PNNL-37338

Evaluation of Howard A. Hanson Dam Juvenile Fish Passage and Survival Study

Downstream Passage and Survival (Acoustic Telemetry) Task Final Report

July 2025

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Preface

This study was funded by the U.S. Army Corps of Engineers (Corps) – Seattle District. It was led by Stephanie Liss Larson (509-375-2988) from Pacific Northwest National Laboratory. The USACE technical lead for the study was Fenton Khan (503-808-4777).

This report should be cited as follows:

Liss Larson SA, Fischer ES, Zionce EL, Harnish RA, Fu T, Ham KD, Carver JM, Deng ZD. 2025. *Evaluation of Howard A. Hanson Dam Juvenile Fish Passage and Survival Study: Downstream Passage and Survival (Acoustic Telemetry) Task*. PNNL-37338. Final Report submitted by the Pacific Northwest National Laboratory to the U.S. Army Corps of Engineers, Seattle, Washington.

Executive Summary

The Downstream Passage and Survival (Acoustic Telemetry) task was one of several tasks for the Evaluation of Howard A. Hanson Dam (HAHD) Juvenile Fish Passage and Survival study. For this task, the field data collection for a juvenile fish passage and survival study was conducted at HAHD from March 9, 2024 through July 9, 2024. Active tag (acoustic telemetry) technology was used to provide biological baseline information for the passage and survival of juvenile salmon. Tagged fish releases occurred over four times from March through May. Results will be used by biologists, engineers, resource managers, and regional decision-makers to provide baseline fish passage conditions and inform the engineering team designing the new fish passage facility (FPF) at HAHD. Hatchery subyearling PS Chinook salmon (*Oncorhynchus tshawytscha*) of the appropriate size for tag implantation during the study period were unavailable (≥ 95 mm in fork length, Geist et al. 2018). Therefore, yearling coho salmon (*O. kisutch*) were used for this acoustic telemetry study.

This study was conducted by researchers from the Pacific Northwest National Laboratory (PNNL). The Juvenile Salmon Acoustic Telemetry System (JSATS) technology was used to evaluate existing HAHD operations to understand baseline fish passage from head of reservoir into the forebay of the dam and downstream passage and survival. Additionally, a combination of reservoir elevation and discharge during spring refill was assessed, to evaluate which depths and discharges were associated with fish passage in the reservoir, fish passage through the dam (existing tunnel), and survival associated with the existing project passage.

A total of 2,684 juvenile coho salmon were tagged and released in the reservoir and used for analyses (n = 2,468 released alive; and n = 216 released dead). One of the primary findings from this study was that few fish were detected downstream of HAHD. Of the 2,468 tagged fish released into the reservoir, 2,261 were detected in the forebay on the cabled array, located at the dam face of HAHD. Of those, 205 fish were detected downstream of HAHD. This is a conservative estimate because the 3-D tracking of fish behavior and passage in the forebay was unable to be performed. There was a data overload on the autonomous and cabled receivers in the forebay of HAHD because fish were not passing the dam, and instead schooling in large groups in front of the intake tower. The data overload caused data cards to fill up faster than expected, which led to data gaps and the inability to perform the 3-D tracking for fish behavior and passage. The data overload also created time jump issues in the data and caused strain on the batteries in the autonomous receivers. Finally, because so few fish were confirmed to have been detected downstream of the dam, fewer fish were tagged and released later in the season than were proposed.

Another key finding was that a greater proportion of fish detected downstream of the dam passed earlier in the season (March) during refill operations when reservoir elevation was lower, compared to later in the season (April and May), when the reservoir was near full pool elevation. This could be attributed to the rise in reservoir elevation, which increased the depth fish needed to sound (dive) to find the outflow tunnel to pass the dam. As a result, the autonomous receivers and cabled array equipment were removed from the reservoir before the battery life of the active tags of fish released later in the season expired, as it was anticipated the continued rise in reservoir elevation would result in even fewer fish passing HAHD and a continued overload of data on the receivers in the forebay.

The joint probability of migration and survival for the March-released fish was estimated from fish release at the head of reservoir (HOR) to the Cumberland Kanasket Bridge (CKB), located

approximately 14.3 river kilometers (rkm) downstream. Only fish from the two March releases were used in this estimate because the battery life of their tags had expired by the time the autonomous and cabled receiver equipment was removed at the end of the study period. The joint probability of migration and survival for those fish was poor, at 0.1280 (SE = 0.0142).

Although there were unexpected challenges encountered for this baseline study, these results can still provide valuable insights into fish passage at HAHD under current operational conditions. Results confirm that fish passage and survival at HAHD are poor under the current conditions. Results may also highlight the need for multiple entrances into a downstream passage tunnel (bypass or otherwise) to account for varying reservoir elevations. The Corps is already working towards engineering a design of a bypass system to improve fish passage and survival in accordance with the National Marine Fisheries Service Biological Opinion (BiOp) requirements for improving fish passage at HAHD (NOAA 2019).

Acknowledgments

This project was a collaborative effort which would not have been possible without the help provided by the U.S. Army Corps of Engineers – Seattle District and Howard A. Hanson Dam (HAHD) Facility Operations staff. These folks were instrumental in study design execution. We would like to acknowledge Nancy Chin for her support and funding, Kevin Heape and Nathan Malmborg for their support of the project, Bill Boyle, Warren Douglas, and staff for accommodations and assistance at the HAHD Facility, and Fenton Khan for study design and implementation collaboration. We thank the Washington Department of Fish and Wildlife for providing study fish. We also thank the Tacoma Public Utilities, including Tyler Patterson, Jeff Bolam, Nikolas Novotny, Matt Peter, and Tyler Traweek, for performing disinfected equipment inspections and granting PNNL access to their property to hold and tag fish, and deploy autonomous receivers. Furthermore, we thank the King County Department of Natural Resources, including Chris Gregersen, for allowing PNNL to deploy autonomous receivers on their property. Finally, we thank several staff at PNNL for their support with permitting: Kris Hand and Dana Vesty; with data collection and analysis: Brandon Boehnke, Noelani Boise, Jenna Brogdon, Margaret Giggie, James Graff, Adam Hall, Jill Janak, Kailan Mackereth, Jayson Martinez, Sophia McKever, Brett Pflugrath, Sandy Rech, Cassy Shaffer, and Ben Vaage; and with administrative assistance: Heather Howell and Taylor Oxman. PNNL's Institutional Animal Care and Use Committee approved the protocol governing the care and use of fish for this study (protocol number 2024-04).

Acronyms and Abbreviations

3-D	3-dimensional
°C	degree(s) Celsius
AMT	acoustic micro transmitter
AT	acoustic telemetry
ATS	Advanced Telemetry Systems
BiOp	Biological Opinion
BWM	binary waveform
CBL	cabled array located at HAHD
CCR	Charlie Creek
cfs	cubic feet per second
CKB	Cumberland Kanasket Bridge
Corps	U.S. Army Corps of Engineers
d	day(s)
D	detection(s)
DSP	digital signal processing
DUW	Duwamish River
ESA	Endangered Species Act
FBY	forebay
FL	fork length
FPF	fish passage facility
FPGA	field-programmable gate array
ft	foot (feet)
g	gram(s)
GPS	global positioning system
h	hour(s)
HAHD	Howard A. Hanson Dam
HOR	head of reservoir
in	inch(es)
JSATS	Juvenile Salmon Acoustic Telemetry System
km	kilometer(s)
L	liter(s)
m	meter(s)
min	minute(s)
mg	milligram(s)
MLE	maximum likelihood estimation
mm	millimeter(s)
MOR	mid of reservoir
n	number (sample size)

NFB	near-forebay
NGR	North Fork Green River
NOAA	National Oceanic and Atmospheric Administration
N_i	dam-passed fish
p_1	detection probability of the HAHD dam face array
PC	personal computer
PIT tag	passive integrated transponder tag
PIT	PIT Barge (Tukwila)
PNNL	Pacific Northwest National Laboratory
PRI	pulse repetition interval
PS	Puget Sound
QA	quality assurance
QC	quality control
R	release
RAM	random access memory
rkm	river kilometer(s)
RPA	reasonable and prudent alternative
s	second(s)
$\hat{S}_R$	joint probability of migration and survival
SE	standard error
TBU	Tacoma juvenile bypass
TOA	time of arrival
TPU	Tacoma Public Utilities (diversion dam)
UHOR	upper head of reservoir
V_D	number of tagged salmon detected
V_R	virtual release group
ViRDCt	Virtual Release/Dead Fish Correction
WDFW	Washington Department of Fish and Wildlife

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1.0 Introduction

1.1 Background

Howard A. Hanson Dam (HAHD), owned and operated by the U.S. Army Corps of Engineers – Seattle District (Corps), is located on the Green River in western Washington State (Figure 1-1). HAHD is primarily a flood risk management project and serves secondary purposes for water supply to the City of Tacoma and flow augmentation during the summer months for fisheries downstream.

The HAHD outlet works are used to pass flows and regulate the release of impounded water. The outlet works are comprised of a 19-foot (ft) wide, 900-ft long horseshoe-shaped concrete outflow tunnel controlled by two 10-ft wide, by 12-ft tall tainter gates, a 700-ft long spillway chute controlled by two 45-ft wide by 30-ft tall radial arm gates, a 48-inch diameter steel bypass pipe regulated with a slide gate near its outlet, and a smaller 36-inch diameter steel bypass pipe. During flood and spring refill seasons, the 19-ft outflow tunnel is primarily used to pass outflows. The larger 48-inch steel bypass pipe has some outflows passed through it, typically during the low flow season, and is solely used when regulated outflows are at or below 500 cubic feet per second (cfs). The spillway may be used only during exceptionally high flow-flood events. The smaller, 36-inch bypass pipe is only used during some maintenance activities. Total outflows from HAHD range from 200 cfs in the summer months to as much as 8,500 cfs during the flood season (October–February). Typical March–July outflows are in the 200–6,000 cfs range, with few exceptions of higher flows.

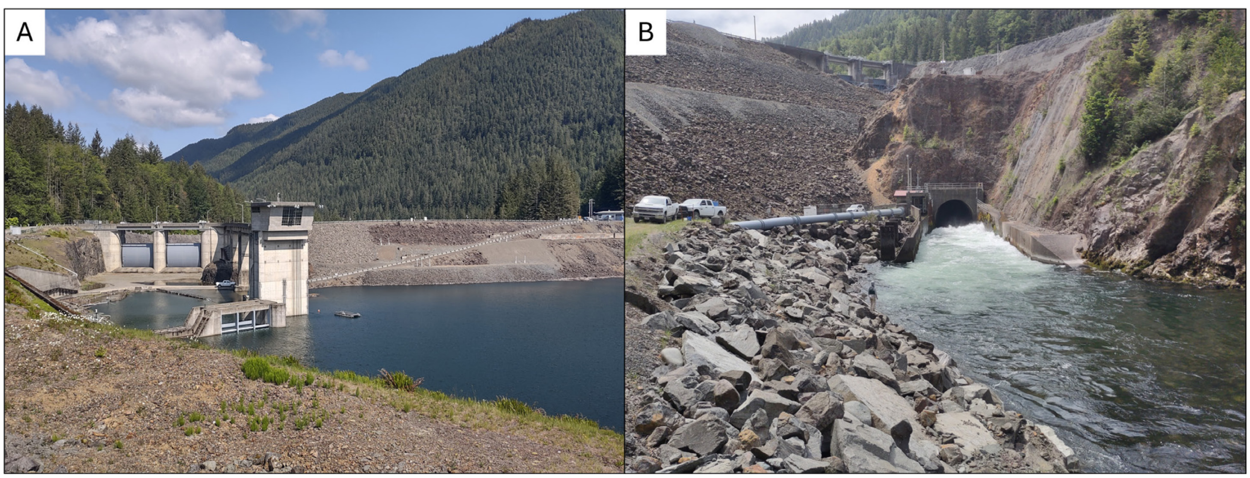


Figure 1-1. Howard A. Hanson Dam viewed from the reservoir (A) and from the tailrace (B).

Currently, information about fish passage and survival at HAHD is lacking. The Endangered Species Act listed Puget Sound (PS) Chinook salmon (*Oncorhynchus tshawytscha*), and steelhead (*O. mykiss*) were historically present in the area and there is a renewed interest in reintroducing them; thus, there is a need to understand current fish passage conditions at HAHD. Understanding current conditions can provide data to inform engineering design updates to improve fish passage. In accordance with the Biological Opinion (BiOp), issued by the National Marine Fisheries Service (NOAA 2019), the Corps is designing a new fish passage project at HAHD, with construction to be completed by 2030. The purpose for the new fish passage facility (FPF) is to provide safe, timely, and effective downstream fish passage throughout the range of operating and reservoir conditions likely to occur during the annual fry and smolt outmigration.

The current concept of the FPF design includes a multi-port collector on the forebay face of the dam (i.e., stacked vertical fish horns) and a steep slope bypass on the downstream side of the dam. The new FPF must meet the fish passage performance criteria as required by Reasonable and Prudent Alternatives outlined in the BiOp (NOAA 2019). These criteria include:

1. An overall juvenile fish project passage survival rate of 75%, from entry into the HAHD Reservoir (Eagle Gorge Reservoir) to release points downstream of HAHD.
2. 95% collection of fish attracted to the FPF.
3. 98% survival of all fish passing through the FPF to release downstream of HAHD.

1.2 Objectives

The purpose of this downstream passage and survival (acoustic telemetry) study was to gather biological baseline information about the current passage conditions and survival of juvenile salmon at HAHD. Results will be used by biologists, engineers, resource managers, and regional decision-makers to inform baseline conditions under current operations and the engineering design of the new FPF at HAHD. There was an unavailability of appropriately sized hatchery subyearling PS Chinook salmon (≥ 95 mm in fork length; Geist et al. 2018) for use during the study period; thus, yearling coho salmon (*O. kisutch*) were used for the study.

This task used the Juvenile Salmon Acoustic Telemetry System (JSATS) technology to evaluate the downstream passage and survival of juvenile PS coho salmon through the HAHD horseshoe tunnel by evaluating:

1. Existing HAHD operations to understand baseline fish passage from head of reservoir into the forebay of the dam and downstream passage and survival and if the current operations and tunnel meet the BiOp requirements (75% overall reservoir to downstream survival, 95% collection, and 98% passage survival; NOAA 2019).
2. Fish passage and survival under a combination of reservoir elevation and discharge during spring refill, to inform the following questions:
    a. At what depth and discharge does the reservoir stop passing 80% of the fish?
    b. At what depth and discharge does the radial gate stop passing 95% of the fish within the forebay?
    c. At what depth/discharge does 2% mortality occur associated with existing project passage?

The following metrics were used to achieve the objectives and estimate baseline passage and survival of juvenile salmonids in the HAHD reservoir and dam:

1. Seasonal and diel distribution, behavior, and movements of juvenile salmonids from the head of reservoir into and within the forebay of the dam.
    a. Different behaviors (i.e., milling, traversing, direct downstream passage), vertical distribution, and approach patterns (3-dimensional [3-D]) of fish in the immediate forebay of the dam will be documented and quantified.
2. Seasonal and diel downstream passage, including reservoir survival, forebay residency time, and dam passage survival.
    a. Dam survival will be measured to a receiver array located downstream of the dam.

2.0 Methods

All field work tasks followed the equipment sterilization procedure as outlined in the Tacoma Public Utilities – Tacoma Water "Requirements for Protection of Water Supply in the Green River Watershed" specifically, "Appendix D: Decontamination of Equipment and Supplies". Any equipment deployed into the HAHD Reservoir was sterilized prior to deployment. Sterilization techniques included using a hot water-pressure washer capable of reaching temperatures of 93°C (200°F). Heat sensitive equipment was rinsed and scrubbed, immersed in chemical agent (e.g., Virkon), and dried prior to deployment. All equipment deployed in the HAHD Reservoir was inspected by a Tacoma Water Aquatic Invasive Species Inspector prior to deploying in the reservoir.

2.1 Receiver Deployment

The use of both cabled and autonomous acoustic telemetry (AT) arrays enabled a high probability of detecting tagged fish within the HAHD Reservoir, the near forebay of HAHD and downstream in the Green and Duwamish rivers. The autonomous receiver (Advanced Telemetry Systems [ATS], Inc., Isanti, MN) detects JSATS tags in a riverine environment. The receivers consist of a hydrophone, a data processing circuit board, a compact flash card for data storage, an internal battery pack, and USB cable connectors (Figure 2-1). The outside housing supports an external beacon tag used for data quality assurance/quality control (QA/QC) and a stabilizing fin to help keep the detecting hydrophone tip upright in the water column. All receivers were tested for acceptable detection performance in a specialized anechoic testing tank prior to deployment (Deng et al. 2010).

Figure 2-1. View of an autonomous receiver (left), a close-up of the hydrophone (top right), and a close-up of the internal (bottom right) components.

A total of 12 autonomous receiver arrays (Table 2-1) were deployed throughout the HAHD Reservoir (Figure 2-2), and downstream in the Green and Duwamish Rivers (Figure 2-3) to detect fish moving through the study area. Autonomous receivers were deployed in a configuration similar to the one described by Titzler et al. (2010; Figure 2-4). Receivers were attached to a 34-kilogram (kg) steel anchor via a section of wire rope. The wire rope was secured to the receiver via an eyebolt located on the compression strap around the receiver's housing at its balance point and to the handle of the anchor. Testing of the near forebay and cabled systems was conducted in the fall of 2023 to determine 3-D detection efficiencies that could be expected in the spring of 2024. Results showed greater than 70% efficiency at distances up to 120 meters and better than 90% efficiency within 80 meters of the dam face with a tracking error of 1-2 meters.

Table 2-1. Acoustic telemetry receiver deployment location, type, number of receivers per array, river kilometer (rkm) location, and study purpose.

Array Location	Receiver Type	Receivers Per Array	RKM	Study Purpose
Head of Reservoir (HOR)	Autonomous	2	106.1	Reservoir Movement and Distribution
Charlie Creek (CCR)	Autonomous	2	105.6	Reservoir Movement and Distribution
North Fork Green River (NGR)	Autonomous	3	105.0	Reservoir Movement and Distribution
Mid of Reservoir (MOR)	Autonomous	3	104.0	Reservoir Movement and Distribution
Forebay (FBY)	Autonomous	3	103.3	Reservoir Movement and Distribution
Near Forebay (NFB)	Autonomous	5	103.1	Reservoir Movement and Distribution
Howard A. Hanson Dam Cabled Array (CBL)	Cabled	8	103.0	Virtual release; dam passage survival; passage efficiencies; tailrace egress and forebay residence times; vertical and horizontal distributions
Tacoma Water Diversion Dam (TPU)	Autonomous	3	97.4	ViRDCt survival; project egress; travel time
Tacoma Juvenile Bypass (TBP)	Autonomous	1	97.37	ViRDCt survival; project egress; travel time
Cumberland Kanasket Bridge (CKB)	Autonomous	2	91.8	Survival array; travel time
PIT Barge (Tukwila) (PIT)	Autonomous	4	18.7	Survival array; travel time
Duwamish River (DUW)	Autonomous	3	4.8	Survival array; travel time

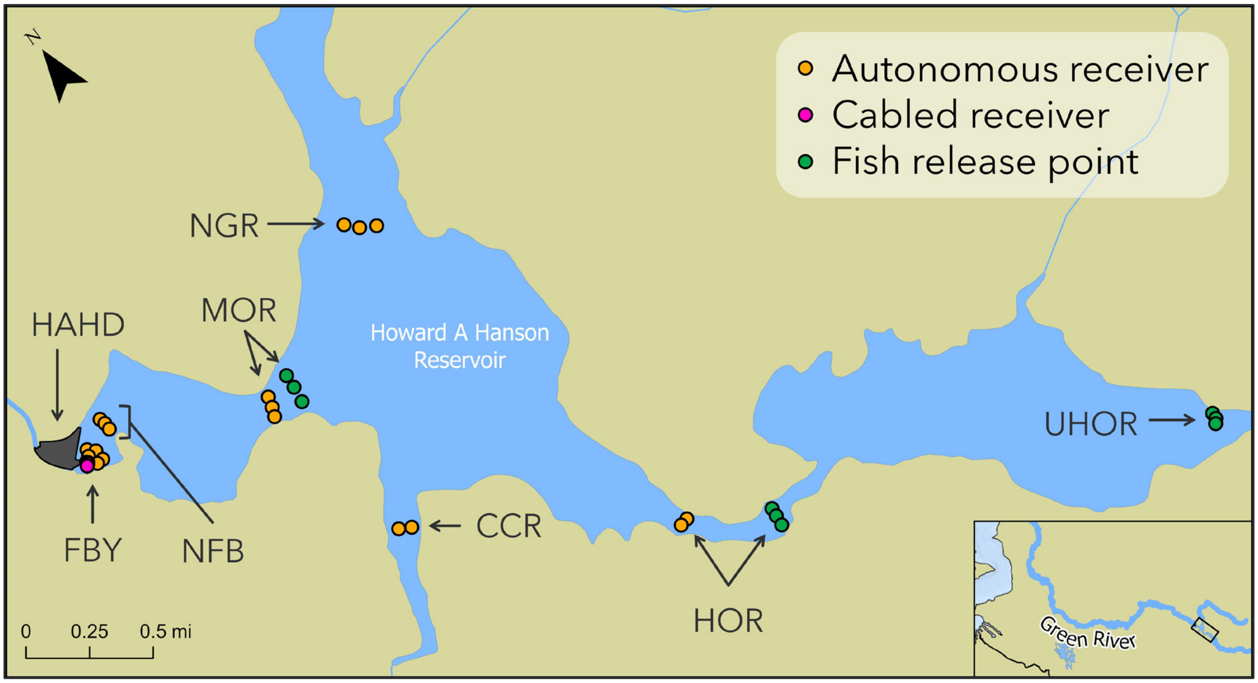


Figure 2-2. Map of the Howard A. Hanson Dam (HAHD) Reservoir study area. Autonomous receiver arrays (orange dots) were located at the HOR (head of reservoir), CCR (Charlie Creek), NGR (North Fork Green River), MOR (mid of reservoir), NFB (near forebay), and FBY (forebay). Cabled receivers (pink dots) were located on the dam face of HAHD. Fish were released alive at the MOR, HOR, and UHOR (upper head of reservoir; green dots).

