized for fishway improvements.

Box 5. Upriver escapement models

Upriver distribution model: RT

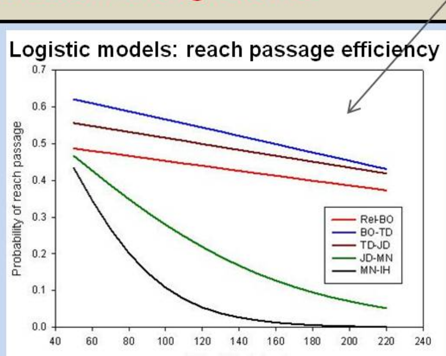
Step 1: Pick starting sample size

Step 2: Generate random numbers

Step 3: Run through series of IF-THEN probability statements based on dam passage efficiencies

Output: original sample is allocated among migration reaches

Hypothesis testing: increase single-dam efficiency estimates and test effects on distribution among reaches



Upriver distribution model: HD

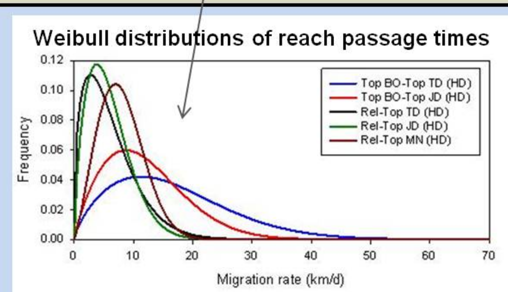
Step 1: Pick sample size and start date distribution; generate random numbers

Step 2: Run sample through sub-routines for lamprey passage times and reach passage efficiency

Step 3: Run through IF-THEN probability statements that determine whether lamprey continue upstream migration

Output: original sample is allocated among migration reaches

Hypothesis testing: increase single-dam efficiency estimates and test effects on distribution among reaches



Upriver escapement models were parameterized using data from radio-tagged or HD PIT-tagged lamprey. The radiotelemetry model included dam-wide dam passage efficiency data (fishway approach to exit from the top of a fishway) from Bonneville- or McNary-tagged lamprey in all study years. Rather than using annual efficiency estimates from individual years, when sample sizes were sometimes limiting, we aggregated the data across all study years for each dam. The aggregated data should reduce the effects of year-to-year variability and provide reasonable data for evaluating 'relative' benefits. We used an individual-based modeling approach to facilitate the incorporation of seasonal effects.

Radiotelemetry model: Box 5 provides an overview of the general approach for the upriver escapement models. The upper left inset shows the steps used for estimating the upriver distribution of lamprey in the radiotelemetry model. Each model run started with 100,000 lamprey below Bonneville Dam. The 'baseline' dam passage efficiency estimates used in the model were: 0.44 (Bonneville), 0.68 (The Dalles), 0.46 (John Day), and 0.72 (McNary). The McNary estimate was the mean for Bonneville- and McNary-tagged samples; estimates at the other dams were means from the Bonneville-tagged samples. A set of random numbers was generated for each fish in the sample and IF-THEN statements were applied for each step along the migration route. For example:

> Lamprey 1 was assigned a random number between 0 and 1for Bonneville Dam passage. If the number was <= 0.44, then the fish passed the dam and moved to the next migration segment; if it was > 0.44, then the fish did not pass and was assigned to the downstream reach.
>
> If Lamprey 1 passed Bonneville Dam, it was assigned a second random number. That number was used to determine whether the fish reached The Dalles Dam or was last detected in the Bonneville reservoir reach.
>
> If Lamprey 1 reached The Dalles Dam, it was assigned a third random number. If the number was <= 0.68, the fish passed the dam and moved to the next migration segment; if it was > 0.68 it did not pass.
>
> This approach was continued for each migration segment through the lower Columbia River past McNary Dam and each of the 100,000 lamprey in the simulation was assigned to a final reach.

We used the model to test the effects of improvements in dam passage efficiency of 2%, 4%, 6%, 8%, and 10% at each dam separately and in at all four dams in combination. Relative increases in upriver escapement were calculated as the percent increase in the number of lamprey in each reach over the baseline estimate. The results converge on a simple model of the joint probabilities of passage through all dams.

HD PIT model: The upper inset in Box 5 shows the steps used for estimating the upriver distribution of lamprey in the HD PIT escapement model. These paralleled the steps used in the radiotelemetry model, with a few exceptions. First, the HD PIT model used reach passage efficiency data (e.g., release–Bonneville top, Bonneville top–The Dalles top) rather than dam passage efficiency data because only top-of-ladder sites were monitored at all dams in the PIT tag studies. Second, we used seasonally varying efficiency estimates rather than point estimates for the efficiency data.

