August 2017
Lower Granite Adult Passage and Post-passage Evaluation

ANCHOR QEA

Final Adult Passage and Post-passage Behavior Report

Prepared for U.S. Army Corps of Engineers

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ABBREVIATIONS

$\mu m/s^2$	micrometer per second squared
ADCP	Acoustic Doppler Current Profiler
ANODEV	Analysis of deviance
ARIS	Adaptive Resolution Imaging System
CSV	comma separated variable
dB	decibel
ESA	Endangered Species Act
FOV	field of view
FTP	file transfer protocol
GLM	generalized linear models
ISO	International Organization for Standardization
kcfs	kilo cubic feet per second
LAPDB	LGR Adult Passage Database
LGR	Lower Granite Dam
m/s^2	meters per second squared
MHz	megahertz
PI	Principal Investigator
PIT	passive integrated transponder
PNNL	Pacific Northwest National Laboratory
PTAGIS	PIT Tag Information Systems
QA	quality assurance
QC	quality control
TCS	temperature control structure
USACE	US Army Corps of Engineers

1 Introduction

This report addresses tasks that were performed at Lower Granite Dam (LGR) under two separate contracts for the U.S. Army Corps of Engineers (USACE): 1) Lower Granite Dam Adult Passage Evaluation (hereafter referred to as "Adult Passage Evaluation"), and 2) Lower Granite Dam Sockeye and Chinook Salmon Post-passage Behavior Evaluation (hereafter referred to as "Post-passage Evaluation"). Both studies analyzed many of the same covariates and had overlapping data collection periods and are therefore presented together in this report. The background, purpose, and objectives of each evaluation in the report are described below.

1.1 Background

1.1.1 Adult Passage Evaluation

Many factors influence the passage of salmonids through fishways, including hydraulics, temperature, lighting, the motivation of the fish, and possibly behavioral response to sound and vibration. The USACE has recently undertaken several construction projects at LGR to specifically improve the passage environment for salmonids. These include the installation of temperature control structures and a juvenile fish bypass.

The planned and ongoing construction activities associated with these projects prompted concern that sound and vibration related to construction activities adjacent to the adult fishway may negatively affect upstream passage of adult salmonids at LGR. The acoustic environment in a fishway is complex, and there are no comparable studies that examine how construction sound and vibration affects salmonid passage in a fishway (Hawkins 2015).

In addition to evaluating sound and vibration, there was also interest in evaluating the post-construction performance of temperature control improvements on adult passage. High summer water temperatures may delay adult salmonid passage and may decrease both spawning success and survival (Caudill et al. 2007, 2013). In the Snake River, the highest temperatures encountered by migrating fish are often in fishways (Keefer and Caudill 2015) and affect multiple species including Endangered Species Act (ESA)-listed sockeye salmon (*Oncorhynchus nerka*; Keefer et al. 2008). Concerns about high temperatures in the LGR fish ladder and their negative impact on adult passage provided the impetus for making improvements intended to cool water temperatures in the fishway ladder.

In 2015, the USACE funded a broad study to evaluate construction related sound and vibration impacts as well as the performance of temperature control improvements on adult fish passage. The study has three components: 1) a comprehensive review and synthesis of literature on the effects of noise and vibration on salmon; 2) measurement of sound and vibration in the fishway; and 3) an evaluation of adult salmonid passage behavior. The first two components have been addressed in previous reports (Hawkins 2015 and Anchor QEA et al. 2017, respectively). This report addresses the third component, adult salmonid passage behavior.

1.1.2 Post-passage Evaluation

The post-passage behavior of salmonids is an important consideration for evaluations of migration success. Fallback of adult sockeye salmon at Snake River dams has been shown to result in multiple counts of the same fish skewing the between-dam conversion estimates and effectively reducing sockeye production in their conversion from LGR to successful spawning in the Stanley Basin. Fallback and re-ascension through the ladder are readily estimated using passive integrated transponder (PIT)-tag detection at ladder facilities. Currently, there is a lack of information describing the behavior of adult salmonids that successfully exit the ladder that may influence their potential for falling back through spill or powerhouse operations (e.g., lateral or vertical movement immediately upon entry into the forebay).

Elevated water temperatures in the Snake River influence the passage and post-passage behavior of adult salmonids at LGR (Caudill et al. 2013). Water temperatures exceeding 68 ° F (20° C) can lead to increased delay and fallback rates, possibly resulting in mortality of adult salmon passing LGR during periods of elevated water temperature. These high temperatures typically occur in late June through early September and may have the greatest influence on upstream passage of adult Snake River Sockeye (FPC 2014). A temperature control structure (TCS) was installed upstream of the LGR adult fishway prior to the 2016 passage season to produce a zone of cool water near the fishway exit and cool the water in the fishway itself. The TCS operates by pulling cool water at depth and then redistributing it at the surface via a spray bar. The cooled surface water is then entrained into the fishway exit and lowers the temperature for salmonids in the ladder. During periods of elevated water temperatures, the TCS may play an important role in improving passage conditions for salmonid stocks that are migrating past LGR. However, the performance of the TCS and its ability to influence passage and post-passage behavior are not known and there is uncertainty about how the TCS would distribute cool water at the dam face and fish exit and whether it could lead to higher fallback rates or to improved success at navigating upstream.

In 2016, the USACE funded a study to evaluate the post-passage behavior of salmonids related to the newly installed TCS. This research report presents the methods and materials, results, and discussion thereof regarding the post-passage study conducted at LGR in 2016.

1.2 Purpose and Objectives

1.2.1 Adult Passage Evaluation

The purpose of the adult passage evaluation was to characterize adult salmonid passage through the LGR adult fishway using non-invasive approaches including PIT tag detections and covariates related to sound and vibration monitoring, water temperature, and dam operations.

The adult passage evaluation included the following objectives as interpreted from the Performance Work Statement:

1. Collect PIT-tag data to identify run-timing dates for adult salmonids
2. Obtain covariate data to characterize dam operations, water temperatures related to TCS operations, and sound and vibration associated with construction and dam operations
3. Quantitatively evaluate the response of adult salmonids passing through the LGR adult ladder to dam operation, water temperature, and sound and vibration covariates. Examine potential effects of sound and vibration associated with construction and dam operations and the potential effects of the new TCS on water temperature at the adult ladder. PIT-tag response variables include:
    - Median ladder transit time from first entry to last detection upon exiting
    - Entrance success measured as the fraction of fish seen at the entrance that are subsequently seen further in the ladder
    - Dropback measured as the fraction of fish seen at the weir arrays or exit that are subsequently seen again at the entrance
    - Reascent rate measured as the fraction of fish that exited the ladder that are subsequently seen again at the entrance
    - Exit success measured as the fraction of fish seen at the weir arrays that are next seen at the exit and not seen thereafter
    - Passage success measured as the fraction of fish that enter the ladder that subsequently exited the ladder
    - Unique number of fish observed during specific blocks of time

1.3 Post-passage Evaluation

The purpose of the post-passage evaluation was to evaluate the effectiveness of the newly constructed TCS that was designed to improve upstream ladder passage and exit rates for adult sockeye and Chinook (*O. tshawytscha*) salmon during warm water periods.

The post passage evaluation focused on the following primary objectives as interpreted from the Performance Work Statement:

1. Quantitatively estimate proportion of adult sockeye and Chinook salmon (summer and fall Chinook salmon passing mid-June through mid-September) passage success, delay, or failure upon exiting the ladder at the scale required to characterize response of fish to real-time changes in operation of the newly constructed water TCS. Specifically, address the following questions:
    a. Upon exiting the ladder do fish attempt to dive to cooler water?
    b. Upon exiting the ladder do fish proceed directly upstream, or move towards the powerhouse and the spillway, where risk of fallback is greatly increased?
    c. What is the fallback and re-ascension rate and exit/return rate of PIT-tagged fish?

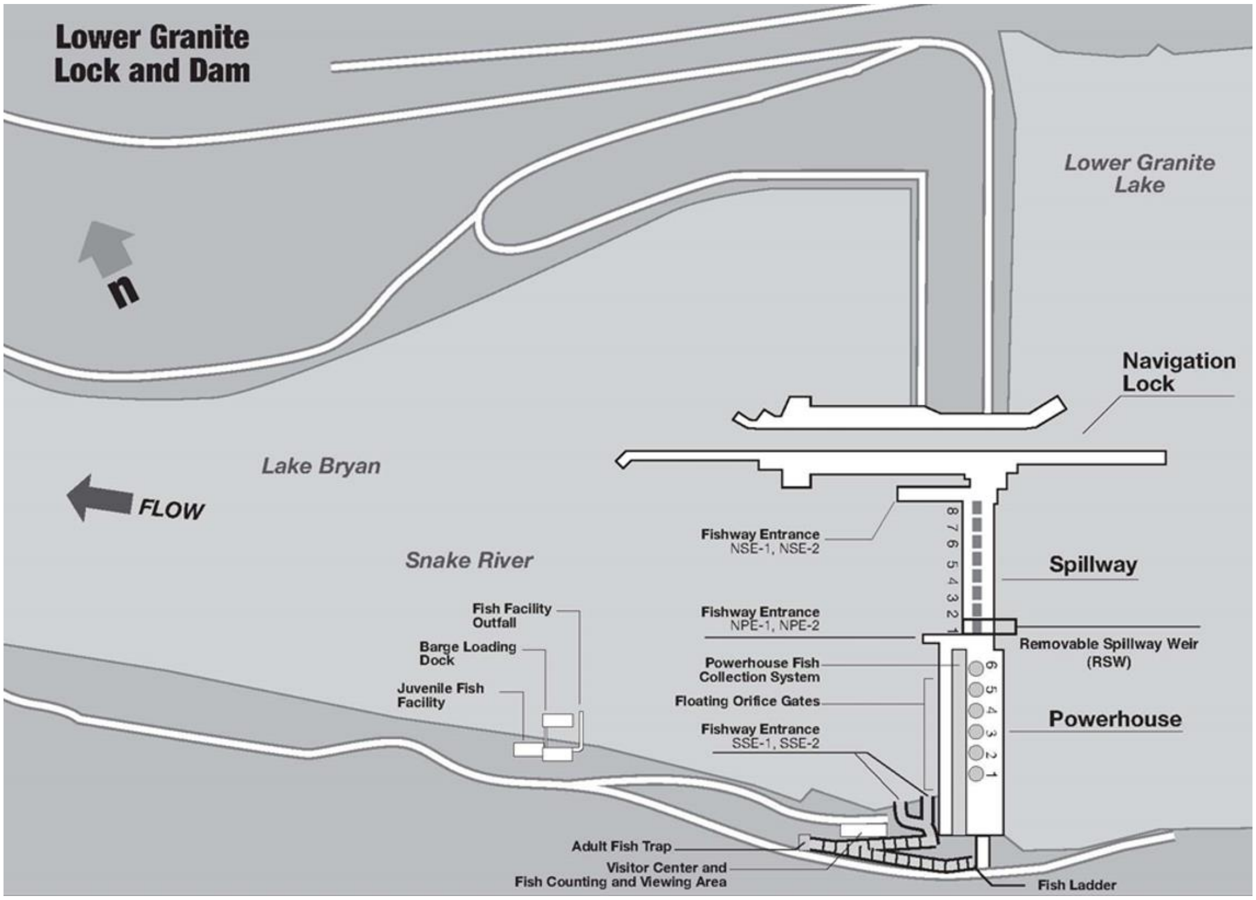
Correlate passage and post-passage behavior (i.e., after fish exit the ladder) behavior of sockeye and Chinook salmon with water temperatures in the forebay, fishway exit, and other influential hydraulic conditions related to the TCS

2. Evaluate whether summer steelhead (O. mykiss) exhibit jumping behavior onto the trash shear boom during TCS operations

1.4 Study Location

All study activities occurred at LGR which is located in Washington State along the Snake River at the upstream end of Lake Bryan. The project provides hydroelectric generation, navigation, recreation, and incidental irrigation. From north to south the primary structures of the project include a navigation lock, an eight-bay spillway, and a six-unit powerhouse. The project has a fishway and ladder that exits on the south side of the powerhouse near the south shore (Figure 1).

Figure 1
Plan View of Lower Granite Dam Showing the Major Structures and Fish Passage Facilities



2 Materials and Methods

The Materials and Methods section of the report covers specific monitoring activities, data management, quality assurance and quality control (QA/QC) procedures and statistical analyses associated with the evaluation. The methods used for sound and vibration monitoring are described briefly in this report and comprehensively in the Sound and Vibration Characterization Report (Anchor QEA et al. 2017).

2.1 Monitoring Activities

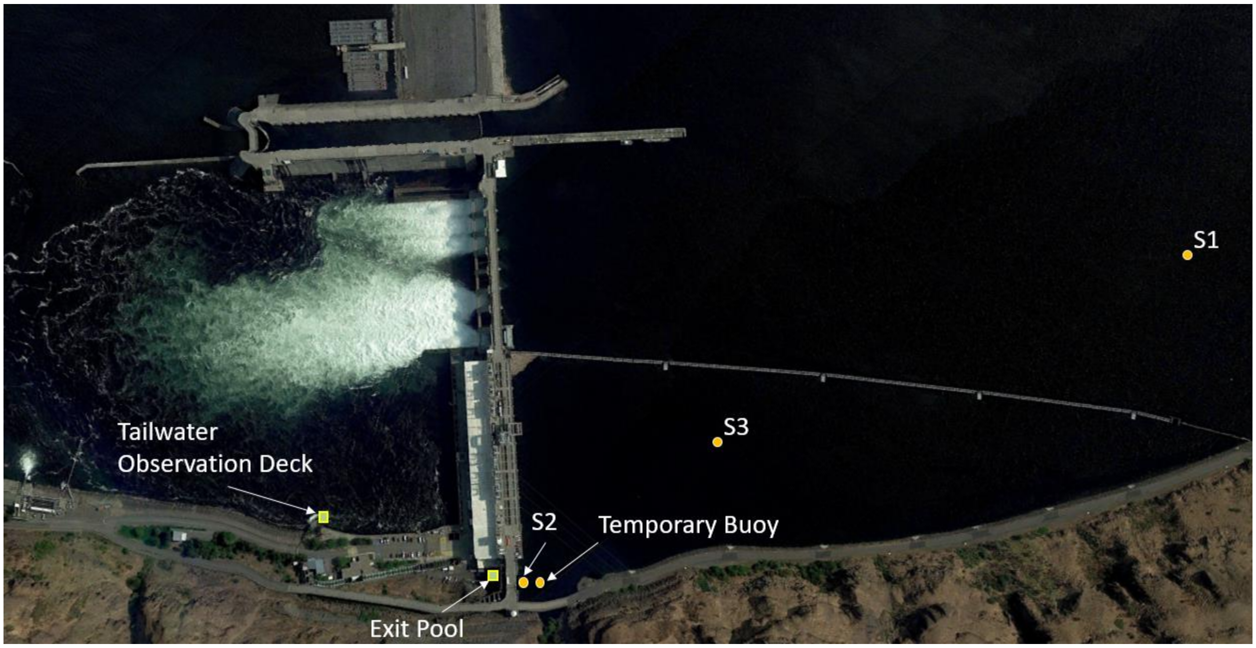
2.1.1 Water Temperature

Water temperature data compiled for the project consisted of water temperatures from the fishway and water column temperature profiles collected within the forebay.

Fishway temperature data were provided by the USACE from four locations: fish ladder entrance, turn pool, diffuser 14, and at the ladder exit pool. In 2016, a temperature sensor was also deployed in the tailwater downstream of the ladder entrance (see Tailwater Observation Deck in Figure 2). Forebay temperature monitoring was conducted using a series of thermistor strings near the ladder exit. The strings included one temporary string installed for the current study and three existing strings (S1, S2, and S3) that had been deployed previously by the USACE (Figure 2). Thermistor string S2 is suspended from the dam face near the ladder exit from existing trolley pipes; thermistor strings S3 and S1 are suspended from buoys located upstream approximately 750 and 2,500 feet from the dam face respectively (Figure 2). Thermistor string S1 has been in operation since 2004, while S2 and S3 were installed in April 2016.

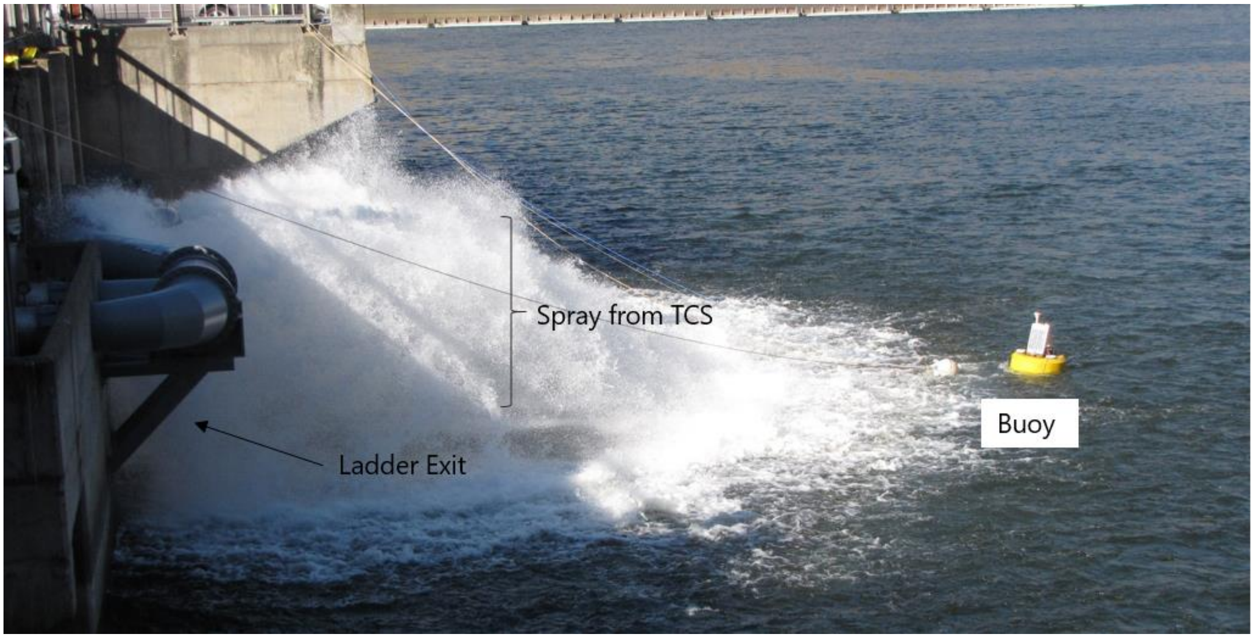
The temporary string was installed approximately 45 feet (15 meters) into the forebay from the TCS and was supported by a buoy (Figure 3). The buoy was held in position by cables tied to the dam face, and two 80-pound anchors on the bottom upstream of the buoy. The thermistor string had 12 sensors spaced at approximately 10-foot intervals with the topmost sensor placed 1.6 feet below the water surface. A pressure sensor was installed near the bottom of the thermistor string to provide water depths.

Figure 2
Relative Locations of Temperature Sensors Used for Monitoring in 2015 and 2016



Note:
Tailwater Observation Deck and Temporary Buoy locations were only active in 2016

Figure 3
Photograph of Temperature Monitoring Buoy Installed at the Edge of the Spray Environment



2.1.2 Adaptive Resolution Imaging System

2.1.2.1 System Deployment

An Adaptive Resolution Imaging System (ARIS) model 1200 (Sound Metrics Corp.) coupled with an X2 dual-axis rotator (Sound Metrics Corp.) was used to monitor post-passage behavior of adult salmonids at the LGR fishway exit. The components of the monitoring system included the ARIS sonar head, X2 rotator, 150-foot ARIS data transmission cable, control module, Ethernet cable, and laptop computer loaded with ARISScope data acquisition software. The ARIS/rotator assembly was attached to the bottom of 80 feet of steel pipe and lowered down an existing trolley pipe (Figure 4) located near the north edge of the fishway exit to a depth of 61 feet. Topside electronic components were housed in a weather-proof environmental box placed along the hand rail in front of a parking space near the fishway exit and powered using a dedicated outlet provided by the LGR project. To keep the electronic components from overheating, the environmental box was covered in heat-reflecting material and electric fans were used to circulate and cool the air inside the box. The system was initially deployed on June 20, 2016. Testing and preliminary data collection was conducted June 20 and 21, and system configuration and setup were finalized at 14:00 hours on June 22.

Figure 4
Photograph Showing Deployment of the ARIS/rotator Assembly Through the Trolley Pipe Adjacent to the North Edge of the Fishway Exit

2.1.2.2 Data Collection and Sampling Design

The ARIS sonar head was aimed up along the dam face and panned over 5.63 degrees to place the fishway exit area into the center of the field of view (FOV) to allow for near equal sample volume coverage on each side of the exit (Figure 5). The rotator was programmed to sample five separate tilt-rotation positions each hour to allow for sampling fish behavior immediately upon exiting the fishway and in the near-forebay environment. Assessment of exit behavior was emphasized so Position 1 (which placed the FOV along the dam face) was sampled for 20 minutes each hour whereas Positions 2 through 5 were each sampled for 10 minutes per hour (Table 1; Figure 6). ARIS data were collected continuously from June 22 through September 20, 2016, using the 1.2 megahertz (MHz) operating frequency. Data were ported directly to 3 GB external hard drives, and drives were changed out daily, typically between 06:00 and 07:00 hours. Data were backed up and archived daily to additional hard drives, and data were uploaded to a server on a weekly basis.

Figure 5
Still Image of ARIS Field of View in Position 1 Showing the Water Surface and the Location of the Fishway Exit

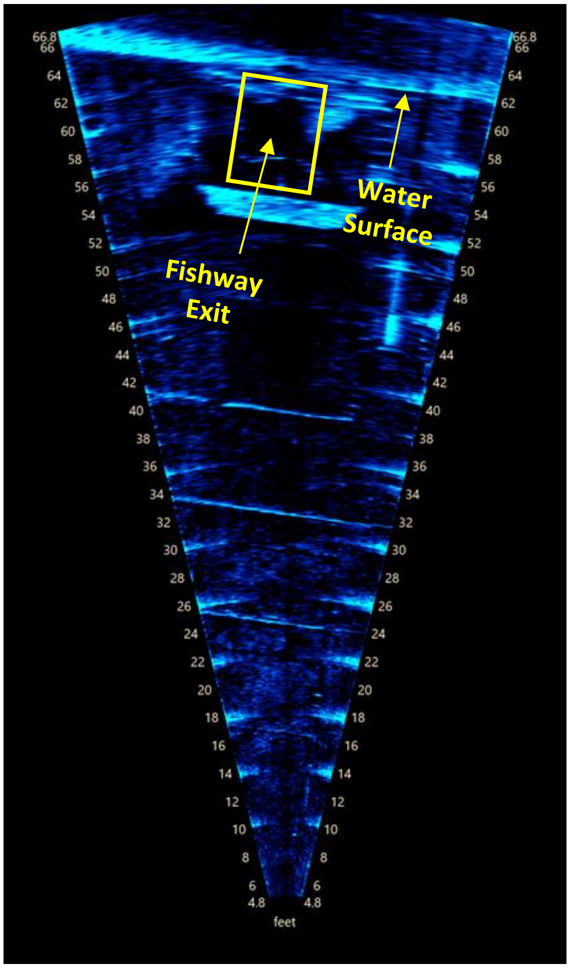
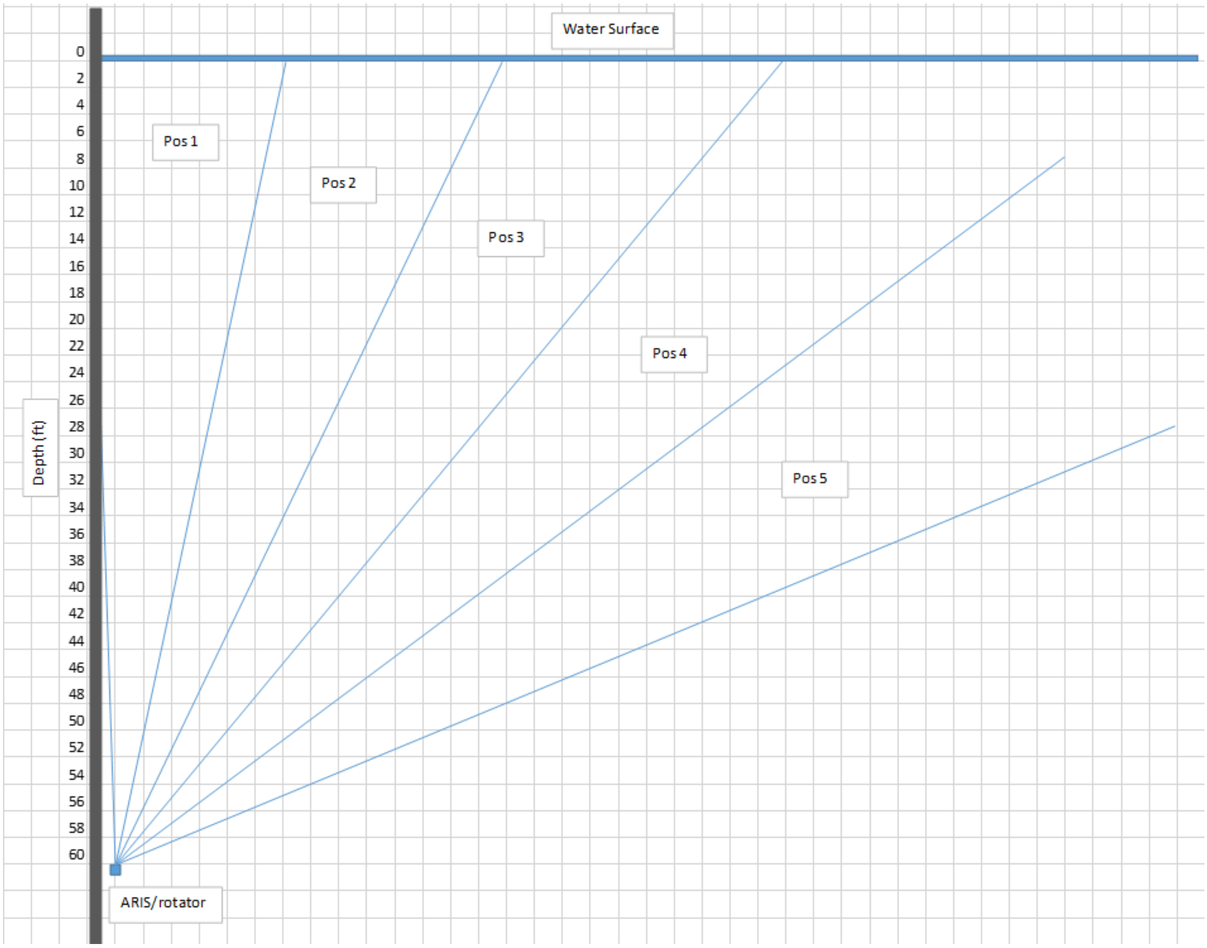


Table 1
ARIS Data Collection Parameters for Each Rotational Position Used at Lower Granite Dam in 2016

Position	Pan Angle (degrees)	Tilt Angle (degrees)	Within-hour Time (min:sec)	Minimum Range from Sonar (feet)	Maximum Range from Sonar (feet)	Minimum Theta (degrees)	Maximum Theta (degrees)
1	5.6	5	00:00 to 19:59	4.8	65.5	-13.7	13.7
2	5.6	19	20:00 to 29:59	4.8	66.5	-13.7	13.7
3	5.6	33	30:00 to 39:59	4.8	71.3	-13.7	13.7
4	5.6	47	40:00 to 49:59	4.8	85.3	-13.7	13.7
5	5.6	61	50:00 to 59:59	4.8	86.0	-13.7	13.7

Figure 6
ARIS Sample Volume Coverage Showing the Side View for Each of the Five Rotational Positions in the Near-forebay of Lower Granite Dam



Note:
The edge of the dam is depicted by the vertical gray rectangle. Each grid is equal to 2 x 2 feet.

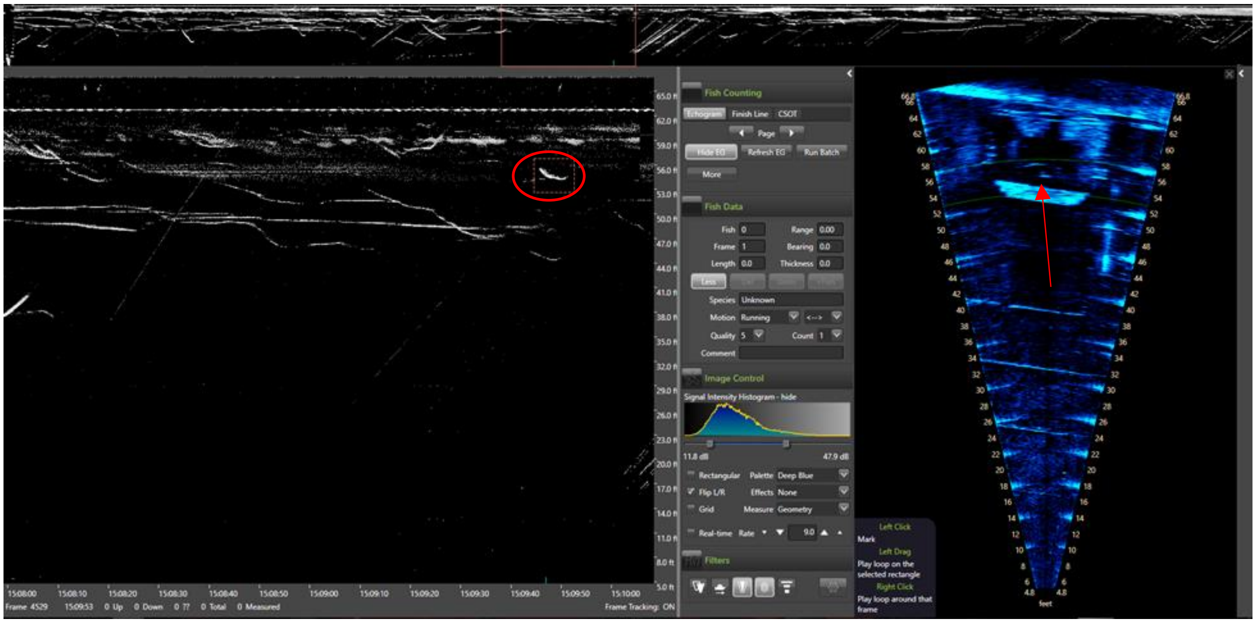
2.1.2.3 Data Processing

Five hours of data were subsampled each day based on a hybrid balanced systematic/randomized design. Given that prior studies conducted at LGR indicated that most adult salmonids pass the project between 08:00 and 17:00 hours (Keefer and Caudill 2008), processing those hours were emphasized. However, USACE was also interested in assessing passage during some crepuscular hours throughout the study, which led to the following subsampling scheme. On alternating days, odd or even hours were processed. For days in which odd hours were processed, four of the five hours selected were for example 09:00, 11:00, 13:00, 15:00 on day 1; 11:00, 13:00, 15:00, 17:00 on day 3; 13:00, 15:00, 17:00, 09:00 on day 5; 15:00, 17:00, 09:00, 11:00 on day 7 and so forth. For days in which even hours were processed, four of the five hours selected were for example 08:00, 10:00, 12:00, 14:00 on day 2; 10:00, 12:00, 14:00, 16:00 on day 4; 12:00, 14:00, 16:00, 08:00 on day 6; 14:00, 16:00, 08:00, 10:00 on day 8 and so forth. For days in which odd hours were processed the fifth hour was randomly selected among 07:00, 19:00 and 21:00; for days in which even hours were processed the fifth hour was randomly selected among 06:00, 18:00 and 20:00. For each hour of the five sub-sampled hours per day the entire hour of ARIS data was processed and used in the analysis.

Data processing involved reviewing data files using the ARISFish (Sound Metrics Corp.) software program. Files were reviewed by presenting the data in both echogram and raw imagery formats (Figure 7). An echogram is a visual representation of an entire image file compressed so that each pixel along the horizontal axis represents a single frame. Fish that swim across the FOV show up as traces, and these traces indicate the location of fish to be processed. Echogram mode allows for examination of large portions of the data file at once (as opposed to having to review entire files in raw imagery mode) increasing the efficiency of the review process. The raw imagery format presents the data in streaming form against the 29 degree FOV. Though the ARIS samples a three-dimensional volume that includes a 14-degree 'thickness' component, the data are limited to two dimensions as the 'thickness' component is spatially compressed.

When a fish trace was observed, the trace was framed with the cursor to prompt that portion of the file to be replayed in imagery mode. Characteristics of the selected fish could then be assessed to determine if that fish should be processed further. Estimated fish size and the occurrence of schooling behavior were the primary criteria for determining whether the fish should be included in the data set. Schooling behavior was assessed as a method of identifying American shad (which were excluded from the analysis), as this species is known to exhibit schooling behavior as migrating adults whereas adult salmonids do not. Schooling was defined as three or more fish swimming in the same direction in a coordinated way. Total length of each fish was estimated using a software sizing tool. All fish that did not exhibit schooling behavior and were greater or equal to 16 inches in estimated total length were included in the data set.