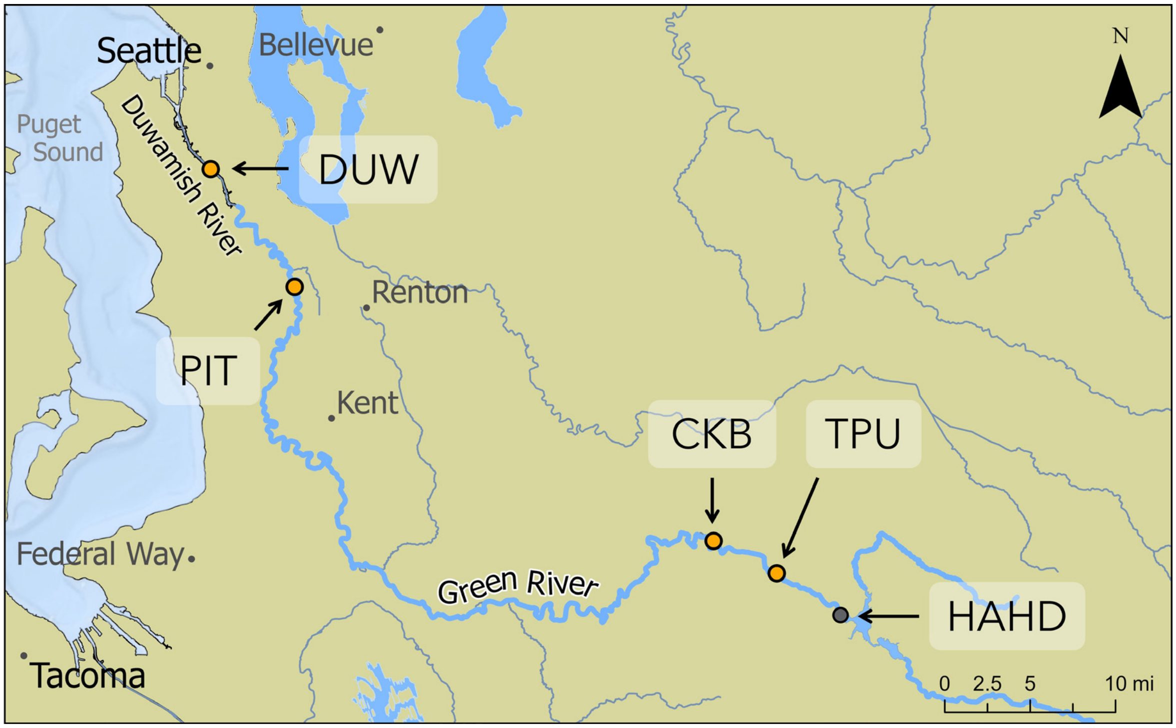


Figure 2-3. Map of the autonomous acoustic telemetry receiver arrays (orange dots) located downstream of the Howard A. Hanson Dam (HAHD; gray dot) in the Green and Duwamish rivers. TPU = Tacoma Water Diversion Dam (which included the Tacoma Juvenile Bypass array), CKB = Cumberland Kanasket Bridge, PIT = PIT barge, and DUW = Duwamish River.

Figure 2-4. Autonomous receiver deployment rigging with a stabilizing fin (yellow piece affixed to the autonomous receiver).

Varying lengths of wire rope connected the receiver to the anchor, depending on the depth of water where the receiver was deployed. In the HAHD Reservoir, a section of rope was run from the receiver up to the surface of the reservoir and attached to a buoy to aid in receiver recovery. Downstream of HAHD different techniques were used to recover the autonomous receivers. At the Cumberland Kanasket Bridge, a section of rope was run from one receiver anchor to another receiver anchor (also 34-kg) and lowered perpendicular to river flows to allow for staff to use a grappling hook to recover the receivers. Further downstream in the Duwamish River, acoustic releases were placed in line between the receiver and the anchor. These releases, when triggered, released the receiver, which was recovered, downloaded, and redeployed.

At HAHD a cabled receiver array was deployed on the dam face. The modular, time-synchronized JSATS cabled dam face receivers used in this study were designed by PNNL for the Corps using an off-the-shelf user-build system design (Weiland et al. 2011). Each cabled-receiver system included a computer, data-acquisition software, digital signal processing cards with field-programmable logic gate array (DSP + FPGA), a global positioning system (GPS) card, a four-channel signal-conditioning receiver with gain control, hydrophones, and cables (Figure 2-5). Components of the cabled-receiver system were tested for performance and calibrated in an anechoic tank prior to deployment (Deng et al. 2010).

The cabled array was deployed on the upstream face of HAHD to detect the tagged migrant salmonids approaching the dam (Figure 2-6). The dam face cabled array consisted of two cabled receivers, each supporting up to four hydrophones (Sonic Concepts, Inc., Bothell, WA). The receivers were housed inside a trailer on the gravel footing on the forebay side of HAHD and the hydrophones were deployed on either side of the intake tower, on the adjacent metal framework and on the side of the intake tower at a 45° angle to look out into the forebay in a known fixed geometry.

A total of 16 hydrophones were deployed on the HAHD intake tower for the cabled array. The three fixed mounts used on the face of the tower were 20 ft long and installed at two different elevations. One mount was installed at elevation 1,085 ft but metal protruding from the intake tower would have blocked acoustic signals, so the two other mounts were installed at elevation 1,108 ft. The 4th mount was 15 ft long and had the hydrophones mounted at a 45° angle to look out into the forebay from the side of the intake tower. This 4th mount was also installed at elevation 1,108 ft. Each mount had two shallow and two deep baffled hydrophones for redundancy. A shallow and deep hydrophone from each mount was used for real-time data collection. Anechoic material was used to line a plastic cone surrounding the hydrophone to reduce the level of sound radiating from or reflected by the dam from reaching the hydrophone.

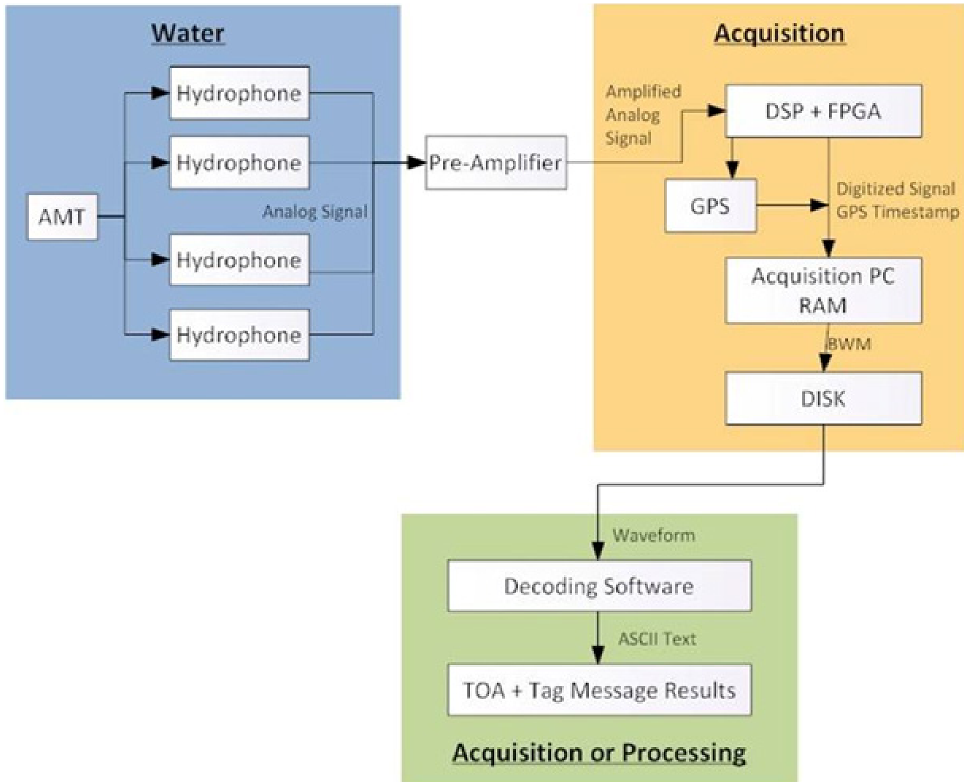


Figure 2-5. Schematic showing the main components and the direction of signal acquisition and processing of a modular cabled-array receiver system. AMT = acoustic micro transmitter (i.e., JSATS tag); DSP = Digital Signal Processing FPGA = Field-Programmable Gate Array; GPS = global positioning system; PC = personal computer; RAM = random access memory; BWM = binary waveform; TOA = time of arrival.

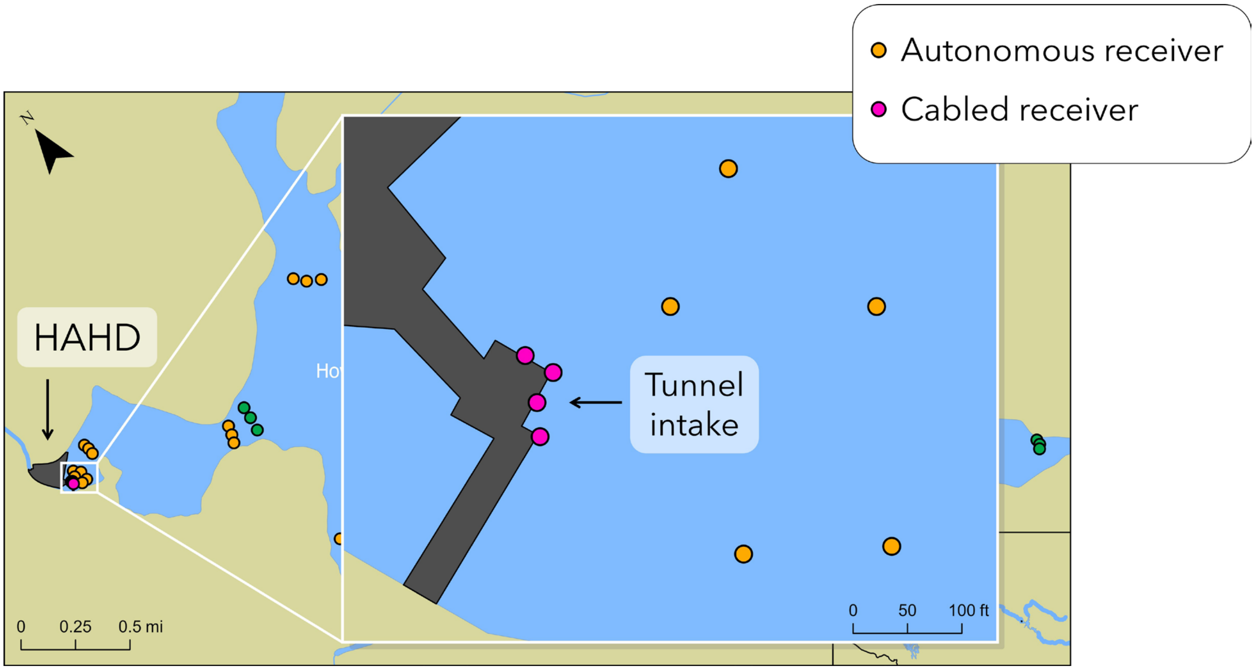


Figure 2-6. Juvenile Salmon Acoustic Telemetry System cabled and autonomous receiver array deployment at HAHD. The pink dots represent shallow and deep hydrophones at the dam face, and orange dots represent autonomous arrays in the near forebay.

A staggered approach was taken in 2024 for the receiver deployment. All four of the 3-D cabled telemetry system mounts were scheduled to be deployed during the week of February 5, 2024. However, due to the low forebay elevation (1,088 ft) only one mount was installed on the northeast corner of dam face. Large metal protruded from the south side of the dam face and a large concrete slab on the north wall prevented the installation of the remaining three mounts. During the week of February 28, 2024, four shore based autonomous receivers were deployed downstream of HAHD at the Tacoma Water Diversion Dam. Once the reservoir rose sufficiently, the three remaining 3-D mounts were installed at HAHD. After the installation of the 3-D cabled mounts, the autonomous receivers were deployed. All receiver arrays in the HAHD Reservoir and immediately below HAHD were deployed before tagging began. The two remaining autonomous receiver arrays further downstream of HAHD (PIT and DUW; Table 2-1) were deployed the week of March 20, 2024.

Autonomous and cabled receiver sites were anticipated to be downloaded every three weeks after the first fish release and throughout the study period. During the first few downloads it became apparent that fish were milling near the HAHD tunnel entrance and not passing the dam. This resulted in a very large volume of data on the autonomous and cabled receivers in the forebay, filling up the data cards in the receivers. Once this was noted, downloading the forebay (FBY) and near forebay (NFB) arrays occurred every two weeks until the end of the study. The cabled array planned to be downloaded as needed because it was remotely monitored. However, after the discovery of the very large volume of data, the cabled array receivers were downloaded every 3–4 days. Data from all other downstream receivers were downloaded on a 3-week basis until the end of the study.

2.2 Acoustic Telemetry Tags

The JSATS tags utilized in this study were model SS400, manufactured by ATS, Inc. (Isanti, MN). Biomark, Inc. – Merck Animal Health (Boise, ID) manufactured the passive integrated transponder (PIT) tags (Figure 2-7). Model SS400 JSATS (216 mg; 15 × 3.38 mm) were ordered with a nominal pulse repetition interval (PRI) of 4 seconds. Tags were shipped in lots throughout the spring tagging season. Of the tags used for the spring 2024 study, 88% (*n* = 2,436) were firmware version 7 and 12% (*n* = 333) were firmware version 8.

Figure 2-7. Juvenile Salmon Acoustic Telemetry System tag (model SS400; ATS, Inc., bottom tag) and passive integrated transponder (PIT) tag (top tag) that were surgically implanted into juvenile Puget Sound coho salmon in spring 2024.

To evaluate the battery life of the SS400 tags, a tag life study was performed. A total of 64 tag samples with a PRI of 4 seconds were randomly pulled from each of the four tagging weeks and used for tag life testing at the Aquatic Research Laboratory at PNNL. Prior to the start of the test, the firmware version of each tag was checked using the ATS Pinger Dish and recorded. Of the 64 tags, 78% (*n* = 50) had firmware version 7, 20% (*n* = 13) had firmware version 8, and 2% (*n* = 1) had an unknown firmware version because it could not be activated. Because of the relatively large quantity of the concurrent test tags in the tag life testing, the tags were split into two different water tanks, and mixed with other tag-life test tags from other studies. Throughout the tag life test, new test tags from different field studies were added into these tanks in accordance with the tagging schedules of those field studies.

2.3 Data Collection

All data were acquired using cabled and autonomous receivers deployed on the face of the dam and throughout the HAHD Reservoir and downstream. These receivers detected fish implanted with JSATS tags. Autonomous receivers provided information on how fish moved within the reservoir, and whether fish made it downstream of the dam. The cabled receivers, deployed on the face of the dam, provided information on the 3-D movement of fish, giving insight into fish behavior when approaching the dam. The 3-D tracking was possible when a single transmission from a tag was detected by multiple receivers (a minimum of four cabled or autonomous receivers) allowing the fish's location to be triangulated (Figure 2-8; Deng et al. 2011).

The proposed method of 3-D tracking was to utilize detections of acoustic-tagged fish from both the cabled dam face hydrophones and the forebay autonomous receivers to study fish movement and behavior in the immediate forebay and assign dam passage. The 3-D tracking was conducted based on time-of-arrival differences of acoustic transmissions among various cabled and autonomous receivers (Watkins and Schevill, 1972).

For this study, time jump issues occurred on the forebay (FBY) autonomous receivers because of the unanticipated large volume of data being collected and causing strain on the equipment; therefore, only tag detections from cabled receivers were used for the 3-D tracking. An efficient and accurate approximate maximum likelihood solver (Li et al., 2014) was employed, which represents an improvement over the methods described by Deng et al. (2011) and Weiland et al. (2011). Fish behavior and movement within the forebay were then characterized using the solved 3-D tracks.

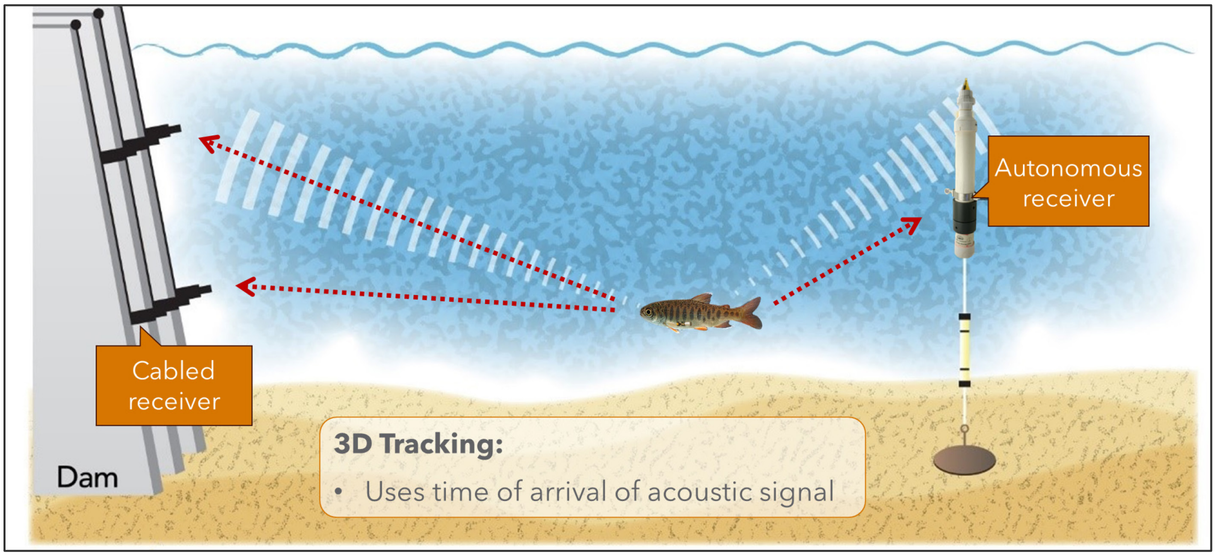


Figure 2-8. The 3-D tracking uses the fish detection time to triangulate its location within the water column.

2.4 Fish Tagging and Releases

Study fish were provided by the Washington Department of Fish and Wildlife (WDFW) Soos Creek Hatchery. Hatchery subyearling PS Chinook salmon were too small (< 95 mm in fork length; Geist et al. 2018) during the study period for the size of the JSATS tags, and hatchery juvenile PS steelhead were not available. However, appropriately sized yearling coho salmon (≥ 95 mm in fork length; Geist et al. 2018) were available and utilized for the study. JSATS tags of a smaller size can be used in smaller salmonids (i.e., the eel-lamprey acoustic tag [ELAT] in salmon ~60 mm in fork length [Fischer et al. 2019; Liss et al. 2021); however, the ELAT has a substantially shorter tag life (< 30 days) compared to the JSATS tag used for this study (estimated 70 days). The shorter tag life was anticipated to be insufficient for evaluating fish passage and survival at HAHD. As such, juvenile coho salmon were used and tagged with the larger SS400 tags. Coho salmon were used to collect baseline information and identify potential trends or timing of migrations for salmon in the reservoir; they were not intended to be a direct comparison nor a replacement for PS Chinook salmon.

Each study fish was surgically implanted with both a JSATS tag and a PIT tag. JSATS tags were activated 12 to 24 hours prior to surgical implantation. On the day of tagging, each JSATS tag was again verified to be active immediately prior to implantation. The surgical team followed the latest guidelines for surgical implantation of acoustic transmitters in juvenile salmonids (Geist et al. 2018) and an established protocol was used to help minimize potential negative effects from surgical procedures and handling. During the tagging process, fish were first placed in a solution of water mixed with an anesthetic (Aqui-S, New Zealand Ltd, New Zealand; active ingredient: eugenol) until all equilibrium was lost. Then, using a sterile surgical blade, the surgeon made a 3-mm incision 2-3 mm above the linea alba, just under the tip of the pectoral fin, and inserted both tags. No sutures were required for this procedure due to the size of the incision and the procedure took < 60 seconds. Fish recovered in fresh river water immediately after the procedure.