Prioritization models

The 100,000 lamprey in each model run were assigned random start dates (from a distribution approximating a typical lamprey run at Bonneville Dam). The sequence of random numbers in the IF-THEN model steps for each lamprey were compared to date-specific reach passage efficiency estimates from logistic regression models for each migration segment (lower left figure in Box 5). Lastly, lamprey passage times for each reach were randomly drawn from Weibull distributions of passage times generated from the original data (lower right figure in Box 5). As in the radiotelemetry model, we used the HD PIT model to test the effects of improvements in dam passage efficiency of 2%, 4%, 6%, 8%, and 10% at each dam separately and in at all four dams in combination. Relative increases in upriver escapement were calculated as the percent increase in each reach over the baseline estimate.

Assumptions: The efficiency and distribution data used in the radiotelemetry and HD PIT baseline models were drawn from actual data. They are therefore the most realistic baseline information available. It is unknown, however, whether the lamprey that pass the dams in the simulation models as a result of the improvements would behave similarly to those in the baseline models at upstream locations. For example, we modeled the increase in efficiency approximately evenly across the migration period and all fish (e.g., large, small, early, late, etc.) were given equal probabilities of passage. These factors presumably average out across a year, but the simulations do not address this level of specificity.

9.2.1 RADIOTELEMETRY ESCAPEMENT MODEL

A common feature of each of the radiotelemetry escapement models was that an increase in dam passage efficiency at a single site resulted in fewer fish with final fates recoded in the reach immediately downstream (Figure 53). For example, improving efficiency at The Dalles Dam resulted in fewer fish last recorded in the Bonneville–The Dalles reach compared to the base model with no improvements. This was expected, as many radio-tagged lamprey were last detected at dams or in dam tailraces and this group was the one that benefited from the improved dam passage efficiency and moved upstream.

All models that included efficiency improvements at single dams resulted in escapement benefits for all reaches above the selected dam (Figure 53). Benefits were in approximate proportion to the percent increase in efficiency at the downstream dam, but varied slightly among reaches and among simulations reflecting the stochastic element built into the model.

Interestingly, improvements at Bonneville Dam often resulted in similar improvements in passage numbers at upstream projects compared to more local improvements. For example, a 10% improvement at Bonneville or John Day both had similar effects on the increase in adults reaching the JDA-MCN reach. Additionally, improved efficiency at Bonneville Dam increased escapement to all upriver reaches, whereas improvements at other dams affected only upriver reaches. All else being equal, this clearly indicates that Bonneville Dam should be the highest priority among dams. Improved efficiency at multiple dams had the largest positive effect on escapement to upriver reaches, with the exception of the Bonneville–The Dalles reach which was relatively unaffected (Figure 53, bottom panel).

9.2.2 HD-PIT ESCAPEMENT MODEL

Simulations using the somewhat more realistic, seasonally sensitive HD PIT models produced results that were qualitatively very similar to those from the radiotelemetry models (Figure 54). HD PIT results were somewhat more variable than the radiotelemetry model results, reflecting both the seasonal differences in reach passage efficiency and the wide variability in lamprey passage times. Improved efficiency at Bonneville Dam provided escapement benefits for all upriver reaches, indicating this should be the priority dam, all else being equal.