Figure 7
Screenshot of ARISFish Data Processing Software Showing the Echogram (left) and Raw Imagery Data (right)



Frame 4529 15:09:53 0 Up 0 Down 0 ?? 0 Total 0 Measured
Frame Tracking: ON

Fish 0
Range 0.00
Frame 1
Bearing 0.0
Length 0.0
Thickness 0.0
Species Unknown
Motion Running <-->
Quality 5
Count 1
Comment
☐ Rectangular
Palette Deep Blue
☑ Flip L/R
Effects None
☐ Grid
Measure Geometry
☐ Real-time
Rate 9.0

Note:
An example fish trace is shown on the echogram (indicated by red oval) and that same fish is shown exiting the fishway in the raw imagery data (indicated by the red arrow).

For each fish that met the above criteria, first and last detection locations and estimated total length data were noted and marked in ARISFish. The first and last detection locations reflected the locations in which fish first entered and exited the FOV and indicated out-range (meters) from the ARIS sonar head and angle (theta) off axis (degrees). For each file processed, a comma separated variable (CSV) file was created that included these variables as well as date and time stamps associated with each marked fish. The CSV files were then uploaded to a SharePoint site where they were backed up to the project database daily.

For data files collected using Position 1 (along the face of the dam), data processing efforts were focused on fish that entered the FOV upon exiting the fishway to assess post-passage directional movement patterns. For data files collected using Positions 2 through 5, data processing included fish observed throughout the FOVs to assess depth distribution patterns of fish in the near-forebay environment.

2.1.2.4 Post-Processing

After ARIS data were processed to obtain fish observations the database was post-processed to prepare the data for analysis. Post-processing included assignment of study week (Table 2), calculation of minimum and maximum depths associated with range-from-sonar fish locations, calculation of a spatial expansion factor to account for variable FOV width by range, assignment of fish species based on length estimates for conducting species-specific analysis, and assignment of location bins associated with each rotational position FOV to allow for assessment of proportional frequency distributions.

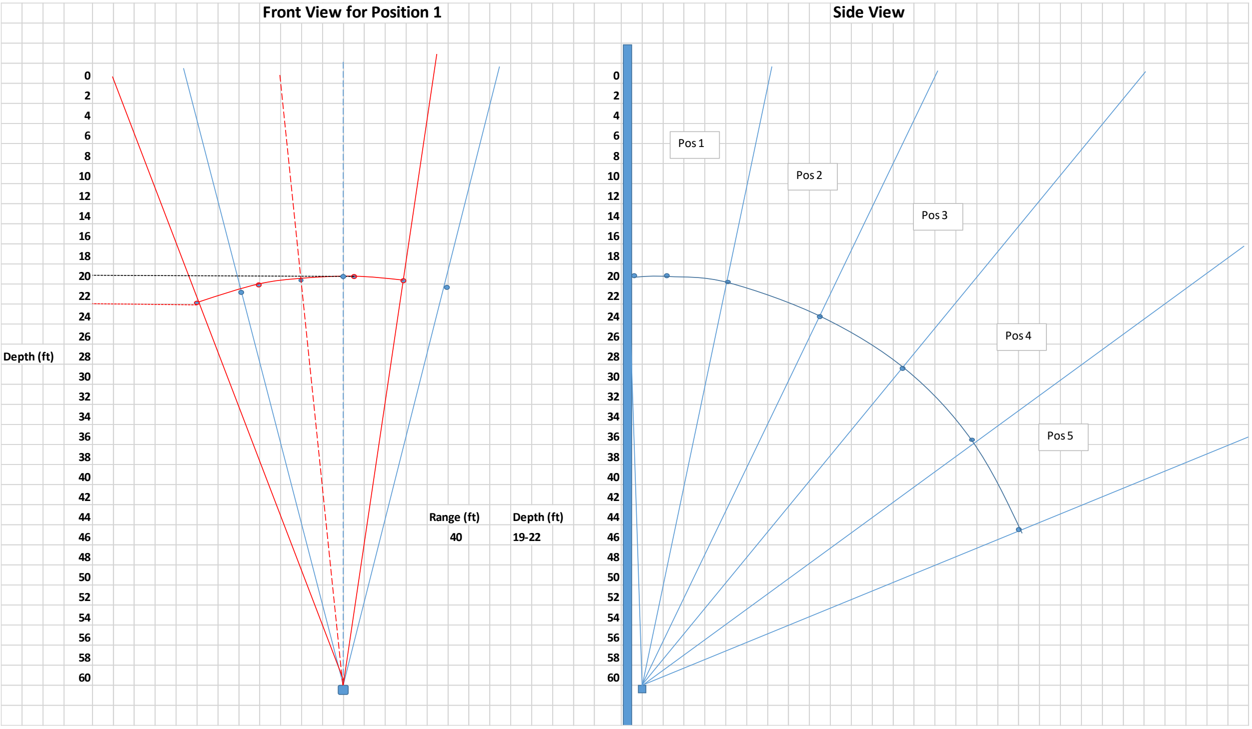
Table 2
Study Weeks as Defined by Dates Within the 2016 Study Period

Study Week	2016 Dates	Study Week	2016 Dates
1	20 Jun – 25 Jun	8	7 Aug – 13 Aug
2	26 Jun – 2 Jul	9	14 Aug – 20 Aug
3	3 Jul – 9 Jul	10	21 Aug – 27 Aug
4	10 Jul – 16 Jul	11	28 Aug – 3 Sep
5	17 Jul – 23 Jul	12	4 Sep – 10 Sep
6	24 Jul – 30 Jul	13	11 Sep – 17 Sep
7	31 Jul – 6 Aug	14	18 Sep – 20 Sep

2.1.2.4.1 Range to Depth Conversions

Fish positions within the volume monitored by the ARIS are recorded as two-dimensional projections onto a plane oriented perpendicular to the direction of flow cut through the center of the ARIS FOV. Each fish position is presented relative to the position of the sonar in polar coordinates as range from the sonar unit (termed herein as range to target) and degrees off the main axis (termed herein as theta). Because the fish positions are recorded as projections on a two-dimensional plane, it is not possible to definitively determine the depth within the water column at which the fish was observed because a given range to target and theta define a range of depths depending on which rotational position the ARIS occupied at the time the fish was observed. This is depicted in the right panel of Figure 8 which shows the range of depths defined by a fish observed at a range to target of 40 feet. The pan angle of the ARIS unit (i.e., 5.63 degrees) introduces additional uncertainty in the depth of observed fishes as shown in the left panel of Figure 8. The procedure outlined below was used to correct for the pan angle and compute the range of depths for each fish position.

Figure 8
Scaled Figure Highlighting the Range of Depths Associated with a Target 40 Feet in Range from the Sonar



Notes:
Panel on the left depicts the elevation perspective field of view (FOV) obtained with rotational Position 1 in red (it is offset by the pan angle of 5.6 degrees relative to a vertical orientation FOV shown in blue). The red arc indicates the range of depths associated with a target observed at 40 feet in range. Panel on the right shows the side view for each of the five rotational positions. The blue arc indicates the range of depths associated with a target at 40 feet of range across all rotational positions for a pan angle of zero (the plot does not consider the effect of the 5.6-degree pan angle on the range of depths.
ft: feet
pos: position

First, ARIS fish positions were converted from polar coordinates to Cartesian coordinates. (i.e., x and y where x is the lateral position relative to the sonar and y is the vertical position relative to the sonar on the two-dimensional plane representing the ARIS FOV) with the sonar at the origin of the Cartesian plane. As previously discussed, this Cartesian plane is rotated 5.6 degrees to the left due to the sonar pan angle. This rotation was removed from the data by projecting Cartesian fish positions onto a plane with the y-axis oriented vertically in the water column using Equation 1.

Equation 1

$$\begin{bmatrix} x_2 \\ y_2 \end{bmatrix} = \begin{bmatrix} \cos 5.63° & -\sin 5.63° \\ \sin 5.63° & \cos 5.63° \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ y_1 \end{bmatrix}$$

where:

x_1, y_1 = the Cartesian coordinates of the fish position relative to the sonar (i.e., with the 5.6-degree pan angle)

x_2, y_2 = Cartesian coordinates of the fish position with y-axis oriented vertically in the water column

Equation 1 corrects for the ARIS pan angle and removes the depth uncertainty depicted in the left panel of Figure 8. The second step in the process was to determine the minimum and maximum depths represented by each ARIS fish position corrected for pan angle (using Equation 1). Minimum and maximum depths were determined by first observing that each y coordinate exists within a range of depths defined by the rotational position of the ARIS at the time the fish was observed. Table 3 shows the minimum and maximum angles of the sample volume for each ARIS rotational position.

Table 3
Minimum and Maximum Angles of the Field of View for Each Rotation Position

Rotational Position	Rotator Tilt	Field of View Extents (feet) Minimum	Field of View Extents (feet) Maximum
1	5	0	12
2	19	12	26
3	33	26	40
4	47	40	54
5	61	54	68

Minimum and maximum depths (feet) for each fish position were computed using Table 3 to lookup the minimum and maximum view extents for the rotational position at which the fish was observed and then plugging these into Equations 2 and 3, respectively, to determine minimum and maximum depths for each fish position in the ARIS dataset.

Equation 2

$$Depth_{min} = Depth_{ref} - y_2 \times \cos(\emptyset_{min})$$

where:

$Depth_{ref}$ = the depth of the ARIS unit below the water surface (i.e., 61 feet)

y_2 = the y coordinate of the fish position corrected for the ARIS pan angle (from Equation 1)

φ_{min} = the extents of the field of view as defined by the tilt angle (Table 3)

Equation 3

$$Depth_{max} = Depth_{ref} - y_2 \times \cos(\emptyset_{max})$$

where:

$Depth_{ref}$ = the depth of the ARIS unit below the water surface

y_2 = the y coordinate of the fish position corrected for the ARIS pan angle (from Equation 1)

φ_{max} = the extents of the field of view as defined by the tilt angle (Table 3)

2.1.2.4.2 Spatial Expansion Factor

Each fish observation was spatially expanded using Equation 4, which is based on the acoustic screen model (Ploskey et al. 2002) to account for variability of ARIS FOV width by range. The expanded fish variable was used for calculation of mean depths for fish exit locations as applied to the analysis of covariates. The expansion was based upon the ratio of the maximum width of the FOV to the width of the FOV at the range of detection:

Equation 4

$$EXP_{Fish} = MAX_{Width}/[MID_R x\ TAN\left(\frac{FOV_{Angle}}{2}\right) x\ 2]$$

where:

MAX_{Width} = maximum width of field of view in meters (13)

MID_R = mid-point range of a fish in meters

TAN = tangent

FOV_{Angle} = angle of field of view in degrees (29)

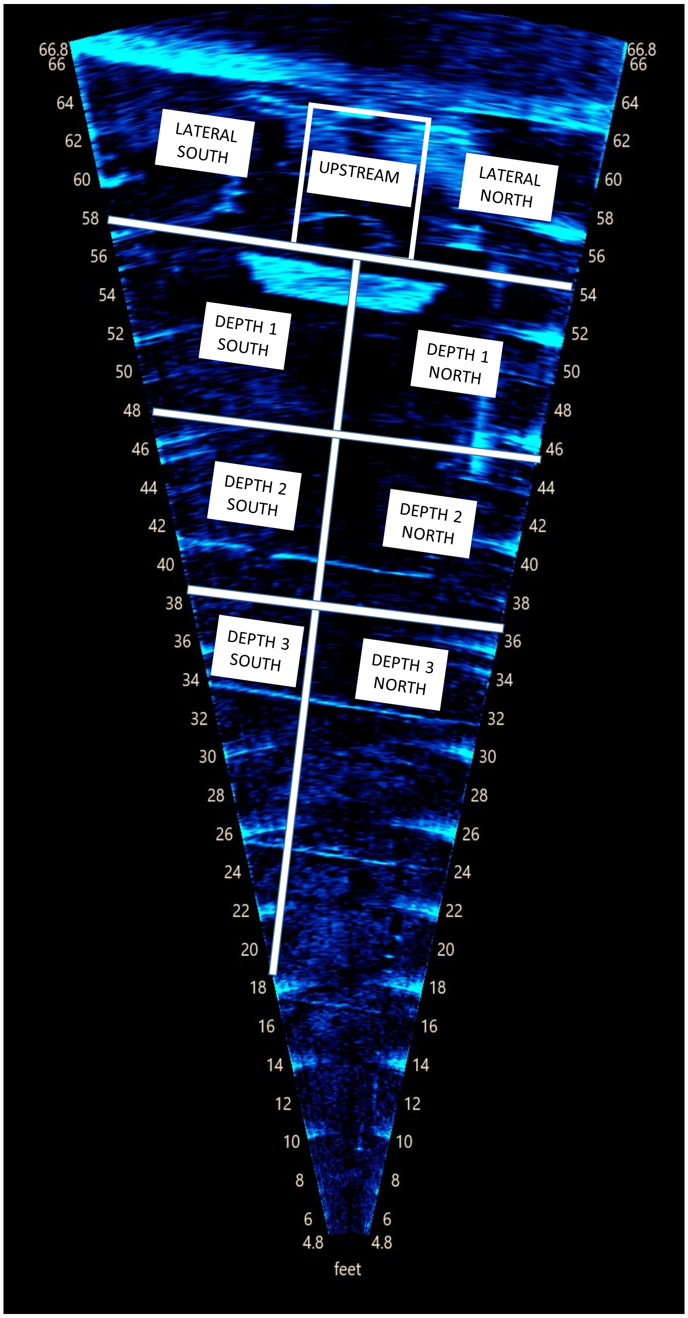
2.1.2.4.3 Species-specific Analysis

Imaging sonar data does not typically allow for identification of species, especially among species with similar body shapes and swimming behaviors. Therefore, post-passage fish behavior relative to specific stocks of Pacific salmonid species was assessed using run-timing data from window counts (see Section 3) and estimated size of individual fish observed with ARIS. Technical reports and agency memorandums were used to obtain general length distributions based on fork length for adult sockeye and Chinook salmon, steelhead, and American shad in the Columbia and Snake rivers for use in classifying ARIS observed fish: adult sockeye salmon typically range in size from 16 to less than 24 inches (USBR et al. 1994; Naughton et al. 2004); adult Chinook salmon from 24 to 36 inches (Bjornn et al. 1992; WDFW 2016); steelhead from 20 to 36 inches (Keefer et al. 2002; Crawford and Herr 2014); jack Chinook from 16 to 24 inches (WDFW 2010; WDFW 2016); and American shad from 15 to 17 inches in length (USACE 2017). Based on the general length distribution data, the following classifications were defined: sockeye-sized fish (greater than 16 to less than 24 inches); adult Chinook salmon-sized fish (greater than 24 inches); and steelhead-sized fish (greater than 24 inches). Species assignments were applied to fish observations that occurred during the middle 90% of the sockeye and summer Chinook salmon runs and the entire fall Chinook salmon run through the study period. The portion of the steelhead run assessed (78%) coincided with the fall Chinook salmon run that started August 18 (see Run-timing results in Section 3.1.1). As stated above American shad could not be separated out from the salmonids using size alone. Instead a combination of size and occurrence of schooling behavior was used to determine whether the fish should be included in the data set. Schooling behavior was defined as three or more fish swimming in the same direction in a coordinated way. All fish that did not exhibit schooling behavior and met the size criteria of greater than or equal to 16 inches in estimated total length were included in the data set.

2.1.2.4.4 Fish Location Bins

For rotational Position 1, sections of the FOV were binned to allow for assessing proportional distributions of ladder-exit-origin fish based on their last detected positions (Figure 9). The bins reflect various lateral and depth zones, as well as one labeled ‘upstream’ which indicates a zone in which fish were observed to move directly upstream after exiting the fishway.

Figure 9
Still Image of ARIS Field of View Showing Discrete Location Bins Used to Assess Distributions for Exit Locations of Fish that Entered the Field of View Upon Exiting the Fish Ladder



2.1.3 PIT Tag Data Collection

The adult fish ladder at LGR has had PIT detection capabilities dating back to 1988. The first year of International Organization for Standardization (ISO) detection was in 2000, and slotted weir detectors were activated in 2003, leading to the array configuration in place until 2016. Under this configuration, more than 150,000 PIT-tagged fish were detected in the fishway, largely comprising summer-run steelhead and hatchery-origin fall-run and spring-run Chinook salmon. During the 2015/2016 dewatering period, two additional antenna groups were installed near the fishway entrance and exit (Figure 10). The project database and integration with PIT Tag Information Systems (PTAGIS) was used to monitor fish passage and behavior further detailed in the description of statistical analyses.

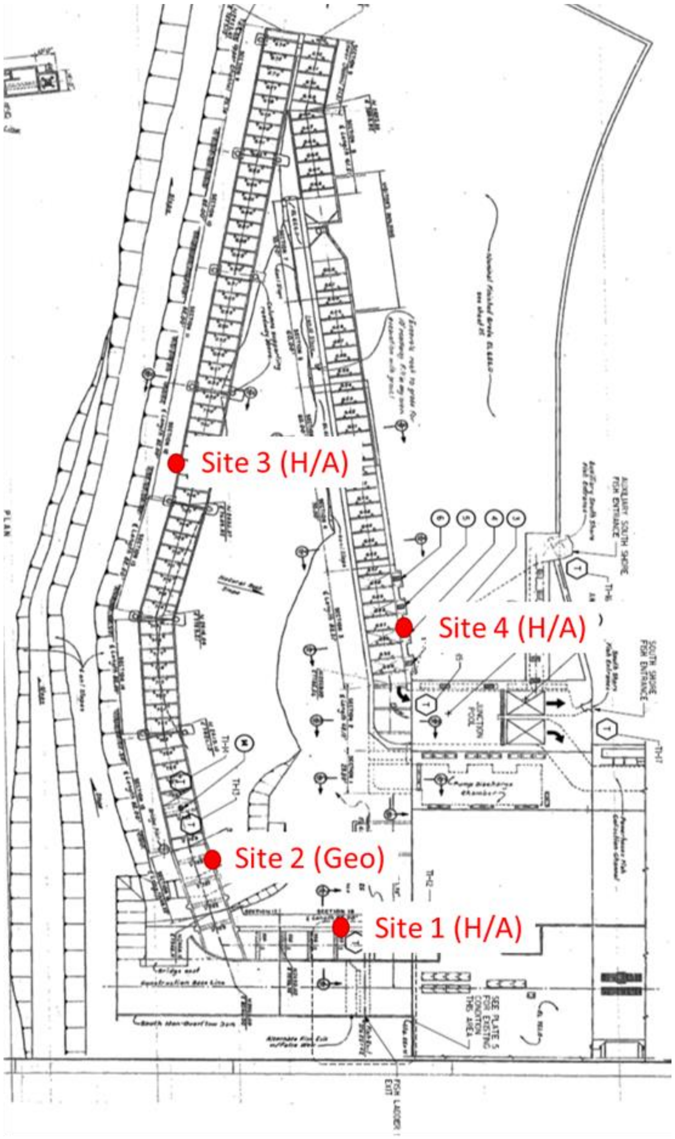
Figure 10
New PIT-detection Arrays in the Lower and Upper Lower Granite Dam Fishway, 2016

2.1.4 *Sound and Vibration*

The methods described here are taken from the Lower Granite Sound and Vibration Characterization Report (Anchor QEA et al. 2017). Sound and vibration monitoring began in July 2015 and then took place concurrently with the Adult Post-passage Study in 2016. For a complete description of the sound and vibration monitoring methods, refer to Anchor QEA et al. (2017).

Low-frequency sound and vibration levels were monitored in the adult fishway at LGR to characterize background levels and to better understand whether construction activities would produce levels that could affect fish movement and possibly cause delays in the adult fishway. Sound and vibration monitoring occurred from July 13, 2015, through September 30, 2016. The movement of the adult fishway concrete walls was measured using accelerometers to estimate the particle motion component of sound that might be detected by upstream migrating adult salmonids as they ascended the adult fishway. Hydrophones were also deployed in the adult fishway to monitor sound pressure, and a geophone was deployed to monitor sound levels in the ground near the fishway from construction activity for correlation with sound and vibration detected in the fishway. The locations of sound and vibration monitoring equipment are provided in Figure 11.

Figure 11
Schematic Plan View of the Adult Fishway at Lower Granite Dam on the Snake River Showing Locations of Sound and Vibration Monitoring Equipment



Note:
The three locations of the hydrophones and accelerometers are denoted by a red "H/A," and the single geophone location is marked by a red "Geo."

After an initial review of accelerometer, hydrophone, and geophone data, it was determined that only the vibration measurements collected with the accelerometers were useful for further evaluation, in part because they best represented the particle motion component of sound which salmonids are most responsive to.

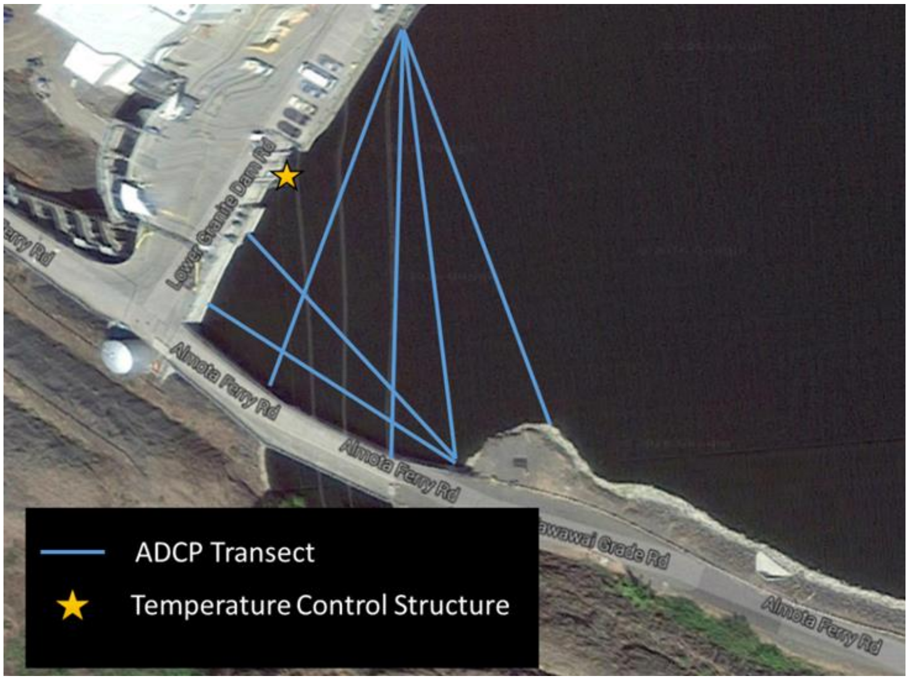
2.1.5 Acoustic Doppler Current Profiler

Water velocity data near the TCS were obtained on July 6, 2016, using an RDI Workhorse Rio Grande Acoustic Doppler Current Profiler (ADCP; Figure 12) mounted on an Ocean Science Trimaran. Sampling was conducted along multiple transects (Figures 13 and 14) during two periods in which the TCS was operational and after it was turned off (see Section 3.1.4). Following field sampling, the ADCP data were processed to create vertical profiles of velocity gradients.

Figure 12
Photograph Showing Acoustic Doppler Current Profiler Unit Mounted on a Trimaran

Figure 13
Acoustic Doppler Current Profiler Sampling in Lower Granite Dam Forebay

Figure 14
Locations of Acoustic Doppler Current Profiler (ACDP) Sampling Transects Within Lower Granite Forebay and Relative to Temperature Control Structure

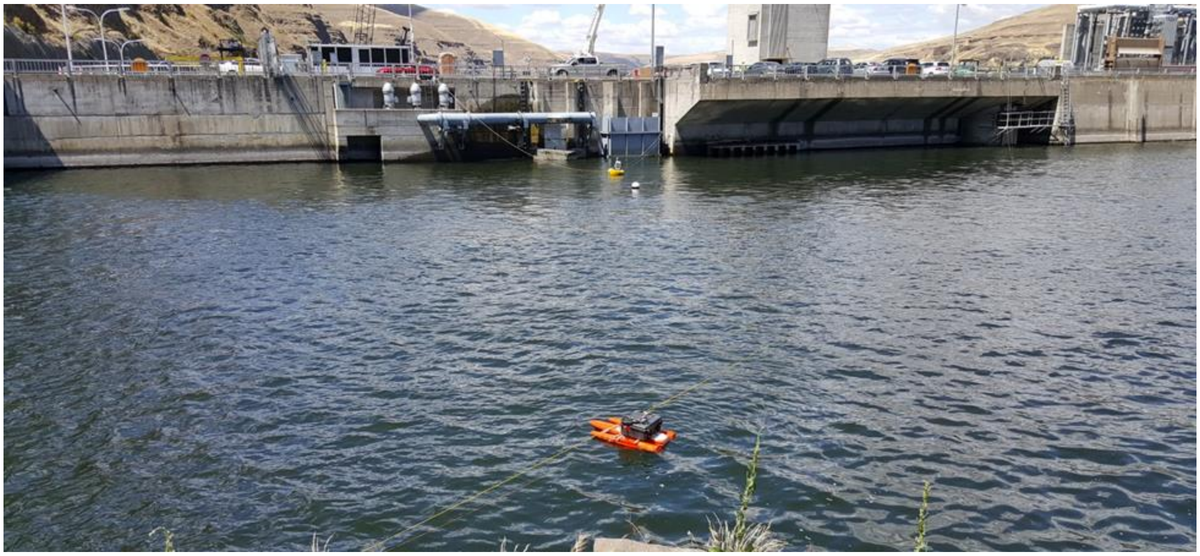


2.1.6 *Temperature Control Structure Operations*

The USACE provided Anchor QEA with operational data to describe the periods when the TCS was turned on or off (Figures 15 and 16). The TCS operational data were used in conjunction with ARIS, temperature, and ADCP results to characterize the behavior of salmon and steelhead exiting the fishway as well as the physical environment in the LGR forebay.

Figure 15
Photograph of Temperature Control Structure Turned On

Figure 16
Photograph of Temperature Control Structure Turned Off



2.1.7 Video Camera Evaluation of Jumping Behavior

A total of four video cameras were installed to document whether summer steelhead exhibited jumping behavior onto the trash shear boom during the TCS operations. The video cameras were mounted on a steel plate (Figure 17) that was lowered into position behind the TCS (Figure 18). Video cameras were run continuously from July 18, 2016, through the completion of TCS operations on September 8, 2016. Video data were recorded on a hard-drive which was subsequently downloaded weekly (Figure 19). A subsample of the video footage was reviewed to look for the presence of jumping steelhead. The subsample focused on periods of time when steelhead would be leaving the fish ladder and traveling under the TCS during operations. Specifically, steelhead PIT-tag passage data were evaluated to determine when peak passage dates and times occurred at the LGR fish-ladder exit and footage from these periods was reviewed by an observer.

Figure 17
Photograph of Video Cameras Mounted on Steel Brackets

Figure 18
Field of View of Video Cameras Relative to the Temperature Control Structure, Trash Shear Boom, and Fish Ladder Exit at Lower Granite Dam

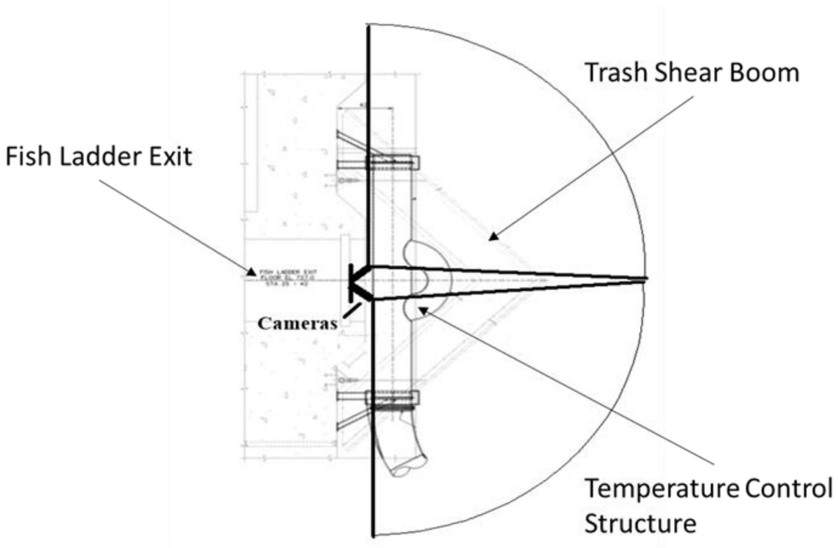


Figure 19
Photograph of Video Recorder and Controller for Camera System

2.2 Data Management

Data compiled for the study were stored in a central relational database run on Microsoft's SQLSERVER, hereafter identified as the LGR Adult Passage Database (LAPDB). The LAPDB was deployed on a server at Anchor QEA's data center with direct access provided to project staff through network connection. Study data were routinely loaded to the LAPDB using a variety of custom routines that pulled data from public web services (e.g., PTAGIS), or custom data infrastructures. Reporting interface queries were established to provide analysts with data reports directly from the LAPDB over the network.

2.2.1 Water Temperature

Water temperature data from the fish ladder were provided by USACE as Microsoft Excel files which were posted to a project data Dropbox and loaded to the project database via automated data loading procedures. Forebay temperature data were taken directly from the USACE website and loaded into the project database. Data from the temporary temperature string were transmitted directly to the project database via a satellite modem.

2.2.2 Adaptive Resolution Imaging System

Raw ARIS data were physically downloaded from the site weekly to hard drives and shipped to Anchor QEA's office in Seattle, Washington. Once at Anchor QEA's office, raw data were archived and secured on Anchor QEA's network. Project analysts accessed the raw data over Anchor QEA's network and processed the data using ARISFish software (Section 2.1.2.3) into fish track files that contained the fish tracks identified for a given monitoring day. Each fish track record contained the position of the fish when it entered and exited the FOV, along with observation time, rotator position, and size of target. Processed fish track files were posted to a shared network location where automated data loading procedures checked the files for consistency and loaded them to the project database.

2.2.3 Fish Passage Data

Fish passage data compiled in the project database consisted of PIT-tag detections and fish window counts from the LGR adult fish ladder and fish tracks from the ARIS deployed to monitor the forebay near the ladder exit. PIT-tag detection data were managed through integration with PTAGIS. Automated queries were established in PTAGIS to obtain LGR adult ladder detection data files from the PTAGIS database daily. An automated data acquisition system obtained the daily PTAGIS data files via the PTAGIS file transfer protocol (FTP) site and loaded the data to the LAPDB. Daily fish window counts were obtained through a similarly automated system that queried a USACE website for adult fish counts at LGR and loaded the data to the database each day.

2.2.4 Vibration Data

Vibration data were physically downloaded from the site each week and brought to the Pacific Northwest National Laboratory (PNNL) in Kennewick, Washington, for processing. To support weekly reporting requirements during the study, data were processed into weekly files that contained key parameters as 1-minute averages reported for every-other minute. Each week, processed vibration data files were posted to a project data Dropbox where automated procedures ran routine checks on the data and loaded it to the project database. Raw data were reprocessed for final reporting into 4-hour averages; data treated in this way were also loaded to the project database.

2.2.5 Operational Data

Operational data compiled for the project included dam operations and daily construction logs provided by USACE. Dam operations data were provided by USACE as Microsoft Excel files. These data consisted of forebay/tailwater elevations and turbine/spillway flows at 5-minute intervals. Operations data were posted to the project data Dropbox where automated data loading procedures loaded the data to the project database.

Daily construction logs provided by USACE were reviewed weekly to determine the construction activities that took place each day. Construction activities described in the daily logs were transcribed to Excel spreadsheets that documented the activities performed and in which shift (i.e., night or day) they were performed in a tabular form. The Excel spreadsheets were used to load the construction information into the database.

2.3 Quality Assurance/Quality Control

2.3.1 Water Temperature

The temperature sensors used in the temporary string were factory calibrated and certified for an accuracy of +/- 0.075 °F covering a water temperature range of 33.13 to 103.50 °F. Data quality from the temperature sensors was checked weekly by comparing paired temperature data from the buoy to data collected by the temperature string (S2) suspended from dam face near the ladder exit.

The depth sensor calibration was tested in the field by attaching the sensor to a tape measure which was lowered from the dam face at approximately 10-foot increments going down 65 feet and the corresponding reading from the depth sensor was compared at each 10-foot increment. No refinements to the factory calibration were necessary.

2.3.2 Adaptive Resolution Imaging System

Prior to the start of data collection, the ARIS system and the AR2 rotator were serviced by Sound Metrics Corp. which included performing a series of maintenance tests to check that the components were fully functional and ready for deployment. Once data acquisition was under way, the ARIS data collection system was checked by an on-site biologist twice each day (in the morning and afternoon) throughout the study period to monitor the system for maintenance and functionality. Each system check was logged in a field notebook with observations regarding system status and function. When system errors occurred, the on-site biologist contacted the Principal Investigator (PI) to assess the problem and work through a solution.