Tagged fish were held for 12–24 hours post-surgery in perforated buckets located in a tank of flow-through river water to ensure short-term effects of the surgical process had dissipated. Once fish had recovered for 12–24 hours, buckets were opened to check for dead or moribund fish. Although rare, if dead or moribund fish were observed they were removed, and JSATS and PIT tag codes were recorded.

Prior to releasing fish, individual buckets holding the tagged fish were placed into a tank equipped with JSATS acoustic receivers to verify that all tags remained active throughout post-surgery holding period. If any tags were not detected during this scan it was noted, so that those tag codes could be removed from analyses. However, any fish whose JSATS tags prematurely deactivated during the post-surgery holding period were still released into the reservoir.

During the spring season, 2,684 juvenile coho salmon were tagged, released, and used for analyses (Table 2-2). Live fish were released by boat along a transect at either the head of the reservoir (HOR) or mid of reservoir (MOR). As the reservoir refilled during the study period, the HOR site was moved further upstream to the upper head of reservoir (UHOR). In addition to live fish releases, dead tagged juvenile coho salmon were released in the HAHD tailrace throughout the refill period. These fish underwent the same surgical procedures and post-surgery recovery as live fish, but were euthanized on the day of release using an overdose of MS-222. Dead tagged fish were important for estimating dam passage survival using the ViRDCt release-recapture model, which requires releases of dead fish to correct the bias that can occur from misidentifying dead fish as alive downstream of the dam (Harnish et al. 2020).

Table 2-2. Juvenile coho salmon released alive (MOR, HOR, and UHOR), or dead (HAHD) by release time during the spring study period and used in analyses.

Release Location	Total Released (*n*)	Fork length (mm)	Weight (g)	Release Time (*n*)			
				Early March	Late March	Late April	Early May
MOR	1,250	121 (95–157)	15.9 (10.0–33.5)	303	346	323	278
HOR	641	114 (96–146)	14.3 (10.0–27.9)	307	334	0	0
UHOR	577	129 (103–151)	17.8 (8.3–30.1)	0	0	308	269
HAHD	216	119 (95–153)	15.5 (9.7–28.2)	57	57	56	46

MOR = mid of reservoir; HOR = head of reservoir; UHOR = upper head of reservoir; HAHD = Howard A. Hanson Dam.

2.5 Statistical Methods

2.5.1 Estimation of Reservoir and Dam Passage

Due to the large volume of data on the receivers in the HAHD forebay from fish not passing HAHD, time keeping (time stamp) issues occurred with the autonomous receivers deployed in the near forebay of HAHD. Thus, they could not be used with cabled receivers deployed on the upstream dam face of HAHD for 3-D tracking. Therefore, 3-D tracking could only be conducted using cabled hydrophones to track tagged fish near the dam face – it could not be used to determine which fish passed HAHD. Because there is a 41-ft gap between the trash rack and the radial gate entrance, located behind the dam face hydrophones, 3-D tracking could not determine the fish's position in the water column before entering the radial gate. In addition, the flow rate was too low to observe any diving behavior or fish being carried by the current in front of the trash rack, making it impossible to determine which fish dived into the outflow channel and passed HAHD. As a result, event-time analyses, which require knowledge of passage timing, could not be used to evaluate the effect of covariates, such as discharge and forebay elevation, on passage.

Detections at arrays downstream of the dam provided a list of tagged fish known to have passed HAHD. Time of passage for these fish was assigned based on last detection time in the HAHD Reservoir. With this limited set of known-passed fish, it was possible to explore correlations of passage timing with dam operations and reservoir conditions. Those correlations were examined by comparing the timing of fish passage with the variation in forebay elevation, flows out or in, temperature, and the diel cycle.

2.5.2 Estimation of Survival

Detections of acoustically tagged fish on receiver arrays deployed at HOR, on the upstream dam face of HAHD, and downstream of HAHD were used in release-recapture models to estimate reservoir and overall project survival. Reservoir survival ($\hat{S}_R$) was estimated from the HOR array to HAHD detection using the single-release model of Skalski et al. (1998), adjusted for the probability of tag failure using results from a tag life study and the methods of Townsend et al.

(2006) implemented in program ATLAS (https://www.cbr.washington.edu/analysis/apps/atlas). The closed form estimator of the single-release model can be written as:

$$\hat{S}_R = \frac{\left(\frac{V_D}{V_R}\right)}{p_1}.$$

For estimating reservoir survival, V_D is the number of acoustically tagged salmon detected by the HAHD cabled array, V_R is the number of acoustically tagged salmon released upstream of the HOR array that were detected by the HOR array, and p_1 is the detection probability of the HAHD dam face array. Releasing tagged fish upstream of the HOR array and requiring detection at the HOR array to form a virtual release group (V_R) allowed tagged fish an opportunity to recover from tagging and handling effects prior to their inclusion in the study and it ensured that only fish with an actively transmitting tag were included in the survival estimation. Because some acoustically tagged fish may have residualized in HAHD Reservoir (between the HOR array and HAHD) beyond the life of their transmitter, the reservoir survival estimate ($\hat{S}_R$) actually represents the joint probability of migration and survival to HAHD. This measure of reservoir survival, which did not require passage through HAHD, is a useful metric to understand the potential effect of the reservoir on overall survival once dam passage conditions are improved at HAHD.

The inability to reliably identify all fish that passed HAHD prevented formation of a virtual release group composed of all fish that passed HAHD for dam passage survival estimation using the ViRDCt model (Harnish et al. 2020). As such, the only measure of survival that included HAHD passage that could be estimated was a single-release estimate of overall project survival from the HOR array (for fish released upstream of the HOR array) to the CKB array, which was located 11.26 km downstream of HAHD. The CKB array was selected as the array to which survival was estimated because dead-released fish were detected at the TPU array but not farther downstream. Again, the estimate of overall project survival represents the joint probability of migration and survival from HOR to CKB because some acoustic-tagged fish may have remained in the HAHD reservoir until their transmitter battery died or the receivers were removed in late June.

2.5.3 Estimation of Travel Times

Travel times were calculated from release to the CBL, TPU, CKB, PIT, and DUW arrays by subtracting the date and time of release from the date and time of first detection. Using the date and time of first detection at the CBL array provided information of how quickly fish moved through the HAHD Reservoir before many of them began traversing back and forth between detection arrays and the dam.

3.0 Results

3.1 Acoustic Telemetry Tags

During the active tag and tag life studies, anomalies were discovered with the version 7 firmware tags. When active tags with version 7 firmware were located close to one another, the active pings of the tags could deactivate other tags. This issue occurred throughout the study with tags being deactivated between tag activation and tagging of live fish (12–24 hours), between tagging and releasing fish (12–24 hours), and during the tag life study. In total, 129 tags deactivated during the overnight holding between tag activation and live fish tagging. These tags were never implanted into the fish. However, a separate 82 tags were implanted into fish and deactivated between fish tagging and fish releases; these fish were removed from analyses but were released into the reservoir.

During the tag life study, a random number of the version 7 tags turned themselves off every time tags were added into the test tanks. Attempts were made to reactivate those tags with the Pinger Dish so they could continue to be included in the tag life test. However, when placing the tags back into the test tank, often times additional version 7 firmware tags would stop transmitting almost simultaneously, apparently as a result of the disturbance of the test environment (staff taking the tags in and out of the tank).

According to the tag manufacturer (ATS, Inc.), this was caused by a software bug in the SS400's version 7 firmware, which caused some active SS400 tags to spontaneously turn themselves off when they were placed in close proximity with one another. The version 8 firmware supposedly had resolved the issue, which was consistent with the tag life study observations: none of the version 8 SS400 tags in the tag life study displayed the same self-deactivation behavior. Therefore, approximately three months after starting the tag life test, no additional attempts were made to re-activate any version 7 tags that had stopped transmitting.

Of the 50 version 7 tags in the tag life study, only 22 of them did not deactivate during the course of the test. Their average tag life was 90.6 days. None of the version 8 tags (n = 13) in the tag life study self-deactivated. Their average tag life was 85.2 days. The average tag life of these version 7 and 8 tags combined was 88.6 days. Tag life was similar between tag versions (Figure 3-1; Log-Rank: χ^2 = 1.993, P = 0.158; Wilcoxon: χ^2 = 1.672, P = 0.196); therefore, they were pooled for survival estimation.

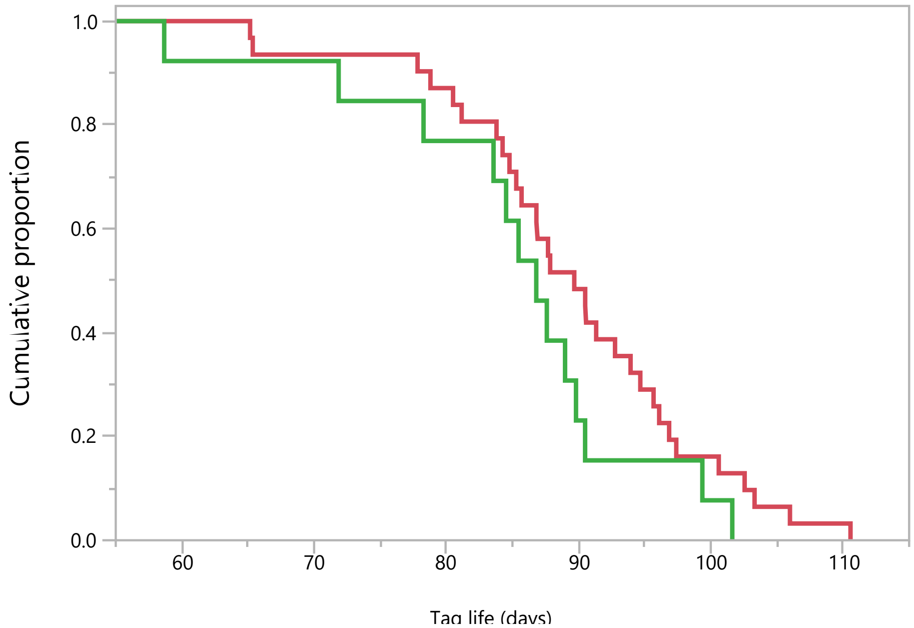


Figure 3-1. Cumulative proportion of firmware version 7 (red) and version 8 (green) tag life JSATS tags transmitting a signal over time.

3.2 Fish Tagging and Releases

Between March 10 and May 12, juvenile coho salmon were double tagged with a JSATS and a PIT tag. Fish releases occurred at four different times throughout the spring reservoir refill period (Table 3-1):

- early March (March 10 – March 14);
- late March (March 22 – March 26);
- late April (April 23 – April 27);
- early May (May 9 – May 12).

A total of 2,769 juvenile coho salmon were tagged during the spring season. There were three post-tagging mortalities that occurred during the 12 to 24 hour post-surgery holding (< 0.11% mortality rate). These fish were not released and were removed from analyses. Of the remaining juvenile coho salmon (*n*= 2,766), 2,540 were released alive at the MOR, HOR, or UHOR. Dead tagged juvenile coho salmon (*n* = 226) were also released in the tailwaters of HAHD.

An additional 82 fish (72 live; 10 dead) were released but removed from analyses because the tags were unable to be detected and confirmed active prior to release. Because of the issues with the version 7 firmware, it was unknown if the tags may have deactivated themselves due to the close proximity of the fish during the post-surgery holding period. As a result, 2,684 fish were used for analyses (2,468 = released alive; 216 = released dead; Table 3-1 and Figure 3-2).

Table 3-1. Juvenile coho salmon released alive (MOR, HOR, and UHOR), or dead (HAHD) by release time during the spring study period and used in analyses.

				Release Time (*n*)			
Release Location	**Total Released (*n*)**	**Fork length (mm)**	**Weight (g)**	**Early March**	**Late March**	**Late April**	**Early May**
HAHD	216	119 (95–153)	15.5 (9.7–28.2)	57	57	56	46
MOR	1250	121 (95–157)	15.9 (10.0–33.5)	303	346	323	278
HOR	641	114 (96–146)	14.3 (10.0–27.9)	307	334	0	0
UHOR	577	129 (103–151)	17.8 (8.3–30.1)	0	0	308	269

HAHD = Howard A. Hanson Dam; MOR = mid of reservoir; HOR = head of reservoir; UHOR = upper head of reservoir.

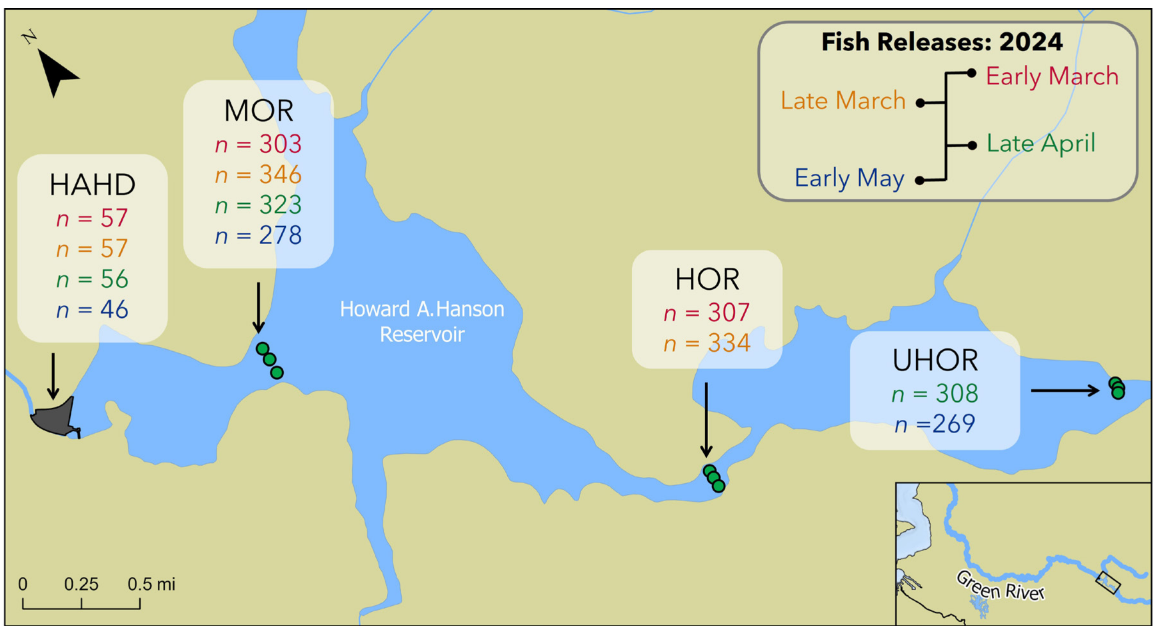


Figure 3-2. Map of the release points within the Howard A. Hanson Dam (HAHD) Reservoir. Live juvenile coho salmon were released either at the mid of reservoir (MOR), head of reservoir (HOR), or upper head of reservoir (UHOR). Dead juvenile coho salmon were released in the tailwaters of HAHD. The sample sizes for each release site are shown color coded by release date.

3.3 Reservoir Elevation and Discharge

HAHD is primarily operated for flood risk management during the winter and early spring months. In spring, the focus shifts to its secondary purpose: water storage for City of Tacoma's water supply and flow augmentation for fish resources. When transitioning from flood risk management to water storage, the amount of water released from HAHD is reduced to below the inflow levels, allowing the reservoir to refill. The timing of this refill and the release rates are adjusted annually based on weather and hydrological conditions, among other factors.

The reservoir elevation at HAHD can range from 1,035 ft (the invert of the outflow tunnel) to 1,206 ft (the top of the spillway gates), with the top of the entrance to the outflow tunnel located at 1,047 ft (Figure 3-3). Data on the forebay elevation during the study period was gathered from a United States Geological Survey gage (USGS 12105800) located at the HAHD Reservoir. When the first fish release occurred on March 10, 2024, the forebay elevation was at 1,099 ft. By the final fish release on April 27, 2023, the elevation had risen to 1,143 ft. On Aug 9, 2023 (89 days after the activation of tags for the final fish release), the forebay elevation had stabilized at approximately 1,157 ft (Figure 3-3).

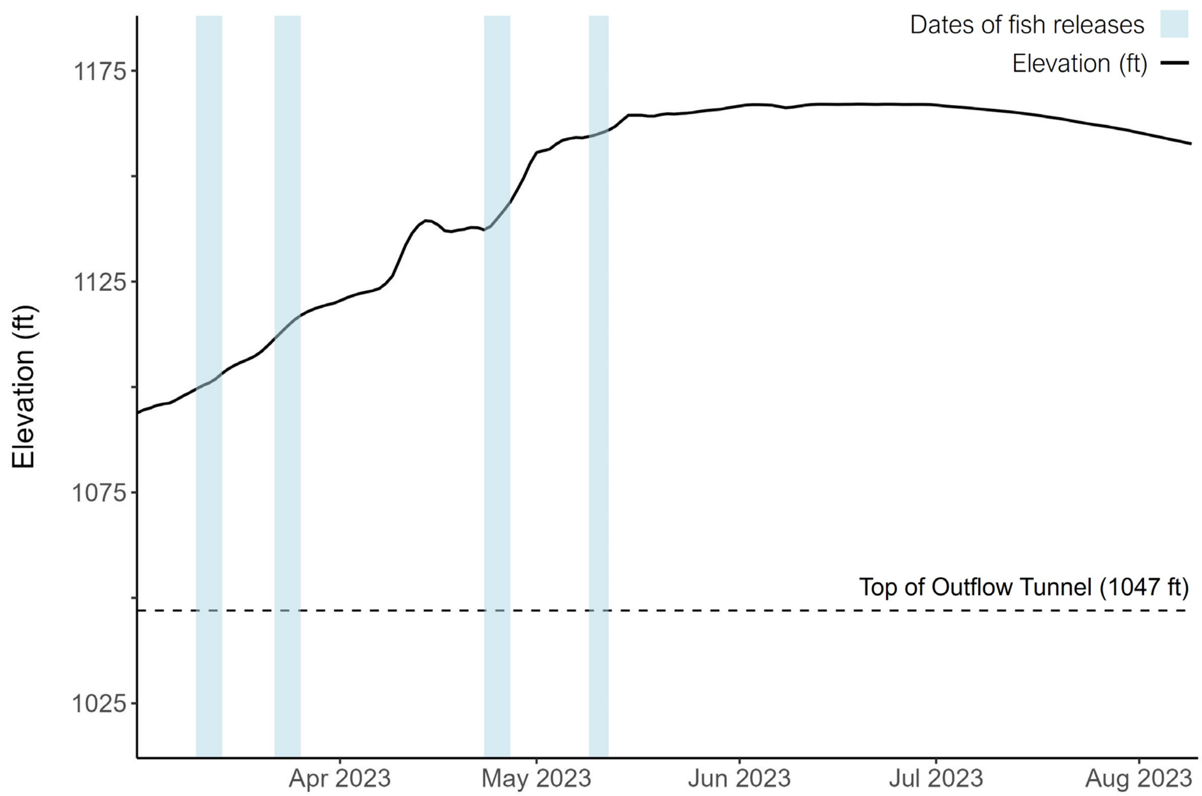


Figure 3-3. Graph showing the reservoir elevation (ft) at Howard A. Hanson Dam throughout the study period. Dates when fish were released into the reservoir are shaded light blue. The dashed line indicates the elevation of the top of the outflow tunnel entrance.

3.4 Data Collection

Data downloads for the autonomous receivers were scheduled to occur every three weeks throughout the spring tagging season and as needed for the cabled 3-D system that was remotely monitored. This schedule was maintained with downloads occurring monthly for most arrays, except for the NFB and FBY arrays, and the cabled array. After the first two fish releases that occurred March 10–14 and 22–26, large quantities of data were being collected and processed in the forebay of HAHD. Approximately 1,200 tagged juvenile coho were released in the first two tagging trips, and it became clear they were not passing HAHD. Instead, fish remained in the forebay of HAHD and began to overwhelm the autonomous and cabled receivers with the large amount of data being collected.

On the 3-D system alone, ~500 GB of data was being collected per day. At times, the processing could not keep up and the system would crash, requiring a reboot. Data drives for the 3-D cabled array were switched every 3–4 days, and the data required extensive post-processing as onboard decoding software was only able to decode 25% of the incoming data.

For the NFB and FBY arrays, a separate issue was identified. Due to the 32-bit operating system of the autonomous receivers, it was discovered that the file size had a maximum of 4.2 GB. All five receivers in the NFB and two of the three receivers in the FBY had stopped collecting data due to insufficient file size and the large volume of fish being detected in the reservoir. This filled the data cards and subsequently caused time jumps in the data that was collected. However, this large amount of data collection did not occur at other locations within the reservoir or downstream. As a result, the downloading frequency for the NFB and FBY arrays increased to every two weeks until the end of the study period. Data from all other downstream receivers were downloaded on the planned three-week basis until the end of the study.