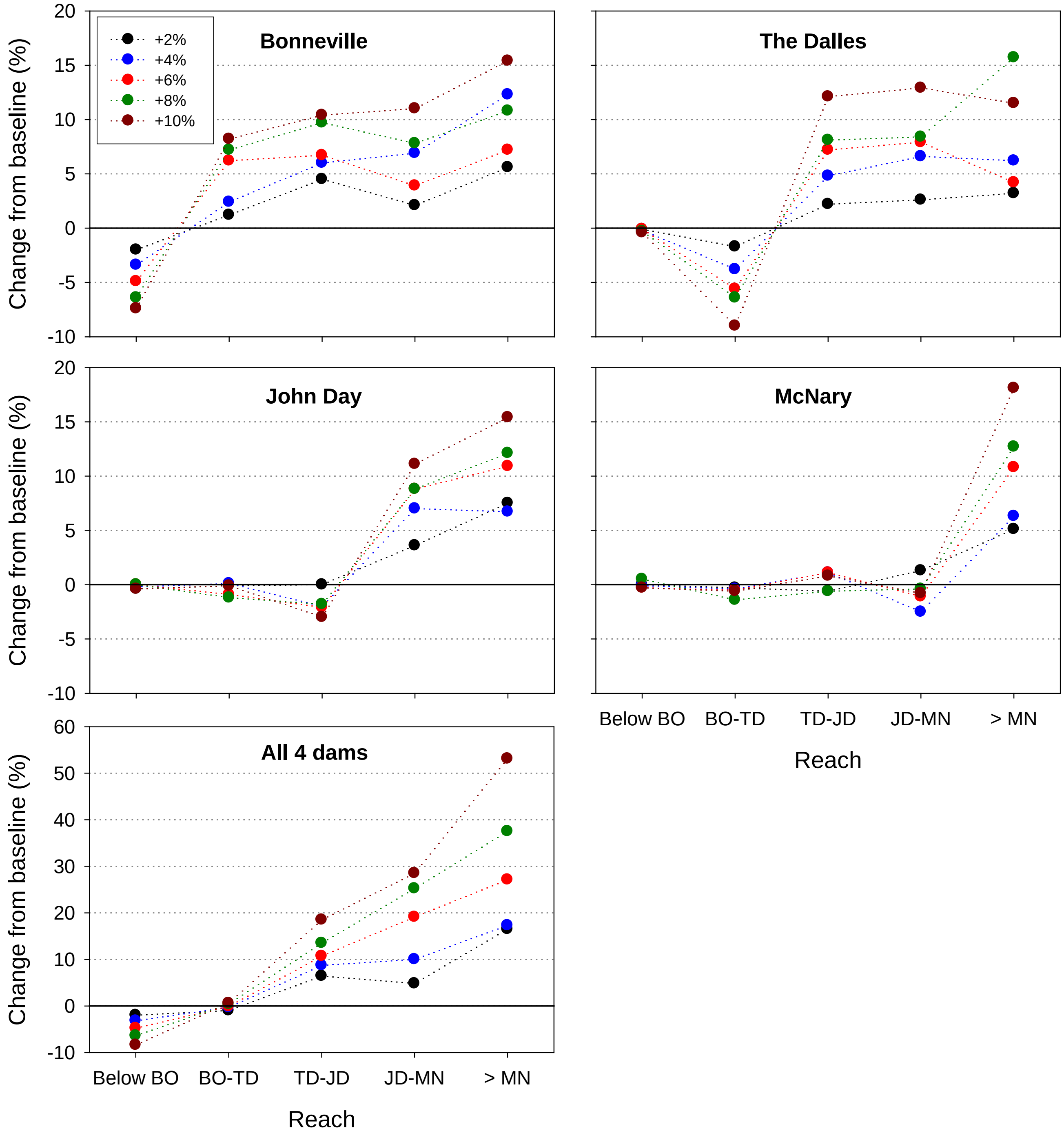


Figure 53. Example output from the radiotelemetry-based upriver escapement models. The five panels represent model runs with increased dam passage efficiency at the four dams individually and at all four dams combined (note difference in y-axis scale on bottom panel). The five symbol colors represent increased efficiency of 2, 4, 6, 8, and 10%. Each model run started with 100,000 lamprey at Bonneville Dam. The change in distribution was calculated as: (Modeled number in reach-Baseline number in reach) / Baseline number in reach.