The external hard drives with newly acquired data were changed out each morning and immediately backed up and archived to additional hard drives. Hard drives were kept safe by storing them in fire boxes (one box was kept on site and one box was kept off site). During the backup process the data file list was examined to confirm all the data files were present and file sizes were within the expected size ranges.

Technicians responsible for processing ARIS data were trained by the PI to make sure data processing protocols were consistently followed. Periodically through the study some data files were processed by both the technicians and the PI as a quality check on the data review process. The data review verification provided a qualitative means to check for deviations from data processing protocols, provide feedback to the technicians, and maintain consistent data review methods.

2.3.3 PIT Data Collection

Detection efficiency was monitored for the PIT antennas used during the study. The new exit antennas' detection efficiencies were calculated using fish that were known to have passed LGR based on PIT detections at upstream tributaries or other upstream detection sites. The prior detection histories of the "known" migrants were then examined to determine if they were specifically detected at the exit antennas at LGR.

2.3.4 Database

Data quality was maintained by incorporating checks and QC processes at each stage of data management. To ensure consistency in data entry operations, protocols were developed and documented for manually executed procedures. To validate the format and integrity of data before being loaded to the system, checks were built into the automated data loading systems. The sequence and details of the automated operations were recorded in log files.

2.4 Analyses

2.4.1 Water Temperature

Temperature data from sensors in the forebay and fishway were plotted to depict 1) seasonal trends and variation across different depths and locations in the forebay and fishway environments; 2) the general relationship between forebay and fishway temperatures; and 3) cooling effects of the TCS on nearfield temperatures in the vicinity of the ladder exit and within the fishway.

To estimate the general cooling effect of the TCS across a range of temperatures, a comparison was made between the difference in temperatures between the forebay (S1) and the exit pool (P1) when the TCS was not operational (2015) and when it was operational (2016). Specifically, time series of forebay surface temperatures (1.6 foot depth) and exit pool temperatures were plotted from each year and TCS "off" and "on" linear relationships were developed where forebay and exit pool temperatures were regressed against one another. Using the forebay-exit pool regressions linear equations for TCS "off" (2015) and TCS "on" (2016) were generated and used to calculate the estimated difference in temperature at the exit pool resulting from TCS operations.

2.4.2 Passage and Post-passage Evaluation

Both PIT-tag and ARIS acoustical imaging data were used to assess adult salmonid responses to temperature, vibration, and other operational covariates. PIT-tag data were used to monitor fish passage behavior within the ladder during 2015 and 2016 while the ARIS data were used to monitor post-passage behavior at the upstream exit of the ladder for 2016 only.

2.4.2.1 PIT-tag Passage Analysis

PIT-tag data analyses focused on 1) exploratory comparisons of passage metrics for all PIT-tagged fish (trapped, shunted, and free-passage) relative to temperature and vibration thresholds and 2) multiple regression analysis focusing on passage metrics and the contribution of specific covariates to explain the passage behavior of free-passage fish (see Section 2.4.2.3 Regression Approach). For 2015, PIT analyses were very limited because of the lack of PIT detection antennas at the entrance and exit of the fishway.

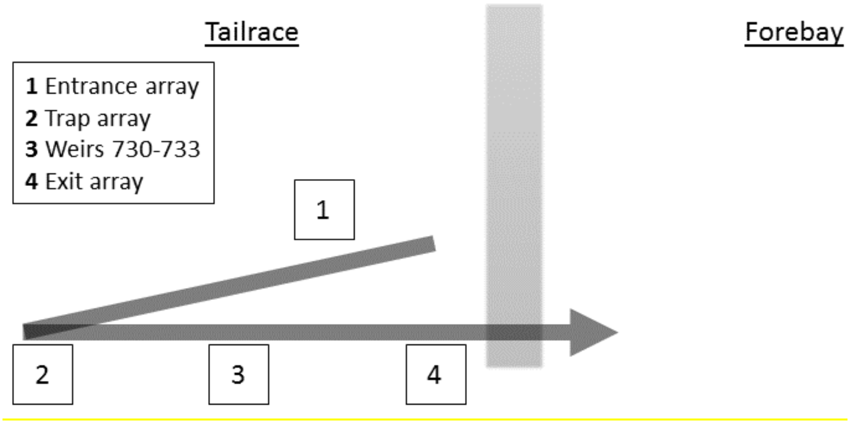
For the temperature and vibration threshold analysis, passage metric comparisons (Table 4) were made for each species relative to 1) a temperature threshold of 20^{o}C (68^{o}F) which represents the level at which stress or passage issues have been observed for salmonids (e.g., Goniea et al. 2006); and 2) a vibration threshold of 0.01m/s^2 (80 dB//1 μm/s^2) which represents the level at which behavioral responses by salmonids are thought to occur (Hawkins 2015).

For the regression analysis, PIT-tag data were only examined during the weekends (14:00 Friday to 14:00 Sunday) when the fish had free passage through the adult ladder (Figure 20). This approach was intended to minimize the confounding effect of trapping on fish passage metrics. The analyses of passage behavior focused on the passage metrics described below and as defined in Table 4. Responses were measured during 4-hour blocks from 04:00 to 16:00. The 4-hour blocks were deemed necessary to have sufficient fish numbers to estimate passage variables. Appendix A provides a comprehensive description of the process used to select the sampling period for fish passage analysis.

Table 4
Passage Metric Terminology and Definitions

Passage Metric Terminology	Definition
Passage attempt	Detections at the ladder entrance array are considered separate attempts when time between consecutive detections at the ladder entrance (B1, B2, B3, B4) are greater than 6 hours.
Array groups	Groups of arrays by location in the ladder Entrance: B1, B2, B3, B4 Trap: 12, 14, 16, 18, 22, 24, 26, 28 Weir: 01, 02, 03, 04, 05, 06, 07, 08 Exit: A1, A2
First detection	Time of first detection at an array group
Last detection	Time of last detection at an array group
Fish attempts	For each fish, an attempt is a contiguous period from first entrance detection to last exit detection. Attempts are considered new when an entrance detection follows an exit detection (fallback) for an entrance detection that occurs more than 6 hours after the last entrance detection (no other detections in between in either case).
First entry	Time of first detection at entrance within the same passage attempt
Median ladder transit time	Median passage time through adult ladder, measured from first entry to time of last detection at exit, within the same attempt
Entrance success rate	Proportion of fish detected at the entrance and then detected at either the trap or weir arrays
Exit success rate	Proportion of fish detected at the weir arrays and then last detected at the exit
Dropback rate	Proportion of fish detected at the exit, at the weir or trap, and at the ladder entrance, in that order
Reascent rate	Proportion of successful exits that were next detected at the ladder entrance (not at weir or trap in between)
Passage success rate	Proportion of entrance success fish that successfully exit
Fish abundance in the ladder	Unique number of fish in the ladder for a specified period

Figure 20
Schematic of the Adult Fish Ladder at Lower Granite Dam and the Position of the PIT-tag Detections Used in the Data Analyses



The dependent PIT-tag response variables analyzed included:

1. Median ladder transit time from first entry to last detection upon exiting
2. Entrance success measured as the fraction of fish seen at the entrance that are subsequently seen further in the ladder
3. Dropback measured as the fraction of fish seen at the weir arrays or exit that are subsequently seen again at the entrance
4. Reascent rate measured as the fraction of fish that exited the ladder that are subsequently seen again at the entrance
5. Exit success measured as the fraction of fish seen at the weir arrays that are next seen at the exit and not seen thereafter
6. Passage success measured as the fraction of fish that enter the ladder that subsequently exited the ladder
7. Unique number of fish seen in 4-hour time blocks

For the regression analysis, response measures 1 through 6 include all free-passage fish that were present in the ladder during a specified 4-hour time block, regardless of when last detected. For example, a fish may enter a 4-hour block, but successfully exit after the block period is over.

2.4.2.2 Post Passage ARIS Analysis

The ARIS data were evaluated to 1) characterize the movement of fish after exiting the LGR fishway (i.e., post-passage behavior), and 2) evaluate the contribution of specific covariates to post-passage behavior through multiple regression analysis (see Section 2.4.2.3 Regression Approach).

The ARIS observations were analyzed on the same 4-hour blocks as the PIT-tag data. However, to improve sample sizes, both weekday and weekend periods were processed. For the ARIS observations, three response variables were analyzed:

1. Proportion of fish observed with the ARIS exiting the fishway and traveling northward toward the spillway
2. Proportion of non-exiting fish observed with the ARIS traveling northward toward the spillway (non-exiting fish are defined as those fish observed in the FOV in Position 1 that did not enter the FOV upon exiting the fishway)
3. Proportion of fish exiting the fishway and traveling downward

Northward fish movement was considered important to quantify because that direction exposed the fish to the spillway and powerhouse where fallback could occur. In addition, the ARIS data were summarized as discrete fish counts by position within the ensonified cone. A total of nine positions within the ensonified cone were numerated (Figure 9). Only the vertical scan nearest to the dam face was examined. Contingency Row × Column table analyses were used to assess changes in occurrence patterns.

2.4.2.3 Regression Approach

A total of 12 covariate relationships were examined for both the PIT-tag and ARIS response variables. The covariates were related to dam operations, temperature, or vibration as follows.

Dam Operations

1. Spill total (kilo cubic feet per second; kcfs)
2. Spill proportion
3. Spill median (kcfs)
4. Flow total (kcfs)
5. Flow median (kcfs)
6. Spillbay 1 (kcfs)
7. Spillbay 1 on or off

Temperature

8. S2 median temperature at surface depth near ladder exit
9. S3 median temperature at surface depth in forebay
10. Difference between S2 and S3

Vibration

11. Mean peak acceleration
12. Number of times vibration levels exceeded threshold of 0.01 m/s^2 (80 dB//1 $\mu m/s^2$)

Fractional responses measured by the PIT-tag detections or the ARIS were analyzed using generalized linear models (GLM) based on binomial error structure and logit-link. Fish counts through the ladder were analyzed using GLM based on a Poisson error structure and log-link. Median travel time were analyzed using GLM based on a Gaussian error structure. Each covariate was assessed using single-variable regression. Separate analyses were performed for each fish run and for the different PIT-tag and ARIS response variables. Analysis of deviance (ANODEV) was used to assess the significance of covariates based on an asymptotic *F*-test that considered overdispersion. Statistical significance was assessed at the $\alpha = 0.05$ level. Multiple, forward step-wise regression analysis was used to find the best combination of covariates that explained fish passage response through the ladder. Because of different deployment times for the equipment — few 4-hour blocks had concurrent information on dam operations, water temperature, and vibration levels —the ability to perform multiple regression analyses was limited.

3 Results

The Results section is organized into five subsections: covariates and supporting information, water temperature, post-passage behavior, adult passage, and video camera evaluation of jumping behavior.

3.1 Covariates and Supporting Information

3.1.1 Run-timing

The run timing for salmonids during 2015 and 2016 is described in Table 5.

Table 5
Run Timing at Lower Granite Dam for Salmonids During 2015 and 2016 Passage Years

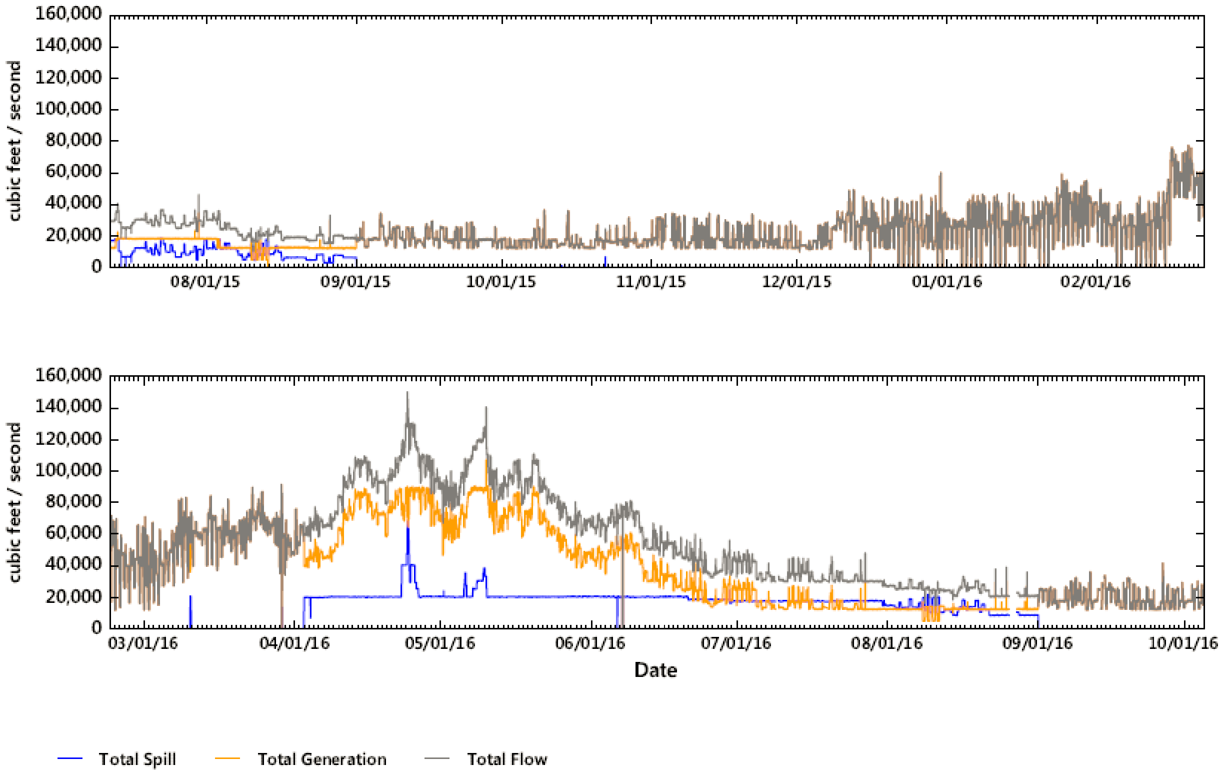
Year	Species	10%	90%	Run Size
2016	Summer-run Chinook Salmon (adults)	19-Jun	1-Aug	12,485
	Summer-run Chinook Salmon (jacks)	19-Jun	27-Jul	2,166
	Fall-run Chinook Salmon (adults)	31-Aug	4-Oct	34,876
	Fall-run Chinook Salmon (jacks)	4-Sep	16-Oct	12,392
	Sockeye Salmon	2-Jul	21-Jul	816
	Steelhead Salmon	20-Aug	26-Oct	100,169
2015	Summer-run Chinook Salmon (adults)	20-Jun	29-Jul	14,958
	Summer-run Chinook Salmon (jacks)	20-Jun	28-Jul	4,222
	Fall-run Chinook Salmon (adults)	5-Sep	6-Oct	59,299
	Fall-run Chinook Salmon (jacks)	8-Sep	20-Oct	11,527
	Sockeye Salmon	27-Jun	9-Aug	440
	Steelhead Salmon	2-Sep	26-Oct	139,754

Note:
Data from Data Access in Real Time (DART) website (http://www.cbr.washington.edu/dart).

3.1.2 Dam Operations

Generation, spill, and the derived value for total river flow passing LGR are summarized in Figure 21. During the study period, spill operations typically occurred in the months of April through August. Unit operations data are not presented here, but were incorporated into the vibration analyses (Anchor QEA et al 2017).

Figure 21
Spill, Generation, and Total Flow (discharge) at Lower Granite Dam July 13, 2015 Through October 1, 2016



3.1.3 *Vibration Evaluation*

The results presented in this section summarize the key findings from the Sound and Vibration Characterization Report (Anchor QEA et al. 2017). As noted in the methods, it was determined that only the vibration measurements collected with the accelerometers were useful for further evaluation, in part because they best represented the particle motion component of sound which salmonids are most responsive to. Within the context of salmonid passage and behavior, an acceleration level of 0.01 m/s2 (80 dB//1 μm/s2) was set as the estimated threshold that would elicit a behavioral response. Based on this threshold value and the monitoring that was conducted at LGR, several key results were identified::

- The lower fishway monitoring station had the lowest level of fishway wall vibration detected, and exceedances of the behavioral response threshold for salmonids were infrequent at this location.
- The highest and most consistent levels of fishway wall vibration occurred in the middle fishway monitoring station where the behavioral response threshold for salmonids was

regularly exceeded. These constant high levels of vibration prevented the detection of vibrations caused by dam operations or construction activities at this location.

- Vibration signals from dam operations and construction activities were most clearly observed in the upper section of the fishway. Vibration of fishway walls at the upper monitoring location could be most readily detected, and exceedances of the behavioral response threshold correlated with turbine operations, pump noise, the TCS, and construction activities.
- At the upper fishway, ladder wall vibration measurements were strongly influenced by turbine operations. Start and stop activities appeared to cause spikes in vibration levels and exceedances of the behavioral response threshold for salmonids.
- The use of emergency and auxiliary fishway pumps in 2015 and the TCS system in 2016 also influenced wall vibration measurements at the upper monitoring location. The TCS appears to be responsible for significant increases in vibration levels in 2016 and contributed to exceedances of the behavioral response threshold for salmonids.
- Concrete mining was the most identifiable construction activity that increased the vibration levels of the fishway for extended periods. Concrete mining often continued for several hours, causing fishway wall vibration levels to exceed the salmonid behavioral response threshold for up to 80% of the duration of the mining activity.
- Ground compacting, back filling, jack hammering, pier drilling, and excavation were also distinguishable contributors to increased fishway wall vibration levels and exceedances of the salmonid behavioral response threshold at the upper and lower monitoring locations.
- Attributing fishway wall vibration levels to specific construction activities was limited by the detail provided in the construction logs.
- Observations of ladder wall vibrations exceeding the salmonid behavioral response threshold do not necessarily indicate that a behavioral response will be observed in transiting salmonids. The transfer of vibrations to water in the fishway and subsequently to fish is dependent multiple factors described in Sound and Vibration Characterization Report (Anchor QEA et al. 2017).

For the analysis of adult passage and post-passage behavior, the analyses focused on two components of the vibration data: peak acceleration (Figures 22 and 23) and exceedances of the behavior threshold [0.01 m/s^2 (80 dB//1 $\mu m/s^2$); Figures 24 and 25] as measured at the monitoring stations in the upper fishway (Site 1) and lower fishway (Site 4; Figure 11). The middle fishway was not included in the analysis because of the constant vibration and lack of variation in vibrations that were was observed there. A more detailed examination of the middle fishway is provided in the accompanying Sound and Vibration Report (Anchor QEA et al. 2017).

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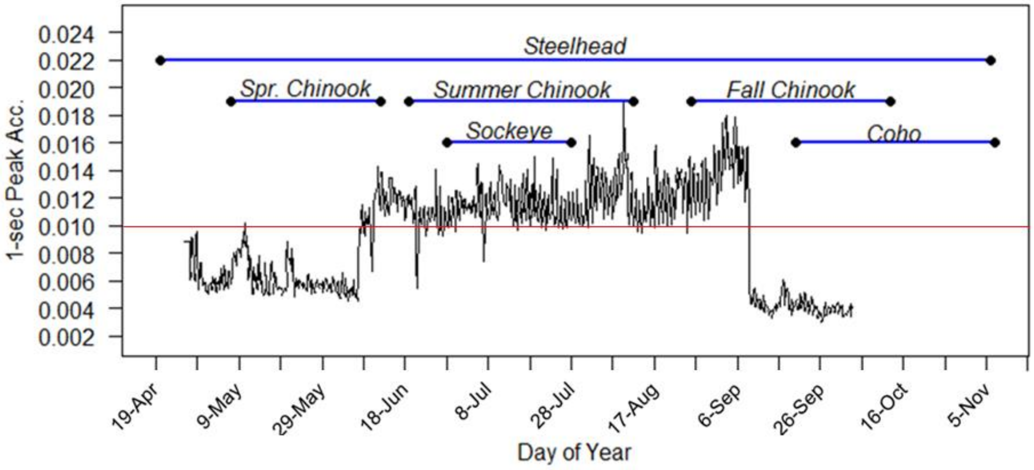
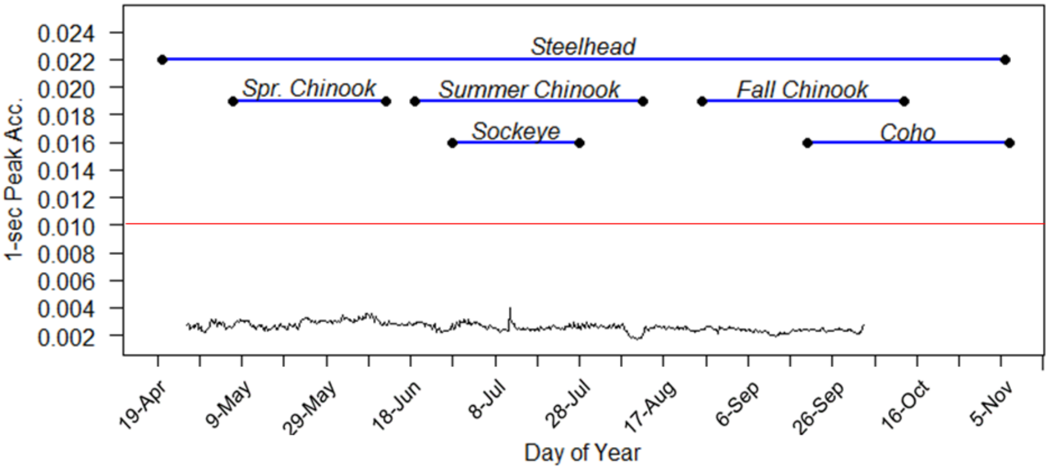
Figure 22
Mean Peak Particle Acceleration Recorded at the Upper Ladder Over Time at Lower Granite Dam in 2016



Notes:
Run timing of adult sockeye salmon, summer Chinook salmon, and fall Chinook salmon/steelhead indicated.
Vibration data were analyzed only during the periods when spring Chinook salmon were present in the ladder as illustrated.
Monitored time blocks based on PIT-tag analyses.
The red line corresponds to the salmonid behavioral threshold of 0.01 m/s^2 (80 dB//1 μm/s^2).

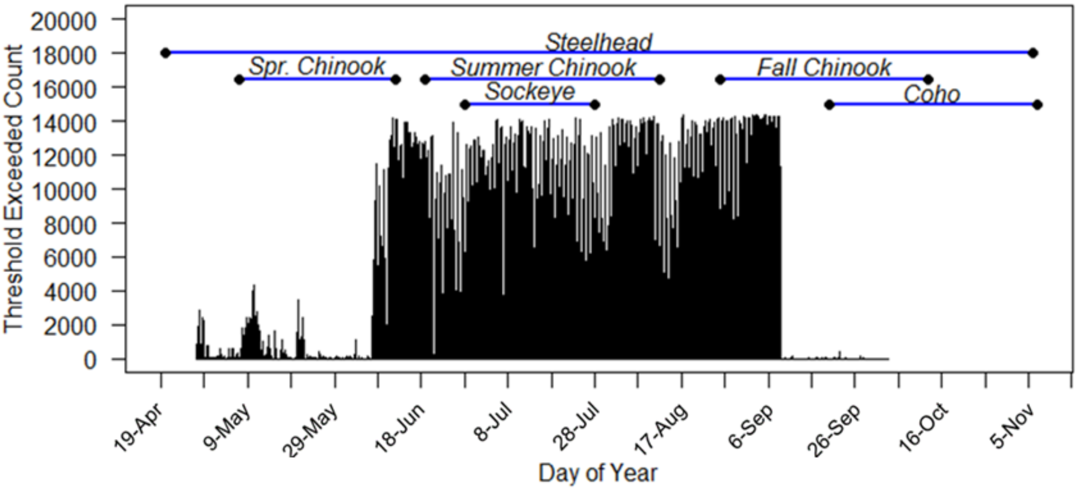
Figure 23
Mean Peak Particle Acceleration Recorded at the Lower Ladder Over Time at Lower Granite Dam in 2016



Notes:
Run timing of adult sockeye salmon, summer Chinook salmon, and fall Chinook salmon/steelhead indicated.
Vibration data were analyzed only during the periods when spring Chinook salmon were present in the ladder as illustrated.
Monitored time blocks based on PIT-tag analyses.
The red line corresponds to the salmonid behavioral threshold of 0.01 m/s^2 (80 dB//1 μm/s^2)

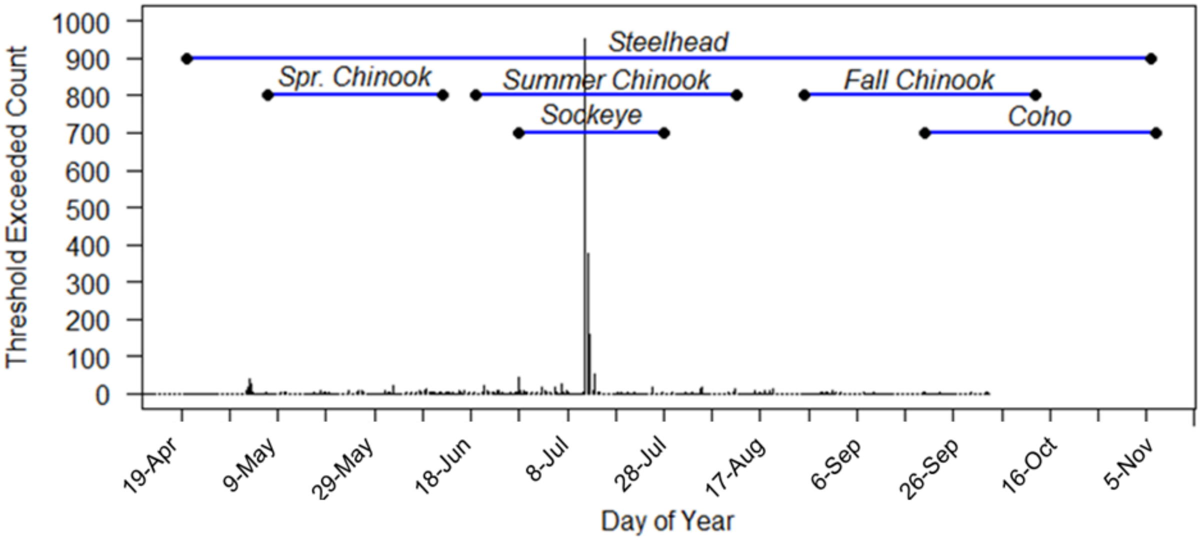
Figure 24

Number of 1-second Intervals During the 4-hour Periods When Peak Acceleration Exceeded the Salmonid Response Threshold Level at the Upper Ladder Over Time at Lower Granite Dam in 2016



Notes:
Run timing of adult sockeye salmon, summer Chinook salmon, and fall Chinook salmon/steelhead indicated.
Vibration data were analyzed only during the periods when spring Chinook salmon were present in the ladder, as illustrated by the data ranges. Threshold level is equal to 0.01 meters per squared second

Figure 25
Number of 1-second Intervals During the 4-hour Periods When Peak Acceleration Exceeded the Salmonid Response Threshold Level at the Lower Ladder Over Time at Lower Granite Dam in 2016



Notes:
Run timing of adult sockeye salmon, summer Chinook salmon, and fall Chinook salmon/steelhead indicated.
Vibration data were analyzed only during the periods when spring Chinook salmon were present in the ladder, as illustrated by the data ranges. Threshold level is equal to 0.01 meters per squared second

3.1.4 *Temperature Control Structure Operations*

USACE operated the TCS during the period of June 6, 2016, through September 8, 2016 (Table 6). During this period, operations were temporarily stopped on two dates: June 9, 2016, for a test of the TCS and on July 6, 2016, to conduct ADCP sampling.

Table 6
Summary of Temperature Control Structure Operations at Lower Granite Dam in 2016

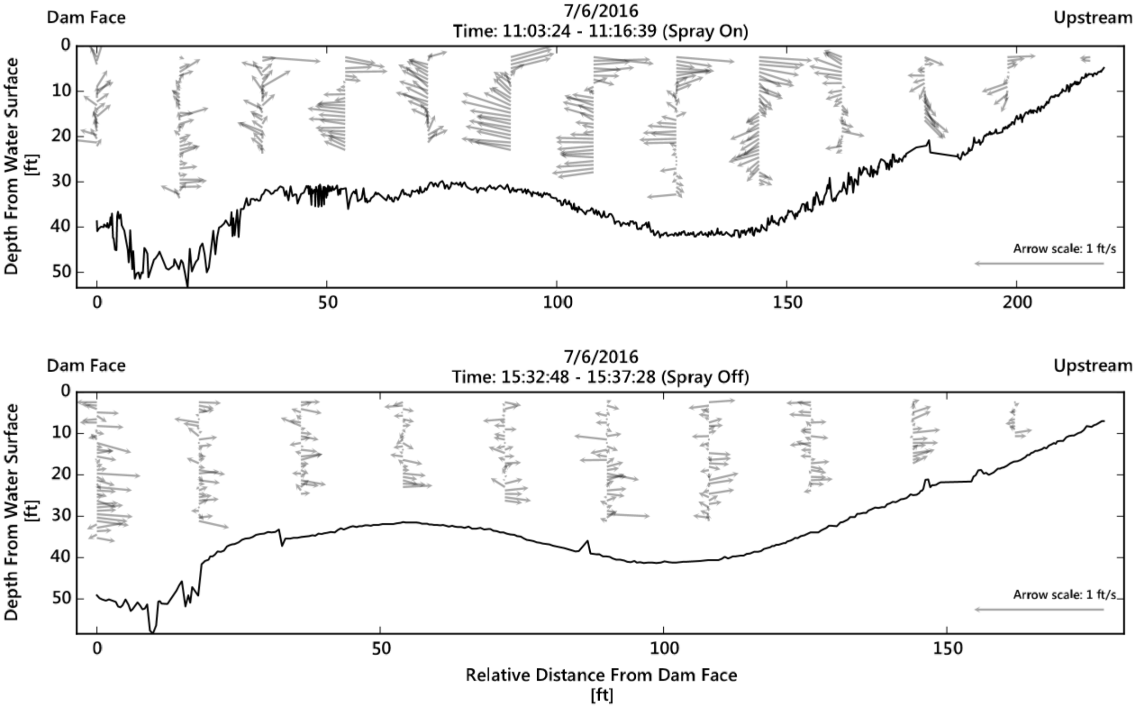
Event	Date	Time	Start or Stop
Beginning of Season	6/6/2016	10:30	Start
Beginning of USACE Operational Test	6/9/2016	10:30	Stop
End of USACE Operational Test	6/9/2016	15:06	Start
Beginning of ADCP Test	7/6/2106	13:05	Stop
End of ADCP Test	7/6/2106	15:45	Start
End of Season	9/8/2016	12:45	Stop

Notes:
ADCP: Acoustic Doppler Current Profiler
USACE: U.S. Army Corps of Engineers

3.1.5 *Acoustic Doppler Current Profiler*

Velocity profiles were developed to characterize changes in water movement in the forebay associated with turning the TCS on and off (Figure 26). When TCS is in operation, a stronger current towards the ladder exit at depth (due to the withdrawal by the pump) and a surface current away from the from the dam face in the vicinity of the ladder exit are established (top panel of Figure 26). When the pump is turned off, the currents are generally weaker and do not exhibit a significant upstream or downstream component overall as would be the case for flow near a barrier (bottom panel of Figure 26).

Figure 26
Velocity Profiles Measured with Acoustic Doppler Current Profiler When the Temperature Control Structure was Turned On (i.e., "Spray On") and Turned Off (i.e., "Spray Off")



3.2 Water Temperature

3.2.1 *Characterization of 2016 Temperature Control Structure Effects*

Temperature data from the thermistor strings were evaluated to assess the effect of TCS operation on the forebay passage environment. Specifically, water temperatures at the forebay (S1) upstream of the TCS were compared with temperatures measured downstream of the TCS along the face of LGR, adjacent to the fishway exit (S2; Figure 2). Figure 27 illustrates temporal patterns and stratification in forebay temperatures upstream and prior to the influence of the TCS at S1. Figure 28 illustrates how temperatures changed immediately adjacent to the fishway exit (S2) after the TCS was operational. In general, surface temperatures fluctuated more frequently and reached higher maximum values at S1 when compared to S2. At S2 the cooling effect of the TCS is most evident in the top 10 feet of the water column where temperatures are comparatively lower than S1 at similar depths (Figure 28). Overall the figures show that TCS operation is effective in producing local cooling of the surface water temperatures near the ladder exit. The analyses described above used temperatures obtained from S2 rather than the temporary buoy because there was little difference in temperatures recorded at both sites and S2 is expected to be in place during future years which will ensure consistency across evaluation years.