Another biproduct of the large volume of data being collected was a greater demand on the batteries within the autonomous receivers (e.g., batteries drained quickly). On average, batteries were estimated to last up to 100 days; however, battery life was severely reduced with an average battery life of approximately 57 days in the NFB and FBY receivers. It was approximately 73 days for receivers in the rest of the reservoir and downstream of HAHD.

3.4.1 Autonomous Receiver Time Correction

The autonomous receivers used in this study occasionally suffered difficulties in keeping time, depending on the firmware version and the numbers of tags within range. In those cases, receivers experienced brief gaps in processing during which timekeeping stopped. No pattern was identified that would allow timekeeping to be restored perfectly, but approximate corrections were made. Corrected times were compared with other uncorrupted detections, and it was determined that corrected times were accurate within approximately 30 minutes of the actual time. This level of correction was insufficient for processing autonomous receivers to compute 3-D locations but was sufficient for evaluation of fish movement within and through the reservoir. The number of receiver deployments that occurred across the season and whether they required correction or removal from the study are listed in Table 3-2. The one receiver removed from the study suffered so many time jumps that correction was infeasible (Table 3-2).

Table 3-2. Autonomous nodes requiring correction or removal from study due to time jumps by array and river kilometer (rkm).

Array	RKM	Not Corrected	Corrected	Removed
HOR	106.1	7	1	
CCR	105.6	6	2	
NGR	105.0	12		
MOR	104.0	10	2	
FBY	103.3	5	16	
NFB	103.1	5	27	1
CBL	103.0	8		
TPU	97.4	21	1	
TBP	97.37	1		
CKB	91.8	4	3	
PIT	18.7	12	1	
DUW	4.8	12		

HOR = head of reservoir; CCR = Charlie Creek; NGR = North Fork Green River; MOR = mid of reservoir; FBY = forebay; NFB = near forebay; CBL = cabled array; TPU = Tacoma Diversion Dam; TBP = Tacoma juvenile bypass; CKB = Cumberland Kanasket Bridge; PIT = PIT Barge (Tukwila); and DUW = Duwamish River

3.5 3-D Tracking

3.5.1 Last Tracked Locations

The 3-D system was set up was to be able to triangulate a fish's location and if the fish entered the tunnel. However, the near forebay autonomous receivers were unable to be utilized because of the volume of data collected due to the lack of fish passage and subsequent time jump issues. Therefore, 3-D triangulation was not possible and the position of the hydrophones on the trash rack, which prevented seeing if the fish entered the tunnel to pass. A fish could only be confirmed to have passed HAHD if it was detected downstream.

The last tracked locations of fish that were known to have passed HAHD could be identified for fish that were detected downstream (Figure 3-4). For fish that did not pass HAHD, they continued to be detected in the reservoir, which was their last tracked location (Figure 3-4). A total of 2,261 fish were detected on the cabled array. Of those, 205 fish were known to have passed the dam, as detected by downstream autonomous receivers/PIT detectors, and they have 3-D tracks. A total of 1,632 fish were tracked and confirmed to have not passed the dam, based on later detections by the forebay autonomous receiver arrays (FBY or NFB) after being detected by the dam hydrophones on the cabled array. There were also 411 fish that were last detected at the cabled array but for which passage could not be determined. Finally, there were 13 fish were detected at the cabled array but did not have 3-D tracks.

Most fish that were known to have passed HAHD were last tracked near the dam face at the south end of the tunnel entrance in front of gate #1, indicating that they may have located the flow before passing the trash rack and entering the radial gate. For the fish known to have not passed, their last tracked locations were concentrated on both the north and south sides of the dam structure, suggesting that they moved either to the north side or the south end before eventually moving upstream and leaving the forebay.

The distribution of the last tracked depths for passed and not passed fish is shown in Figure 3-5. Both groups exhibit similar distributions, with median depths of -9.0 m for passed fish and -8.4 m for not passed fish. A scatter plot of the last tracked elevations for both groups is presented in Figure 3-6. Although the radial gate top elevation is at 1,047 ft, only very few of the passed fish were last tracked below 1,080 ft. This suggests that passed fish did not dive down to the lower water column before entering the trash rack, but instead descended below 1,047 ft while traveling the 41-ft gap between the trash rack and the radial gate entrance.

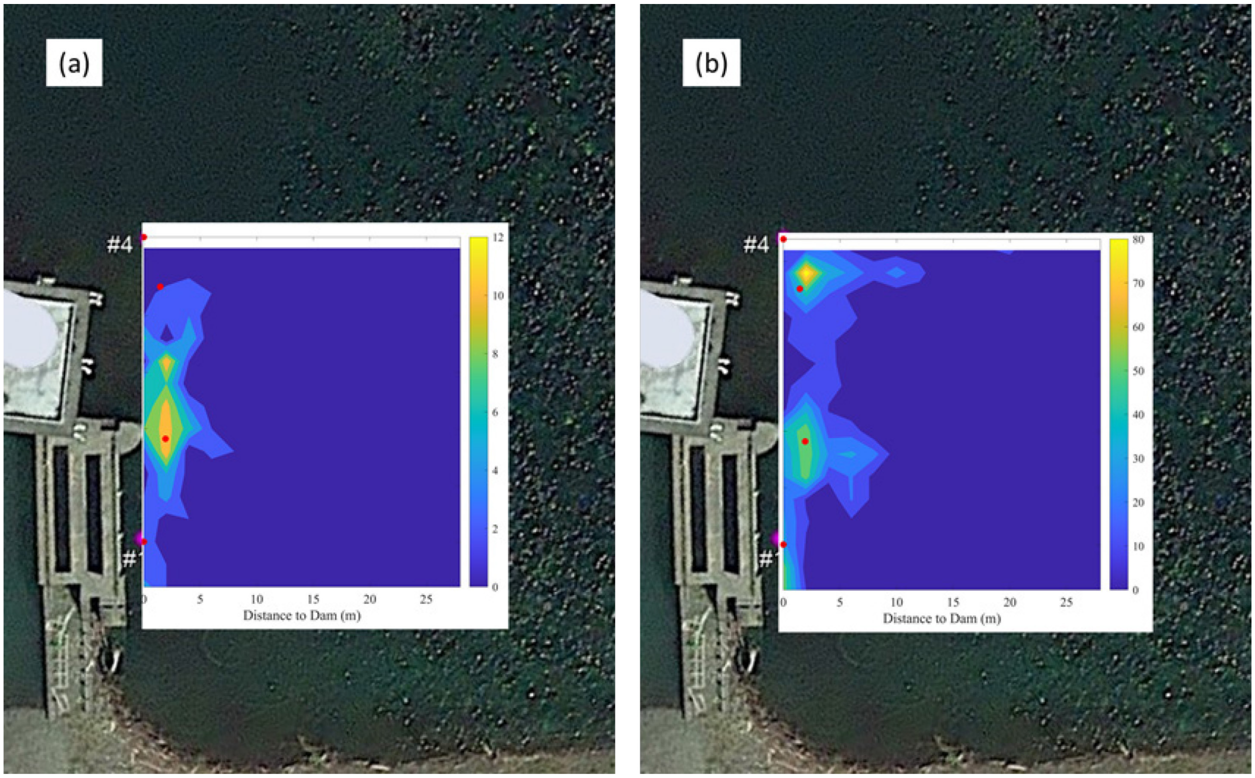


Figure 3-4. Heat maps of the last tracked location of passed (a) and not passed Fish (b) at the dam face of the Howard A. Hanson Dam. The colors show the number of fish. Yellow indicates a higher density of fish; green is a medium density and light blue is a low density. The red dots show where the cabled array hydrophones were located.

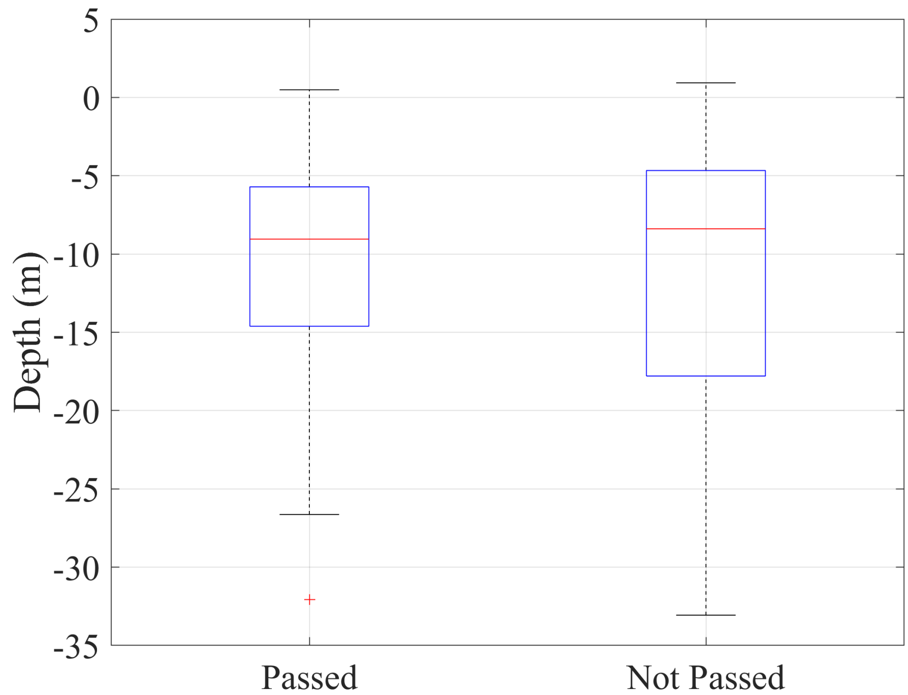


Figure 3-5. Distribution of last tracked depths (meters) for passed and not passed fish. Box plots show the median (red line), 75th and 25th percentiles, and the whiskers represent the 95th and 5th percentiles. Outliers are the red plus signs. A depth of 0 is the reservoir elevation. Negative depths are below the water surface.

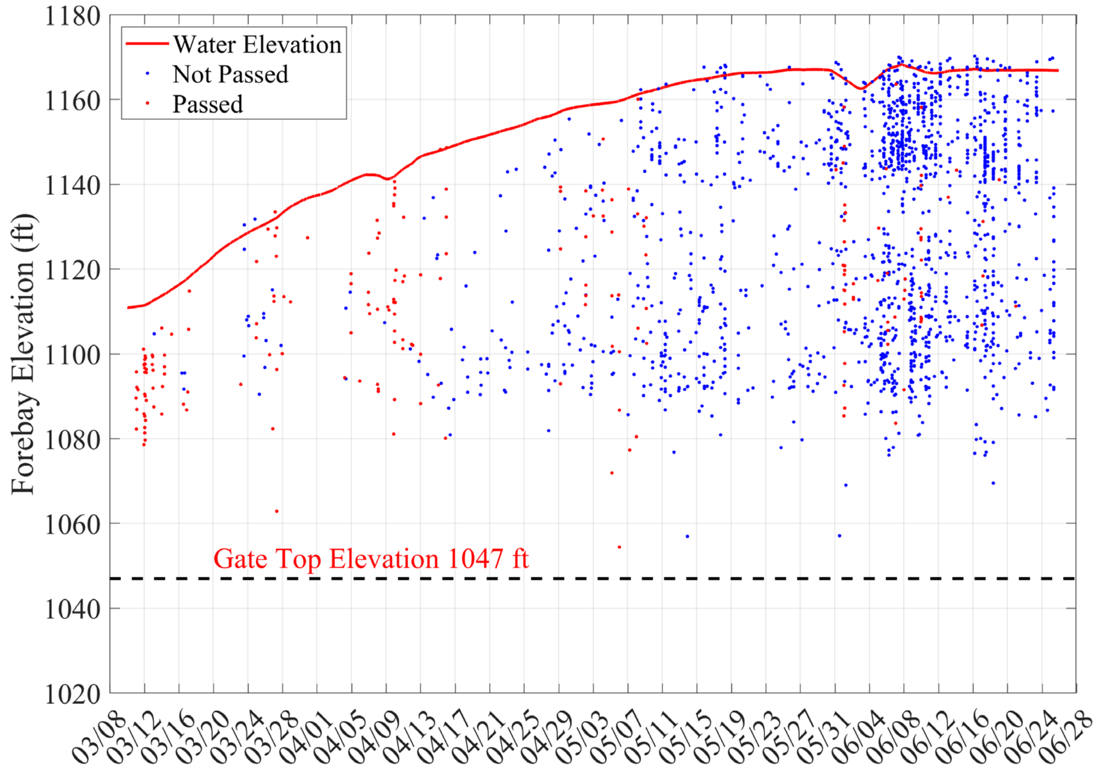


Figure 3-6. Last tracked elevations for passed (red dots) and not passed (blue dots) fish by forebay elevation (feet) and date.

3.5.2 Fish Depths

The distribution of depths based on the first detection at HAHD (i.e., time at which fish were first tracked in front of the dam face) is illustrated in Figure 3-7. Fish generally remained in the top 25 ft of the water column, regardless of whether the fish was first detected during the day or at night (Figure 3-7). The median depth during the daytime was –10.6 m, which is slightly deeper than the nighttime median of -8.8 m. In both periods, the data exhibited a bimodal distribution. A relatively higher proportion of fish were first tracked at shallower depths (-5 m to 0 m), while a second peak occurred between -15 m and -20 m, where approximately 25% of the fish were first tracked.

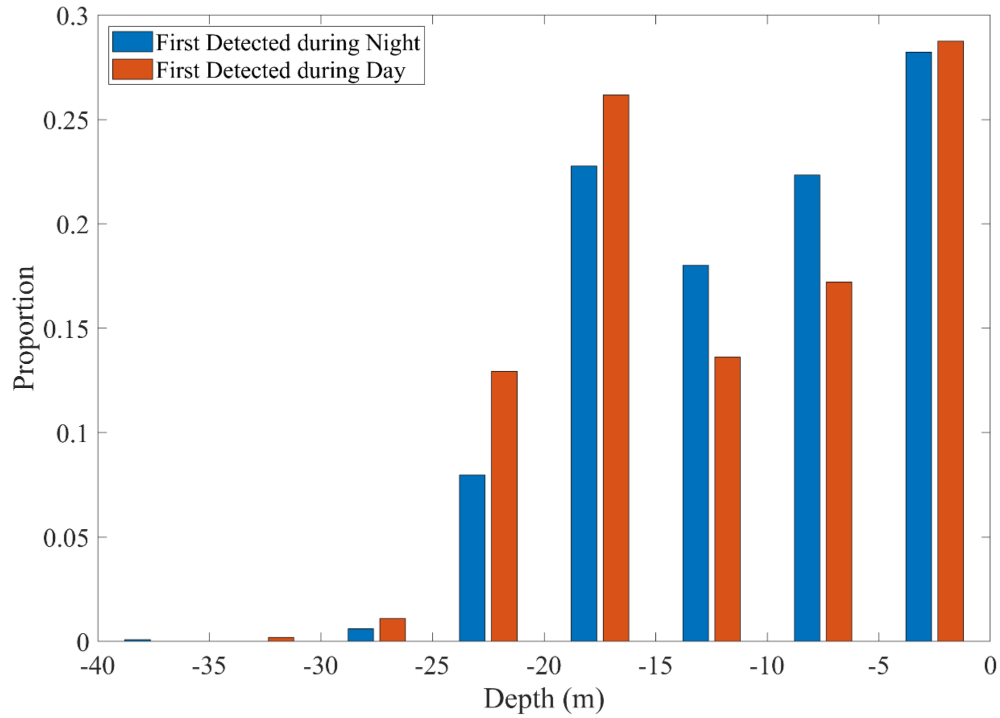


Figure 3-7. Distribution of depths upon approach to the dam (i.e., first tracked depths; meters) for fish during the day and night.

The distribution of the tracked depths for fish that passed and did not pass HAHD during the day and night is shown in Figure 3-8. The median depth of each fish during the day and night is used as a sample point. Both fish groups tended to stay in the upper water column near the surface at night and deeper water during the day. The median depth of fish that passed HAHD was slightly deeper than that of the fish that did not pass, at -5.0 m vs. -4.1 m during the night and -14.6 m vs. -14.3 m during the day. The difference between those fish that passed and those that did not pass may be due to the smaller sample size of passed fish, and the longer residence time in the forebay of the fish that did not pass. Additional details on horizontal and vertical fish distributions in the forebay are shown in Appendix A.

The hourly distribution of tracked depth for fish that passed and did not pass HAHD is depicted in Figure 3-9. Passed fish tended to remain slightly deeper in the water column in the early morning and during the day, whereas fish that did not pass remained at a slightly deeper depth during the evening hours (19:00–21:00). In addition, fish that did not pass generally exhibited greater depth variation, especially during the day, which may be attributed to their larger sample size and longer residence time in the forebay.

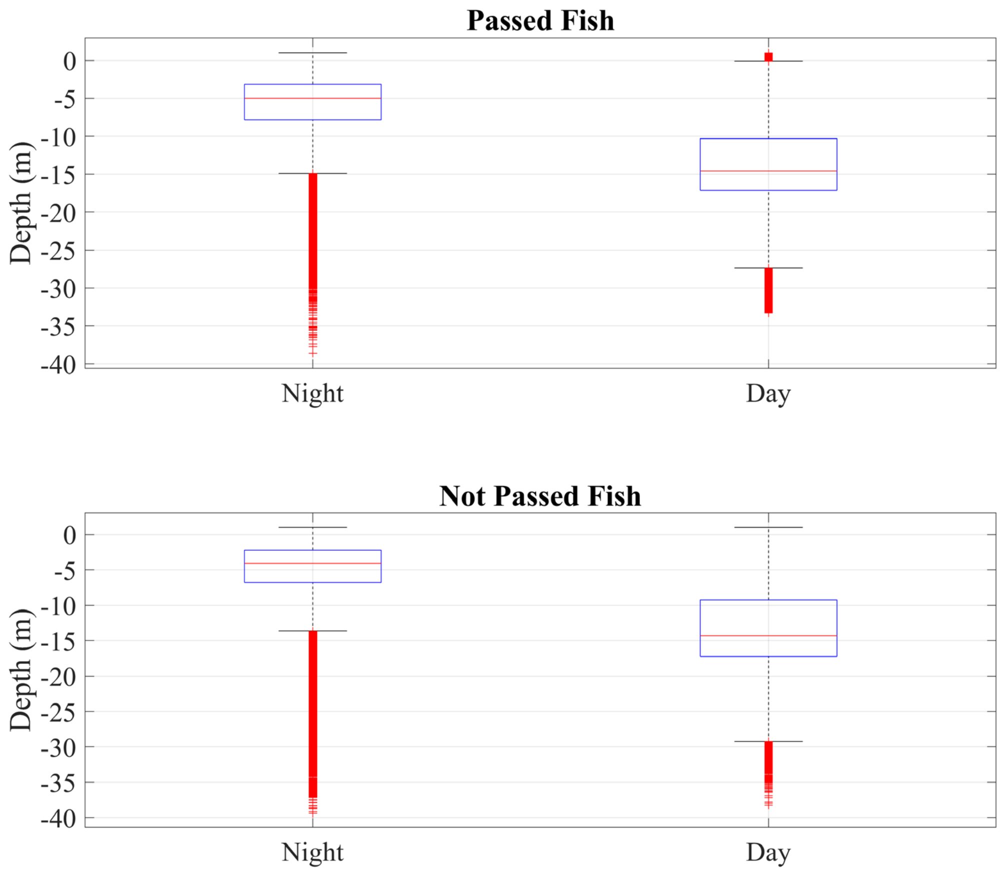


Figure 3-8. Distribution of tracked depths (meters) for fish that passed and did not pass during the day and night. Box plots show the median (red line), 75th and 25th percentiles, and the whiskers represent the 95th and 5th percentiles. Outliers are the red lines. A depth of 0 is the reservoir elevation. Negative depths are below the water surface.