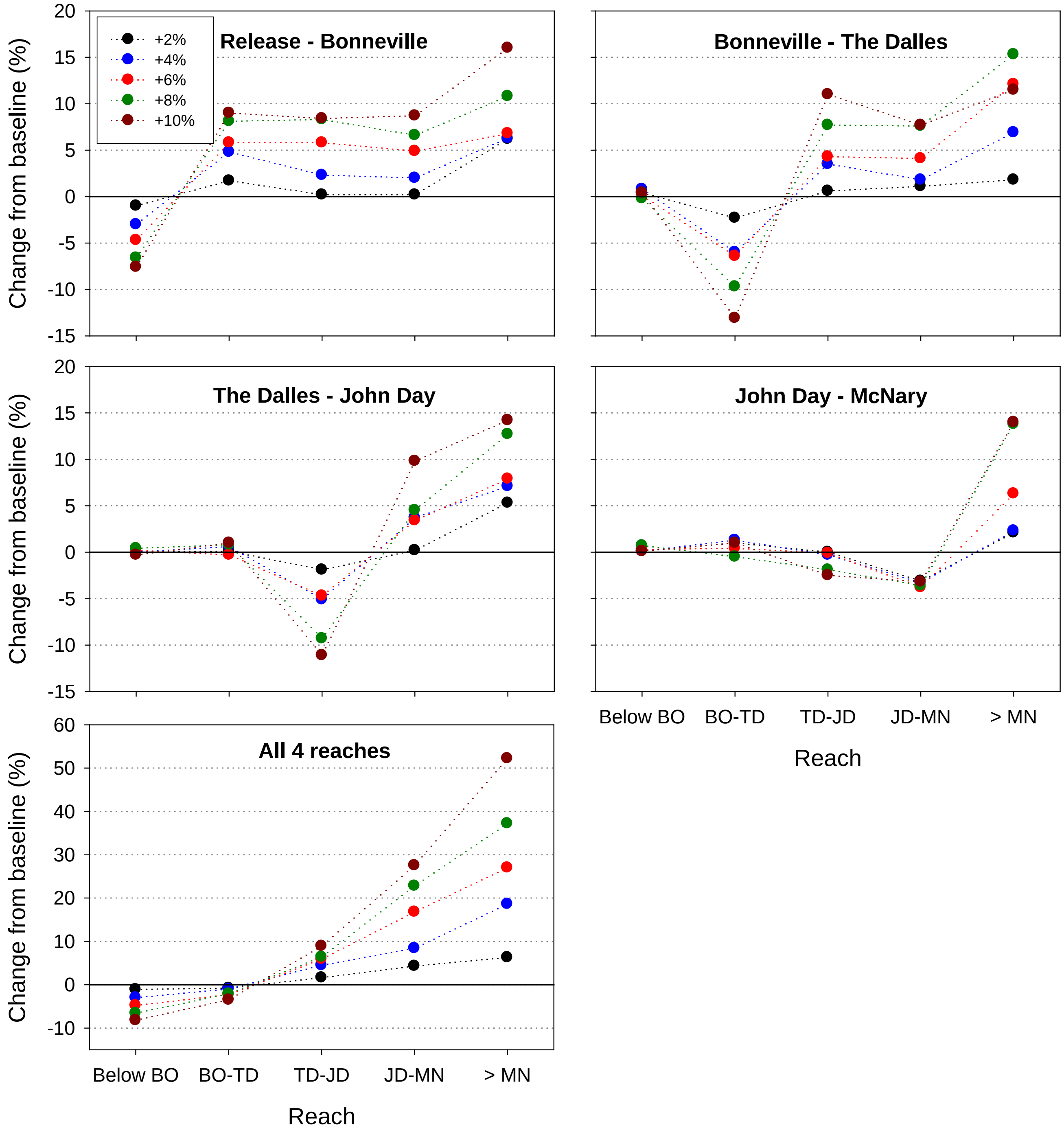


Figure 54. Example output from the HD PIT-based upriver escapement models. The five panels represent model runs with increased reach passage efficiency at the four river reaches individually and at all four reaches combined (note difference in y-axis scale on bottom panel). The five symbol colors represent increased efficiency of 2, 4, 6, 8, and 10%. Each model run started with 100,000 lamprey at Bonneville Dam. The change in distribution was calculated as: (Modeled number in reach-Baseline number in reach) / Baseline number in reach.

10.0 APPENDICES

Appendix A. Annual radiotelemetry and HD PIT monitoring arrays used at Columbia and Snake River dams, 1997-2002 and 2005-2011.

Appendix B. Annual distributions of where radio-tagged adult Pacific lamprey approached, entered, and exited fishways at Columbia and Snake River dams.

Appendix C. Annual dam-wide passage efficiency metrics estimated for radio-tagged adult Pacific lamprey at Columbia and Snake River dams.

Appendix D. Annual site-specific fishway entrance efficiency estimates for radio-tagged adult Pacific lamprey at Columbia and Snake River dams.

Appendix E. Annual route-specific fishway passage efficiency estimates for radio-tagged adult Pacific lamprey at Columbia and Snake River dams.

Appendix F. Annual fishway segment efficiency estimates for radio-tagged adult Pacific lamprey at Columbia and Snake River dams.

Appendix G. Annual distributions of fishway turn-arounds by radio-tagged adult Pacific lamprey at Columbia and Snake River dams.

Appendix H. Annual reservoir conversion estimates for radio-tagged adult Pacific lamprey in the lower Columbia River.

Appendix I. Annual reach-specific escapement estimates for radio- and HD PIT-tagged adult Pacific lamprey in the lower Columbia and Snake rivers.

Appendix J. Maps of HD PIT antennas locations at Columbia and Snake River dams.