Figure 27
Time Series of Vertical Temperature Profiles at the Forebay (S1) of Lower Granite Dam Upstream of the Temperature Control Structure in 2016

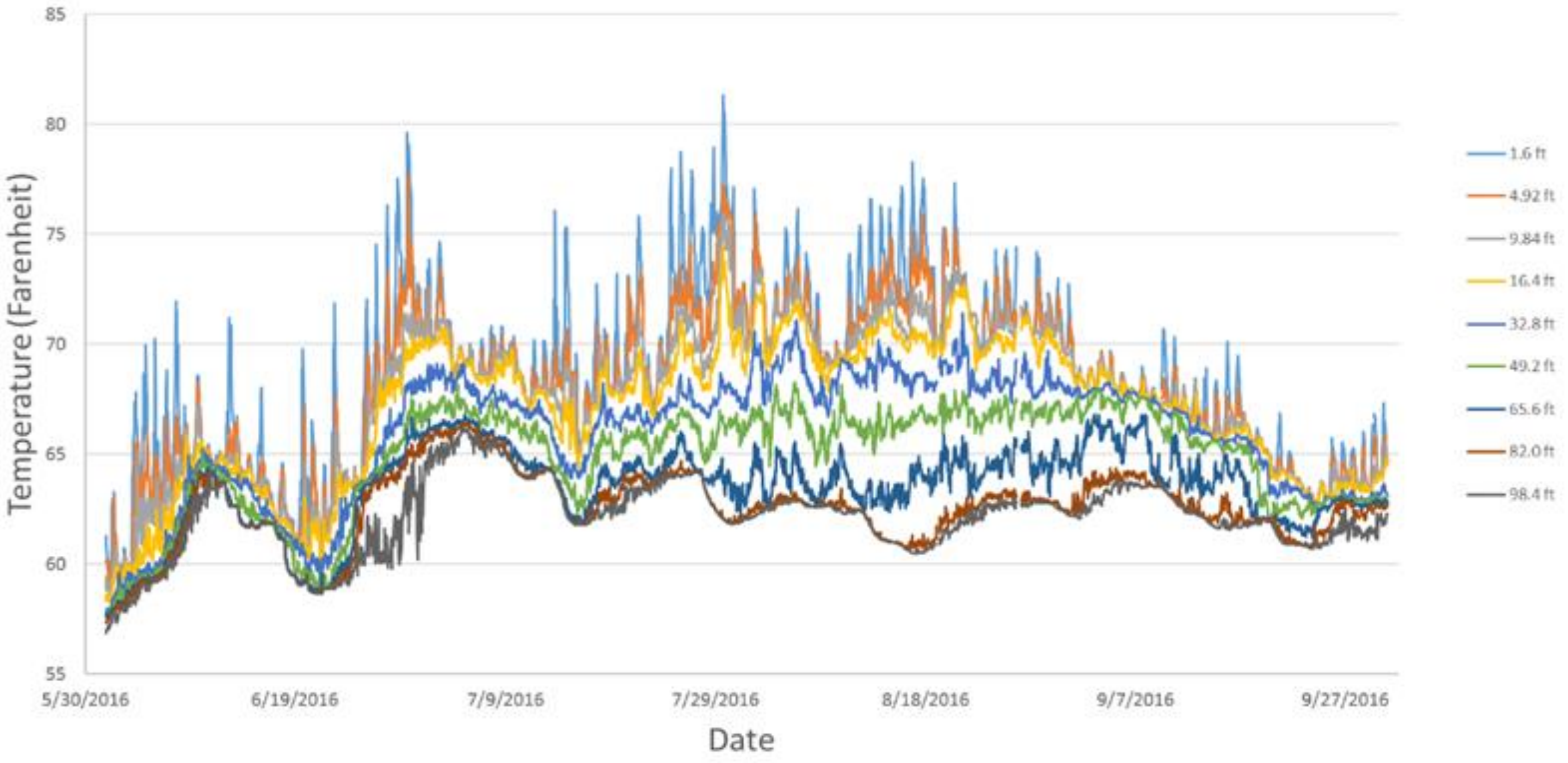
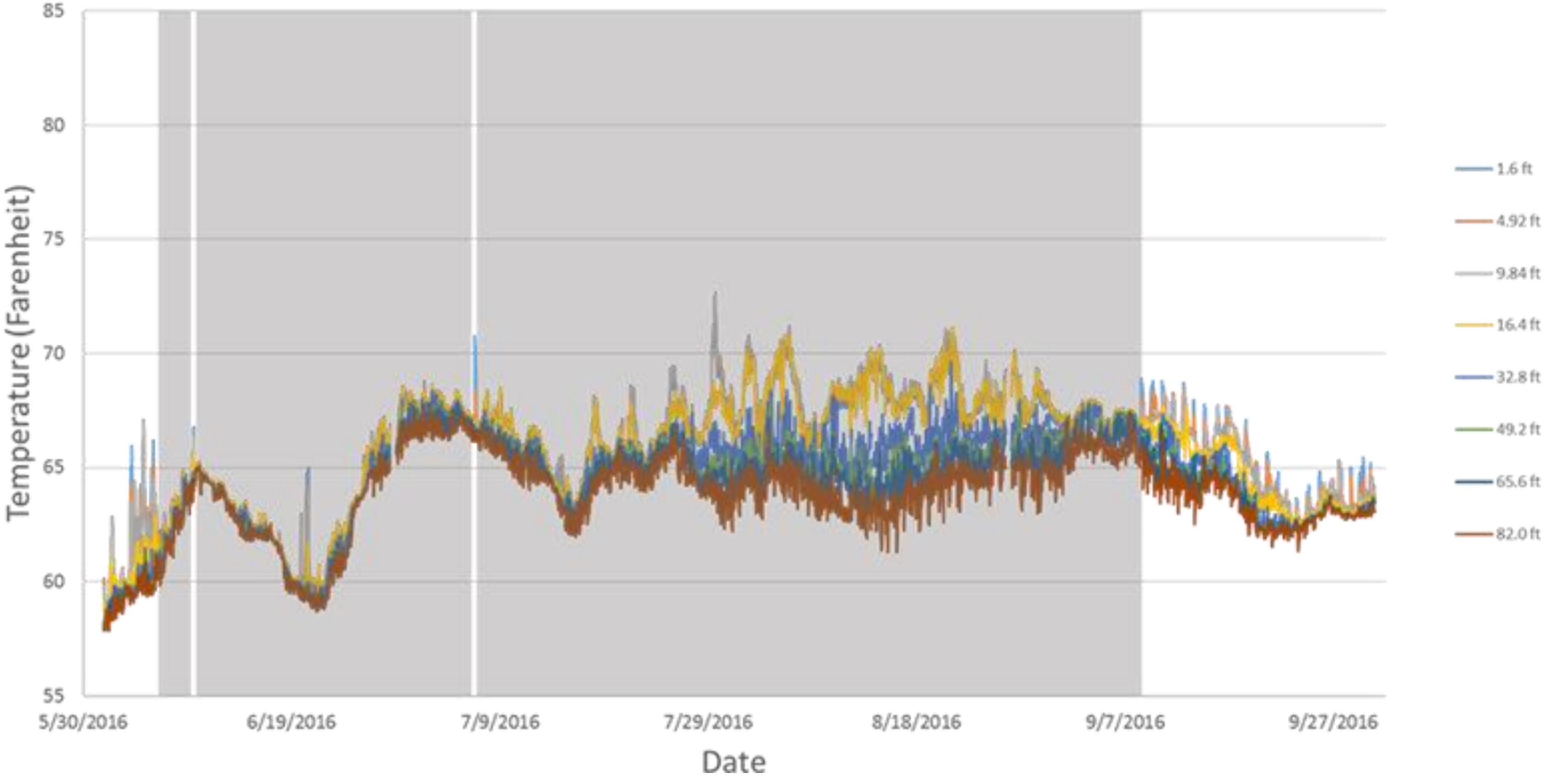


Figure 28
Vertical Temperature Profiles Along the Face of Lower Granite Dam Adjacent to Fishway Exit (S2) Downstream of the Temperature Control Structure in 2016



Note: Shaded areas represent periods when the temperature control structure was operational.

The hourly changes in the vertical temperature gradient at the surface of S2 and within the ladder exit pool (Table 7) also indicate that the cooling from the TCS translates to temperatures within the fishway. Ladder exit pool temperatures increased by 1.5 °F (0.8 °C) during the period when the TCS was turned off. During the off period, the water temperatures in the forebay along the dam face (S2) at depths of 1.6 feet and 4.9 feet were higher and lower, respectively, than the water temperature in the ladder. The differences in temperature between the two forebay depths and the fact that the ladder exit pool temperature was intermediate confirms surface and deeper waters are mixing in the ladder. Following the period in which the TCS was turned off, temperatures in the ladder and at forebay depths of 1.6 feet and 4.9 feet cooled and homogenized within an hour (Table 7).

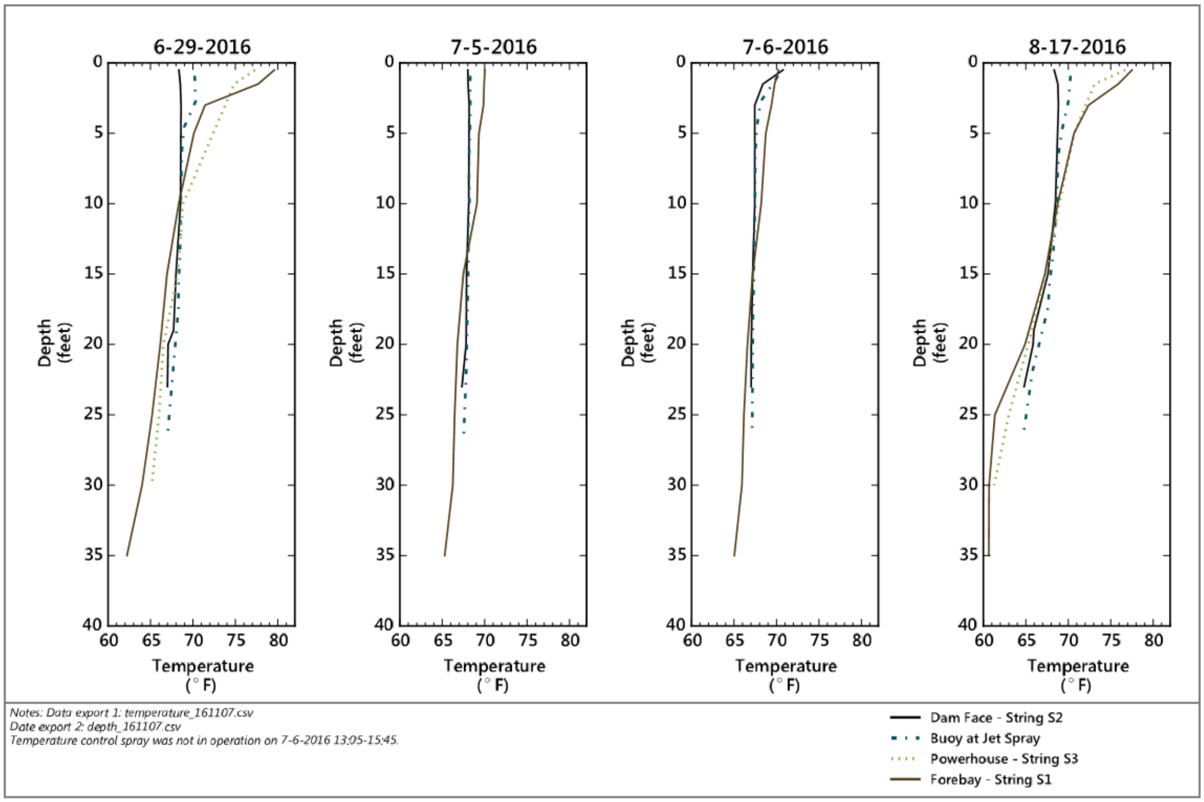
Although the timing of the July 6, 2016, test was not chosen based on expected water temperatures, the results highlight that the TCS kept water temperatures below the 68°F fish passage threshold (e.g., Goniea 2006) during operations, and temperatures quickly exceeded 68°F when the TCS was off.

Table 7
Temperatures in the Lower Granite Ladder at the Exit Pool and in the Forebay at Depths of 1.6 Feet and 4.9 Feet During Periods When the Temperature Control Structure Was Turned On and Off on July 6, 2016

Time	TCS Operation	Ladder	Forebay at Dam Face (S2)	
		Exit Pool [°F (°C)]	1.6 foot depth [°F (°C)]	4.9 foot depth [°F (°C)]
12:00	On	66.8 (19.3)	66.8 (19.3)	66.9 (19.4)
13:00	On	66.6 (19.2)	66.7 (19.3)	66.8 (19.3)
14:00	Off	67.6 (19.8)	70.8 (21.6)	67.3 (19.6)
15:00	Off	68.1 (20.1)	70.0 (21.1)	67.5 (19.7)
16:00	On	68.1 (20.1)	69.8 (21.0)	68.4 (20.2)
17:00	On	66.7 (19.3)	66.7 (19.3)	66.8 (19.3)
18:00	On	66.7 (19.3)	66.7 (19.3)	66.8 (19.3)

Figure 29 shows depth profiles of temperatures at the four locations on select dates during the summer period and provides another illustration of the effect of surface heat flux from solar radiation in the upstream buoys S1 and S3. Temperatures in the top 5 feet are significantly warmer in the upstream thermistor strings, whereas the spray operation is effective in keeping a nearly constant temperature near the ladder exit. When spray operation is turned off, the surface temperature near the ladder exit is more reflective of conditions upstream (compare panels corresponding to July 5 and July 6).

Figure 29
Depth Profiles of Daily Maximum Water Temperatures at the Ladder Exit and Forebay



Notes: Data export 1: temperature_161107.csv
Date export 2: depth_161107.csv
Temperature control spray was not in operation on 7-6-2016 13:05-15:45.

3.2.2 Characterizing Seasonal Cooling Impact of the TCS

The short term shut-down of the TCS on July 6, 2016, provided strong evidence of local cooling resulting from the TCS. However, without additional tests during the warmest months of fish passage season, evaluation of the general effectiveness of the TCS at cooling the temperatures within the LGR fishway relied upon an indirect comparison of TCS operations across years. To characterize the influence of the TCS on fishway temperatures during summer months, surface forebay and exit pool temperatures during 2015 and 2016 time series were plotted (Figures 30 and 31) prior to and during TCS operations, respectively. The TCS is located between the forebay (S1) and the exit pool and cooling in the exit pool caused by the TCS should be apparent in years when the TCS is operational. In 2015, when the TCS was not operational, exit pool temperatures closely followed and often overlapped changes in forebay surface temperatures (Figure 30). In 2016, when the TCS was operated, there was still concordance between forebay surface temperatures and the exit pool, but during warmer months, July and August, the exit pool remained several degrees cooler than the forebay (Figure 31). In early September of 2016 when the TCS was turned off for the season, forebay surface and exit pool temperatures fluctuated synchronously and were nearly the same, similar to

2015 (Figure 31). Collectively, these results show that the TCS reduces surface water temperatures between the forebay and fishway during the warmest summer months. Because the TCS appears to reduce fishway temperatures, fish entering the fishway below LGR from the cooler mainstem (e.g., tailwater observation deck) would likely experience a less dramatic difference between temperatures (Figure 31) which may encourage use of the fishway when the TCS is operational.

Figure 30
Seasonal Temperature Profile for Forebay at Surface and Exit Pool for 2015

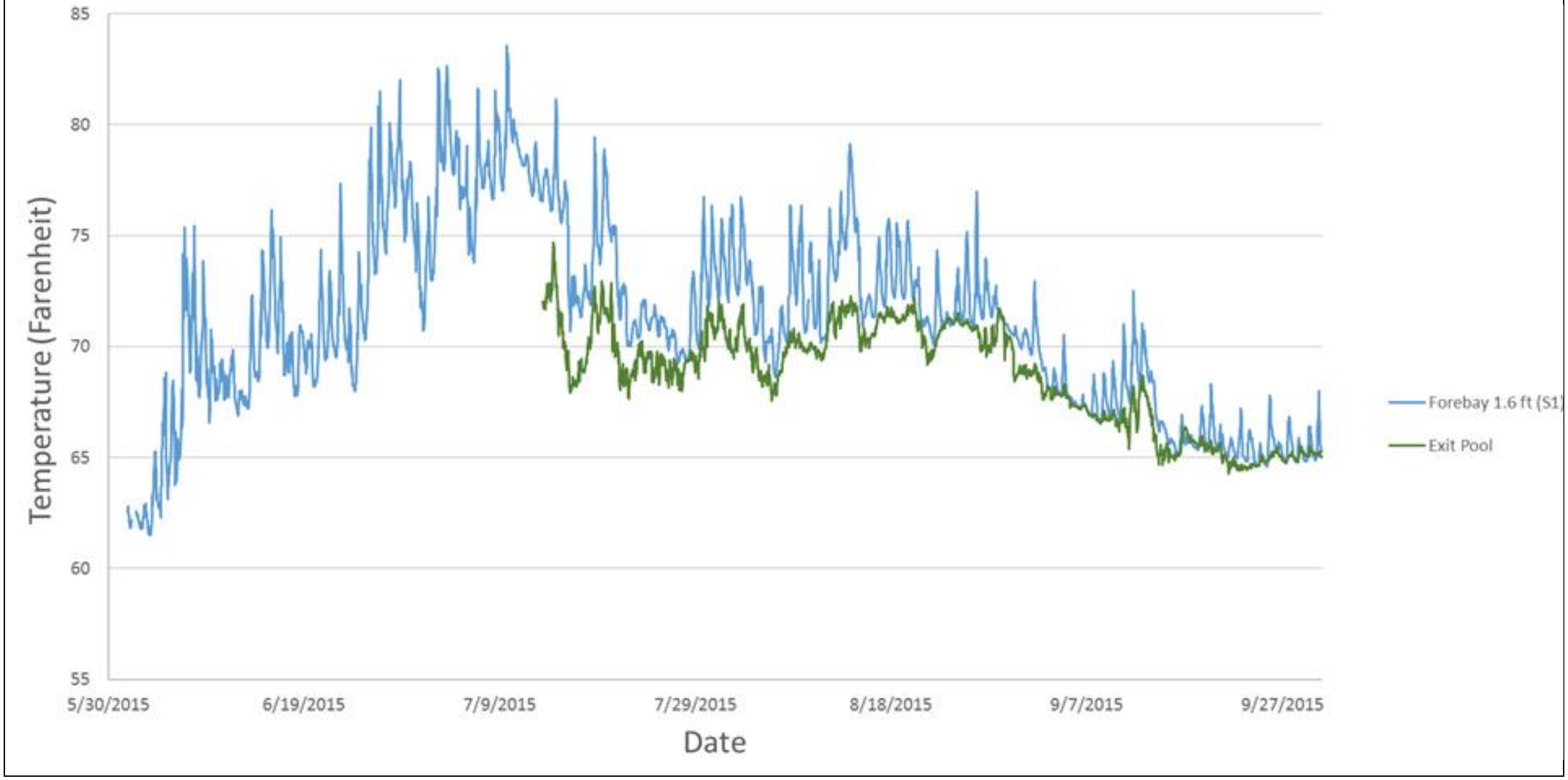
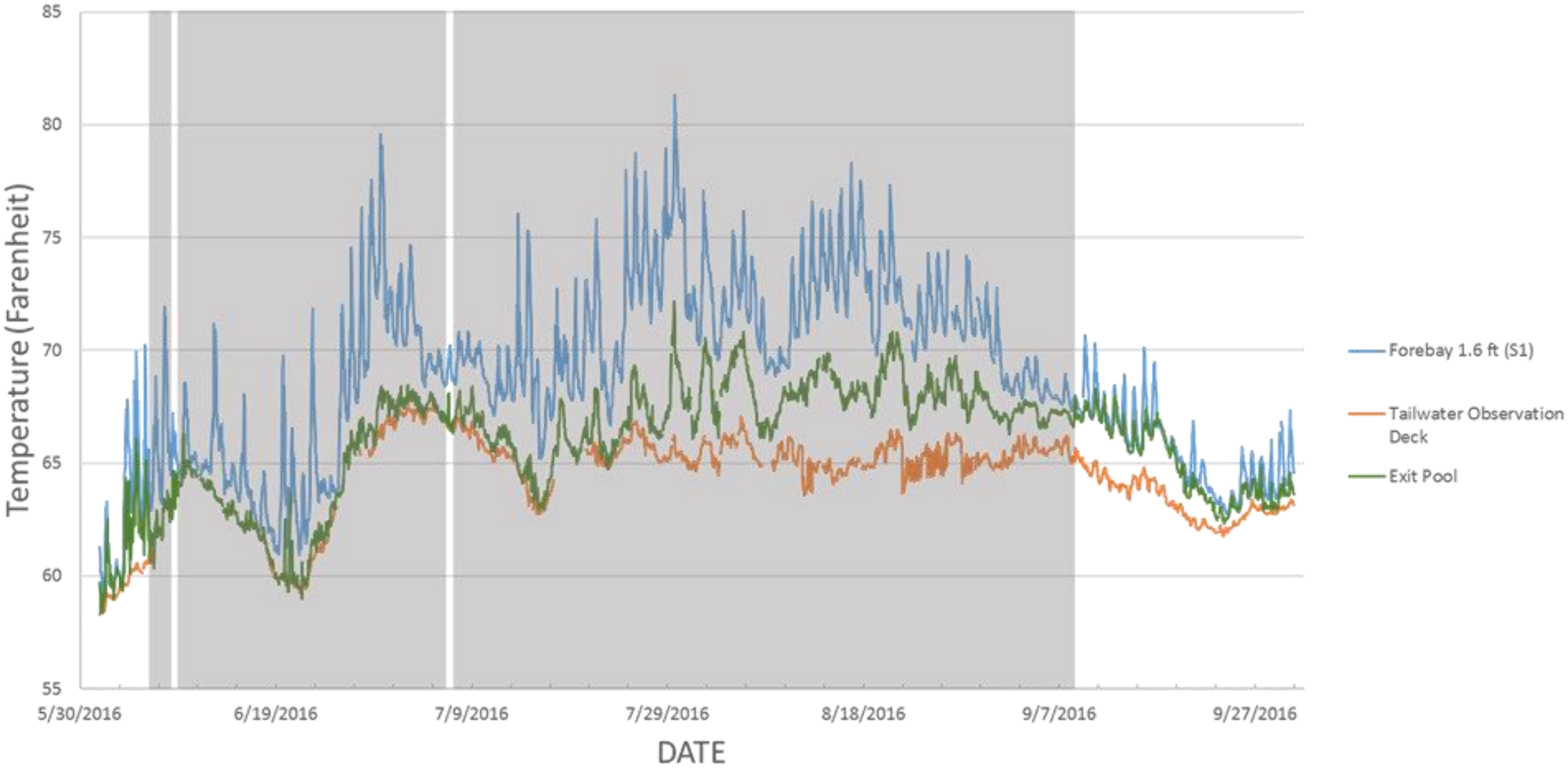


Figure 31
Seasonal Temperature Profile for Forebay at Surface and Exit Pool and Tailwater Observation Deck for 2016

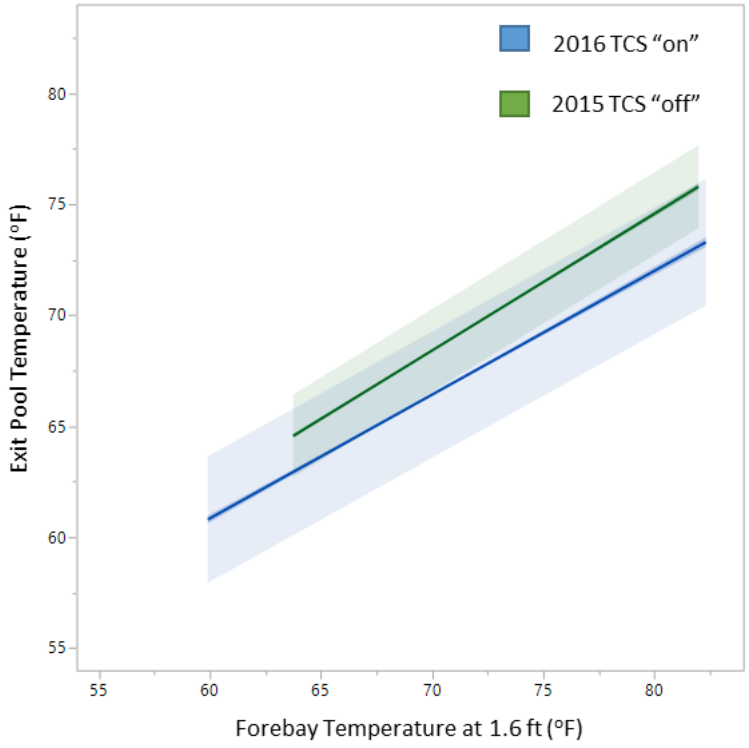


Note:
Greyed areas represent periods when the temperature control structure was operational.

3.2.2.1 Estimating Temperature Control Structure Cooling Effect based on 2015 and 2016 Data

The linear relationships between the forebay and exit pool for the TCS "on" and "off" periods are depicted in Figure 32 and demonstrate that at a given forebay temperature, exit pool temperatures were lower when the TCS was turned on.

Figure 32
Plot of Exit Pool and Forebay Surface Temperatures During Periods in Which the Temperature Control Structure was Turned Off and On



The TCS appeared to reduce the exit pool temperatures from 1.7 °F (0.9 °C) to 2.6°F (1.4 °C) across the range of forebay temperatures we examined, with the greatest cooling occurring at higher temperatures (See notes below Table 8). These results provide additional evidence that the TCS is effective at reducing fishway temperatures during the warmest summer months. It should be noted that the comparison of TCS operations across years provides general, extrapolated evidence of the TCS cooling effect, but the only way to verify the actual cooling effect would be to conduct structured comparisons where the response can be measured in a given year.

Table 8
Estimated Cooling Effect of the Temperature Control Structure (TCS) Based on Calculated Linear Relationships Between Forebay Surface and Exit Pool Temperatures When TCS Was "On" Versus "Off"

Forebay Temperature		Calculated Exit Pool Temperature					
		TCS "on"		TCS "off"		Difference between "on" and "off"	
(°F)	(°C)	(°F)	(°C)	(°F)	(°C)	(°F)	(°C)
65	18.3	63.6	17.6	65.3	18.5	1.7	0.9
66	18.9	64.2	17.9	65.9	18.8	1.7	0.9
67	19.4	64.8	18.2	66.6	19.2	1.8	1.0
68	20.0	65.3	18.5	67.2	19.6	1.9	1.1
69	20.6	65.9	18.8	67.8	19.9	1.9	1.1
70	21.1	66.4	19.1	68.4	20.2	2	1.1
71	21.7	67	19.4	69	20.6	2	1.1
72	22.2	67.5	19.7	69.6	20.9	2.1	1.2
73	22.8	68.1	20.1	70.3	21.3	2.2	1.2
74	23.3	68.7	20.4	70.9	21.6	2.2	1.2
75	23.9	69.2	20.7	71.5	21.9	2.3	1.3
76	24.4	69.8	21.0	72.1	22.3	2.3	1.3
77	25.0	70.3	21.3	72.7	22.6	2.4	1.3
78	25.6	70.9	21.6	73.3	22.9	2.4	1.3
79	26.1	71.4	21.9	73.9	23.3	2.5	1.4
80	26.7	72	22.2	74.6	23.7	2.6	1.4

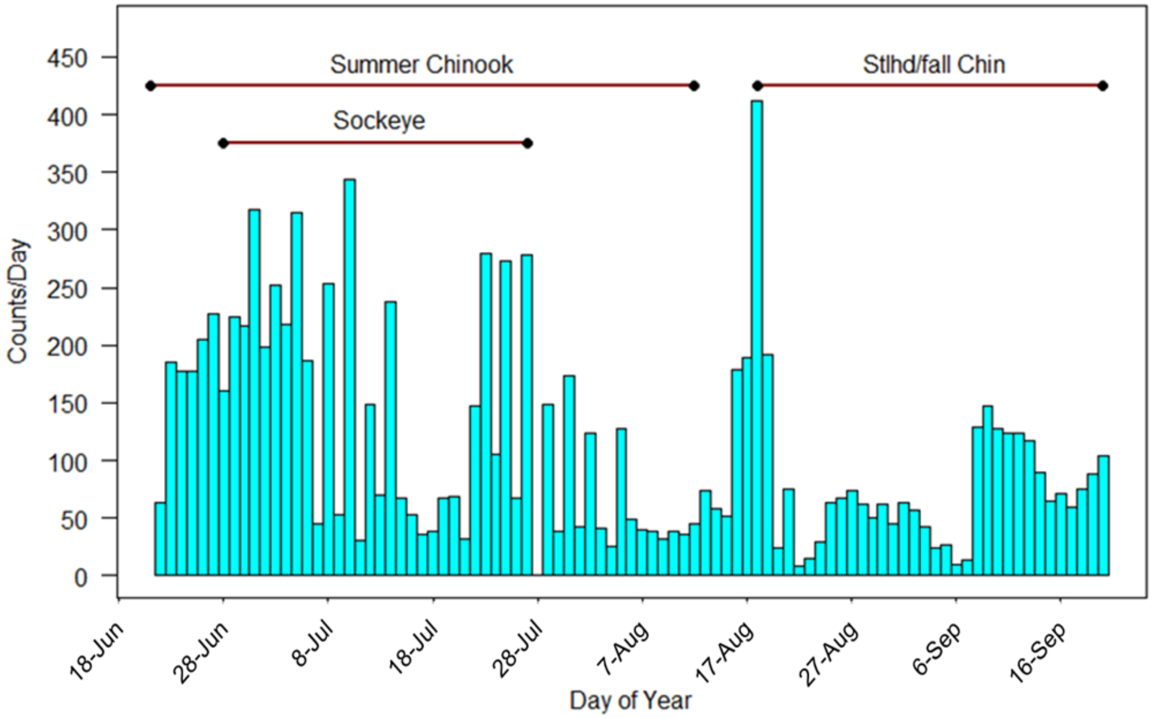
Notes:
"On": Temperatures observed during the periods in which the temperature control structure was turned on in 2016
"Off": Temperatures observed during the periods in which the temperature control structure was not operational in 2015
Forebay surface = 1.6 feet
Linear equation for TCS "on": y = 27.4 + .5575*x
Linear equation for TCS "off": y = 25.29 + .6159*x
TCS: temperature control structure

3.3 Post Passage Behavior- Adaptive Resolution Imaging System

3.3.1 Data Collection Effort and Data Quality

The ARIS system ran continuously through the study period with a few exceptions (Figure 33). A system error occurred the morning of July 28 that caused the data collection process to shut down. The error was discovered the morning of July 29 and the system was restarted. Data were not acquired from 07:00 on July 28 through 06:30 on July 29. Several hours of data were not collected from 10:00 to 14:00 on August 15 when the system was shutdown to accommodate testing of the power supply to assess noise/interference problems with PIT-tag antennas in the fish ladder.

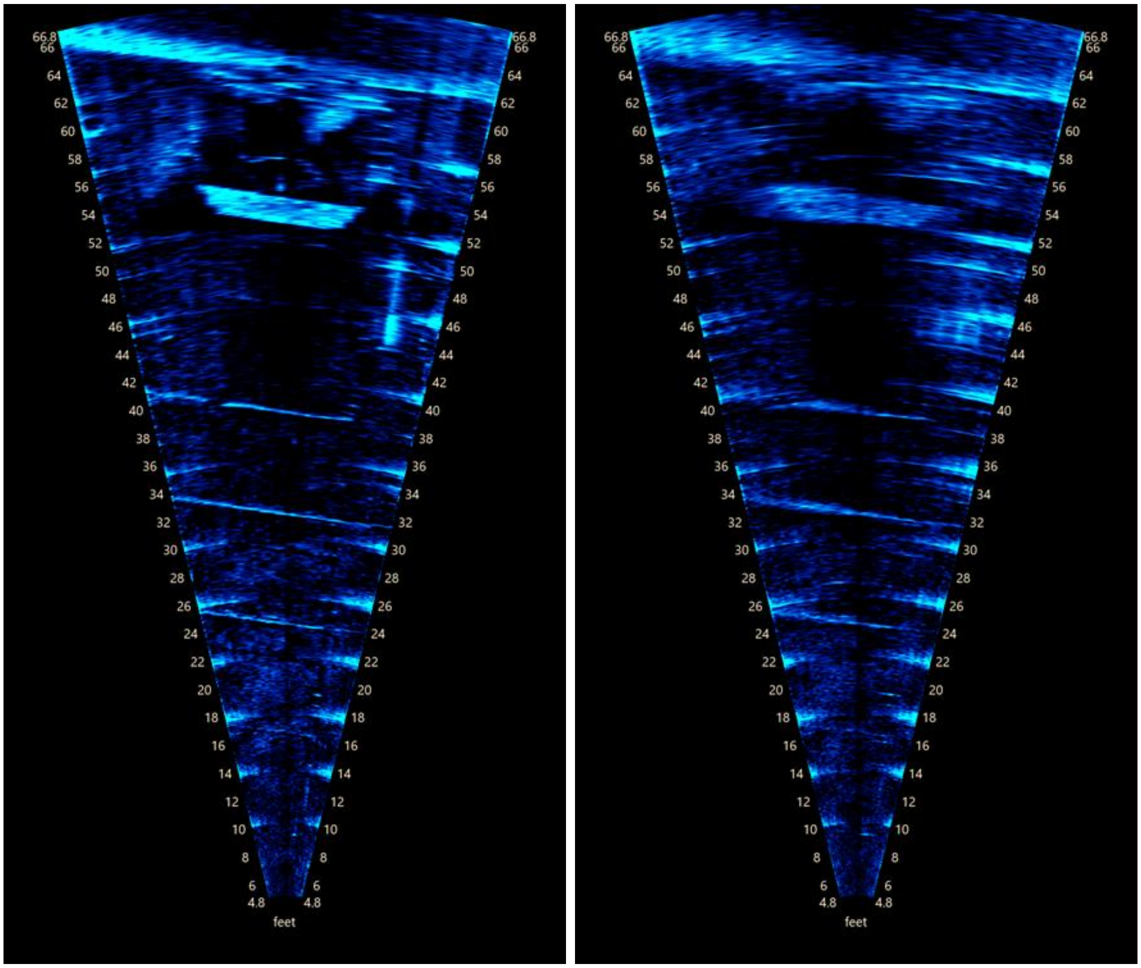
Figure 33
Period of ARIS Observations at Lower Granite Adult Ladder Exit and ARIS Counts per Day of Adult Sockeye Salmon, Summer Chinook Salmon, and Fall Chinook Salmon/Steelhead



Some of the data files collected were shorter in duration than intended. Though the system was programmed to collect 20 minutes of data with Position 1 and 10 minutes of data for each of Positions 2 through 5 each hour, there were a number of instances when the file start times were delayed by brief periods (typically a few seconds) due to some drift with the timing of the software recording function. Additionally, some files were truncated as a result of stopping data collection during the switching out of the hard drives.