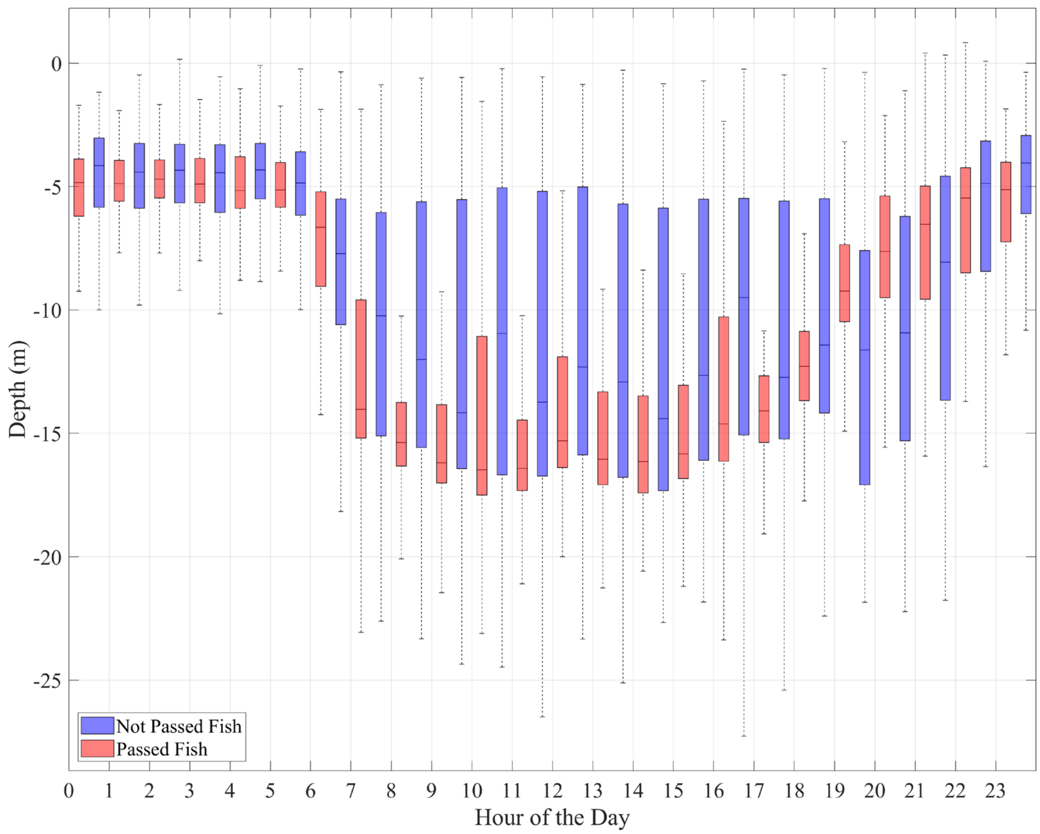


Figure 3-9. Hourly distribution of tracked depth (meters) for fish that passed Howard A. Hanson Dam (HAHD; red) and fish that did not pass HAHD (blue).

3.6 Reservoir and Dam Passage

3.6.1 Detection in the Reservoir

The number of fish remaining in the reservoir for an extended time resulted in an extremely large number of detections on receivers. Each detection required computations that required power; thus, the batteries of some receivers expired before the end of their anticipated battery life. Because nearby receivers were typically serviced at the same time (i.e., data downloaded and batteries replaced), these early expirations resulted in a gap of detection in the upper forebay from mid-May through early June (Figure 3-10). In addition, some unrelated gaps at the CBL and NFB arrays exceeded one day.

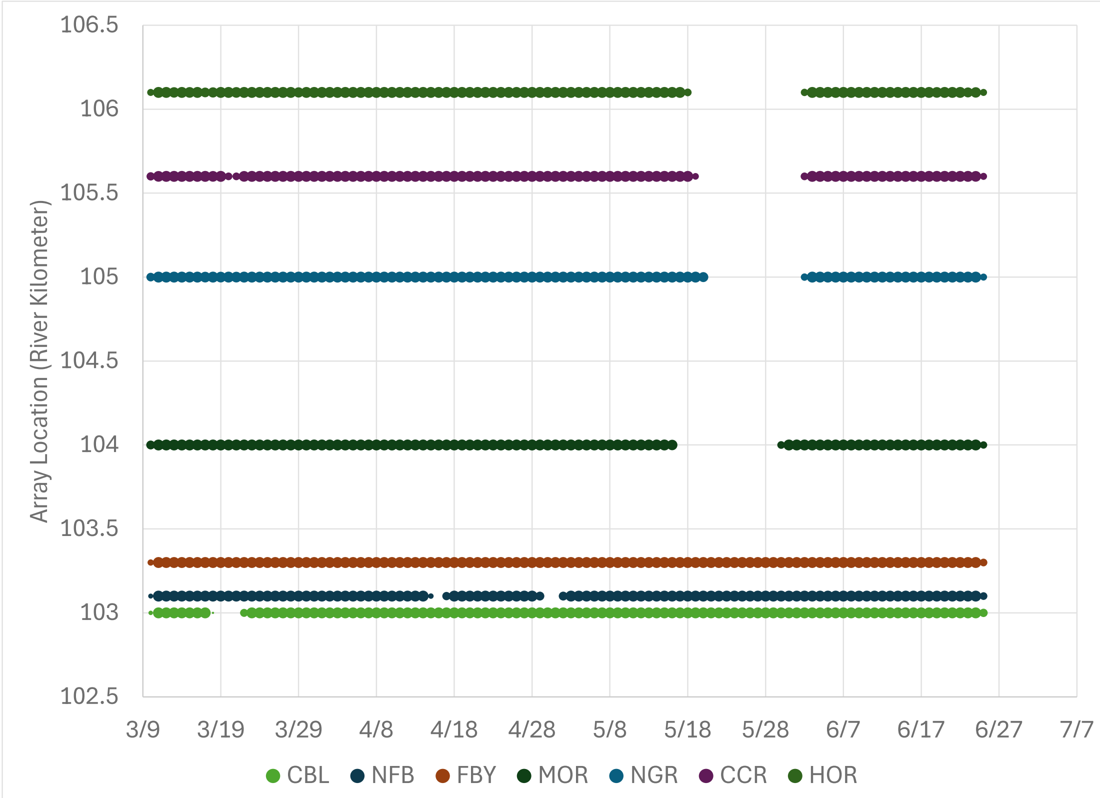


Figure 3-10. Array detection gaps by array location. Marker size is scaled to the number of hours where a tag was detected. A small or missing marker indicates that all nodes at an array were not operational during some or all of the day. CBL = cabled array; NFB = near forebay; FBY = forebay; MOR = mid of reservoir release location; NGR = North Fork Green River; CCR = Charlie Creek; HOR = head of reservoir release location.

3.6.2 Movement in the Reservoir

A large proportion of the fish released in the reservoir did not pass downstream of HAHD during the study period. To better understand why this was the case, it is helpful to examine how fish moved through the reservoir and whether they were likely to encounter the dam. Figure 3-11 illustrates the numbers of times fish moved from one array to another. Fish staying at the same array from one event to the next were not included in the diagram. The movement patterns reflect numerous movements among the three arrays closest to the dam. These three arrays are within a few hundred meters of each other, so it would not require swimming a great distance to move to another array. The arrays in the upper portion of the reservoir are farther apart, resulting in far fewer movements from one array to another.

To reduce the influence of distance, Figure 3-12 standardizes the number of events at the originating array. This approach emphasizes the proportions of fish leaving an array that will arrive at the other arrays. The results show a general tendency to move downstream. Boundary effects are also evident. For example, as only arrays upstream of the CBL array were included, all movement from CBL is to an upstream array.

Those diagrams summarize tendencies, but individual fish may exhibit a variety of behaviors in the forebay. Figure 3-13 illustrates how a single fish moved among arrays in the reservoir prior to passing downstream. This individual encountered the near forebay environment and was close enough to be detected by the cabled array many times and across many days prior to eventually passing the dam.

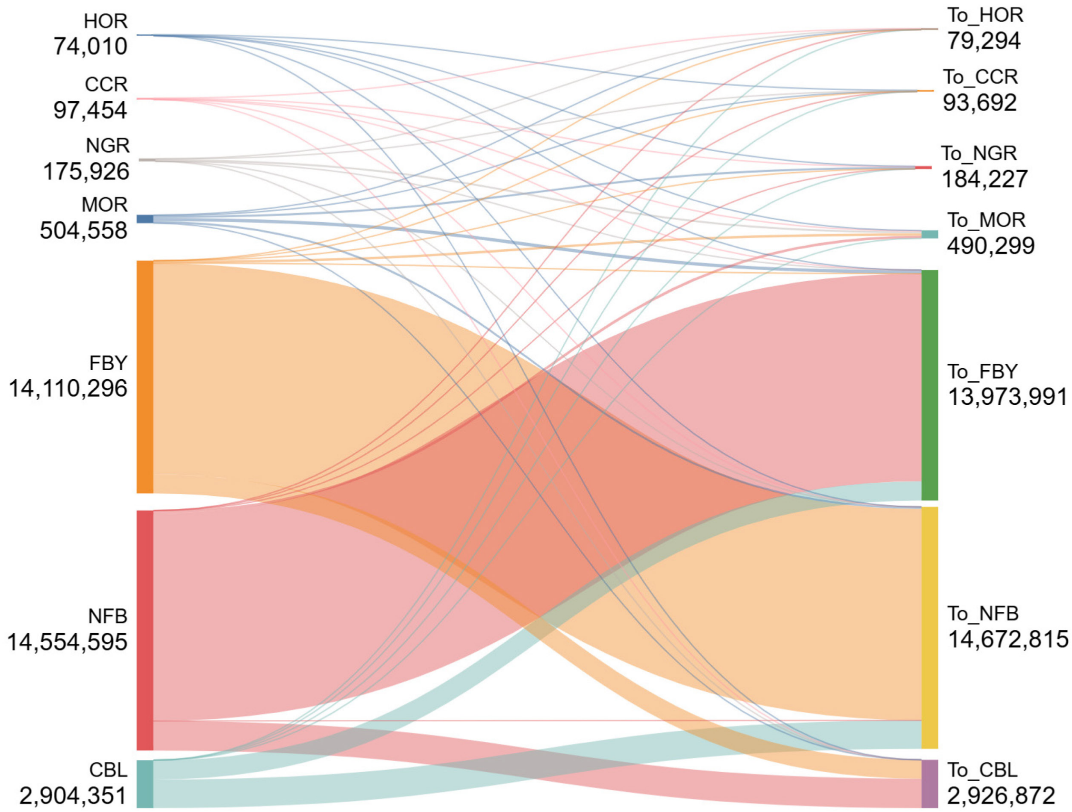


Figure 3-11. Counts of movement events from array to array in the Howard A. Hanson Dam Reservoir. Numbers and arrays in the left column indicate the origin of each movement. Numbers and arrays in the right column indicate where fish arrived at the end of that movement. CBL = cabled array; NFB = near forebay; FBY = forebay; MOR = mid of reservoir release location; NGR = North Fork Green River; CCR = Charlie Creek; HOR = head of reservoir release location.

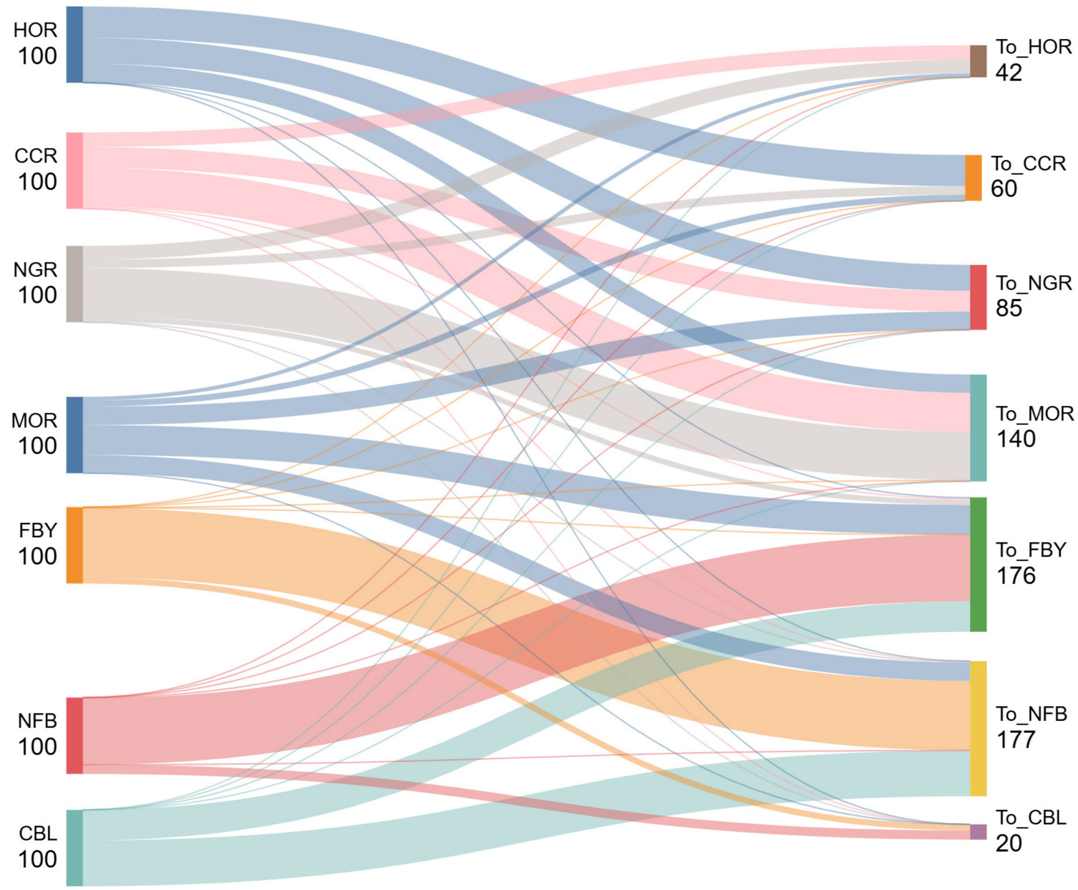


Figure 3-12. Relative movement from array to array in the Howard A. Hanson Dam Reservoir. The number of fish beginning at each array (left column) standardized to 100% for each array source (left column) showing relative movement to the next array (right column). CBL = cabled array; NFB = near forebay; FBY = forebay; MOR = mid of reservoir release location; NGR = North Fork Green River; CCR = Charlie Creek; HOR = head of reservoir release location.

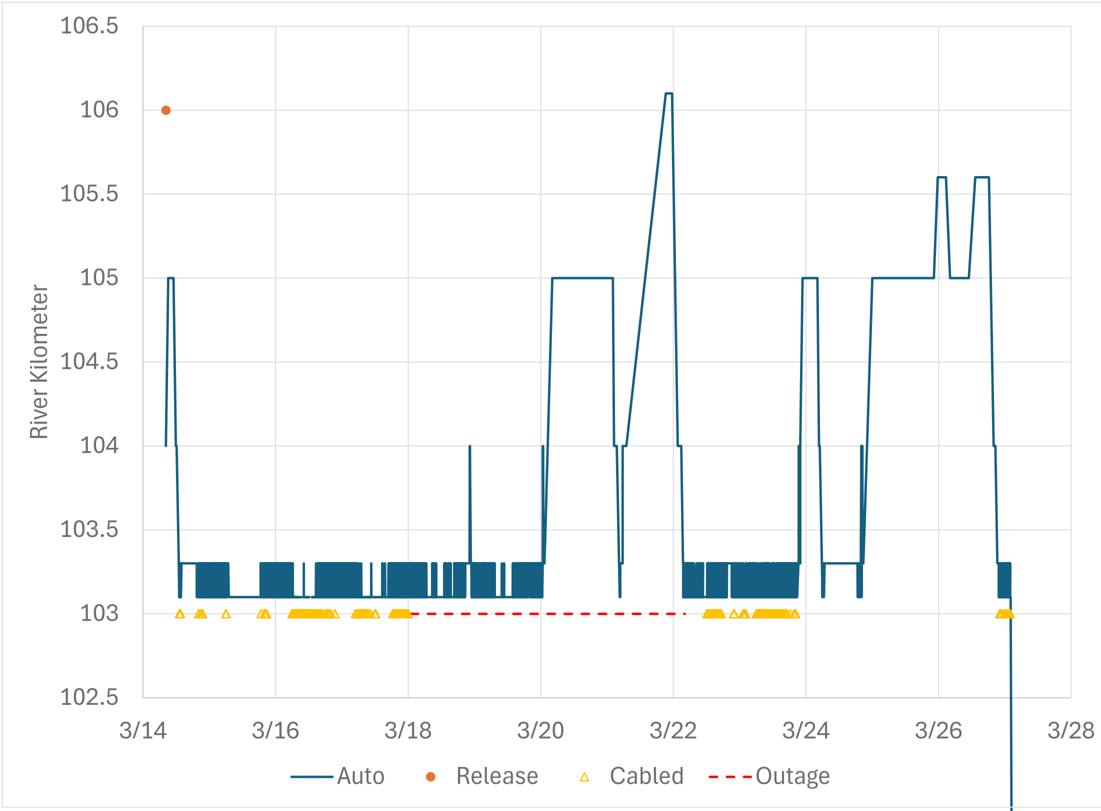


Figure 3-13. River kilometer position through time in the Howard A. Hanson Dam (HAHD) Reservoir for a single fish (G72160487) that passed HAHD.

3.6.3 Factors Influencing Timing of Fish Passing the Dam

The timing of fish passing HAHD may have been influenced by factors such as fish maturity, the number of fish near the dam, dam operations, or environmental conditions within the reservoir. Important parameters of a reservoir include the elevation of the forebay, flows in and out, and water temperature. In general, fish activity is strongly influenced by temperature, but the intermittent periods of fish passage in Figure 3-14 do not appear to align with variation in temperature. The lack of daytime passage in the latter half of the season coincides with higher temperatures during that time, but more information would be needed to determine whether a causal relationship exists.

Flow through the 48-inch bypass pipe occurred beginning in late April and continued through most of May before beginning again in early- to mid-June through the end of the tracking period (Figure 3-15). These periods included some fish passing downstream, but the peaks in timing were not clearly correlated with the operation of the bypass.

The timing of major peaks in fish passage line up with peaks in flow out of HAHD (Figure 3-16). This reflects the fact that fish exit the reservoir through the outlets passing water downstream. Forebay elevation rises throughout the study period, providing another potential causal factor for lack of daytime passage in the latter portion of the study period.

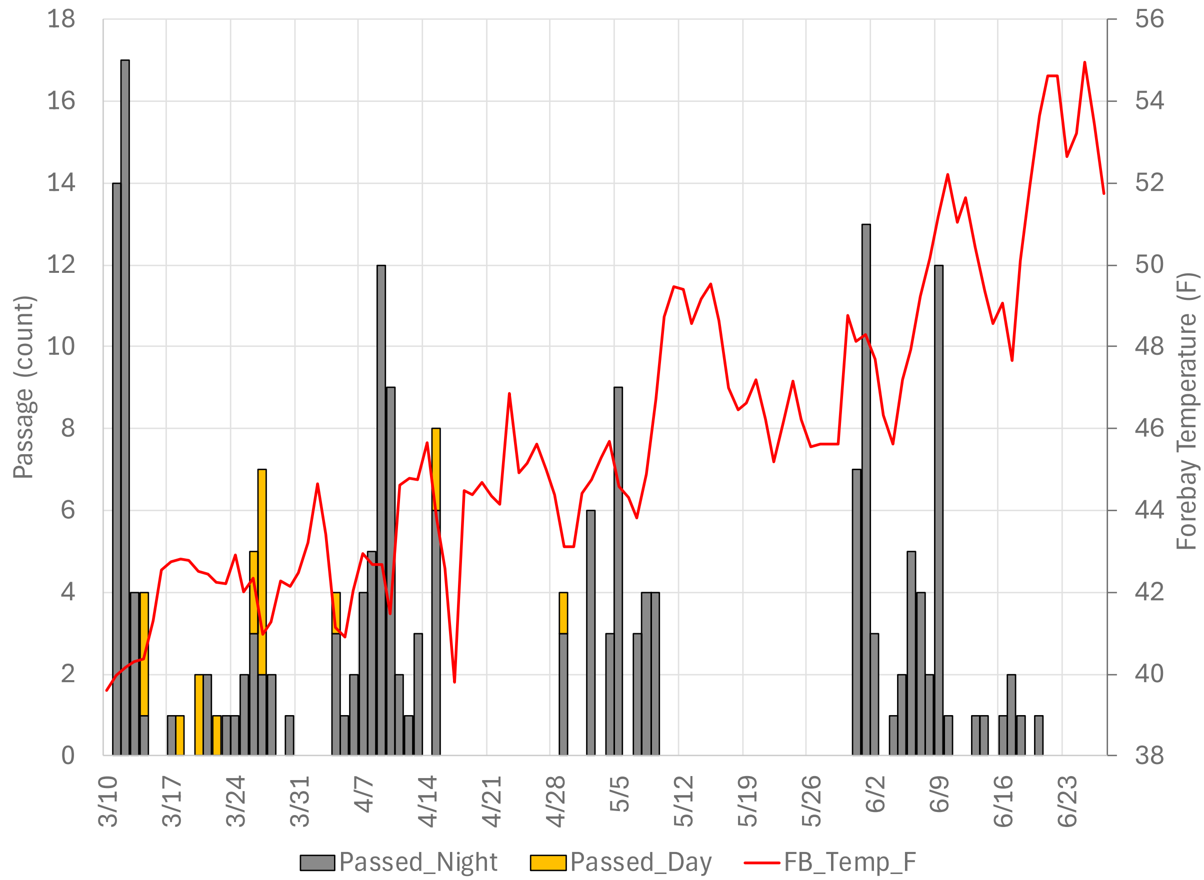


Figure 3-14. Acoustic tagged fish passing downstream of Howard A. Hanson Dam correlated with forebay temperature.