The image resolution and consequent data quality was typically very good throughout much of the study period. In the latter part of the study the image resolution degraded intermittently resulting in the collection of some data of lesser quality (Figure 34). For the periods 14:00 on August 20 through 16:00 on August 24; 20:00 September 1 through 14:00 on September 7; and 11:00 on September 14 through 23:00 on September 20, the clarity of the imagery was too poor to allow for estimating total length of fish. However, first and last location data for fish entering the FOV immediately upon exiting the fishway were still obtainable. For all files collected during these dates and times, data processing was limited to just the data acquired with the Position 1 rotation for fishway origin fish, but these data were not included in the analysis given that total length estimates could not be obtained. After the data collection period, the ARIS unit was serviced by the manufacturer and they determined that the intermittent problem with system resolution was the result of the delamination of the rubber butyl in the lens housing.

Figure 34
Still Images of ARIS Data Showing Examples of Varying Degrees of Data Quality as Evidenced by the Clarity of the Trapezoidal Structure Below the Fishway Exit



Note:
The image on the left is from 19:00 on September 1 and reflects the typical high resolution data collected throughout most of the study period. The image on the right is from 20:00 on September 1 and reflects the lower resolution data collected intermittently during the latter part of the study period.

3.3.2 Exit and Near-Forebay Behavior Characterization

Post-passage movement behaviors of exit-origin fish indicated that across species groups there were both consistent and inconsistent patterns observed (Table 9; Figure 35). All groups showed minimal to no direct upstream movement (no change in lateral or vertical position) and all groups exhibited considerable preference (64 to 76%) for heading north towards the powerhouse. Fairly low proportions of each group were observed to maintain their vertical positions upon entering the forebay before exiting the FOV with summer Chinook salmon showing the lowest proportion (5.5%) for this behavior among the groups. The largest disparity in movement behaviors among species groups was the depth at which they were last detected. Over 75% of sockeye/jack Chinook salmon were last observed in areas indicating less than a 10-foot drop in their vertical position and 12% in areas indicating greater than a 10-foot drop in vertical position. In contrast 57% of summer Chinook salmon and 53% of fall Chinook salmon/steelhead groups were shown to exit the FOV with less than a 10-foot change in depth and 38 and 32%, respectively at depths greater than 10 feet.

Movement behaviors were also assessed relative to low (less than 68° F) and high (greater than or equal to 68° F) water temperature conditions in the forebay near the fishway exit (Table 9). Temperature values at S2 for sensors located at 1.6 and 4.9 foot depths were averaged to characterize the temperature conditions the exit origin fish encountered upon entering the forebay. For summer Chinook salmon and sockeye/jack Chinook salmon, behaviors varied little between temperature conditions for movement directly upstream, towards the powerhouse, towards the south shore and no change in depth was observed. During high temperature conditions, summer Chinook salmon showed a 12% decrease in occurrence of changes in depth of less than 10 feet and 15% increase in occurrence of changes in depth greater than 10 feet. Sockeye and jack Chinook salmon showed an opposite trend as observed for summer Chinook salmon during high temperature conditions: occurrence of less than 10 feet change in depth increased by 10% and occurrence of greater than 10 feet change in depth decreased by 6%. For fall Chinook salmon and steelhead, occurrence of some behaviors varied between temperature conditions: high temperature conditions resulted in a 9% decrease in occurrence of movement towards the spillway, 9% increase in movement towards the south shore, 10% increase in the lack of change in depth, 38% decrease in less than 10 foot change in depth and 28% increase in greater than 10 foot change in depth. Results for fall Chinook salmon and steelhead should be viewed with caution as they rely on a very small sample size during high temperature conditions (n=13).

Estimates of overall mean depth for exit-origin fish indicate that the sockeye/jack Chinook salmon group was distributed on average higher in elevation when they exited the Position 1 FOV than were the summer Chinook salmon and fall Chinook salmon/steelhead groups (Figure 36). Note that the results for fall Chinook salmon/steelhead are limited by the smaller sample size relative to the other groups as a result of ARIS resolution limitations (discussed above) that occurred during the fall

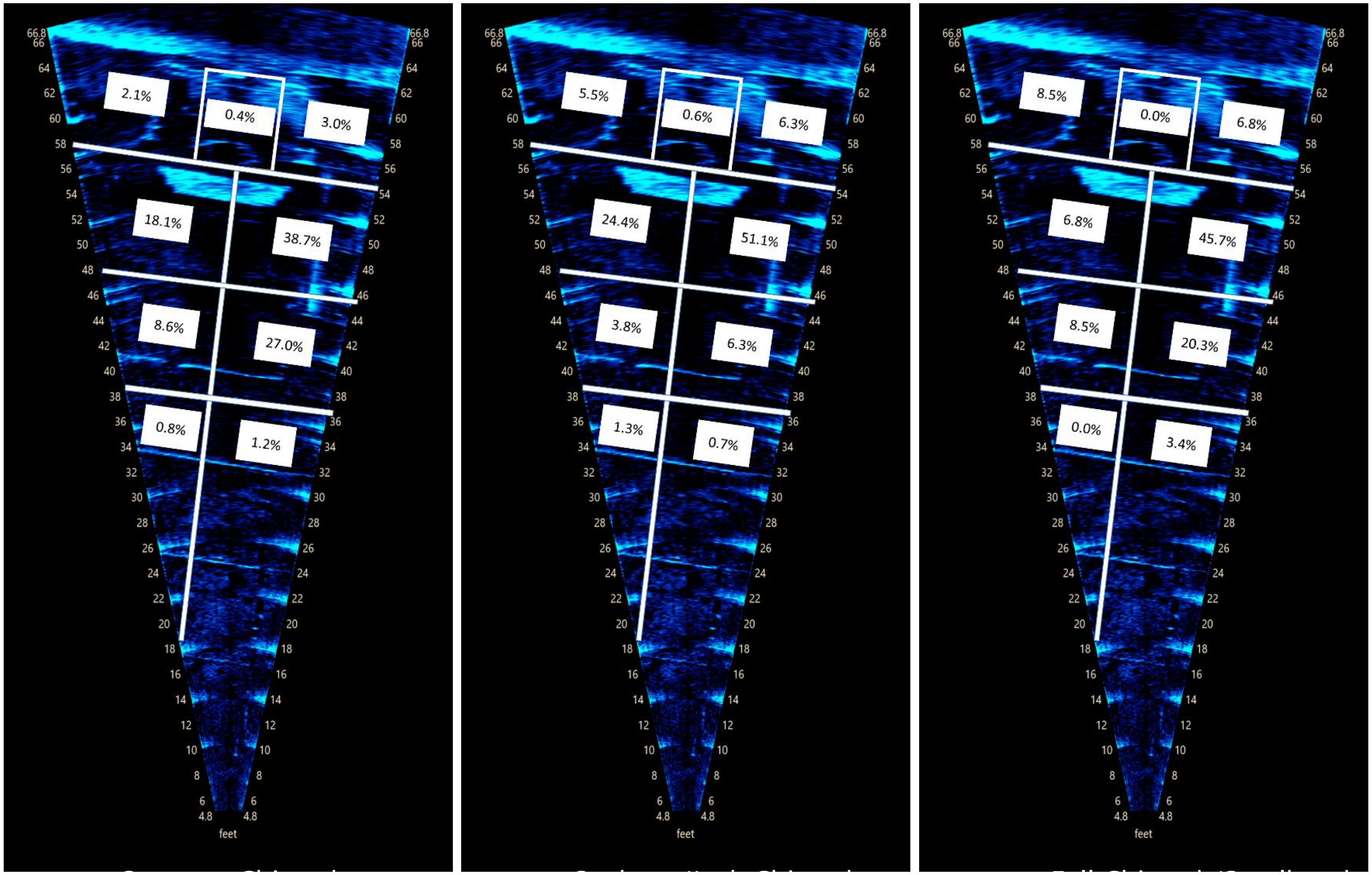
Chinook salmon/steelhead passage season. A slight increase followed by a slight decrease in depth through time was observed for summer Chinook salmon whereas sockeye/jack Chinook salmon maintained similar exit depths through their run period. Fall Chinook salmon and steelhead were shown to exit the FOV with decreasing depth from study week 11 through 13. Estimates of overall mean depth were fairly similar for both summer Chinook salmon and sockeye/jack Chinook salmon for Positions 2 through 5, whereas fall Chinook salmon/steelhead were shown to be distributed slightly deeper compared to the other two groups in the near forebay areas (Figure 36).

Table 9
Proportion of Movement Behaviors for Exit-origin Fish by Species Group and Temperature Condition

Movement Behavior	Species Group								
	Summer Chinook Salmon			Sockeye / Jack Chinook Salmon			Fall Chinook Salmon / Steelhead		
	Overall n=477	Low Temp n=374	High Temp n=78	Overall n=532	Low Temp n=416	High Temp n=88	Overall n=59	Low Temp n=46	High Temp n=13
Directly Upstream	0.4%	0.5%	0.0%	0.6%	0.7%	0.0%	0.0%	0.0%	0.0%
Towards Powerhouse/Spillway	69.8%	68.2%	73.1%	64.3%	63.7%	64.8%	76.3%	78.3%	69.2%
Towards South Shore	29.8%	31.3%	26.9%	35.2%	35.6%	35.2%	23.7%	21.7%	30.8%
No Change in Depth	5.5%	5.9%	3.8%	12.4%	13.5%	9.1%	15.3%	13.0%	23.1%
Less than 10-foot Change in Depth	56.8%	58.6%	44.9%	75.5%	73.6%	84.1%	52.5%	60.9%	23.1%
Greater than10-foot Change in Depth	37.7%	35.6%	51.3%	12.3%	12.9%	6.8%	32.2%	26.0%	53.8%

Note:
Low and high temperature conditions are defined as less than 68° and greater than or equal to 68° (F), respectively. Temperature values reflect the average values between the temperature sensors located at 1.6 and 4.9 foot depths at S2. Temperature data from S1 were not always available during time periods when fish were detected which explains why the overall n value does not equal the sum of the low and high temperature n values for a given species group.

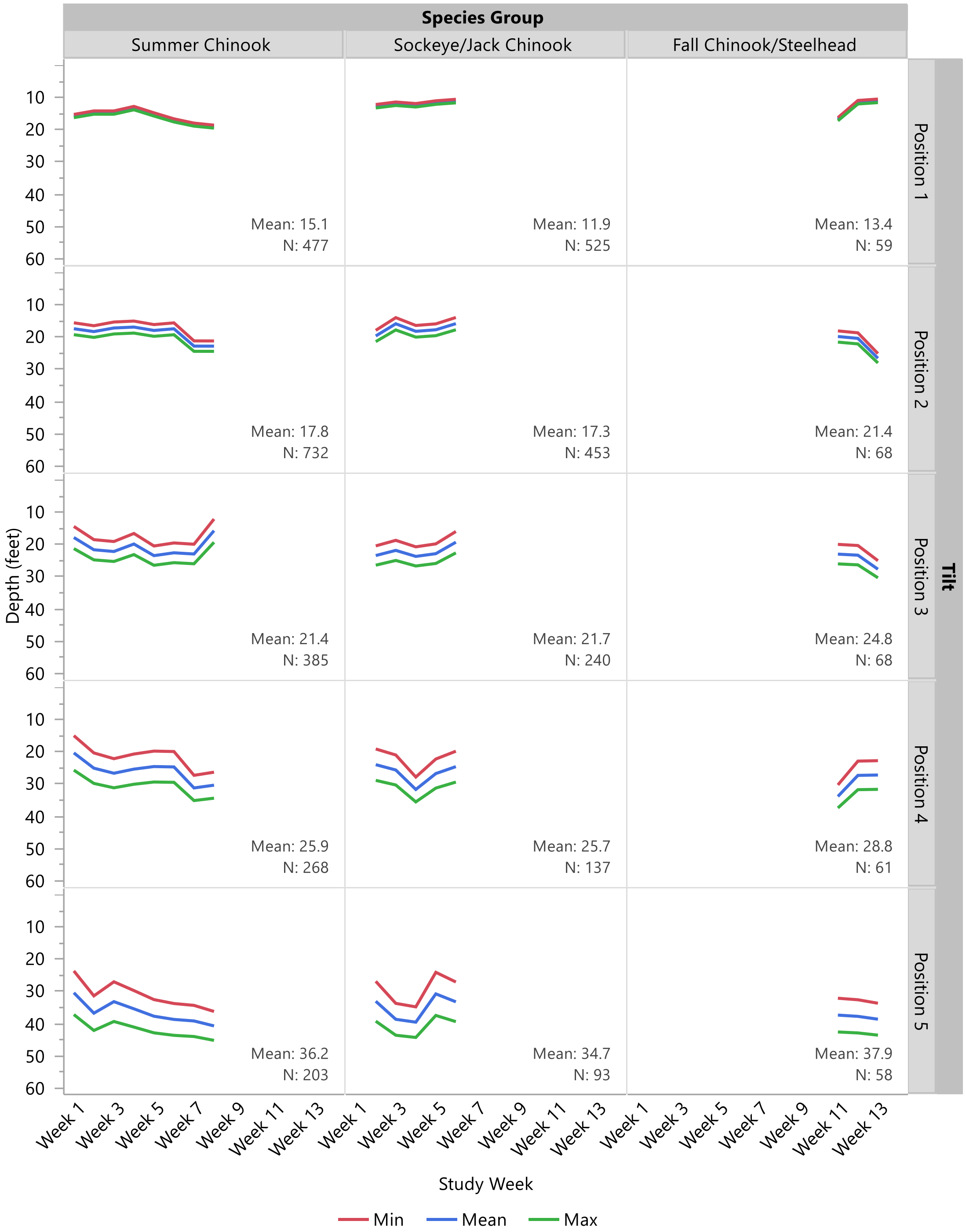
Figure 35
Frequency Distributions of Exit-origin Fish Based on Last Detections Within Discrete Areas of Position 1 Field of View for Each Species Group



Notes:
Left panel summer Chinook salmon n=475; middle panel sockeye/jack Chinook salmon n=525; right panel fall Chinook salmon/steelhead n=59.
The perspective of the field of view (FOV) is from the forebay looking towards the dam. The powerhouse and spillway are to the right of the FOV.

Figure 36

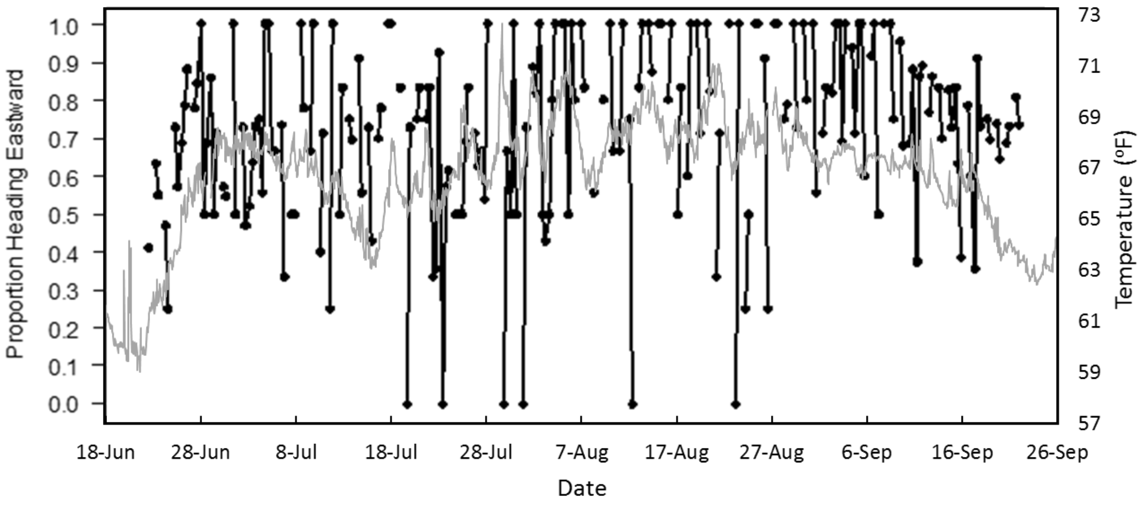
Mean, Min, and Max Depths for Each Species Group by Study Week and Rotational Position for Field of View Fish Exit Locations



Notes:
For Position 1, only exit-origin fish are shown. The min and max depth variables reflect averaged minimum and maximum range of depth values associated with a given mean depth as converted from range detections from sonar (see Figure 8).

The ARIS observations were quantitatively used to monitor the fraction of the fish exiting or milling below the adult ladder that travel northward toward the powerhouse and spillway. Plots of the proportion of fish exiting or milling fish traversing to the east were noisy, but relatively constant over the course of the study (Figures 37 through 39). The small sample variability and lack of trends suggest few covariate relationships may be found to explain changes over time.

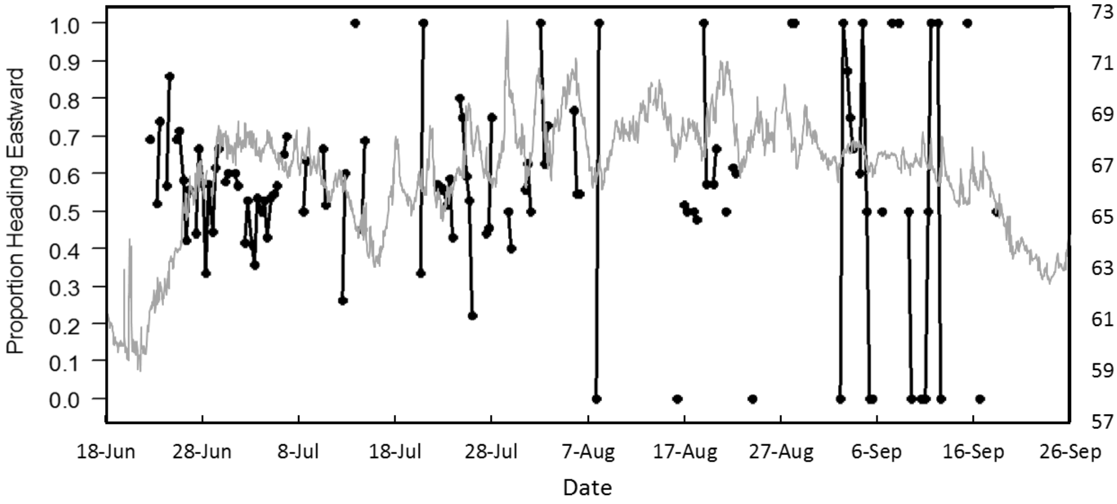
Figure 37
Trends Over Time in ARIS Measured Proportions of Fish Moving Northward for Ladder Exiting Fish Superimposed on Temperature at 10 ft depth along Dam Face (S2)



Notes:
Results show daily proportions and only include Position 1 fish observed to enter FOV upon exiting fishway.
Temperature is plotted in grey

Figure 38

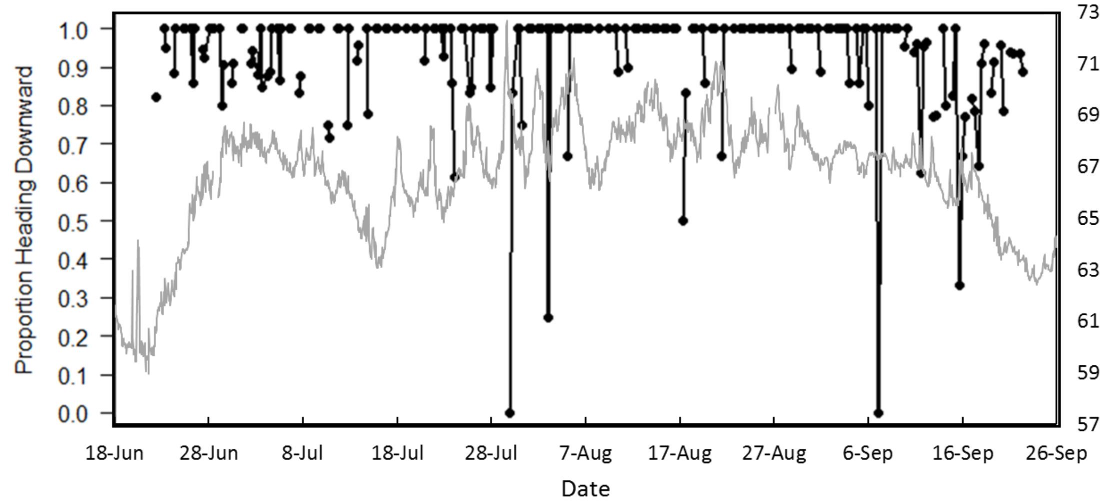
Trends Over Time in ARIS Measured Proportions of Non-Exiting Fish Observed Milling Below Ladder Superimposed on Temperature at 10 ft Depth along Dam Face (S2)



Notes:
Results show daily proportions and only include Position 1 fish not observed to enter FOV upon exiting fishway.
Temperature is plotted in grey

Figure 39

Trends Over Time in ARIS Measured Proportions of Exiting Ladder Fish Moving Downward Superimposed on Temperature at 10 ft depth along Dam Face (S2)



Notes:
Results show daily proportions and only include Position 1 fish observed to enter FOV upon exiting fishway.
Temperature is plotted in grey

3.3.3 Regression Analyses

The northerly movement of fish exiting or in front of the ladder exit was the focus of the ARIS analysis. Fish moving north along the face of the dam would be exposed to the spillbays and turbine units that could result in fallback. Factors that contributed to fallback could be considered detrimental. A total of 108 single-variable (i.e., 12 covariates × 3 responses × 3 fish runs) regressions were performed (Appendix B, Tables B1–B9). In all cases, indicator variables for weekend versus weekday was forced into the models first to account for trapper versus free passage periods. Time of the week was not a significant factor ($P > 0.05$), except for exit-origin sockeye in a downward direction.

For the northward proportion analyses, spill measured either as total spill or median spill was found to be significant ($P < 0.05$) for non-exit-origin sockeye salmon (non-exit-origin fish are those fish detected with ARIS in Position 1, but not observed to enter FOV upon exiting the fishway; these fish were milling in the FOV but not seen to exit the fishway). Flow measured as either total flow or median and proportion spill were significant for summer Chinook salmon (Table 10). It should be noted that total and median flows or spill measures are highly correlated. Vibration appeared to be significant only for the non-exit-origin summer Chinook salmon. Temperature covariates were never found to be significant. The lack of reproducibility of the flow or spill effects across fish runs and response variables suggests these observed effects may be spurious. Therefore, we conclude that neither dam operations, nor temperature, nor vibrations had a demonstrable effect on fish behavior at the exit of the fish ladder as measured by the ARIS.

Analyses of the downward proportion found that both flow (total and median) and proportion spill were significant for exit-origin summer Chinook salmon (the same covariates as eastward analysis), and total flow for fall Chinook salmon/steelhead.

The number of 4-hour blocks with current information on dam operations, temperature, vibration, and ARIS observations were small—for summer Chinook salmon, 43 blocks; sockeye salmon, 13 blocks; and fall Chinook salmon/steelhead, 21 blocks. In no instance did multiple regression analysis identify additional covariates ($P < 0.05$) beyond the single-variable regression results reported in Table 10.

Table 10
Summary of Single-variable Regression Analysis for ARIS Responses by Fish Stock

Fish Stock	Response Variable	Significant Covariates	Sign	r^2
Sockeye salmon	% exit fish moving north	None		
	% non-exit fish moving north	Total spill	–	0.0652
		Median spill	–	0.0896
Summer Chinook salmon	% exit fish moving north	Total flow	–	0.0683

Fish Stock	Response Variable	Significant Covariates	Sign	r^2
		Median flow	–	0.0659
		Proportion spill	+	0.0568
	% non-exit fish moving north	Mean peak acceleration	–	0.0575
		No. threshold exceeded	–	0.0751
Fall Chinook salmon/steelhead	% exit fish moving north	None		
	% non-exit fish moving north	None		
Sockeye salmon	% exit fish move down	None		
Summer Chinook salmon	% exit fish move down	Total flow	–	0.0914
		Median flow	–	0.0818
		Proportion spill	+	0.0816
Fall Chinook salmon/steelhead	% exit fish move down	Total flow (kcfs)	+	0.2022

Note:
Only covariates found to be significant at α = 0.05 are listed from among the 12 covariates tested (see Appendix B for a complete summary of the analysis). Relationship indicated by sign (i.e., + for positive, – for negative relationship) and r^2 values. The r^2 value indicates fraction of variability explained by covariate.
kcfs: kilo cubic feet per second

3.3.4 Temperature Control Structure Operations

The TCS at the top of the LGR ladder was run nearly continuously after it was successfully installed. There was no plan to conduct an experiment to assess the effects of the spray bar on ambient water temperature or passage behavior of adult salmonids. However, the TCS outage associated with ADCP sampling on July 6, 2016, provided a 2-hour opportunity to compare adult passage behavior with the TCS turned on and off. This unexpected event allowed examination of fish movement patterns 2 hours before, 2 hours during, and 3 hours after the outage event.

Although surface water temperatures increased during the spray bar outage (Table 7), there was no discernable change in fish movement patterns. Chi-square tests of homogeneity found no difference in exit orientation ($P(\chi_8^2 \geq 9.4167) = 0.3084$) or position at the face of the dam between the 2-hour periods before, during, or 3 hours after the outage. However, small sample sizes (i.e., 23 fish before, 6 during, and 8 after) could have affected the power of the test.

3.4 Adult Passage

3.4.1 General Patterns

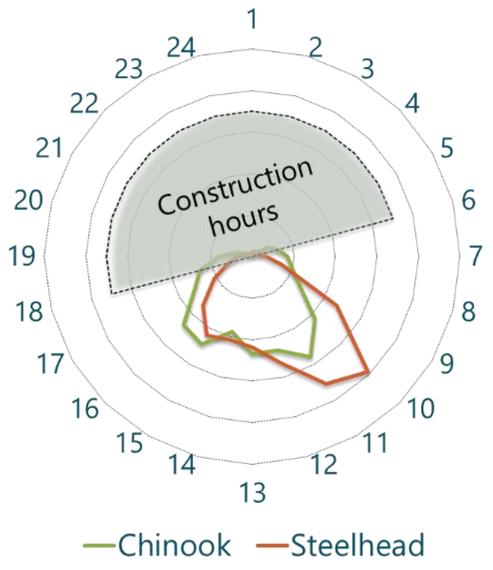
3.4.1.1 2015 PIT-tag Summary Statistics

In 2015, the PIT antennas at LGR did not include detection capabilities at the entrance or exit of the fishway (Figure 2) and therefore provided no opportunity for quantifying detailed passage metrics. The antennas did provide an opportunity to evaluate the general timing of PIT tagged fish entering the fishway relative to construction timing and the number of fish that passed through the trap route (i.e., trapped or shunted) or were allowed free passage (Figure 40).

The 2015 PIT-tag data illustrated that the majority of fish passed during daylight hours outside the nighttime construction window. Only 10.8% of the Chinook salmon, 6.8% of steelhead (Figure 40) and 26.7% of sockeye passed at night when construction took place at LGR. These results suggest that the scheduling of construction activities at night was effective at temporally separating passing fish from potential construction/vibration impacts.

Through 2015, the adult ladder at LGR was operated such that the vast majority of adult fish were diverted into the trap-loop and either trapped or allowed to transit the fishway after passing through trap-loop pipes. Fish are diverted (i.e., "shunted") into the trap-loop (and trapping facility) by a closed swing-gate in the ladder turning-pool. The orange arrow in Figure 41 illustrates how the swing-gate diverts fish into the trap-loop. A portion of the fish are trapped to support fish management objectives including tagging and broodstock collection and the remaining shunted fish must pass through 12-inch PIT coil conduits to return to the fishway. The 2015 operational plans for the ladder did not provide free passage of adults through the ladder. This meant virtually all adults through the ladder had their migration impacted by the trap operation to some unknown degree which confounds the interpretation of vibration or temperature effects on adult passage

Figure 40
Summary of Hourly Construction and Passage of Chinook Salmon and Steelhead at the Lower Granite Dam Fishway in 2015



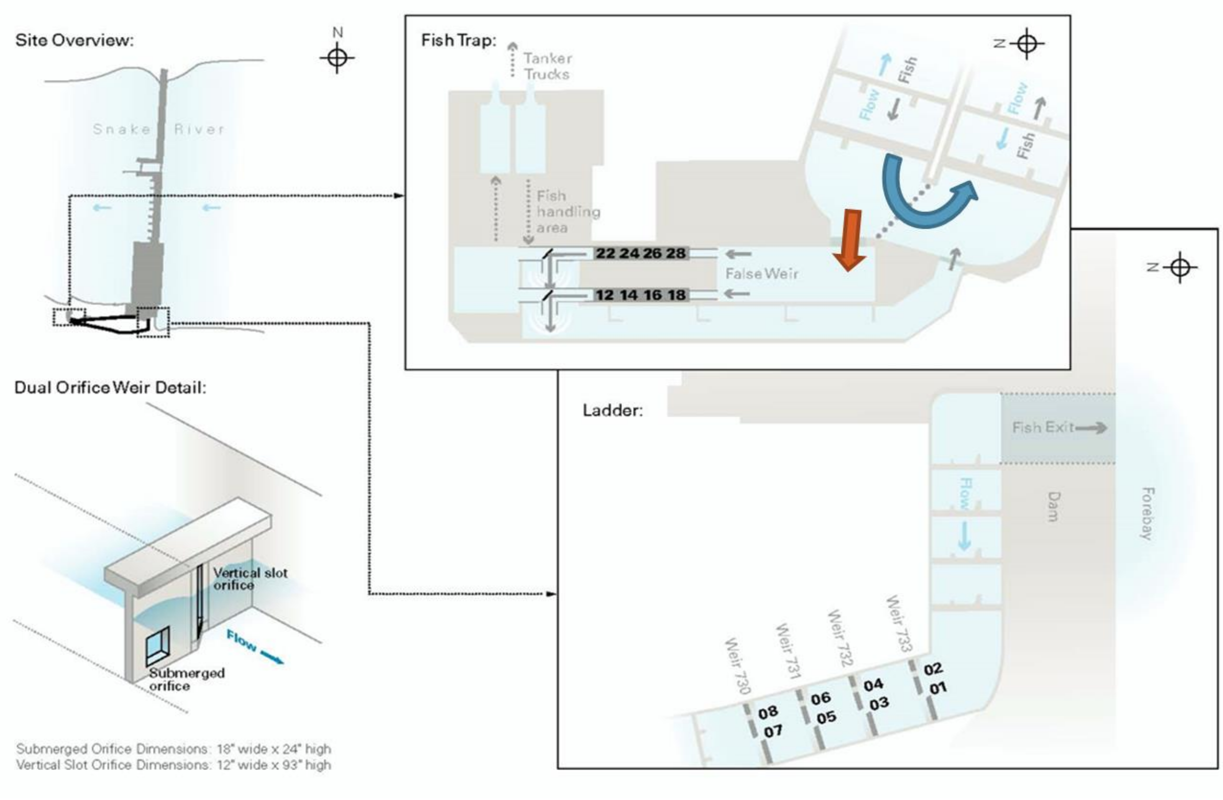
To document passage through these alternate routes fish were assigned to one of three different passage route categories based on detection locations in the LGR fishway (Figure 41):

- Free passage: only detected at weir (arrays: 01, 02, 03, 04, 05, 06, 07, 08)
- Shunted: detected in trap-loop pipes (arrays: 12, 14, 16, 18, 22, 24, 26, 28),
- Trapped: a shunted tag also listed in recap file at LGR and released at LGR ladder

Overall, 96% of the PIT tagged fish entering the LGR fishway were either trapped or routed away from the fishway (i.e., shunted; Figure 41) resulting in very few free passage events where fish behavior was not affected by the trap operations.