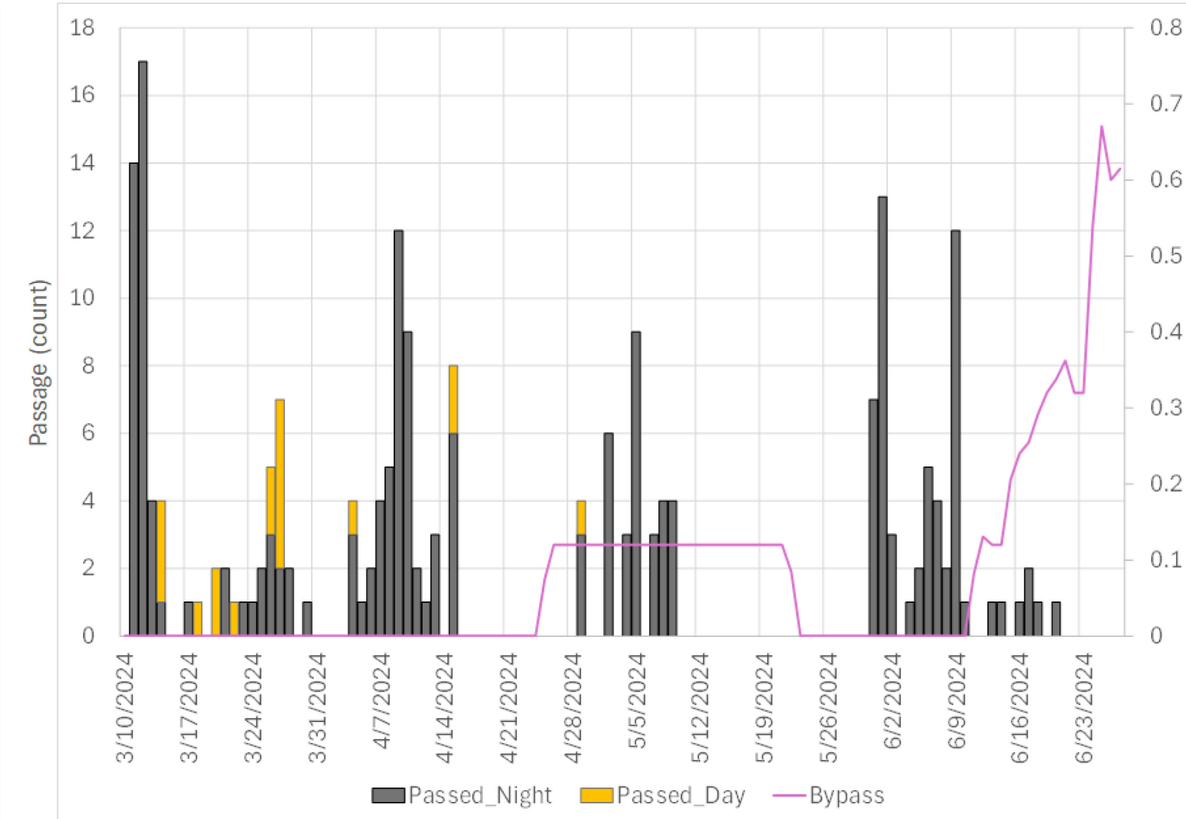


Figure 3-15. Acoustic tagged fish passing downstream of Howard A. Hanson Dam correlated with bypass outflow.

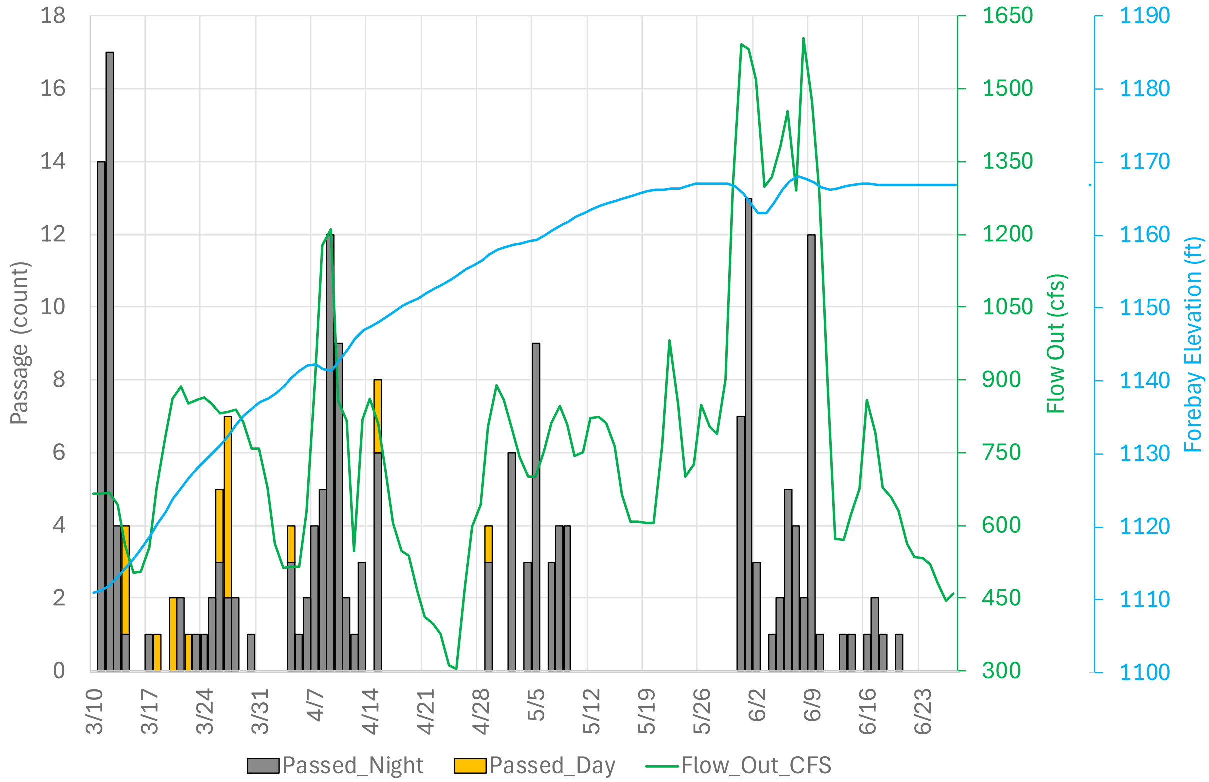


Figure 3-16. Acoustic tagged fish passing downstream of Howard A. Hanson Dam, correlated with forebay elevation (feet) and flow out (cfs).

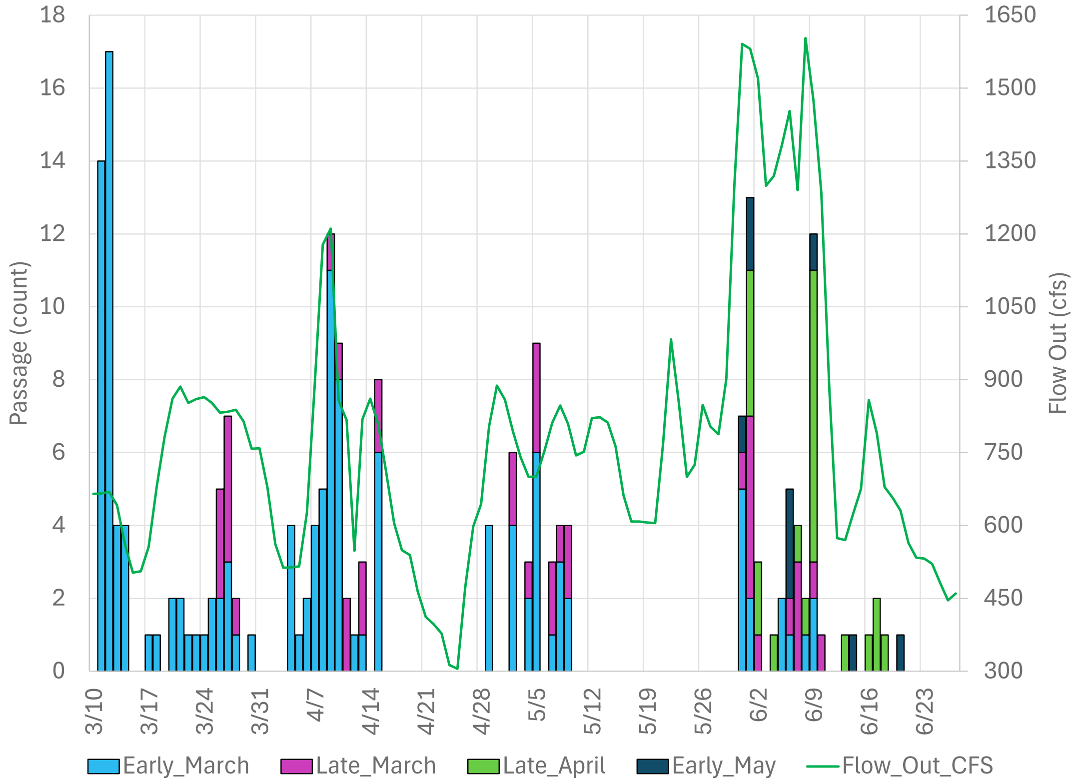


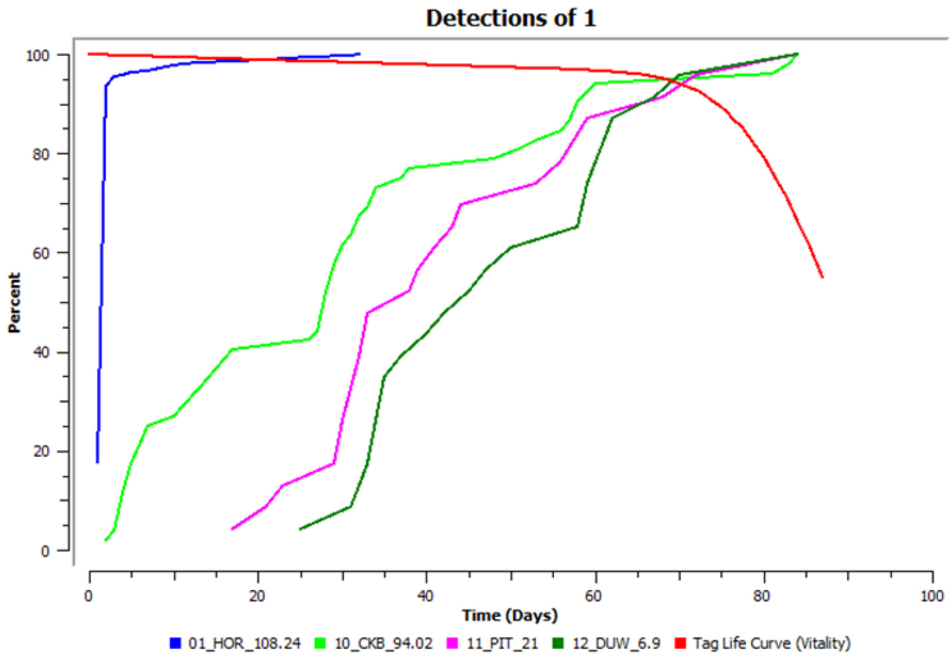
Figure 3-17. Acoustic tagged fish passing downstream of Howard A. Hanson Dam correlated with flow out (cfs).

3.7 Survival

A total of 1,155 tagged coho salmon released at the HOR and UHOR release sites were detected at the HOR array and formed the virtual release group for estimating survival to HAHD (no passage required). This group of fish had an estimated survival probability of 0.9477 (SE = 0.0120) from the HOR array to the HAHD array (no passage required), which had a detection probability of 0.9903 (SE = 0.0097).

Because autonomous arrays were pulled from the water in late June, fish with actively transmitting tags remained in the study area at the end of the study. Based on the results of the tag life test (Figure 3-1), only the fish released in early March were monitored throughout the life of their tags. A small number of fish were still passing HAHD in mid-June and being detected downstream of HAHD into early July at the DUW array, which remained in the river longer than other arrays. All detections downstream of HAHD that occurred after 11 June were from fish that were released in April and May. Therefore, overall project survival from the HOR array to the CKB array was only estimated for the two groups of fish released in March since these fish appeared to have sufficient time to migrate through the study area before the receivers were removed and the study period ended.

A total of 303 fish from the first HOR release (March 10–14) and 331 fish from the second HOR release (March 22–26) were detected at the HOR array. These fish formed virtual release groups for estimating overall project (HOR to CKB) survival. Fish from the first HOR release had an estimated survival probability of 0.1831 (SE = 0.0230) from the HOR array to the CKB array, which had a detection probability of 0.9655 (SE = 0.0339) for this release. Fish from the second HOR release had an estimated survival probability of 0.0792 (SE = 0.0181) from the HOR array to the CKB array, which had a detection probability of 0.8000 (SE = 0.1265) for this release. For both releases combined, survival probability was estimated to be 0.1280 (SE = 0.0142) with a detection probability of 0.9227 (SE = 0.0429). Fish from these releases that were detected downstream of HAHD were detected before estimated tag life dropped below 70% (Figure 3-18). However, it should be noted that estimates of overall project survival represent the joint probability of tagged fish surviving *and* migrating through the study area within the life of the tag and before the end of the study period (receivers were removed). It is possible that some fish continued to migrate through the study area after their tag stopped transmitting and/or after receivers were removed. In addition, dead-tagged fish were only released from HAHD through May 12, 2024. Although no dead-released fish were detected downstream of TPU, it is possible that dead-tagged fish drifted downstream as far as the CKB array during the period of high discharge in early June. If dead-tagged fish were detected at CKB, the overall project survival estimates presented here would be biased high.



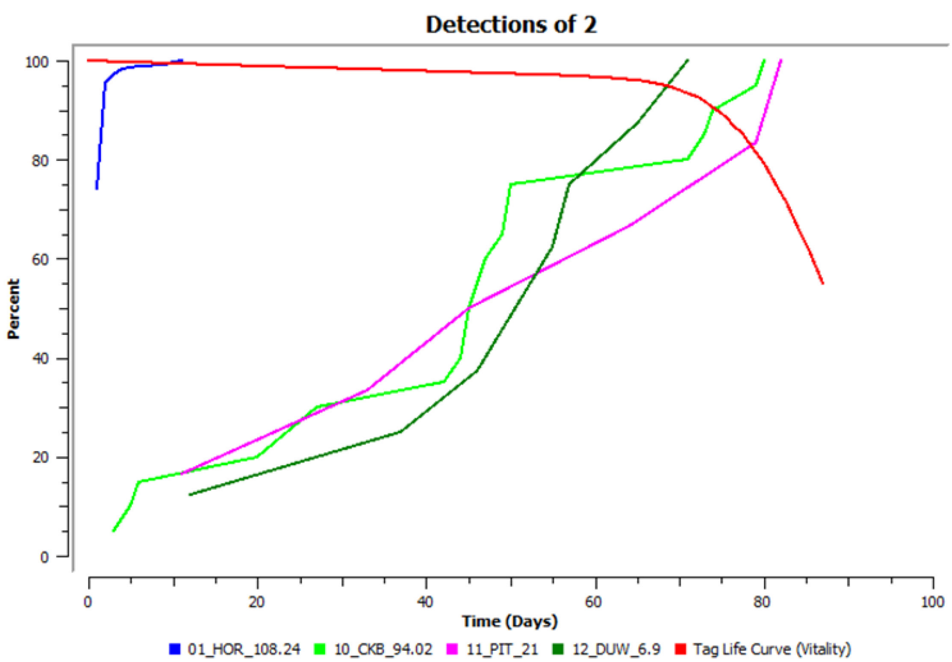
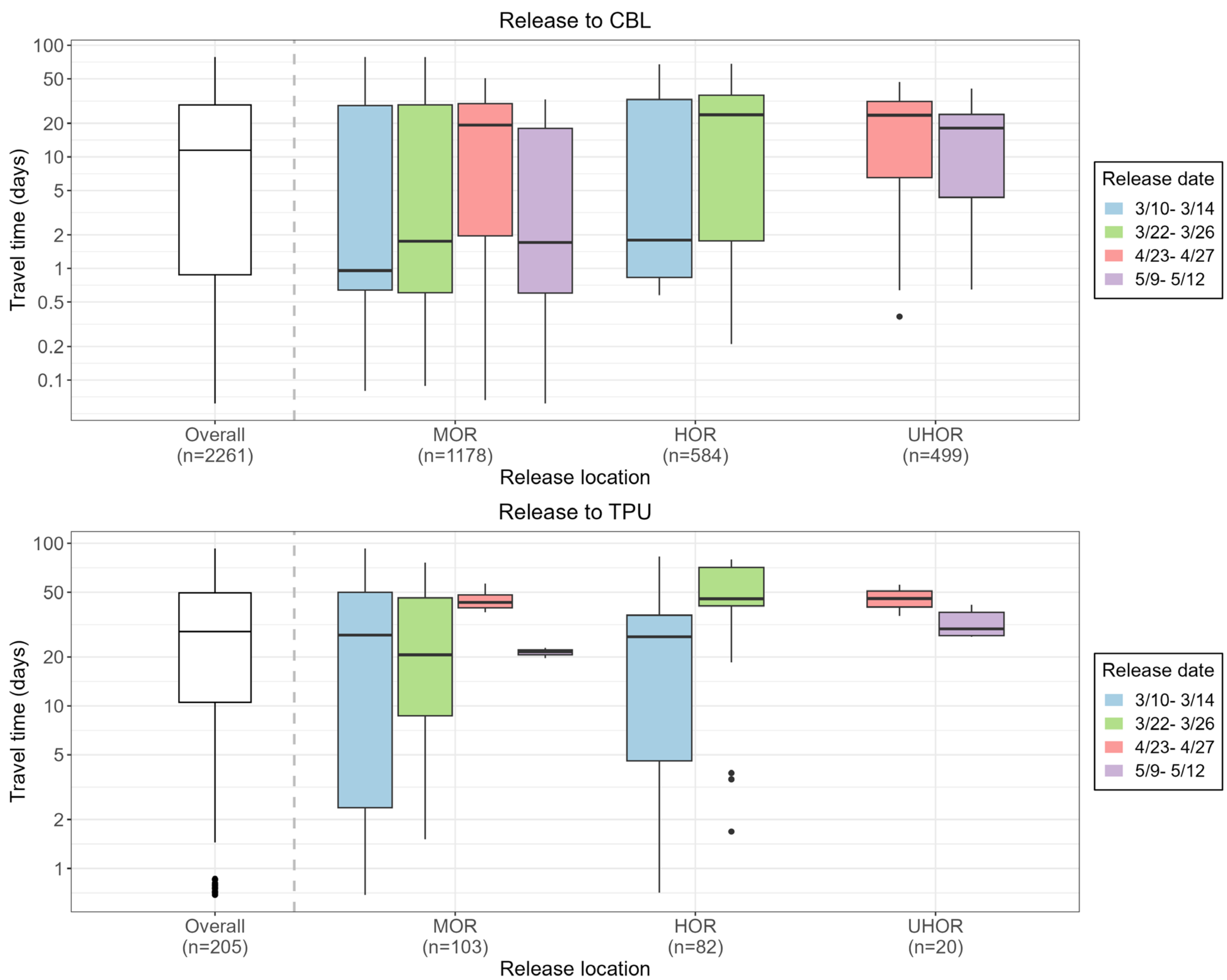


Figure 3-18. Cumulative percent of fish passing the head of reservoir (HOR; blue), Cumberland Kanasket Bridge (CKB; light green), PIT barge (PIT; pink), and Duwamish River (DUW; dark green) arrays compared to the estimated tag life survival (red) for fish from release group 1 (Mar 10–14; top) and release group 2 (Mar 22–26; bottom).

3.8 Travel Times

From release to first detection on the cabled array (CBL), tagged coho salmon had a median travel time of 11.5 d (25th percentile = 0.9 d; 75th percentile = 29.2 d), regardless of release date or location (Figure 3-19). Fish released at the MOR and HOR in early March, when forebay elevation was lower, generally moved through the reservoir more quickly than those released later in the season. However, a relatively high degree of variability was observed in release to CBL travel times regardless of release date or location. From release to TPU and CKB, fish had overall median travel times of 28.6 d and 27.7 d, respectively, with March released fish generally having the shortest travel times (Figure 3-19). From release to the PIT array, fish had a median travel time of 40.6 d (25th percentile = 29.13 d; 75th percentile = 55.0 d) (Figure 3-19). From release to DUW, fish had an overall median travel time of 51.9 d (25th percentile = 38.6 d; 75th percentile = 62.1 d); Figure 3-19). The median travel time from release for reach release time group and each reservoir release location for all fish released alive in the reservoir is tabulated in Table 3-3. The rate of travel between fish arriving at the upstream face of the dam (CBL) and the first downstream array (TPU) is contrasted in Table 3-4. Because not all fish traveled downstream, the travel rates help illustrate whether fish that would pass the dam are moving through the reservoir at a different rate. Finally, the duration (i.e., number of hits) at each array within the forebay region is shown in Figure 3-20. Additional travel times from release to the first detection at the near forebay array (NFB) are outlined in Appendix B.