At the conclusion of the 2015 field season, Anchor QEA notified the USACE that the low number of free passage fish would preclude meaningful analyses of PIT data and suggested that reduced trapping operations would improve the interpretability of data in 2016. A reduced trapping schedule was implemented in 2016.

Figure 41
Lower Granite Dam 2015 Adult PIT Interrogation Coil Map



Notes:
The blue curved arrow in the upper right panel depicts the route of fish that had "free passage," and the orange arrow depicts the route of fish that were either "trapped" or "shunted" through the trap bypass.
Source: Figure provided by PTAGIS (2015)

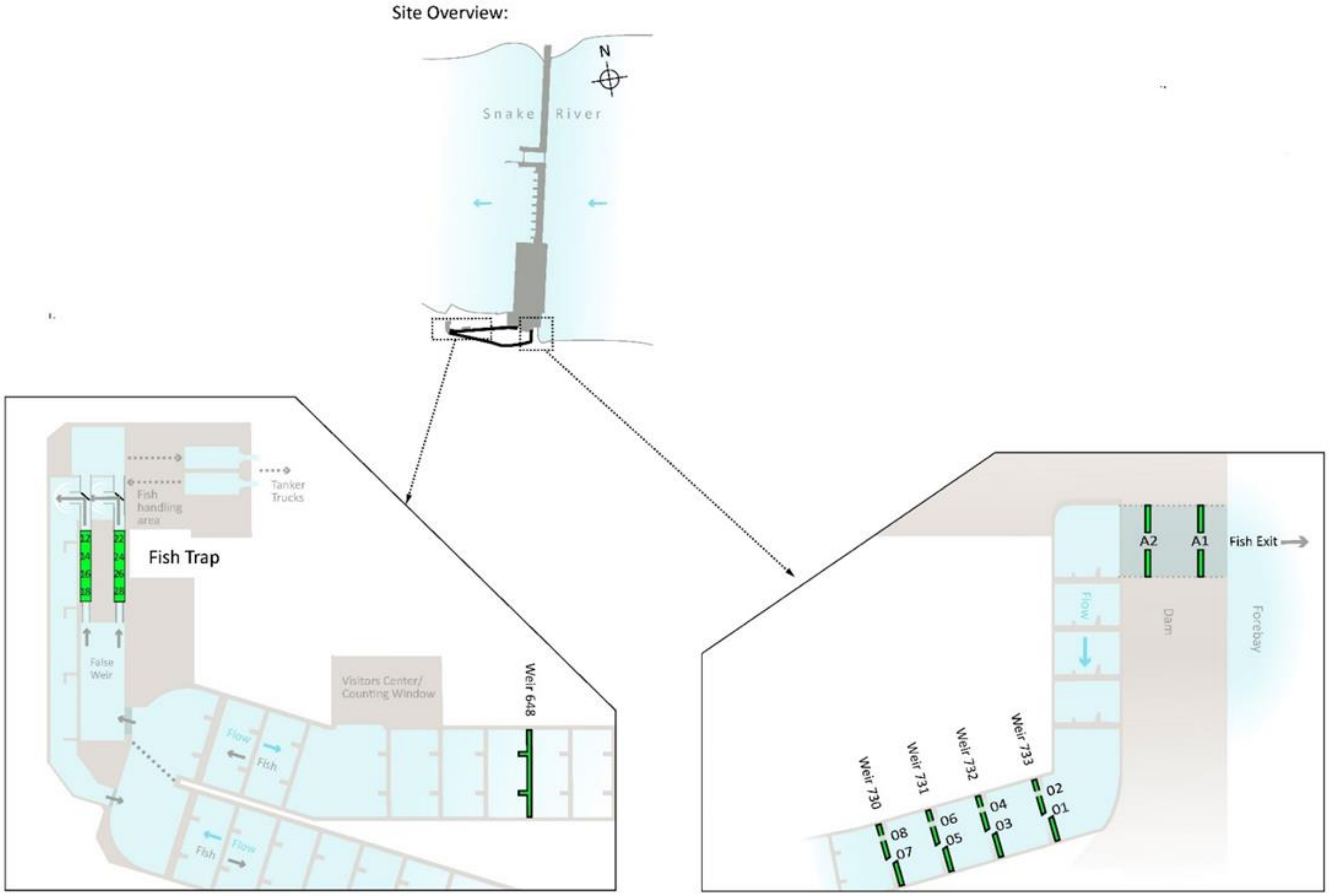
3.4.1.2 2016 PIT-tag Passage Summary Statistics

In 2016, additional PIT antennas at the entrance (Weir 648) and exit of the LGR fishway (A1 and A2; Figure 42) provided expanded interrogation capabilities at LGR and provided for the quantification of detailed passage metrics.

Fish passing through the fishway were categorized into one of three passage route groups based on existing and new PIT tag detection antennas:

- Free passage: only detected at entrance weir 648 (arrays: B1, B2, B3, B4), weir (arrays: 01, 02, 03, 04, 05, 06, 07, 08), and/or exit (arrays: A1, A2)
- Shunted: detected in trap-loop pipes (arrays: 12, 14, 16, 18, 22, 24, 26, 28), weir, and/or exit
- Trapped: a shunted tag also listed in recap file at LGR and released at LGR ladder

Figure 42
Schematic of Adult Ladder at Lower Granite Dam, Indicating Weir Locations and the Fish Trap



Notes:
Free-passage, PIT-tagged fish were detected entering the ladder at weir 648, passing through weirs 730–773, and exiting through weirs A2–A1. Shunted fish would have the same possible detection histories as free-passage fish, plus being detected in pipes (arrays 12–18, 22–28). Trapped fish would have the same possible detection histories as shunted fish, plus the additional PTAGIS notation of being "recaptured."
Source: Figure provided by PTAGIS (2016)

3.4.1.2.1 Temperature

Using all trapped, shunted, and free-passage fish, PIT-tag based passage metrics for spring-, summer-, and fall-run Chinook salmon; sockeye salmon; and steelhead were summarized relative to a temperature threshold of 68°F (20°C) to provide a coarse scale evaluation of the contribution temperature had on fish passage behavior (Table 11). There was no significant difference in transit time for any species, but sockeye had significantly higher entrance success rate under high temperatures; spring and summer-run Chinook salmon had significantly higher reascent rates at low temperatures; summer-run Chinook salmon had significantly higher exit success rates and passage at high temperatures while fall-run Chinook salmon and steelhead were higher at low temperatures. These results provide a very preliminary account of the role of temperature on fish passage and do not consider the effects of trapping, role of migration timing, or other covariates that could contribute to the observed patterns. Multivariate regression analyses were also performed on free passage fish to eliminate potential biases caused by trapping or shunting fish and to account for potential covariate relationships.

3.4.1.2.2 Vibration

PIT-tag based passage metrics for spring-, summer-, and fall-run Chinook salmon; sockeye salmon; and steelhead relative to a vibration threshold of 0.01 m/s^2 (80 dB//1 $\mu m/s^2$) were summarized to provide a coarse scale evaluation of the contribution ladder wall vibration had on fish passage behavior in the lower and upper portions of the fishway (Tables 12 and 13). At the lower fishway, there was no significant relationship between transit rate and vibration for any species, but entrance success was higher for summer Chinook salmon and steelhead when the vibration levels were lower than the threshold; reascent rates were lower for sockeye, summer-run Chinook salmon and steelhead when vibration levels were below the threshold; and exit and passage success were higher for summer- and fall-run Chinook salmon and steelhead when vibration levels were below the threshold (Table 12).

At the upper ladder there was no significant relationship between transit rate and vibration for any species, but entrance success was higher for steelhead when vibrations were above the threshold; reascent rates were lower for sockeye and steelhead when vibrations were below the threshold; and exit and passage success were higher for spring-, summer- and fall-run Chinook salmon and steelhead when vibration levels were below the threshold. As with the temperature analysis these results provide a very preliminary account of the role of ladder wall vibration on fish passage and do not consider the effects of trapping, role of migration timing, or other covariates that could contribute to the observed patterns. Multivariate regression analyses were also performed on free passage fish to eliminate potential biases caused by trapping or shunting fish and to account for potential covariate relationships.

Table 11
2016 Adult Passage Summary Statistics Under High and Low Exit Pool Temperature Ranges Based on PIT-tag Detections

Passage Metrics	**Species Group**									
	Spring Chinook Salmon		**Sockeye Salmon**		**Summer Chinook Salmon**		**Fall Run Chinook Salmon**		**Steelhead**	
	High ≥68°F	**Low <68°F**	**High ≥68°F**	**Low <68°F**	**High ≥68°F**	**Low <68°F**	**High ≥68°F**	**Low <68°F**	**High ≥68°F**	**Low <68°F**
	n=8	**n=849**	**n=14**	**n=112**	**n=11**	**n=368**	**n=37**	**n=248**	**n=48**	**n=1,705**
Median ladder transit time (hours)	49.08 **4**	2.44 **757**	4.24 **13**	6.27 **85**	3.76 **9**	2.42 **320**	8.50 **8**	3.57 **132**	2.46 **18**	4.04 **1,164**
Entrance success rate (%)	62.5 (17.1) **8**	94.9 (0.8) **849**	100 (<0.1) **14**	92.9 (2.4) **112**	81.8 (11.6) **11**	94.6 (1.2) **368**	83.8 (6.1) **37**	90.3 (1.9) **248**	83.3 (5.4) **48**	73.4 (1.1) **1,705**
Dropback rate (%)	0 (<0.1) **8**	0.1 (0.1) **849**	0 (<0.1) **14**	0 (<0.1) **112**	0 (<0.1) **11**	0 (<0.1) **368**	0 (<0.1) **37**	0 (<0.1) **248**	0 (<0.1) **48**	0.1 (0.1) **1,705**
Reascent rate (%)	0 (<0.1) **5**	2.9 (0.6) **799**	0 (<0.1) **13**	2.2 (1.6) **90**	0 (<0.1) **9**	4.2 (1.1) **330**	0 (<0.1) **8**	0.7 (0.7) **151**	3.6 (3.5) **28**	2.2 (0.4) **1,571**
Exit success rate (%)	83.3 (15.2) **6**	93.7 (0.8) **845**	92.9 (6.9) **14**	81.7 (3.7) **109**	100 (<0.1) **9**	92.9 (1.4) **354**	26.7 (8.1) **30**	95.4 (1.7) **153**	54.2 (7.2) **48**	93.0 (0.6) **1,661**
Passage success rate (%)	80 (17.9) **5**	93.9 (0.8) **806**	92.9 (6.9) **14**	87.6 (3.3) **97**	100 (<0.1) **9**	92.8 (1.4) **354**	30.8 (9.1) **26**	95.7 (1.7) **138**	52.8 (8.3) **36**	93.5 (0.7) **1,246**

Notes:
68°F = 20°C
n: total unique fish attempts in the ladder for each category
Bold indicates total unique fish used in each passage metric per category
Standard errors provided when available in parenthesis
Not all fish attempts had all data available (e.g., entrance/exit detections, temperatures at time of passage)
Tests of significance were conducted assuming a Normal distribution between categories. Significant results (i.e., P(>|Z|) ≤ 0.05) are indicated by shading.
Temperature at the exit pool was measured every 5 minutes. Each fish passage attempt was assigned to the < 68°F (20°C) category if, at the time of the first detection at the last array detected in the passage attempt sequence, both temperature readings at the exit pool were less than 68°F (20°C). The last array a fish was detected at usually was either at the weir arrays or the exit, but could be the entrance array (for those attempts that did not enter the ladder) or the trap (for those that were not detected again afterwards).

Table 12
Non-construction Year 2016 Adult Passage Summary Statistics During Periods When the Mean of the 1-second Peak Vibration Acceleration Estimates for the 4-hour Time Interval Were at or Above and Below the Behavioral Threshold at the Lower Ladder Based on PIT-tag Detections

	Species Group									
	Spring Chinook Salmon		**Sockeye Salmon**		**Summer Chinook Salmon**		**Fall Run Chinook Salmon**		**Steelhead**	
	At or Above Threshold	**Below Threshold**	**At or Above Threshold**	**Below Threshold**	**At or Above Threshold**	**Below Threshold**	**At or Above Threshold**	**Below Threshold**	**At or Above Threshold**	**Below Threshold**
Passage Metrics	**n=145**	**n=685**	**n=114**	**n=10**	**n=212**	**n=172**	**n=80**	**n=181**	**n=199**	**n=1,140**
Median ladder transit time (hours)	2.91 **128**	2.39 **644**	5.19 **93**	10.48 **9**	2.61 **173**	2.32 **166**	3.84 **32**	3.65 **108**	2.98 **145**	4.27 **1044**
Entrance success rate (%)	98.6 (1.0) **145**	99.4 (0.3) **685**	99.1 (0.9) **114**	100 (<0.1) **10**	94.8 (0.6) **212**	99.4 (0.6) **172**	96.2 (2.1) **80**	98.3 (0.9) **181**	91.0 (2.0) **199**	98.1 (0.4) **1,140**
Dropback rate (%)	0 (<0.1) **145**	0.1 (0.1) **685**	0 (<0.1) **114**	0 (<0.1) **10**	0 (<0.1) **212**	0 (<0.1) **172**	0 (<0.1) **80**	0 (<0.1) **181**	1.0 (0.7) **199**	0 (<0.1) **1,140**
Reascent rate (%)	3.1 (1.5) **128**	2.8 (0.6) **651**	5.3 (2.3) **94**	0 (<0.1) **9**	7.5 (2.0) **174**	2.4 (1.2) **166**	6.2 (4.3) **32**	0.9 (0.9) **113**	11.0 (2.5) **154**	0.9 (0.3) **1,057**
Exit success rate (%)	90.1 (2.5) **142**	94.4 (0.9) **682**	83.0 (3.5) **112**	90.0 (9.5) **10**	87.4 (2.4) **198**	97.1 (1.3) **171**	58.2 (6.7) **55**	98.2 (1.3) **110**	80.2 (3.0) **182**	93.6 (0.7) **1,115**
Passage success rate (%)	90.1 (2.5) **142**	94.4 (0.9) **682**	87.7 (3.2) **106**	90.0 (9.5) **10**	87.4 (2.4) **198**	97.1 (1.3) **171**	59.3 (6.7) **54**	98.2 (1.3) **110**	83.0 (2.8) **176**	93.8 (0.7) **1,114**

Notes:
Threshold equals greater than or equal to 0.01 m/s^2 (80 dB//1 μm/s^2)
n: is the total unique fish attempts in the ladder for each category
Bold indicates total unique fish used in each passage metric per category
Standard errors provided when available in parenthesis
Not all fish attempts had all data available (e.g., entrance/exit detections, temperatures at time of passage)
Tests of significance were conducted assuming a Normal distribution between categories. Significant results (i.e., P(>|Z|) ≤ 0.05) are indicated by shading
Vibration acceleration in the lower ladder was averaged in 4-hour periods daily (0000-0400, 0400-0800, 0800-1200, 1200-1600, 1600-2000, 2000-2400). Each fish passage attempt was assigned to the < 0.01 m/s^2 (80 dB//1 μm/s^2) category if, at the time of the first detection in lower ladder (entrance arrays) in the passage attempt sequence, the mean 1-sec peak acceleration for the 4-hour period was < 0.01 m/s^2 (80 dB//1 μm/s^2). Fish not detected at the entrance arrays were not used.

Table 13
Non-construction Year 2016 Adult Passage Summary Statistics During Periods When the Mean of the 1-second Peak Vibration Acceleration Estimates for the 4-Hour Time Interval Were at or Above and Below the Behavioral Threshold at the Upper Ladder Based on PIT tag Detections

	Species Group									
	Spring Chinook Salmon		Sockeye Salmon		Summer Chinook Salmon		Fall Run Chinook Salmon		Steelhead	
	At or Above Threshold	Below Threshold	At or Above Threshold	Below Threshold	At or Above Threshold	Below Threshold	At or Above Threshold	Below Threshold	At or Above Threshold	Below Threshold
Passage Metrics	**n=156**	**n=708**	**n=116**	**n=14**	**n=198**	**n=180**	**n=58**	**n=125**	**n=219**	**n=1,501**
Median ladder transit time (hours)	3.50 **131**	2.38 **641**	5.19 **93**	5.64 **9**	2.64 **174**	2.22 **165**	3.52 **33**	3.67 **107**	2.88 **137**	4.28 **1,052**
Entrance success rate (%)	96.8 (1.4) **156**	94.9 (0.8) **708**	94.0 (2.2) **116**	92.9 (6.9) **14**	98.5 (0.9) **198**	96.7 (1.3) **180**	94.8 (2.9) **58**	88.0 (2.9) **125**	80.4 (2.7) **219**	74.6 (1.1) **1,501**
Dropback rate (%)	0.6 (0.6) **156**	0 (<0.1) **708**	0 (<0.1) **116**	0 (<0.1) **14**	0 (<0.1) **198**	0 (<0.1) **180**	0 (<0.1) **58**	0 (<0.1) **125**	0.9 (0.6) **219**	0 (<0.1) **1,501**
Reascent rate (%)	3.7 (1.6) **136**	2.9 (0.6) **679**	6.1 (2.4) **98**	0 (<0.1) **9**	5.6 (1.7) **178**	2.3 (1.2) **171**	5.9 (4.0) **34**	0.8 (0.8) **125**	11.5 (2.4) **183**	0.9 (0.3) **1,425**
Exit success rate (%)	86.5 (2.7) **156**	95.1 (0.8) **708**	83.6 (3.4) **116**	64.3 (12.8) **14**	89.4 (2.2) **198**	95.0 (1.6) **180**	58.6 (6.5) **58**	96.0 (1.8) **125**	78.4 (2.8) **218**	93.9 (0.6) **1,500**
Passage success rate (%)	86.2 (2.8) **152**	95.4 (0.8) **672**	90.3 (2.9) **103**	69.2 (12.8) **13**	89.2 (2.2) **195**	94.8 (1.7) **174**	60.0 (6.6) **55**	98.2 (1.3) **109**	80.2 (3.0) **172**	94.2 (0.7) **1,118**

Notes:
Threshold equals to greater than or equal to 0.01 m/s^2 (80 dB//1 μm/s^2)
n: is the total unique fish attempts in the ladder for each category
Bold indicates total unique fish used in each passage metric per category
Standard errors provided when available in parenthesis
Not all fish attempts had all data available (e.g., entrance/exit detections, temperatures at time of passage)
Tests of significance were conducted assuming a Normal distribution between categories. Significant results (i.e., P(>|Z|) ≤ 0.05) are indicated by shading
Vibration acceleration in the upper ladder was averaged in 4-hour periods daily (0000-0400, 0400-0800, 0800-1200, 1200-1600, 1600-2000, 2000-2400). Each fish passage attempt was assigned to the < 0.01 m/s^2 (80 dB//1 μm/s^2) category if, at the time of the first detection in upper ladder (weir and exit arrays) in the passage attempt sequence, the mean 1-sec peak acceleration for the 4-hour period was < 0.01 m/s^2 (80 dB//1 μm/s^2). Fish not detected at the weir or exit arrays were not used.

3.4.2 Regression Analysis

For 2016, a total of seven response variables were estimated on ladder passage performance from PIT-tag detections at the LGR adult ladder. Responses were measured on 4-hour time blocks during weekends when adult fish had free passage through the ladder. The intent of the PIT-tag analyses was to assess the effects of vibration and temperature on passage performance of free-passage (i.e., non-trapped, non-shunted) adult salmonids through the LGR adult ladder. During the study, a total of 377 spring Chinook salmon, 32 sockeye salmon, 11 steelhead, and 0 coho salmon were allowed free passage through the ladder. Only spring Chinook salmon had enough free-passage fish for statistical regression analyses. The median number of spring Chinook salmon observed in the ladder during a 4-hour block was 3. Temporal patterns in ladder performance were relatively stable over time, but subject to large sampling error due to small sample sizes (Figure 43). Season-wide detection efficiency of the exit PIT array ranged from 82% (± 4% SE) for sockeye salmon to 92% (± 1%) for Chinook salmon.

Single-variable regression analyses consistently found surface temperatures at S2 (i.e., ladder exit) and S3 (i.e., forebay) to be significantly related to ladder passage performance ($P < 0.05$) (Table 14; Appendix C, Tables C1–C7). Median ladder transit times were positively correlated with temperatures at S2 and S3 (i.e., longer passage times were related to higher temperatures). Temperatures were also positively correlated with ladder exit success. On the other hand, entrance success, dropback rates, reascent rates, and fish abundance in the ladder were negatively correlated with surface water temperatures at both S2 and S3 (Table 14).

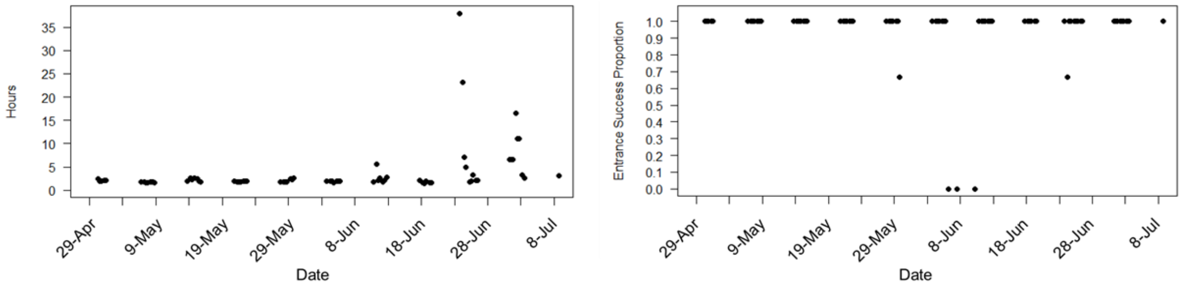
Vibration disturbances, as measured by mean peak acceleration and the frequency the vibration threshold of 0.01 m/s^2 (80 dB//1 $\mu m/s^2$) was exceeded, were found to be positively correlated with ladder transit time. Vibration disturbances were found to be generally negatively associated with entrance success rate, reascent rate, and fish abundance in the ladder (Table 14).

In no case did multiple stepwise regression find more than a single covariate model to be significant ($P < 0.05$). In examination of r^2 values, temperature was more influential than vibration covariates when both factors were evident in single-variable regression (Table 14).

Figure 43
Trends in Ladder Passage Performance for Spring Chinook Salmon at the Adult Ladder at Lower Granite Dam, 2016

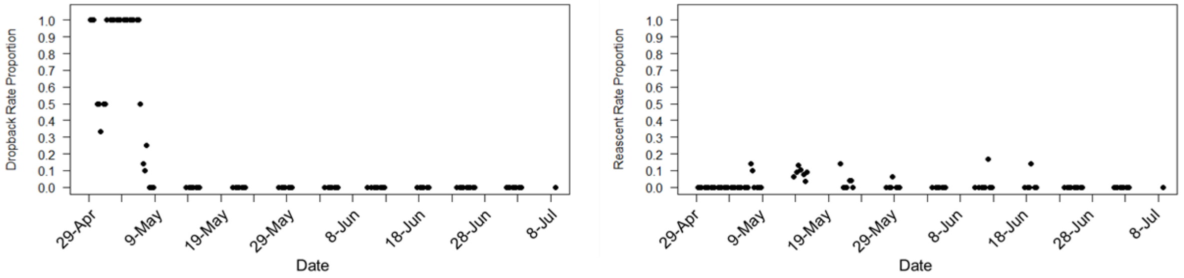
a. Median travel time

b. Entrance success



c. Dropback rate

d. Reascent rate



e. Exit success

f. Passage success

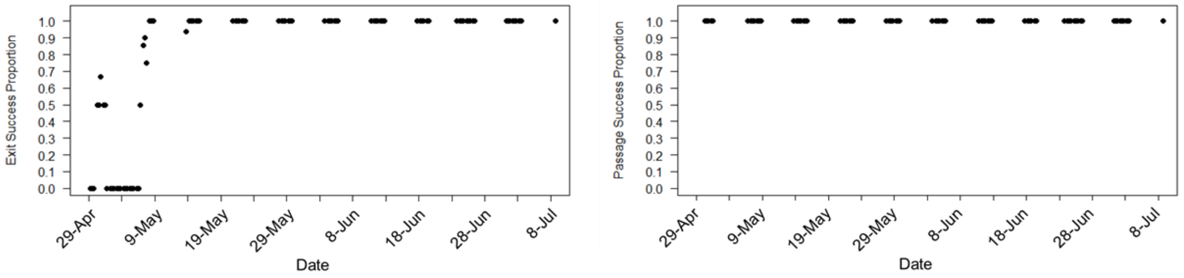


Table 14
Summary of Single-variable Regression Results for PIT-tag Measured Responses of Ladder Passage Performance for Spring Chinook Salmon

Response Variable	Significant Covariates	Sign	r^2
Median ladder transit time	Mean peak acceleration – ladder exit	+	0.0765
	No. times vibration threshold exceeded – ladder exit	+	0.0836
	No. times vibration threshold exceeded – ladder entrance	+	0.1369
	Surface temperature – S2	+	0.0795
	Surface temperature – S3	+	0.1004
	Temperature change – S2, S3	+	0.1641
Entrance success rate	Mean peak acceleration – ladder entrance	–	0.1299
	No. times vibration threshold exceeded – ladder exit	–	0.0559
	Surface temperature – S2	–	0.0871
	Surface temperature – S3	–	0.0980
Dropback rate	No. times vibration threshold exceeded – ladder exit	–	0.0628
	No. times vibration threshold exceeded – ladder entrance	+	0.0894
	Surface temperature – S2	–	0.3277
	Surface temperature – S3	–	0.2699
Reascent rate	Mean peak acceleration – ladder entrance	–	0.1157
	No. times vibration threshold exceeded – ladder exit	–	0.0506
	Surface temperature – S2	–	0.1482
	Surface temperature – S3	–	0.1244
Exit success rate	No. times vibration threshold exceeded – ladder exit	+	0.0660
	No. times vibration threshold exceeded – ladder entrance	–	0.0868
	Surface temperature – S2	+	0.3427
	Surface temperature – S3	+	0.2796
Passage success rate	N/A – All fish always succeeded		
Fish abundance in ladder	Mean peak acceleration – ladder exit	–	0.1227
	No. times vibration threshold exceeded – ladder exit	–	0.1018
	No. times vibration threshold exceeded – ladder entrance	–	0.1192
	Median temperature – ladder exit	–	0.4451
	Median temperature – ladder entrance	–	0.2844
	Surface temperature – S2	–	0.0608
	Temperature change – S2, S3	–	0.0669

Notes:
Variables significant at $P < 0.05$ listed, their association (I.e., + for positive relationship, - for negative relationship), and r^2 values. The r^2 indicates fraction of variability explained by covariate.

3.4.3 Effects of Trapping Operations on Fishway Passage Rates

In 2016, the fishway transit time of fish from all routes (i.e., free passage, shunted, and free passage) were compared. For inclusion in the analysis all fish had to be detected at the entrance of the ladder (i.e., weir 648, antennas B1:B4; Figure 42) and the duration was measured by subtracting the last detection at antennas 01:08 or A1:A2. Transit time varied among species but for all species, trapped fish had the longest duration between entrance and last detection in the fishway (Table 15). For fish that fell back and ascended multiple times, only the time for the first attempt was recorded. Fish that were not detected by the entrance arrays were excluded from the analysis.

Table 15
Time from Entrance (B1:B4) to Last Detection (01:08, A1:A2) at Lower Granite Dam by Passage Route and Run for 2016.

Run/Species	Route	n	Median (hrs)	Mean (hrs)
Sockeye	Free Passage	31	4.77	6.70 (0.72)
	Shunted	57	4.66	5.69 (0.37)
	Trapped	26	15.41	16.63 (2.2)
Spring Chinook	Free Passage	234	1.88	2.70 (0.17)
	Shunted	414	2.40	3.63 (0.22)
	Trapped	153	15.84	18.53 (1.61)
Summer Chinook	Free Passage	107	2.06	4.35 (0.73)
	Shunted	179	2.36	3.80 (0.78)
	Trapped	66	20.35	19.65 (2.66)
Steelhead	Shunted	529	2.98	8.20 (4.25)
	Trapped	503	8.98	16.10 (3.11)
Fall Chinook	Shunted	101	2.90	4.27 (0.4)
	Trapped	55	7.94	13.42 (1.58)

Notes:
Standard error for the mean is reported in parentheses
For fish that fell back and ascended multiple times, only the time for the first attempt was recorded
Fish that were not detected by the entrance arrays were excluded from the analysis

The occurrence of different trapping operations during 2016 also provided an opportunity to evaluate passage performance between periods with different trapping intensities (i.e., reduced and normal). Reduced trapping occurred April through August 17, 2016, and was characterized by free passage on weekends (i.e., 14:00 Friday to 14:00 Sunday), but normal trapping occurred during midweek (i.e., the adult ladder at LGR was operated such that adult fish either entered the trap or were shunted through the trap-loop pipes). From August 18 through the end of the season, normal trapping operations resumed 7-days per week. Chinook salmon were the focal species of this analysis because they had adult returns in both the reduced and normal trapping periods, albeit by different run types (Table 16).

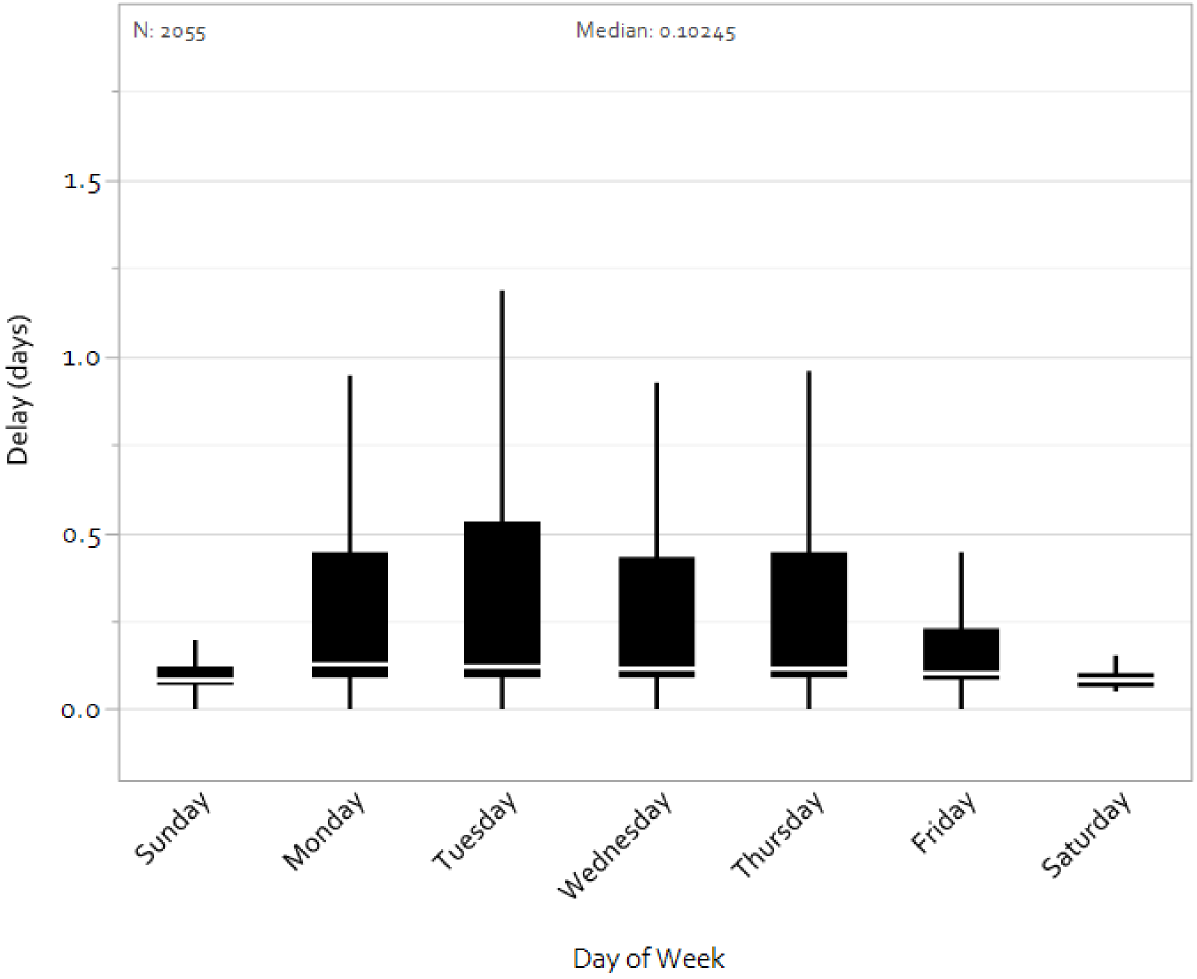
During the reduced trapping period, the duration spent by Chinook salmon in the fishway was significantly shorter on weekends when free-passage was allowed compared to midweek when trapping occurred (Figure 44; Median Test, $p < 0.001$). Spring-run Chinook salmon were the most abundant run-type in the LGR fishway during this period.