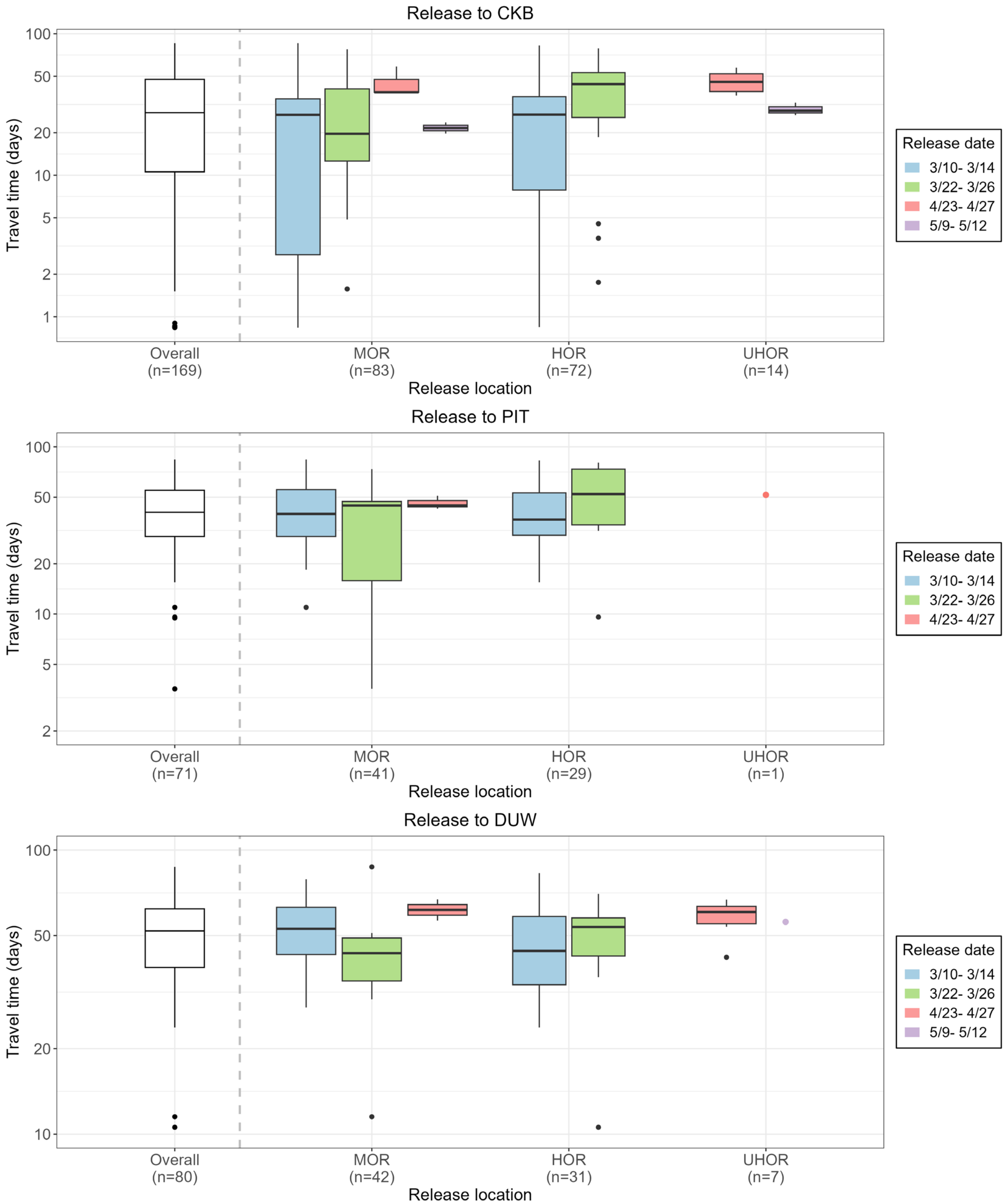


Figure 3-19. Travel times from release to first detection at downstream arrays overall and by release date and location. Box plots show the median (black line inside the box), 75th and 25th percentiles (top and bottom of the box, respectively), and the whiskers represent the 95th and 5th percentiles. Outliers are black dots.

Table 3-3. Median times from release to array location by release date and release location. The *n* value includes all fish released alive on any date at any location in the reservoir that were detected at that location.

				3/10-3/14		3/22-3/26		4/23-4/27		5/9-5/12	
Array	**RKM**	***n***	**Overall**	**MOR**	**HOR**	**MOR**	**HOR**	**UHOR**	**MOR**	**UHOR**	**MOR**
CBL	105.28	2261	11.4	0.9	1.8	1.7	23.8	23.6	19.3	18.1	1.7
TPU	99.59	205	28.6	27.2	26.6	20.6	45.5	45.7	43.3	29.8	21.5
TBP	97.37	16	1.7	1.5	2.96		3.9				
CKB	94.02	169	27.7	26.7	26.8	19.7	44.1	45.7	38.6	28.6	21.7
PIT	21	71	40.6	39.7	36.7	44.6	53.1	51.6	44.6		
DUW	6.9	80	51.9	52.8	44.2	43.4	53.6	60.5	61.8	55.9	

Table 3-4. The travel rate to the array nearest the dam and to the first downstream array. The *n* value includes all fish released alive on any date at any location in the reservoir that were detected at that location.

				3/10–3/14		3/22–3/26		4/23–4/27		5/9–5/12	
Array	**RKM**	***n***	**Overall**	**MOR**	**HOR**	**MOR**	**HOR**	**UHOR**	**MOR**	**UHOR**	**MOR**
CBL	105.28	2261	0.26	0.79	1.55	0.42	0.11	0.2	0.04	0.26	0.43
TPU	99.59	205	0.25	0.24	0.32	0.31	0.18	0.23	0.15	0.35	0.3

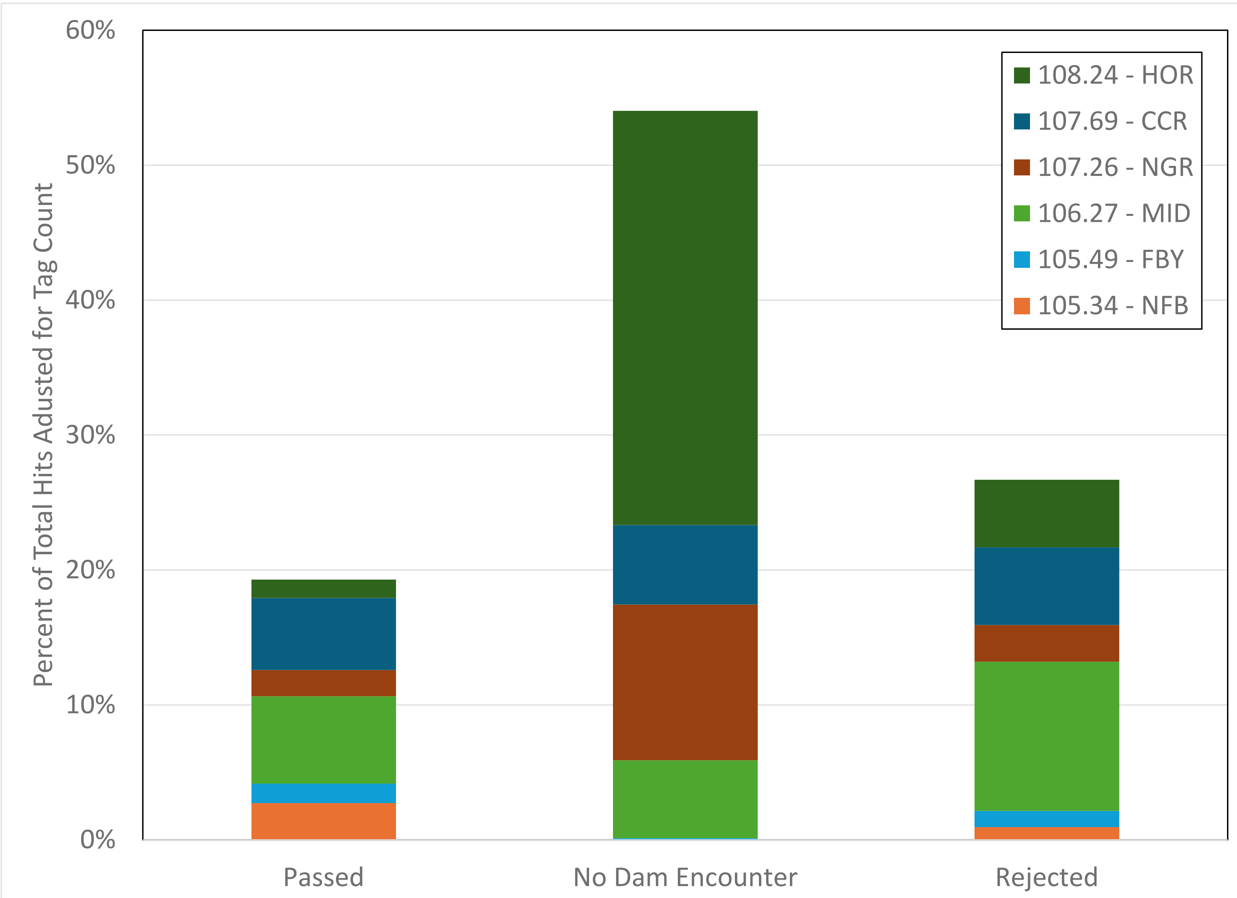


Figure 3-20. Relative number of hits at each array for fish prior to first arrival at the dam (cabled array). Total number of hits was adjusted by dividing each value by the total number of tags in each category.

4.0 Discussion

This study was the first acoustic telemetry fish passage and survival study ever conducted at HAHD. There were two main objectives: (1) evaluate existing HAHD operations to understand baseline fish passage and survival under current operations and through the tunnel of the dam and if they meet the BiOp requirements for fish passage (75% overall reservoir to downstream survival, 95% collection, and 98% passage survival; NOAA 2019), and (2) evaluate fish passage and survival under a combination of reservoir elevation and discharge during spring refill, to inform the following questions: (a) at what depth and discharge does the reservoir stop passing 80% of the fish? (b) at what depth and discharge does the 19-ft tunnel stop passing 95% of the fish within the forebay? (c) at what depth/discharge does 2% mortality occur associated with existing project passage?

For objective 1, results indicated that existing HAHD operations do not meet the BiOp requirements for fish passage. The majority of the tagged fish did not pass HAHD, particularly as the reservoir elevation increased. For those fish that were detected downstream of HAHD, a greater number of fish passed earlier in the season, when the reservoir elevation was lower. During the first March releases, the depth to the tunnel entrance was 52 feet (elevation: 1,099 ft). By the time the final fish were released in May, the depth increased to 96 feet (elevation: 1,143 ft). Fish in this study resided at a depth of 5–15 m (16–50 feet; median values), which may have been why more fish passed HAHD during the March releases. This is not an uncommon finding; salmon naturally swim in the upper portion of the water column and do not typically sound (dive) to find a route of passage to move downstream. As the reservoir elevation rose, the depth to find the tunnel entrance increased, minimizing the likelihood of fish finding it and passing the dam.

Results related to fish depth and project passage from the current study generally aligned with the findings from previous studies. Dilley (1994) observed that juvenile Chinook salmon showed a strong preference for the upper water column (i.e., within the first 15 m), with 80–97% of fish occupying this depth range from April through July. Other studies (Dilley and Wunderlich 1992, 1993) found that both subyearling Chinook salmon and yearling coho salmon predominantly passed the dam between late March and early May, prior to refill operations, when reservoir elevations were below 1,080 ft. These studies also documented smaller, secondary pulses of subyearling Chinook and yearling coho passage in June at higher reservoir elevations (> 1,130 ft), consistent with observations from the current study. These previous studies did, however, observe notable differences in the timing of yearling Chinook passage between their 1992 and 1993 studies. In 1992, peak passage for yearling Chinook occurred in late April at reservoir elevations below 1,080 ft, whereas in 1993, peak passage occurred in June when the reservoir elevation exceeded 1,140 ft (Dilley and Wunderlich 1992, 1993). This may have been due to interannual environmental or fish differences. Collectively, previous findings and findings from the current study highlight the challenges of juvenile salmon passage under existing dam operations at HAHD, particularly during summer months when elevated reservoir levels increase the vertical distance between the upper water column–where fish are concentrated–and the tunnel entrance.

For fish passage survival, overall reservoir to downstream survival could only be estimated for the two groups of March-released fish. Survival was estimated as the joint probability of survival and migration, and it was poor (12.8%; SE = 1.42%). This lack of migration downstream past the dam and poor survival tied into objective 2. The fish passage rate downstream of HAHD was low regardless of the depth and discharge during spring refill. As the reservoir elevation increased, fish passage continued to decrease. However, the increased discharge appeared to promote fish passage even as the reservoir elevation rose. For those fish that were detected downstream of

HAHD, their survival was poor and greater than 2% mortality occurred for the two groups of March-released fish. This was when the reservoir elevation was lowest and promoted the highest amount of fish being detected downstream of HAHD. However, because of the inability to perform 3-D tracking it was unknown how many fish passed HAHD but died before reaching the arrays downstream of HAHD (i.e., immediate dam passage survival).

There were a few notable takeaways from this study that may be useful to inform baseline conditions and the design of the new FPF at HAHD. Of the fish that were detected downstream of HAHD, most were from the groups of fish released earlier in the spring (March). This may suggest that the lower reservoir elevations are a benefit to downstream-migrating salmon. Interestingly, few fish continued to be detected downstream of HAHD even when the reservoir was at full pool (June); these downstream detections were correlated with increased flow events. This indicated that regardless of reservoir elevation, fish were more likely to pass when there was an increase in flow out of the reservoir. Taken together, the design of the FPF for HAHD should consider having entrances at multiple depths, to allow fish the opportunity to pass the dam even as reservoir elevation rises throughout the season. Increasing flow out of the reservoir to promote fish passage may not be feasible at HAHD, as water must be stored to provide drinking water to the City of Tacoma; however, design considerations for the ability to increase flow out should be discussed.

For the fish that were detected downstream of HAHD, they were last detected at night on the forebay cabled array. Their true time of passage, and if they passed at night, was unknown as the fish were unable to be 3-D tracked through the trash rack to their ultimate passage fate and time of passage. Based on the depth distributions by diel period, fish tended to reside lower in the water column during the day, and higher in the water column at night. Being lower in the water column during the day may have been representative of a holding pattern to avoid visual exposure to predators. Fish residing higher in the water column at night may have been representative of migration and again to avoid predators, as visual exposure to predators was less apparent. Based on the 3-D tracking, it is likely that fish moved through the trash rack at night when the cabled array could detect them, which provided the last detection. Then, when the fish tended to be at deeper depths (lower in the water column) during the day, it may have allowed them to find the tunnel entrance and pass downstream. These fish would have been close to the tunnel entrance (~50 ft in depth, with the tunnel entrance at 52 ft) early in the study period when the reservoir elevation was lower (March). When the reservoir elevation was high, fish remained at ~50 ft in depth but the tunnel entrance depth increased to 96 ft. During periods of high flows and high reservoir elevations, there may have been an increased attraction flow into the tunnel or fish may have been able to be entrained into the tunnel. Having entrances at multiple depths may benefit fish passage so it could be irrespective of diel depth patterns or where fish reside in the water column.

Although several unexpected challenges affected the outcomes of this study, the results still provided valuable insights regarding baseline fish passage and survival conditions at HAHD. Results highlighted the need for design of the FPF at HAHD because fish passage and survival under the current conditions were poor. Results also identified reservoir conditions that seemed to have the greatest effect on fish passage. These included the elevation of the forebay and flows into and out of the reservoir. As such, these variables should be taken into consideration for the new design updates to HAHD.

5.0 Management Applications

Although several challenges were encountered, the Downstream Passage and Survival (Acoustic Telemetry) task from the Evaluation of Howard A. Hanson Dam Juvenile Fish Passage and Survival study provided critical insights regarding baseline conditions for fish passage and survival, and for informing the design of future studies and an effective juvenile fish passage facility at HAHD. A key finding was that as the reservoir filled through the spring, the depth to the outflow tunnel increased, and results suggested fewer fish were detected downstream of HAHD as the study season continued. However, the receivers were removed before the tag life of the April and May released fish; therefore, it is possible fish still could have passed at the high reservoir elevations. Regardless, installing bypass pipes with inputs at various elevations may improve fish passage during the spring season as the reservoir fills. This approach could ensure that fish can pass through the dam at progressively higher elevation points as the reservoir elevation rises.

Future studies may consider modifications to the study design to better understand fish behavior with the current HAHD configuration. One potential consideration is the timing of fish releases, specifically releasing fish earlier in the season (e.g., February) when the reservoir elevation is sufficiently low. The lower elevation may allow fish to pass more readily through the outflow tunnel and may provide entraining flows that aid in fish movement downstream.

Additionally, future studies may also consider evaluating different receiver configurations to account for the possibility of fish milling in the forebay during high pool conditions, which may provide clearer insights into fish behavior when the reservoir is full. This could involve determining whether fish aggregate in specific areas or maintain certain depth preferences during high pool. If study fish are seen congregating in the forebay and near forebay and not passing downstream, delaying future tagging and release sessions may be necessary, as to not overwhelm the 3-D cabled system and autonomous receivers. Such analyses can offer valuable insights into fish passage strategies, particularly those influenced by changes in reservoir depth.

Finally, future studies should also continue dead tagged fish releases through the end of tag life of the last live fish release. This will ensure the assumptions of the ViRDCt model for immediate dam passage survival estimation can be met. It is also recommended that the autonomous and cabled receivers monitor for detection through the end of tag life of the last release. For this study, keeping the autonomous and cabled receivers in the water for the duration of the tag life of the tags may have allowed for deciphering which fish passed, and which fish did not, to provide immediate dam passage survival. However, for the purposes of this study, removing the equipment outweighed the benefits of understanding the fate of the remaining fish. There were 411 fish with undetermined passage fates and 1,632 fish were tracked and confirmed to have not passed the dam because they moved away from the CBL array. Even if the receivers remained in the water and all 411 passed, study results may suggest that the fish passage remains low if 1,632 fish did not pass.

Although several challenges were encountered during this acoustic telemetry study, it provided valuable information to improve future study designs of fish passage evaluations at HAHD. A few lessons were learned from the 2024 study. The first lesson learned was something that PNNL has not dealt with before. Most of the acoustic transmitters used for this study had a version of firmware (version 7) that when placed near other tags would turn off. This version 7 firmware caused numerous issues between tag activation, surgical implantation, fish releases, and ultimately fish movement and survival. PNNL was able to successfully track tag failure between tag activation and surgical implantation using our standard protocols. We were also able to track tag failure prior to fish releases using the acoustic telemetry bucket scanning software. However, once fish were released into the reservoir it was not possible to quantify if tags had been deactivated or the final fate of the fish with a tag that deactivated after release. It is possible that due to the schooling nature of juvenile coho salmon and the volume of fish in the forebay of HAHD tags deactivated themselves in fish after release. This firmware 7 issue was brought to the attention of the manufacturer, who was unaware of the issues with that firmware. Upon discovering the issue, new firmware was created during the spring of 2024. The firmware version 8 was more stable and worked as intended (i.e., tags remained active after activation). Unfortunately, we were not able to replicate the early spring reservoir conditions of fish tagged and released with version 7 software tags during that time. This created some uncertainty in the analyses; 88% of the tags used for this study were version 7 firmware and tag performance may not have been as reliable as was anticipated to be, once fish were in the water (i.e., the potential for tags to deactivate themselves). Previously, tag life testing could be performed in parallel to the field studies; however, in future studies it will be imperative to start tag life testing prior to any field tagging (using tags for the tag life study that are manufactured at the same time as the tags used in the field), to make sure tags are performing as intended and address any potential issues that arise prior to the beginning of the field studies.

The second lesson learned was caused by the lack of fish migration and passage at HAHD. During the first two tagging events, ~1,200 fish were released into the HAHD Reservoir. Those fish migrated downstream into the forebay of HAHD and remained there. This caused extremely large quantities of data to be collected on the cabled system on the face of HAHD and on the autonomous receivers in the near forebay and forebay. The cabled system was collecting ~500 GB of data a day over the course of several weeks. At times, the processing could not keep up and the system would crash, requiring a reboot. Data drives were switched every 3–4 days, and the data required extensive post-processing as onboard decoding software was only able to decode 25% of the incoming data.

The lack of fish migration and passage also affected the autonomous receivers, and several key issues were identified that led to data gaps throughout the spring. The first issue was the 32-bit system in the receivers is only able to store ~4 GB worth of data on the data card before shutting down. This issue was brought up to the manufacturer to see if new software would allow for either multiple files to be created or a way to increase file size in the system. In future studies where a lack of fish moment is detected, the frequency of data downloads should be increased to ensure data cards in the receivers do not fill up. The large volume of data being collected also caused time jumps in the data. This issue was also brought up with the data card manufacturer. At present there is no way to correct these time jumps or know the exact extent of data gaps caused by the time jumps.