After August 18 when normal trapping resumed, delays were not significantly longer on weekdays than weekends (Median Test, $p = 0.098$; Figure 45); although delays were significantly longer than prior to August 18 ($p < 0.001$). Fall-run Chinook salmon were the most abundant in the LGR fishway during the normal trapping period.

Table 16
Run Type Composition and Numbers of Chinook Salmon Passing the Lower Granite Fishway During Periods of Reduced and Normal Trapping Intensity in 2016

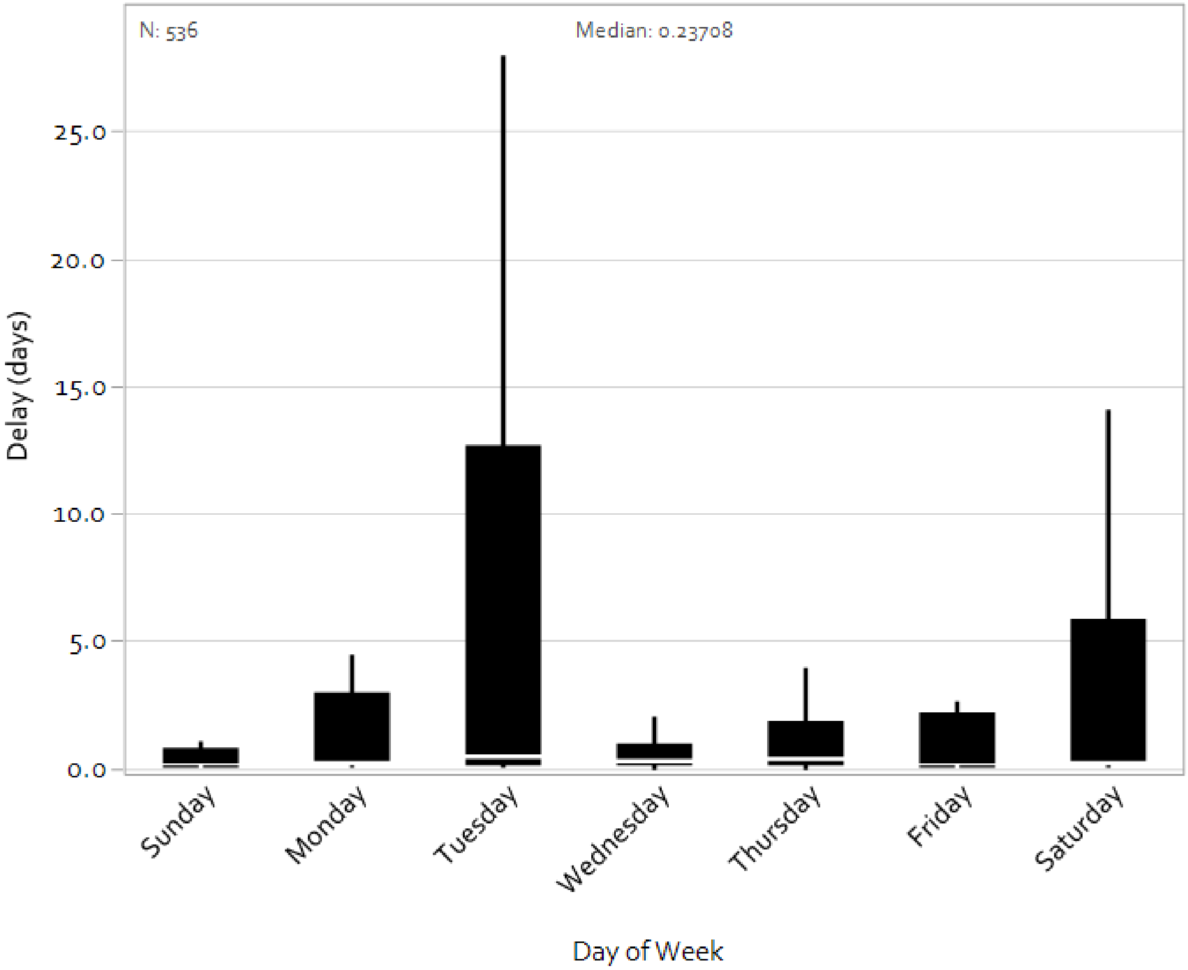
		Rear Type Code			
Period	**Chinook Run Type**	**Hatchery**	**Unknown**	**Wild**	**All**
"Reduced Trapping"-Prior To August 18	Fall	18	0	0	18
	Spring	664	3	172	839
	Summer	273	0	94	367
	Unknown	31	664	136	831
	All	986	667	402	2,055
"Normal Trapping"-August 18 and After	Fall	405	1	9	415
	Summer	2	0	0	2
	Unknown	0	111	8	119
	All	407	112	17	536

Figure 44
Box Plots of Passage Duration (From Entrance to Exit) of PIT-tagged Adult Chinook Salmon at Lower Granite Dam in 2016 by Day of Week Prior to August 18



Notes:
Whiskers represent Q1 – 1.5 × interquartile range or Q3 + 1.5 × interquartile range; the box encompasses Quartile 1, Quartile 2 (median, shown by transparent line), and Quartile 3. Positive outliers and maximum values are not shown to focus on a scale representing a majority of passage events.

Figure 45
Box Plots of Passage Duration (From Entrance to Exit) of PIT-tagged Adult Chinook Salmon at Lower Granite Dam in 2016 by Day of Week After August 18



Notes:
Whiskers represent Q1 – 1.5 × interquartile range or Q3 + 1.5 × interquartile range; the box encompasses Quartile 1, Quartile 2 (median, shown by transparent line), and Quartile 3. Positive outliers and maximum values are not shown to focus on a scale representing a majority of passage events.

3.4.4 Effects of Trapping Operations on Migration Success

For purposes of this temperature and vibration evaluation, the USACE changed ladder operations in 2016 to include free adult passage during weekends (i.e., 14:00 Friday to 14:00 Sunday), when fish trapping crews were not operational. The decision by USACE to allow free passage through the adult ladder on weekends provided the unique opportunity to examine the possible consequences of different adult passage configurations on upstream migration success.

Only adult fish that were PIT-tagged as juveniles with known origin above LGR were used in the analysis. Migration success was measured as any PIT-tag detection occurring at detection arrays upstream of LGR as an index to migratory success, not prespawning survival, per se. Timing of the weekend free-passage option did not coincide with adult run-timing for all fish stocks (Figure 46). For sockeye, spring Chinook, and summer Chinook salmon, free passage, shunted, and trapped passage options at the LGR adult ladder coincided with upmigration timing (Figure 46). An unconfounded comparison between the three alternative passage options at LGR could only be performed for sockeye, spring Chinook, and summer Chinook salmon. For steelhead and fall Chinook salmon, the free-passage option did not occur during their upriver migration periods (Figure 46).

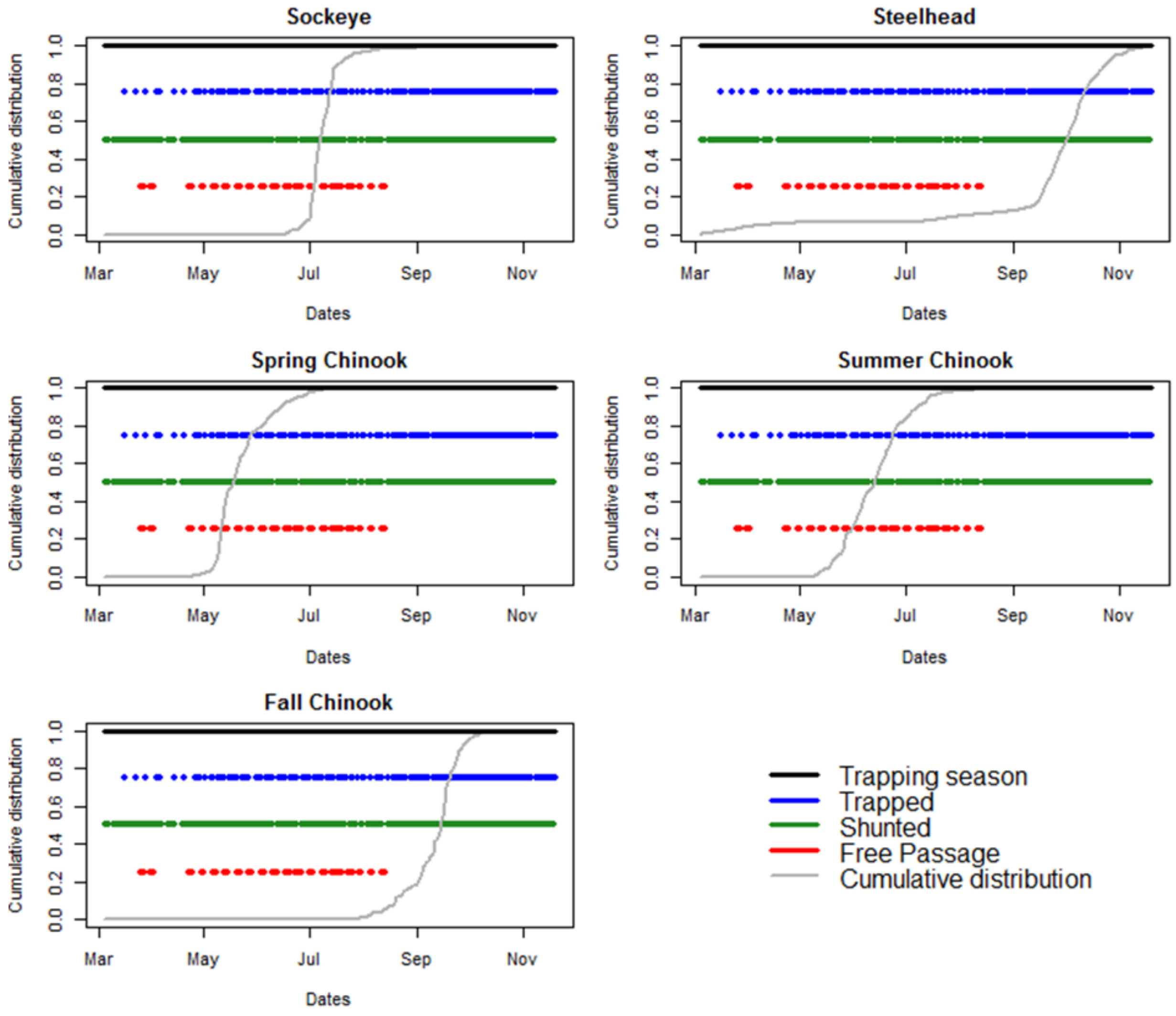
Free-passage summer Chinook salmon had a significantly higher upstream detection rate than trapped fish at LGR ladder. For sockeye and spring Chinook salmon, route of passage had no significant effect on upstream detection. For fall Chinook salmon, shunted fish had a significantly higher upstream detection rate than trapped individuals (Table 17). It should be noted that sample sizes for fall Chinook salmon are relatively small (n= 62 to 106).

The processing of the 2016 LGR ladder PIT-tag data were based on the following criteria:

- Only PIT-tagged fish that were released above Lower Granite Dam were considered in this comparison.
- Detection in LGR adult ladder between midnight (morning) of 4 March through midnight (evening) of 20 November 2016. This is based on when the trap was in operation. The goal is not to look at all passage results, but to compare the three routes to each other (free passage, passage through the shunt pipes, and passage through the shunt pipes and handling in the trap facility). Passage through the ladder when the trap was not in operation would be during different environmental conditions that could affect post-passage behavior.
- For this initial analysis, only whether the trap affected success (detection upriver of LGR) was examined. A future study may include analysis of route influence on upmigration.
- Fish that are only detected at the entrance, or last detected at the entrance after having exited the ladder at the top (fall back/reascent), or dropped back from the exit to the entrance (fall downs) were not included.
- Fish last seen at the trap were not included (not observed at the weir or exit), because comparison of upmigration behavior after a particular passage route in LGR ladder was desired. Queries for upriver detections begin on 4 March through 31 May 2017 which gave steelhead enough time to make it to spawning grounds above LGR.

- Tags must be detected (or reported as a mortality) upriver of LGR. Those that are detected below LGR only are considered a failure, given that they were released above LGR to get them to return and spawn there.
- Free passage: only detected at entrance (arrays: B1, B2, B3, B4), weir (arrays: 01, 02, 03, 04, 05, 06, 07, 08), and/or exit (arrays: A1, A2)
- Shunted: detected in trap-loop pipes (arrays: 12, 14, 16, 18, 22, 24, 26, 28), weir, and/or exit
- Trapped: a shunted tag also listed in recap file at LGR and released at LGR ladder

Figure 46
2016 Passage Routes by Calendar Date for Previously Tagged Salmonids



Notes:
In 2016, the trap was operated from 4 March to 20 November. The longest stretch where all three passage routes were taken occurred between 22 April and 14 August. Analysis based on known-source fish with natal locations above LGR.

Table 17
Total Number of Hatchery Origin Salmonids Initially Released as Juveniles and Returned to LGR as Adults by Route of Passage in 2016 and the Percent and Total Number Detected Anywhere Upstream After Leaving the LGR Ladder

Dates	Run/Species	Trapped			Shunted			Free Passage		
		n	x	%	n	x	%	n	x	%
22 Apr–14 Aug	Sockeye	28	20	71.4 (8.5)	58	41	70.7 (6.0)	34	27	79.4 (6.9)
	Spring Chinook salmon	129	59	45.7 (4.4)	354	138	39.0 (2.6)	204	79	38.7 (3.4)
	Summer Chinook salmon	55	35	63.6 (6.5)	138	96	69.6 (3.9)	96	76	79.2 (4.1)
4 Mar–20 Nov	Steelhead	581	194	33.4 (2.0)	574	217	37.8 (2.0)	N/A	N/A	N/A

Notes:
Shaded values significantly different at α = 0.05, two-tailed
Standard errors are reported parenthetically.
n: route of passage
x: total number detected anywhere upstream after leaving LGR ladder
%: percent detected anywhere upstream after leaving LGR ladder

3.5 Video Camera Evaluation of Jumping Behavior

During the period in which the TCS was operational (June 6, 2016 to September 8, 2016) the highest number of run-at-large, PIT-tagged steelhead passing the ladder exit occurred in the months of August and September. From those months, video subsamples were selected from the highest individual passage days and during the 8-hour period in which the highest number of PIT-tagged fish were observed at the exit: 09:00 thru 14:59. The video subsamples that were reviewed covered 71% of total daily passage (during TCS operations), but no steelhead were observed jumping.

4 Discussion

4.1 Water Temperatures

Water temperature measurements conducted during the study indicate that the TCS effectively reduces near-surface water temperatures near the ladder exit. Furthermore, the ADCP data illustrated that the operation of the TCS produced a local surface water current away from the ladder exit that provides a cooler surface water environment projecting into the forebay. However, because the TCS was operated nearly continuously over the warmest months of the year, there were very limited opportunities to directly measure the temperature change in the fish ladder or contrast fish passage or behavior under off and on conditions. Nonetheless, during the 2-hour TCS outage on July 6, 2016, it appears that the TCS reduced ladder temperatures by a minimum of 1.5 °F (0.8 °C). The between year comparison of forebay and exit pool temperatures prior to the TCS operations (2015) and after operations commenced (2016) suggests that the actual fishway cooling effect may increase with increasing temperatures and account for 1.7 °F (0.9 °C) of cooling when the forebay is at 65°F (18.3°C) up to 2.6°F (1.4 °C) when the forebay is at 80°F (26.7 °C). Based on the comparisons of forebay, exit pool, and tailwater temperatures in 2016, the TCS is also effective at reducing the temperature gradient between warmer water at the top of the LGR fishway and cooler water at the bottom of the fishway.

Previous work by Keefer et al. (2008), Caudill et al. (2013), and Goniea et al. (2006), illustrate that when salmon migrate through high water temperatures, passage delays or mortality may occur. The importance of temperature reductions in the ladder may be very significant in situations where maximum water temperatures are approaching the thermal tolerance thresholds of migrants (e.g., 68 to 75.2 °F or 20 to 24 °C for sockeye; Keefer et al. [2008]); or are high enough to cause migration delay (e.g., greater than 20°C for Chinook salmon; Goniea et al. [2006]). In addition, reducing the temperature gradient between the top of the ladder and bottom of the ladder to minimize the "delta" between the two is likely to increase passage rates (Caudill et al. 2013). At lower maximum temperatures, the TCS may provide sufficient cooling to achieve optimum temperature for migration (e.g., optimum range of 60.8 to 62.6°F or 16 to 17°C for Chinook salmon and steelhead; Salinger and Anderson 2006).

Additional on and off operational tests of the TCS under a range of temperatures and operational conditions would be useful to confirm the temperature response in the ladder and to directly evaluate the behavioral passage response by salmonids.

4.2 Post-passage Behavior

General patterns of post-passage fish behavior with the spray-bar in operation indicate that upon entering the forebay from the ladder exit, fish rarely move directly upstream without changing lateral or vertical position (Table 9; Figure 35). Based on proportional movement behavior, fish exiting the ladder show a clear preference for movement towards the powerhouse and spillway regardless of species group. This result suggests that the typical movement behavior of fish may increase the likelihood of fallback given the preference for moving towards the powerhouse and spillway upon entry into the forebay.

Patterns of depth distributions for exit-origin fish indicate movement behaviors may differ between the larger-sized Chinook salmon and steelhead, and the smaller-sized sockeye and jack Chinook salmon (Table 9; Figures 35 and 36). Only about 12% of the sockeye/jack Chinook salmon group were observed to increase their depth position by greater than 10 feet upon entering the forebay, whereas about one-third of the summer and fall Chinook salmon/steelhead were shown to increase their depth position by greater than 10 feet. This apparent disparity in depth distributions between sockeye/jack Chinook salmon and adult Chinook salmon suggests that sockeye and jack Chinook salmon may be more susceptible than adult Chinook salmon to the negative effects of increased water temperatures in the ladder exit area given that their distributions are closer to the water surface than are the distributions for adult Chinook salmon.

The movements of summer Chinook and sockeye/jack Chinook salmon after exiting the fishway suggest that these species groups may behave differently when encountering variable water temperature conditions upon entry into the forebay. Analysis assessing low (less than 68° F) and high (greater than or equal to 20°C or 68° F) water temperatures associated with each exit origin fish observation indicates that higher temperatures periods appear to result in summer Chinook salmon becoming distributed at greater depths than during lower temperature periods (Table 9). In contrast, sockeye/jack Chinook salmon appear to have a shallower distribution during periods of higher water temperature than during periods of lower water temperature.

Depth distributions in the near-forebay area were less revealing than what was observed for exit-origin fish at the face of the dam (Figure 36). Mean estimated depths by rotational position were fairly consistent when comparing sockeye/jack Chinook salmon to summer Chinook salmon, suggesting that once the fish move away from the area immediately downstream of the face of the dam, distribution patterns between these two groups do not differ. Mean depths for fall Chinook salmon and steelhead were shown to be deeper than for summer Chinook salmon and sockeye/jack Chinook salmon in the near-forebay area, but that may be a specious result given the much smaller relative sample size for this group.

The effects of vibrations, water temperatures, and dam operations on adult salmonid passage performance through the adult fishway at LGR in 2016 were examined. Passage performance was measured via ARIS observations on fish movements immediately upon exiting the fishway. ARIS observations in front of the fishway included both weekday (i.e., trapped) and weekend (i.e., non-trapped) periods. ARIS variables measured the proportion of fish moving northward toward the spillway and turbine units and proportion of fish moving downward. An increase in northerly movement was of concern because it may indicate an increased probability of adult fish experiencing fallback to below the dam. No consistent results were found between vibration levels, temperature, or dam operation variables and ARIS measured responses (Table 10). ARIS analyses included the up migrations of sockeye/jack Chinook salmon, summer Chinook salmon, and fall Chinook salmon/steelhead.

There were some important limitations of the ARIS data that should be considered with respect to examination of the study results. As stated above, some intermittent problems with image resolution occurred in the latter part of August and in September that resulted in the inability to obtain estimates of target fish length during those periods that coincided with the fall Chinook salmon and steelhead runs. Consequently, the sample size was much smaller for the fall Chinook salmon/steelhead group than for summer Chinook salmon and sockeye/jack Chinook salmon; therefore, results of the analysis with respect to fall Chinook salmon and steelhead should be viewed with caution.

Identification of species with imaging sonar data is another limitation to point out with regards to the results of this study. Species-specific size data from previous studies were coupled with run-timing data obtained from window counts to classify the three species groups that were assessed: summer Chinook salmon, sockeye/jack Chinook salmon, and fall Chinook salmon/steelhead. With the sampling ranges used in 2016, ARIS data did not provide enough detail on individual fish to definitively discern body shape or fin placement, which would be useful to differentiate species (e.g., American shad from sockeye). To try and remove shad from the data set, filtering was based on occurrence of schooling behavior, as shad are known to school whereas adult sockeye and jack Chinook salmon do not school. It is likely though that some individual shad that were not schooling and were of similar size to sockeye/jack Chinook salmon were included in the data set. Steelhead overlap in size with summer and fall Chinook salmon. The majority of steelhead passed the project during September but some steelhead were counted from the window throughout the entire study period, indicating the results for summer Chinook salmon likely includes some steelhead. Given the overlap in size, it was not possible to conduct separate analysis of fall Chinook salmon and steelhead.

4.3 Adult Passage

In the first year of the study (2015), the interpretability of passage data was constrained by the absence of PIT-tag detection capabilities at the entrance and exit of LGR. The data that were available did clearly illustrate that fish were passing LGR outside of the time that most of the construction activities were occurring. This suggests that the construction windows established for LGR were effective at separating fish from potential construction impacts. One of the other key findings from the 2015 data was the observation that the vast majority of fish passing LGR (96%) were either trapped or shunted through 12-inch pipes in the trap-loop prior to transiting the fishway.

Based on the high proportion of trapped and shunted fish observed in 2015 and associated concerns about the behavioral impacts associated with these routes of passage, the USACE changed trapping operations at LGR to provide free passage on weekends from April through August 18, 2016. In 2016, new PIT-tag antennas were also installed at the entrance and exit of the LGR fishway which provided an opportunity for a more detailed characterization of passage behavior.

Using the expanded PIT-tag detection data from 2016, the passage analysis first considered general passage performance using all trapped, shunted, and free-passage fish (e.g., all routes), and then focused on free passage fish only.

For the all routes analyses, passage performance relative to temperature and vibration thresholds was evaluated. For fall-run Chinook salmon and steelhead, passage metrics improved (i.e. exit success and passage success rate) with temperatures less than the 68°F (20°C) threshold as expected. For spring- and summer-run Chinook and sockeye salmon, the opposite was true and some passage metrics improved when temperatures were above the threshold. Passage performance generally improved (i.e., entrance success, reascent rate, exit success and passage success) when ladder wall vibrations were below the 0.01 m/s^2 (80 dB//1 $\mu m/s^2$) threshold in the upper and lower fishway. The one exception was entrance success rate for steelhead which was significantly higher when vibrations were above the threshold in the upper ladder. As noted previously, these results do not consider the effects of trapping, role of migration timing, or other covariates that could contribute to the observed patterns. Multiple regression analyses were also performed on free passage fish to eliminate potential biases caused by trapping or shunting fish and to account for potential covariate relationships.

For the multiple regression analyses, the PIT-tag data used were limited to the weekend periods when the adult trap was shut down and fish were allowed free passage through the adult ladder at LGR. This restricted the observation period and limited the PIT-tag analyses to only spring Chinook salmon. Vibration disturbances, as measured by 1) mean peak acceleration and 2) the frequency that the vibration threshold of 0.01 m/s^2 (80 dB//1 $\mu m/s^2$) was exceeded, were found to be positively correlated with ladder transit time. Vibration disturbances were found to be generally negatively associated with entrance success rate, reascent rate, and fish abundance in the ladder (Table 15). These associations were generally small with $r^2 \leq 0.10$ (Table 15), but do suggest some level of avoidance behavior by salmonids to intense vibrations. Detailed behavioral observations outside the scope of this study would be needed to provide a high-resolution characterization of the response of salmonids to sound or vibration in a fish ladder (Hawkins 2015).

Temperature variables had higher associations with PIT-tag ladder responses than vibration. Median ladder transit times were positively correlated with surface temperatures at S2 and S3, i.e., longer passage times were associated with higher temperatures. These results are consistent with previous work by Goniea et al. (2006) where the occurrence of passage delays increased with increasing water temperatures and slowed significantly above 68°F (20°C). Entrance success, dropback rates, and reascent rates in the ladder were negatively correlated with surface water temperatures at both S2 and S3 and fish abundance was negatively correlated with surface water temperatures at S2 (Table 15). Temperatures were also positively correlated with ladder exit success, which is counterintuitive, because higher temperatures are generally associated with lower passage performance.

In 2016, the combination of reduced trapping operations early in the season (prior to August 18) and normal trapping operations later (August 18 and thereafter) provided an opportunity to characterize and compare passage performance between and within the periods. In general, Chinook salmon passage times were reduced when trapping occurred. This pattern was evident during the reduced trapping period when midweek fish traveled significantly slower through the fishway compared to the weekends when free passage was permitted. After normal trapping resumed (August 18, 2016), fish transiting the fishway had significantly slower median transit times than fish traveling during the reduced trapping period.

In 2016, the opportunity to compare the upstream migratory success of free-passage, shunted, and trapped adults through the LGR ladder became available. Only three fish stocks could be examined—sockeye, spring, and summer Chinook salmon. For summer Chinook salmon, free-passage adults had a higher upriver detection rate than trapped adults ($P < 0.05$). Polled across the three available fish stocks, no differences were detected.

Given the large proportion of fish from the run at large that were trapped or shunted in both 2015 and 2016, and in years prior, the route of passage (free versus trapped or shunted) is an important variable that can affect passage rates and result in delays for large numbers of migrating fish. Additional monitoring of fishway passage rates, delays, and migratory success related to trapping is advised given the ESA status of many LGR adult migrants and previous case studies that demonstrate the potential for unintentional but significant negative impacts to accrue from trapping (Murauskas et al. 2014).

4.4 Summary of Recommendations

- Perform additional tests of the TCS to verify the extent of temperature decreases in the ladder and directly evaluate adult salmonid passage and post passage behavior during on and off periods.
- Consider conducting additional behavioral studies (e.g., active tags) if a high-resolution characterization of the response of salmonids to sound or vibration in a fish ladder is needed.
- Evaluate additional years of trapping data to parse out the significance of trapping to overall migration success. Consider reducing trapping of adult salmonids to the extent possible to improve migration success.

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Appendix A

Selecting Sampling Periods for Fish Passage Analysis

A key fish response examined was the entrance rate of fish into the ladder at LGR. These fish were also analyzed to estimate other responses, such as ladder fallback and exit success. Over the course of the LGR monitoring in 2016, 1,751 Chinook salmon, 844 steelhead, 124 sockeye salmon, and 12 coho salmon were detected entering the ladder at LGR during both trapped and non-trapped weekend periods. Only Chinook salmon, steelhead, and sockeye salmon have enough counts to examine statistically for relationships.

The diel trends for ladder entry by Chinook salmon and steelhead indicate the vast majority entered during the hours 04:00 to 16:00 (Figure A1). It would be prudent from a count perspective to focus analyses during that time frame. It is unfortunate from the study perspective that the majority of the construction activity was purposefully performed at night when passage rates were low.

Examining the seasonal pattern of ladder entry, the majority of Chinook salmon arrived between Julian days 120–190, and steelhead, between Julian days 240–276 (Figure A2). Consequently, passage evaluations were conducted in those time intervals.

Using the arrival counts between 04:00–16:00 hours during the seasonal peaks for Chinook salmon and steelhead, the fish counts for 2-, 3-, 4-, and 6-hour sampling periods were calculated and distributions plotted (Figures A3 and A4). Using 2-hour intervals, 44% of the observations were zero counts for Chinook salmon and 36% of the observations were zero counts for steelhead. Using 4-hour intervals, these percentages of zero counts drop to 29% and 19% for Chinook salmon and steelhead, respectively. There are 213 Chinook salmon and 111 steelhead 4-hour intervals in the dataset as we defined by season and times within a day. No advantage was observed in extending the time period to 6 hours; the percent zero counts did not drop much, sample sizes were cut by a third, and any short-duration effects, further diluted. Therefore, vibration and fish responses were measured on the 4-hour interval basis in this report.

Figure A1
Diel Trends in Ladder Entry at Lower Granite Dam by Fish Species in 2016 for Coho Salmon, Chinook Salmon and Steelhead, and Sockeye Salmon

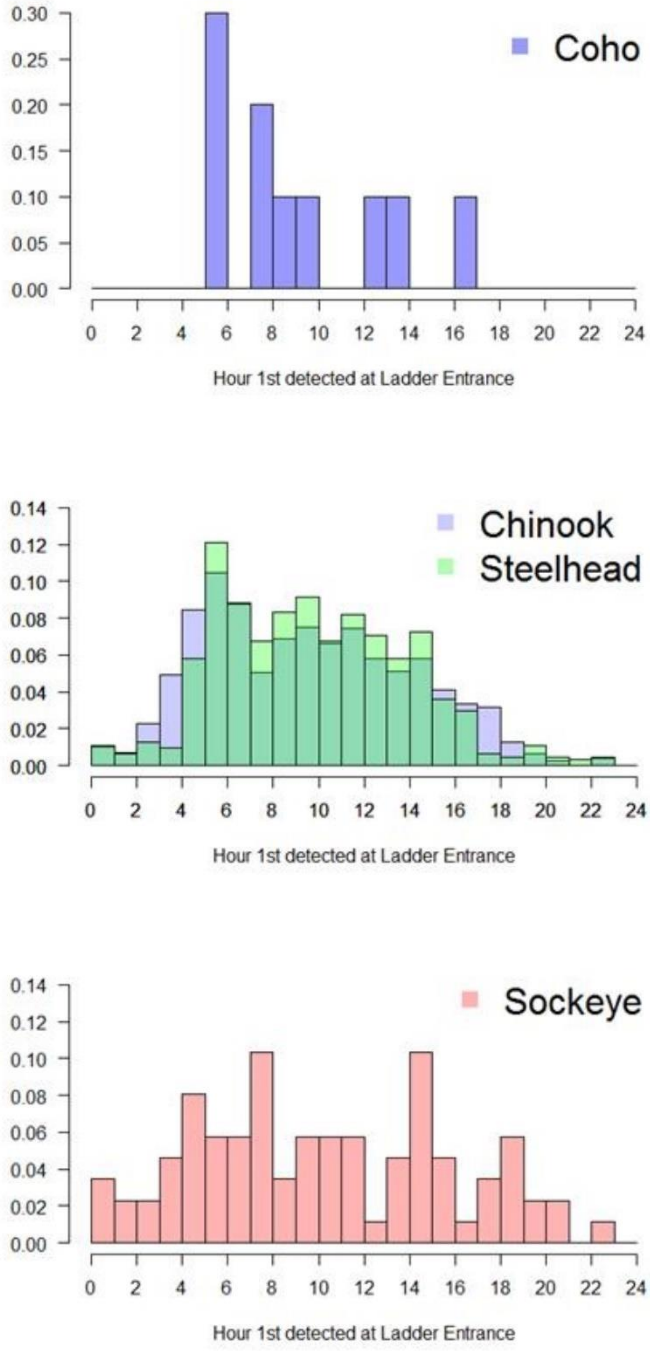


Figure A2
Ladder Entry Counts at Lower Granite Dam by Julian Date for Coho Salmon, Chinook Salmon and Steelhead, and Sockeye Salmon in 2016

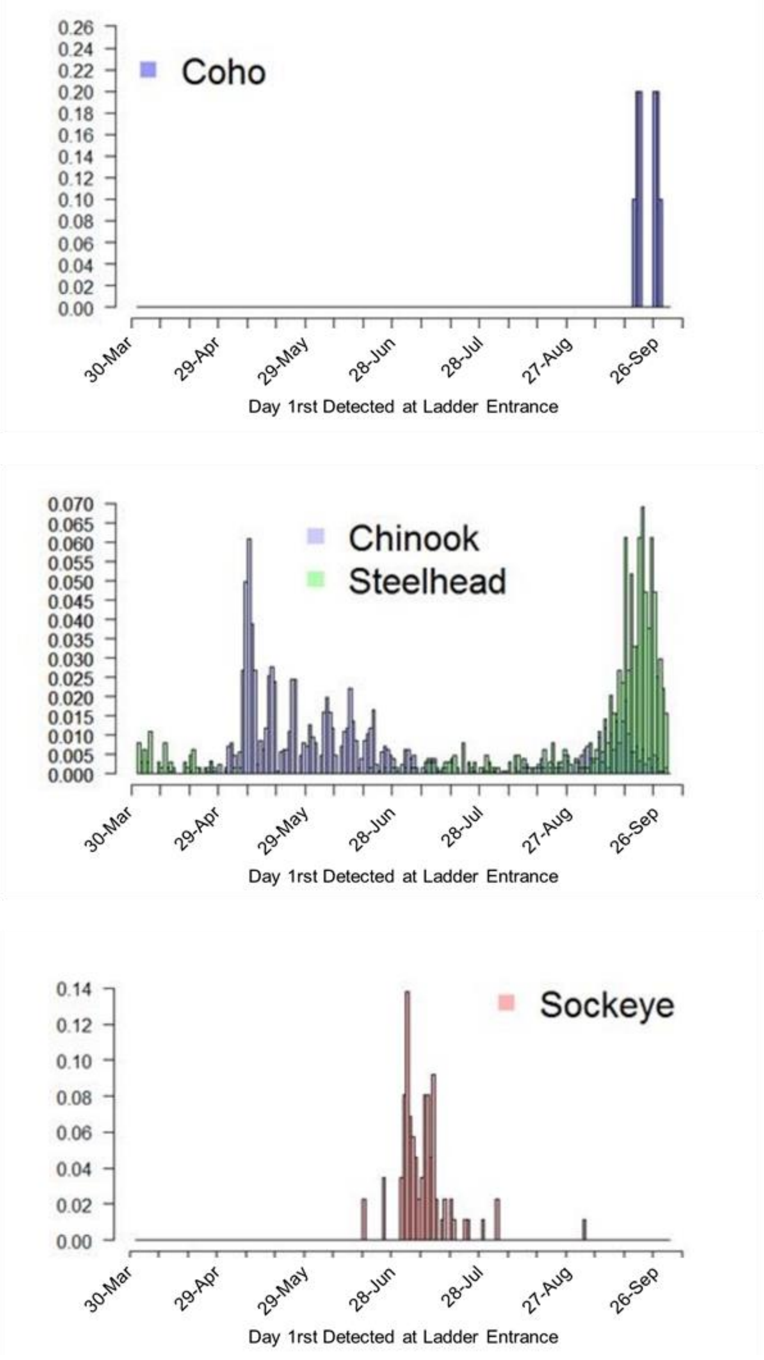
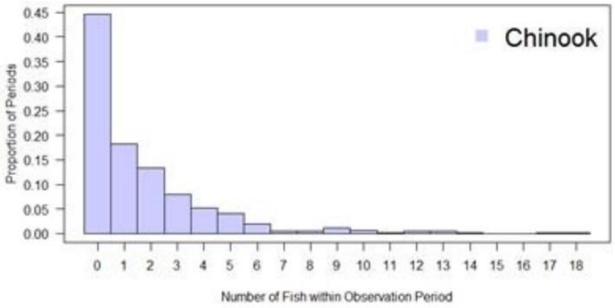
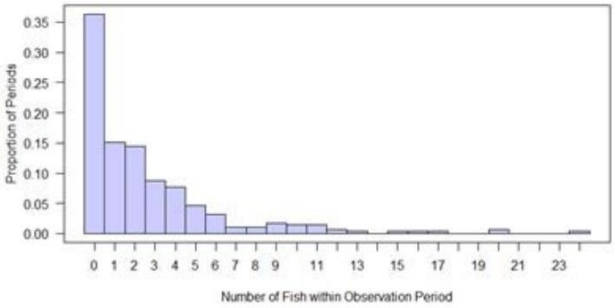
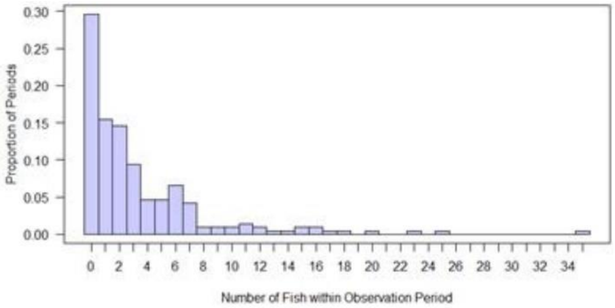
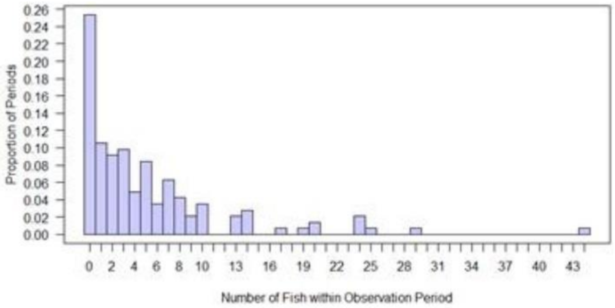
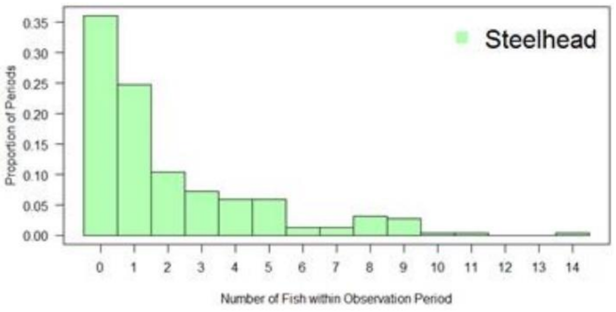
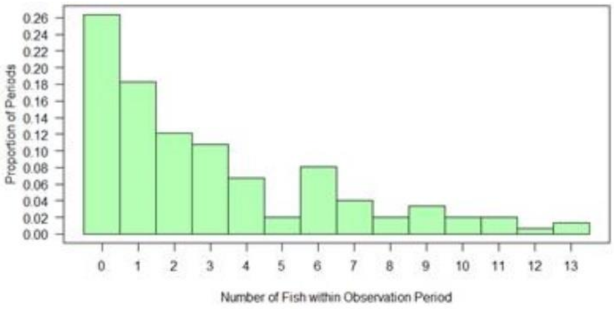
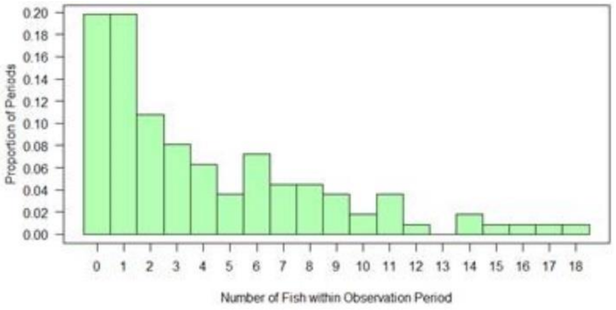
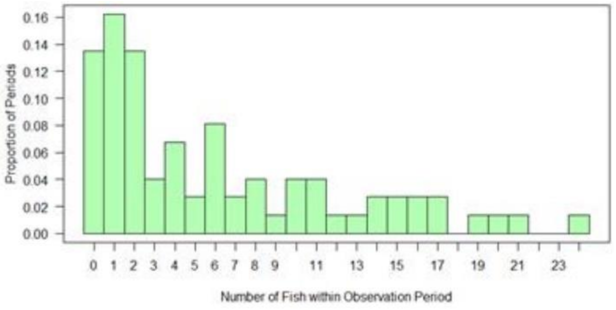


Figure A3
Frequency Distributions of Chinook Salmon Counts Entering the Lower Granite Ladder

Period Length (hours)	Count		Histogram
	Range	Median	
2	0-18	1	
3	0-24	1	
4	0-35	2	
6	0-44	3	

Notes:
Based on time blocks of 2, 3, 4, or 6 hours. Summary Includes median count per block and range.

Figure A4
Frequency Distributions of Steelhead Counts Entering the Lower Granite Ladder

Period Length (hours)	Count		Histogram
	Range	Median	
2	0-14	1	
3	0-13	2	
4	0-18	2	
6	0-24	4	

Notes:
Based on time blocks of 2, 3, 4, or 6 hours. Summary Includes median count per block and range.

Appendix B

Analysis of Deviance Results for Single-variable Regressions of ARIS Response Variables

Table B1
Results of Single-variable Regressions for ARIS Response Variable of Proportion of Exit-origin Fish Leaving in a Northerly Direction for Sockeye Salmon

Source	DF	*P(>F)*	AIC	Direction
Initial model - Operations				
$\text{Total}_{\text{Cor}}$	59		174.77	
Weekend (Saturday, Sunday)	1	0.8957	176.75	–
Total Spill (kcfs)	1	0.5372	176.24	+
Median Spill (kcfs)	1	0.9942	176.77	+
Total Flow (kcfs)	1	0.8700	176.74	–
Median Flow (kcfs)	1	0.7548	176.64	–
Proportion Spill	1	0.8581	176.73	+
Spill Bay 1 (kcfs)	1	0.8387	176.72	+
Spill Bay 1 (on/off)	1	0.4632	176.01	+
Initial model – Pool Temperature				
$\text{Total}_{\text{Cor}}$	12		40.815	
Weekend (Saturday, Sunday)**--only weekdays available**	0	*NA*	*NA*	
S2 - surface	1	0.6855	42.475	–
S3 - surface	1	0.5495	42.079	+
Surface Difference (S3-S2)	1	0.3741	41.225	+
Initial model – Vibration at Ladder Exit	63		188.24	
Weekend (Saturday, Sunday)	1	0.9507	190.23	+
Mean Peak Acceleration	1	0.4029	189.20	–
N Exceed threshold	1	0.0570	184.97	–

Notes:
P-value for *F*-test from analysis of deviance (ANODEV) reported, AIC value, and sign of regression coefficient (i.e., positive or negative direction).
AIC: Akaike information criterion
DF: Degrees of freedom
F: F-statistic
kcfs: kilo cubic feet per second
P: probability

Table B2
Results of Single-variable Regressions for ARIS Response Variable of Proportion of Non-exit-origin Fish Leaving in a Northerly Direction for Sockeye Salmon

Source	DF	*P(>F)* (bold if significant)	AIC	Direction
Initial model - Operations				
$\text{Total}_{\text{Cor}}$	62		264.91	
Weekend (Saturday, Sunday)	1	0.8150	266.83	–
Total Spill (kcfs)	1	**0.0434**	261.51	–
Median Spill (kcfs)	1	**0.0171**	259.49	–
Total Flow (kcfs)	1	0.7099	266.72	+
Median Flow (kcfs)	1	0.7672	266.79	+
Proportion Spill	1	0.6589	266.64	–
Spill Bay 1 (kcfs)	1	0.3670	265.80	–
Spill Bay 1 (on/off)	1	0.8699	266.87	+
Initial model – Pool Temperature				
$\text{Total}_{\text{Cor}}$	12		59.164	
Weekend (Saturday, Sunday)**--only weekdays available**	0	*NA*	*NA*	
S2 - surface	1	0.1501	58.480	+
S3 - surface	1	0.5334	60.620	+
Surface Difference (S3-S2)	1	0.9728	61.163	–
Initial model – Vibration at Ladder Exit	66		282.61	
Weekend (Saturday, Sunday)	1	0.7378	284.44	–
Mean Peak Acceleration	1	0.4298	283.69	–
N Exceed threshold	1	0.5961	284.19	–

Notes:
P-value for *F*-test from analysis of deviance (ANODEV) reported, AIC value, and sign of regression coefficient (i.e., positive or negative direction).
AIC: Akaike information criterion
DF: Degrees of freedom
F: F-statistic
kcfs: kilo cubic feet per second
P: probability

Table B3
Results of Single-variable Regressions for ARIS Response Variable of Proportion of Exit-origin Fish Leaving in a Northerly Direction for Summer Chinook Salmon

Source	DF	*P(>F)* (bold if significant)	AIC	Direction
Initial model - Operations				
Total$_{Cor}$	82		201.31	
Weekend (Saturday, Sunday)	1	0.8279	203.24	+
Total Spill (kcfs)	1	0.4506	202.53	–
Median Spill (kcfs)	1	0.4716	202.59	–
Total Flow (kcfs)	1	**0.0170**	195.73	–
Median Flow (kcfs)	1	**0.0192**	196.00	–
Proportion Spill	1	**0.0302**	197.01	+
Spill Bay 1 (kcfs)	1	0.6056	202.94	–
Spill Bay 1 (on/off)	1	0.4488	202.52	–
Initial model – Pool Temperature				
Total$_{Cor}$	42		99.33	
Weekend (Saturday, Sunday)	1	0.0744	96.95	+
S2 - surface	1	0.0546	96.28	+
S3 - surface	1	0.1917	98.94	+
Surface Difference (S3-S2)	1	0.8936	101.31	+
Initial model – Vibration at Ladder Exit	85		207.87	
Weekend (Saturday, Sunday)	1	0.6660	209.62	+
Mean Peak Acceleration	1	0.3809	208.83	+
N Exceed threshold	1	0.3319	208.59	+

Notes:
P-value for *F*-test from analysis of deviance (ANODEV) reported, AIC value, and sign of regression coefficient (i.e., positive or negative direction).
AIC: Akaike information criterion
DF: Degrees of freedom
F: F-statistic
kcfs: kilo cubic feet per second
P: probability

Table B4
Results of Single-variable Regressions for ARIS Response Variable of Proportion of Non-exit-origin Fish Leaving in a Northerly Direction for Summer Chinook Salmon

Source	DF	$P(>F)$ (bold if significant)	AIC	Direction
Initial model - Operations				
$\text{Total}_{\text{Cor}}$	101		372.41	
Weekend (Saturday, Sunday)	1	0.2555	372.89	–
Total Spill (kcfs)	1	0.2006	372.49	+
Median Spill (kcfs)	1	0.2424	372.80	+
Total Flow (kcfs)	1	0.9593	374.40	+
Median Flow (kcfs)	1	0.9308	374.40	–
Proportion Spill	1	0.6108	374.10	+
Spill Bay 1 (kcfs)	1	0.0676	370.53	+
Spill Bay 1 (on/off)	1	0.0554	370.15	+
Initial model – Pool Temperature				
$\text{Total}_{\text{Cor}}$	52		172.47	
Weekend (Saturday, Sunday)	1	0.7812	174.38	–
S2 - surface	1	0.2612	173.16	–
S3 - surface	1	0.1686	172.51	–
Surface Difference (S3-S2)	1	0.1869	172.67	–
Initial model – Vibration at Ladder Exit	106		392.77	
Weekend (Saturday, Sunday)	1	0.4305	393.98	–
Mean Peak Acceleration	1	**0.0129**	387.10	–
N Exceed threshold	1	**0.0043**	384.76	–

Notes:
P-value for *F*-test from analysis of deviance (ANODEV) reported, AIC value, and sign of regression coefficient (i.e., positive or negative direction).
AIC: Akaike information criterion
DF: Degrees of freedom
F: F-statistic
kcfs: kilo cubic feet per second
P: probability

Table B5

Results of Single-variable Regressions for ARIS Response Variable of Proportion of Exit-origin Fish Leaving in a Northerly Direction for Fall Chinook Salmon or Steelhead

Source	DF	*P(>F)*	AIC	Direction
Initial model - Operations				
Total$_{Cor}$	20		35.71	
Weekend (Saturday, Sunday)	1	0.2614	36.02	–
Total Spill (kcfs)	1	0.8885	37.68	–
Median Spill (kcfs)	1	0.8907	37.68	–
Total Flow (kcfs)	1	0.2397	35.87	+
Median Flow (kcfs)	1	0.6944	37.50	+
Proportion Spill	1	0.8884	37.68	–
Spill Bay 1 (kcfs) – no spill through SB1	0	*NA*	*NA*	
Spill Bay 1 (on/off) – no spill through SB1	0	*NA*	*NA*	
Initial model – Pool Temperature				
Total$_{Cor}$	21		36.15	
Weekend (Saturday, Sunday)	1	0.2366	36.35	–
S2 - surface	1	0.8392	38.10	–
S3 - surface	1	0.8516	38.10	–
Surface Difference (S3-S2)	1	0.9054	38.13	–
Initial model – Vibration at Ladder Exit	21		36.15	
Weekend (Saturday, Sunday)	1	0.2366	36.35	–
Mean Peak Acceleration	1	0.9567	38.15	+
N Exceed threshold	1	0.8270	35.09	+

Notes:

P-value for *F*-test from analysis of deviance (ANODEV) reported, AIC value, and sign of regression coefficient (i.e., positive or negative direction).

AIC: Akaike information criterion

DF: Degrees of freedom

F: F-statistic

kcfs: kilo cubic feet per second

P: probability

Table B6
Results of Single-variable Regressions for ARIS Response Variable of Proportion of non-exit-origin Fish Leaving in a Northerly Direction for Fall Chinook Salmon or Steelhead

Source	DF	$P(>F)$	AIC	Direction
Initial model - Operations				
$\text{Total}_{\text{Cor}}$	23		100.08	
Weekend (Saturday, Sunday)	1	0.3017	99.61	+
Total Spill (kcfs)	1	0.5357	101.18	–
Median Spill (kcfs)	1	0.5347	101.17	–
Total Flow (kcfs)	1	0.2568	99.12	+
Median Flow (kcfs)	1	0.0778	95.21	+
Proportion Spill	1	0.5328	101.16	–
Spill Bay 1 (kcfs) – no spill through SB1	0	*NA*	*NA*	
Spill Bay 1 (on/off) – no spill through SB1	0	*NA*	*NA*	
Initial model – Pool Temperature				
$\text{Total}_{\text{Cor}}$	24		106.01	
Weekend (Saturday, Sunday)	1	0.2349	104.70	+
S2 - surface	1	0.5901	107.31	–
S3 - surface	1	0.8620	107.94	–
Surface Difference (S3-S2)	1	0.9342	108.00	+
Initial model – Vibration at Ladder Exit	24		106.01	
Weekend (Saturday, Sunday)	1	0.2349	104.70	+
Mean Peak Acceleration	1	0.8571	107.94	–
N Exceed threshold	1	0.8897	107.97	–

Notes:
P-value for *F*-test from analysis of deviance (ANODEV) reported, AIC value, and sign of regression coefficient (i.e., positive or negative direction).
AIC: Akaike information criterion
DF: Degrees of freedom
F: F-statistic
kcfs: kilo cubic feet per second
P: probability

Table B7
Results of Single-variable Regressions for ARIS Response Variable of Proportion of Exit-origin Fish Leaving in a Downward Direction for Sockeye Salmon

Source	DF	*P(>F)* (bold if significant)	AIC	Direction
Initial model - Operations				
$\text{Total}_{\text{Cor}}$	59		99.70	
Weekend (Saturday, Sunday)	1	**0.0275**	96.84	–
Total Spill (kcfs)	1	0.1999	100.01	+
Median Spill (kcfs)	1	0.4121	101.00	+
Total Flow (kcfs)	1	0.3536	100.81	+
Median Flow (kcfs)	1	0.3257	100.70	+
Proportion Spill	1	0.3839	100.91	–
Spill Bay 1 (kcfs)	1	0.3242	100.69	+
Spill Bay 1 (on/off)	1	0.3840	100.91	+
Initial model – Pool Temperature				
$\text{Total}_{\text{Cor}}$	12		13.08	
Weekend (Saturday, Sunday)**--only weekdays available**	0	*NA*	*NA*	
S2 - surface	1	0.9964	15.08	–
S3 - surface	1	0.7723	15.04	+
Surface Difference (S3-S2)	1	0.7356	15.03	+
Initial model – Vibration at Ladder Exit	63		102.61	
Weekend (Saturday, Sunday)	1	**0.0326**	100.11	–
Mean Peak Acceleration	1	0.2111	103.03	–
N Exceed threshold	1	0.0656	101.23	–

Notes:
P-value for *F*-test from analysis of deviance (ANODEV) reported, AIC value, and sign of regression coefficient (i.e., positive or negative direction).
AIC: Akaike information criterion
DF: Degrees of freedom
F: F-statistic
kcfs: kilo cubic feet per second
P: probability

Table B8
Results of Single-variable Regressions for ARIS Response Variable of Proportion of Exit-origin Fish Leaving in a Downward Direction for Summer Chinook Salmon

Source	DF	*P(>F)* (bold if significant)	AIC	Direction
Initial model - Operations				
$\text{Total}_{\text{Cor}}$	82		79.40	
Weekend (Saturday, Sunday)	1	0.9069	81.39	–
Total Spill (kcfs)	1	0.1680	80.18	–
Median Spill (kcfs)	1	0.2364	80.50	–
Total Flow (kcfs)	1	**0.0055**	76.64	–
Median Flow (kcfs)	1	**0.0088**	77.14	–
Proportion Spill	1	**0.0089**	77.15	+
Spill Bay 1 (kcfs)	1	0.6548	81.27	–
Spill Bay 1 (on/off)	1	0.4719	81.06	–
Initial model – Pool Temperature				
$\text{Total}_{\text{Cor}}$	42		41.30	
Weekend (Saturday, Sunday)	1	0.0845	41.47	–
S2 - surface	1	0.1877	42.22	+
S3 - surface	1	0.4323	42.91	+
Surface Difference (S3-S2)	1	0.8711	43.29	–
Initial model – Vibration at Ladder Exit	85		80.49	
Weekend (Saturday, Sunday)	1	0.9923	82.49	–
Mean Peak Acceleration	1	0.4807	82.18	–
N Exceed threshold	1	0.7009	82.40	+

Notes:

P-value for *F*-test from analysis of deviance (ANODEV) reported, AIC value, and sign of regression coefficient (i.e., positive or negative direction).

AIC: Akaike information criterion
DF: Degrees of freedom
F: F-statistic
kcfs: kilo cubic feet per second
P: probability

Table B9
Results of Single-variable Regressions for ARIS Response Variable of Proportion of Exit-origin Fish Leaving in a Downward Direction for Fall Chinook Salmon or Steelhead

Source	DF	$P(>F)$ (bold if significant)	AIC	Direction
Initial model - Operations				
Total$_{Cor}$	20		19.07	
Weekend (Saturday, Sunday)	1	0.7585	21.00	–
Total Spill (kcfs)	1	0.0634	18.74	+
Median Spill (kcfs)	1	0.0634	18.74	+
Total Flow (kcfs)	1	**0.0409**	18.30	+
Median Flow (kcfs)	1	0.0748	18.91	+
Proportion Spill	1	0.0634	18.74	+
Spill Bay 1 (kcfs) – no spill through SB1	0	*NA*	*NA*	
Spill Bay 1 (on/off) – no spill through SB1	0	*NA*	*NA*	
Initial model – Pool Temperature				
Total$_{Cor}$	21		19.21	
Weekend (Saturday, Sunday)	1	0.7318	21.13	–
S2 - surface	1	0.9990	21.21	+
S3 - surface	1	0.3066	20.49	+
Surface Difference (S3-S2)	1	0.2007	20.09	+
Initial model – Vibration at Ladder Exit	21		19.21	
Weekend (Saturday, Sunday)	1	0.7318	21.13	–
Mean Peak Acceleration	1	0.4562	20.82	+
N Exceed threshold	1	0.4381	20.79	+

Notes:
P-value for *F*-test from analysis of deviance (ANODEV) reported, AIC value, and sign of regression coefficient (i.e., positive or negative direction).
AIC: Akaike information criterion
DF: Degrees of freedom
F: F-statistic
kcfs: kilo cubic feet per second
P: probability

Appendix C

Analysis of Deviance Results for Single-variable Regressions of PIT-tag Measures of Ladder Passage Performance

Table C1
Results of Single-variable Regression of PIT-tag Response Variables for Median Passage Time for Spring Chinook Salmon

Source	Total DF	Covariate DF	*P(>F)*	AIC	Direction	*R*^{2}
Vibration Covariates						
Ladder Exit – Mean Peak Acceleration	70	1	**0.0196**	440.259	+	0.0765
Ladder Entrance – Mean Peak Acceleration	70	1	0.7039	445.758	–	0.0021
Ladder Exit – No. Threshold Exceeded	70	1	**0.0145**	439.708	+	0.0836
Ladder Entrance – No. Threshold Exceeded	70	1	**0.0015**	435.455	+	0.1369
Temperature Covariates						
Ladder Exit – median temperature	51	1	0.0697	339.069	+	0.0643
Ladder Entrance – median temperature	31	1	0.7674	222.474	+	0.0030
Ladder median differential temperature	31	1	0.3849	221.750	+	0.0253
S2 array – median surface temperature	69	1	**0.0180**	434.793	+	0.0795
S3 array – median surface temperature	66	1	**0.0090**	415.986	+	0.1004
S2-S3 median differential temperature	65	1	**0.0007**	405.913	+	0.1641

Notes:
P-values for the F-test from analysis of deviance (ANODEV) reported, AIC value, sign of regression coefficient, and the pseudo-R^2 of the deviance explained by the covariate.
AIC: Akaike information criterion
DF: Degrees of freedom
F: F-statistic
P: probability

Table C2
Results of Single-variable Regression of PIT-tag Response Variables for Entrance Success Rate for Spring Chinook Salmon

Source	Total DF	Covariate DF	*P(>F)*	AIC	Direction	R^2
Vibration Covariates						
Ladder Exit – Mean Peak Acceleration	73	1	0.0647	53.334	–	0.0466
Ladder Entrance – Mean Peak Acceleration	73	1	**0.0016**	49.309	–	0.1299
Ladder Exit – No. Threshold Exceeded	73	1	**0.0426**	52.886	–	0.0559
Ladder Entrance – No. Threshold Exceeded	73	1	0.0807	53.538	–	0.0418
Temperature Covariates						
Ladder Exit – median temperature	54	1	0.1863	49.891	–	0.0327
Ladder Entrance – median temperature	33	1	0.3847	39.510	–	0.0237
Ladder median differential temperature	33	1	0.0611	36.812	–	0.1053
S2 array – median surface temperature	72	1	**0.0112**	51.356	–	0.0871
S3 array – median surface temperature	69	1	**0.0083**	50.667	–	0.0980
S2-S3 median differential temperature	68	1	0.2341	54.349	–	0.0211

Notes:

P-values for the F-test from analysis of deviance (ANODEV) reported, AIC value, sign of regression coefficient, and the pseudo-R^2 of the deviance explained by the covariate.

AIC: Akaike information criterion

DF: Degrees of freedom

F: F-statistic

P: probability

Table C3
Results of Single-variable Regression of PIT-tag Response Variables for Dropback Rate for Spring Chinook Salmon

Source	Total DF	Covariate DF	*P(>F)*	AIC	Direction	R^2
Vibration Covariates						
Ladder Exit – Mean Peak Acceleration	89	1	0.2019	196.559	–	0.0184
Ladder Entrance – Mean Peak Acceleration	89	1	0.7726	199.740	–	0.0010
Ladder Exit – No. Threshold Exceeded	89	1	**0.0172**	188.482	–	0.0628
Ladder Entrance – No. Threshold Exceeded	89	1	**0.0042**	183.661	+	0.0894
Temperature Covariates						
Ladder Exit – median temperature *(p=0)*	52	1	1.0000			
Ladder Entrance – median temperature *(p=0)*	32	1	1.0000			
Ladder median differential temperature*(p=0)*	32	1	1.0000			
S2 array – median surface temperature	84	1	**< 0.0001**	119.731	–	0.3277
S3 array – median surface temperature	85	1	**< 0.0001**	150.084	–	0.2699
S2-S3 median differential temperature	80	1	0.3824	167.676	–	0.0097

Notes:

P-values for the F-test from analysis of deviance (ANODEV) reported, AIC value, sign of regression coefficient, and the pseudo-R^2 of the deviance explained by the covariate.

AIC: Akaike information criterion

DF: Degrees of freedom

F: F-statistic

P: probability

Table C4
Results of Single-variable Regression of PIT-tag Response Variables for Reascent Rate for Spring Chinook Salmon

Source	Total DF	Covariate DF	*P(>F)*	AIC	Direction	R^2
Vibration Covariates						
Ladder Exit – Mean Peak Acceleration	89	1	0.2724	75.678	–	0.0137
Ladder Entrance – Mean Peak Acceleration	89	1	**0.0010**	71.534	–	0.1157
Ladder Exit – No. Threshold Exceeded	89	1	0.5206	76.042	–	0.0047
Ladder Entrance – No. Threshold Exceeded	89	1	**0.0331**	74.178	–	0.0506
Temperature Covariates						
Ladder Exit – median temperature	52	1	0.6203	37.733	–	0.0048
Ladder Entrance – median temperature	32	1	0.9720	30.227	+	< 0.0001
Ladder median differential temperature	32	1	0.4619	29.945	+	0.0176
S2 array – median surface temperature	84	1	**0.0003**	69.821	–	0.1482
S3 array – median surface temperature	85	1	**0.0009**	70.501	–	0.1244
S2-S3 median differential temperature	80	1	0.2289	74.270	–	0.0183

Notes:

P-values for the F-test from analysis of deviance (ANODEV) reported, AIC value, sign of regression coefficient, and the pseudo-R^2 of the deviance explained by the covariate.

AIC: Akaike information criterion

DF: Degrees of freedom

F: F-statistic

P: probability

Table C5
Results of Single-variable Regression of PIT-tag Response Variables for Exit Success Rate for Spring Chinook Salmon

Source	Total DF	Covariate DF	*P(>F)*	AIC	Direction	R^2
Vibration Covariates						
Ladder Exit – Mean Peak Acceleration	88	1	0.1904	195.632	+	0.0196
Ladder Entrance – Mean Peak Acceleration	88	1	0.7543	198.946	+	0.0011
Ladder Exit – No. Threshold Exceeded	88	1	**0.0151**	187.327	+	0.0660
Ladder Entrance – No. Threshold Exceeded	88	1	**0.0051**	183.597	–	0.0868
Temperature Covariates						
Ladder Exit – median temperature *(p=1)*	51	1	1.0000			
Ladder Entrance – median temperature *(p=1)*	31	1	1.0000			
Ladder median differential temperature	32	1	1.0000			
S2 array – median surface temperature	83	1	**< 0.0001**	117.978	+	0.3427
S3 array – median surface temperature	84	1	**< 0.0001**	148.289	+	0.2796
S2-S3 median differential temperature	80	1	0.5033	168.060	+	0.0058

Notes:

P-values for the F-test from analysis of deviance (ANODEV) reported, AIC value, sign of regression coefficient, and the pseudo-R^2 of the deviance explained by the covariate.

AIC: Akaike information criterion

DF: Degrees of freedom

F: F-statistic

P: probability

Table C6
Results of Single-variable Regression of PIT-tag Response Variables for Passage Success Rate for Spring Chinook Salmon

Source	Total DF	Covariate DF	*P(>F)*	AIC	Direction
Vibration Covariates					
Ladder Exit – Mean Peak Acceleration	70	1	N/A		
Ladder Entrance – Mean Peak Acceleration	70	1	N/A		
Ladder Exit – No. Threshold Exceeded	70	1	N/A		
Ladder Entrance – No. Threshold Exceeded	70	1	N/A		
Temperature Covariates					
Ladder Exit – median temperature	51	1	N/A		
Ladder Entrance – median temperature	31	1	N/A		
Ladder median differential temperature	31	1	N/A		
S2 array – median surface temperature	69	1	N/A		
S3 array – median surface temperature	66	1	N/A		
S2-S3 median differential temperature	65	1	N/A		

Notes:

P-values for the F-test from analysis of deviance (ANODEV) reported, AIC value, sign of regression coefficient, and the pseudo-R^2 of the deviance explained by the covariate. In all cases, passage survival was 100% for all periods.

AIC: Akaike information criterion

DF: Degrees of freedom

F: F-statistic

P: probability

Table C7
Results of Single-variable Regression of PIT-tag Response Variables for Fish Abundance for Spring Chinook Salmon

Source	Total DF	Covariate DF	*P(>F)*	AIC	Direction	*R*²
Vibration Covariates						
Ladder Exit – Mean Peak Acceleration	91	1	**0.0006**	768.316	–	0.1227
Ladder Entrance – Mean Peak Acceleration	91	1	0.1782	823.930	–	0.0200
Ladder Exit – No. Threshold Exceeded	91	1	**0.0019**	779.658	–	0.1018
Ladder Entrance – No. Threshold Exceeded	91	1	**0.0008**	770.237	–	0.1192
Temperature Covariates						
Ladder Exit – median temperature	54	1	**< 0.0001**	329.169	–	0.4451
Ladder Entrance – median temperature	33	1	**0.0012**	261.401	–	0.2844
Ladder median differential temperature	33	1	0.4516	313.908	–	0.0178
S2 array – median surface temperature	86	1	**0.0213**	763.145	–	0.0608
S3 array – median surface temperature	86	1	0.0922	792.952	–	0.0326
S2-S3 median differential temperature	82	1	**0.0182**	735.063	–	0.0669

Notes:

P-values for the F-test from analysis of deviance (ANODEV) reported, AIC value, sign of regression coefficient, and the pseudo-R^2 of the deviance explained by the covariate.

AIC: Akaike information criterion

DF: Degrees of freedom

F: F-statistic

P: probability