Finally, the large volume of data that was collected from the lack of fish migration taxed the power consumption of the autonomous receivers, causing batteries to fail much sooner than the manufacturer's estimation of 100 days. Future studies will need to pay close attention to battery voltage on receivers and set up a schedule to replace batteries at an increased timeline to prevent batteries from dying while being deployed and limit data gaps.

Despite these challenges, this baseline study confirms the need for the design of the FPF at HAHD to improve downstream fish passage and survival. Future studies will also benefit from the lessons learned in this study.

6.0 References

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Appendix A – Forebay Horizontal and Vertical Fish Distributions

Appendix A highlights fish vertical and horizontal distributions within the HAHD forebay. Two examples are provided for each of the four months of the study (March, April, May, and June).

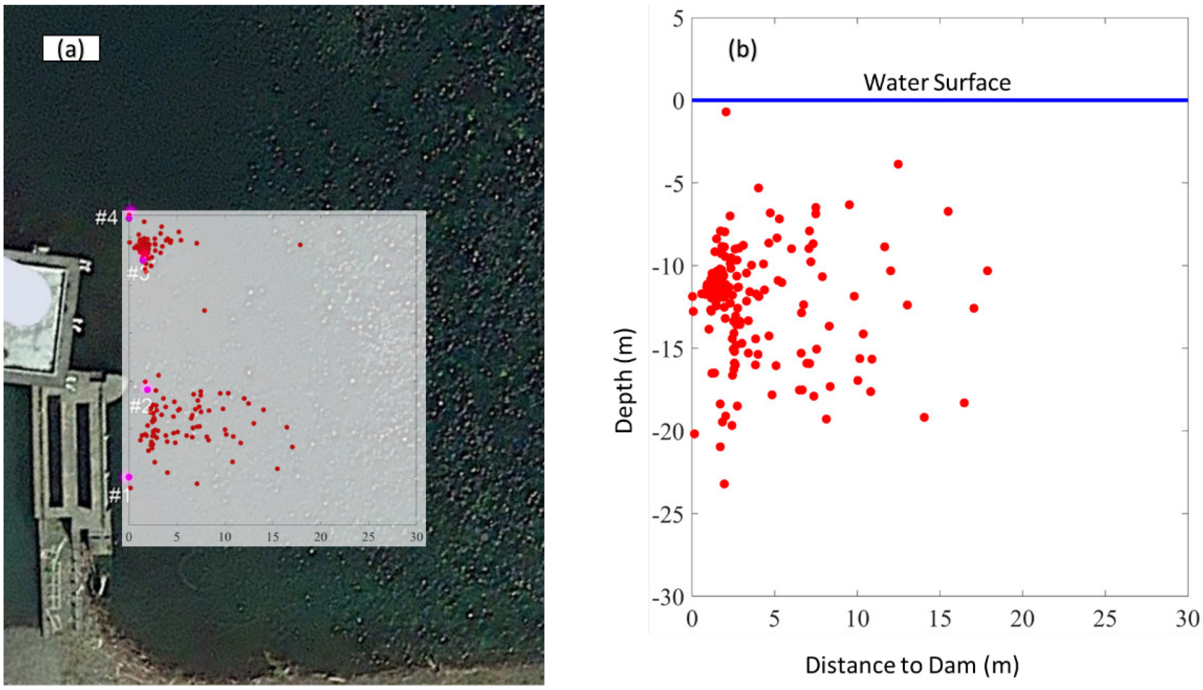

Figure 6-1. Detection of schools of fish (red dots) in the forebay on 3/30/2024 at 19:01:20. (a) Top-down view showing the spatial distribution of fish within the forebay. (b) Side view illustrating the vertical distribution of fish relative to the water surface (indicated by the blue line at 0 m depth).

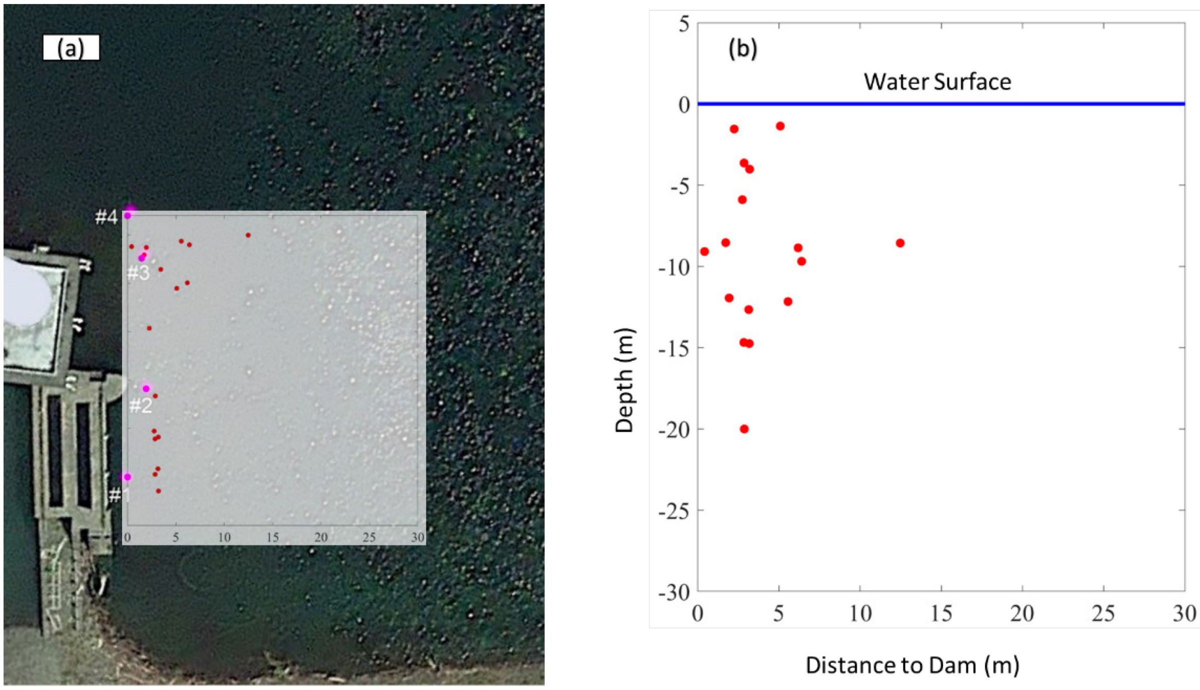

Figure 6-2. Detection of schools of fish (red dots) in the forebay on 3/30/2024 at 23:01:20. (a) Top-down view showing the spatial distribution of fish within the forebay. (b) Side view illustrating the vertical distribution of fish relative to the water surface (indicated by the blue line at 0 m depth).

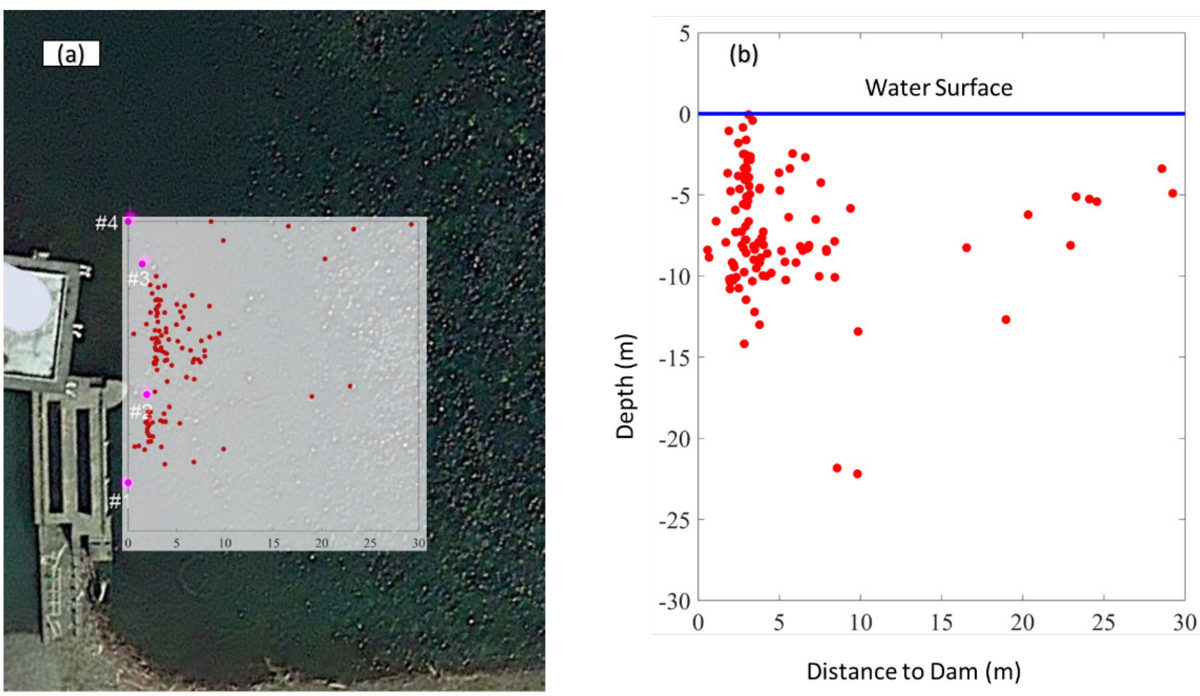

Figure 6-3. Detection of schools of fish (red dots) in the forebay on 4/8/2024 at 19:31:20. (a) Top-down view showing the spatial distribution of fish within the forebay. (b) Side view illustrating the vertical distribution of fish relative to the water surface (indicated by the blue line at 0 m depth).

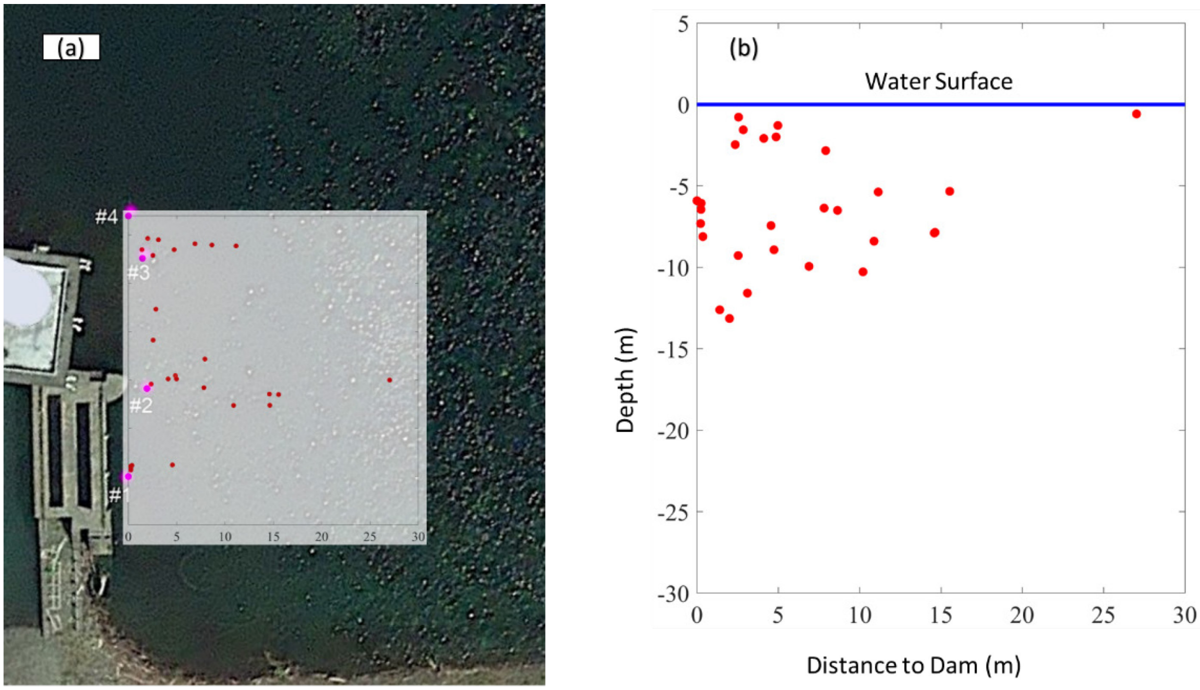

Figure 6-4. Detection of schools of fish (red dots) in the forebay on 4/8/2024 at 23:31:21. (a) Top-down view showing the spatial distribution of fish within the forebay. (b) Side view illustrating the vertical distribution of fish relative to the water surface (indicated by the blue line at 0 m depth).

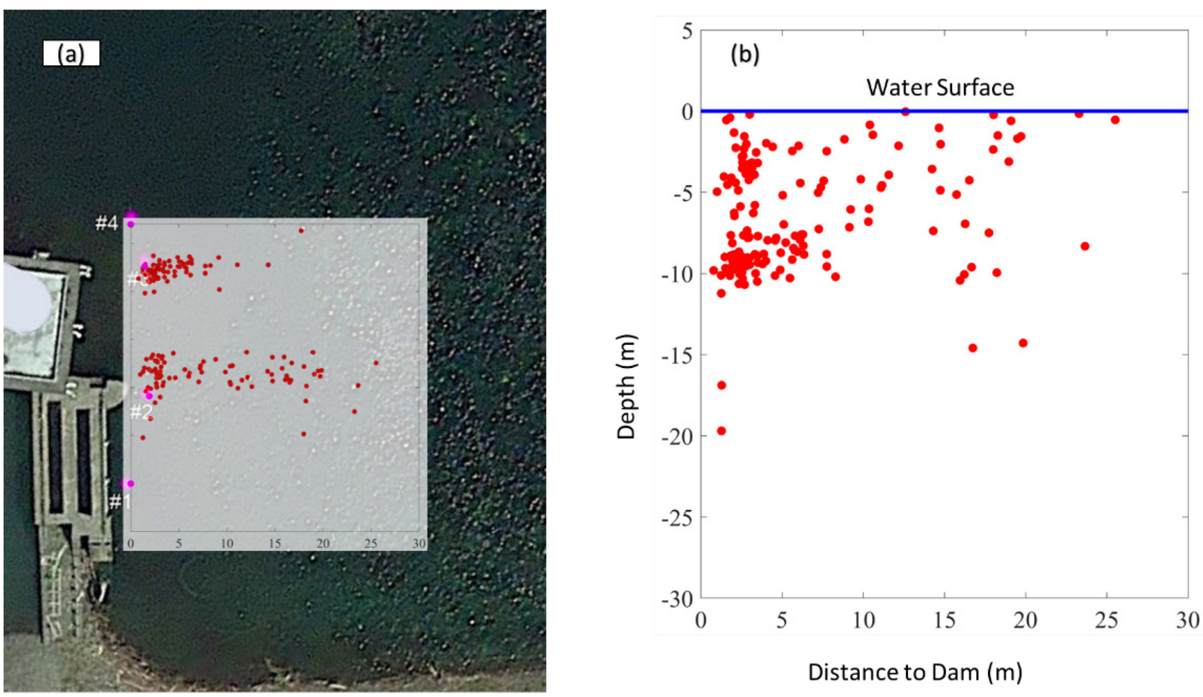

Figure 6-5. Detection of schools of fish (red dots) in the forebay on 5/6/2024 at 05:01:20. (a) Top-down view showing the spatial distribution of fish within the forebay. (b) Side view illustrating the vertical distribution of fish relative to the water surface (indicated by the blue line at 0 m depth).

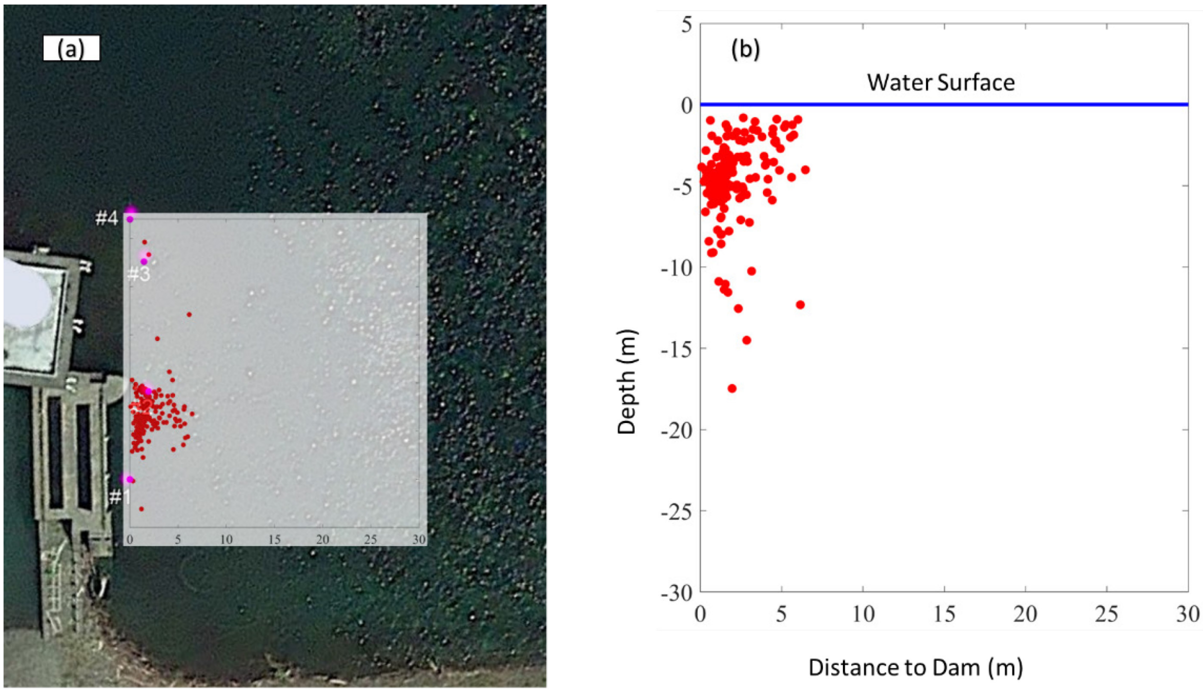

Figure 6-6. Detection of schools of fish (red dots) in the forebay on 5/10/2024 at 15:31:33. (a) Top-down view showing the spatial distribution of fish within the forebay. (b) Side view illustrating the vertical distribution of fish relative to the water surface (indicated by the blue line at 0 m depth).

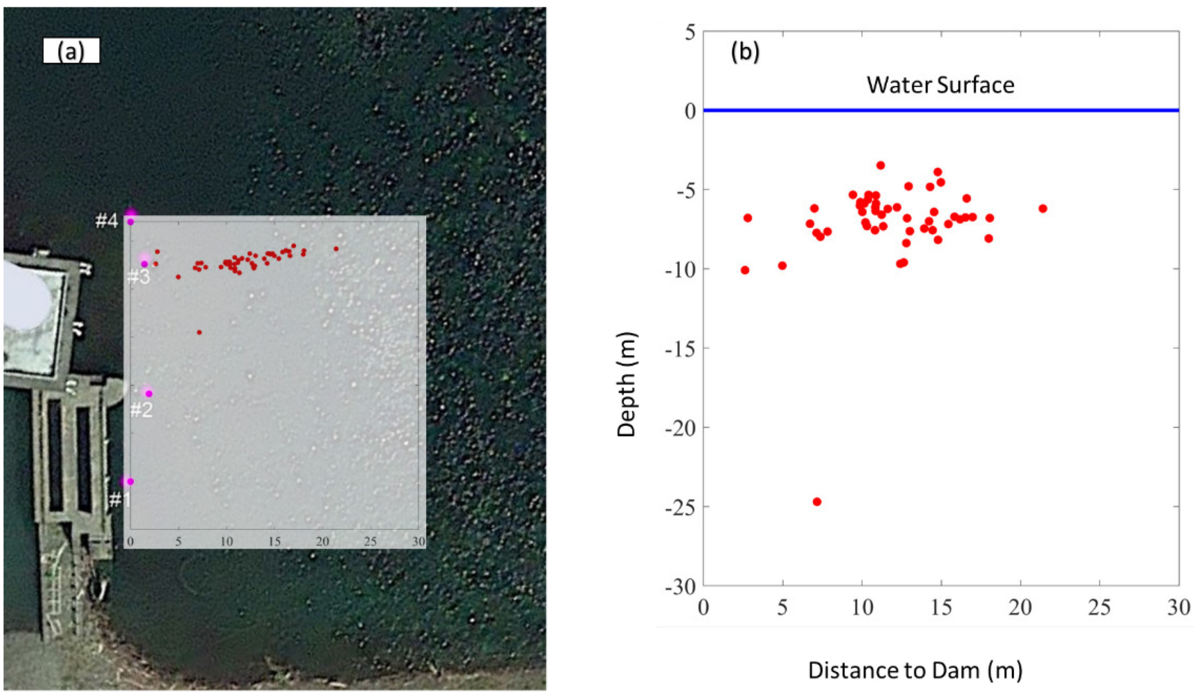

Figure 6-7. Detection of schools of fish (red dots) in the forebay on 6/9/2024 at 12:31:20. (a) Top-down view showing the spatial distribution of fish within the forebay. (b) Side view illustrating the vertical distribution of fish relative to the water surface (indicated by the blue line at 0 m depth).

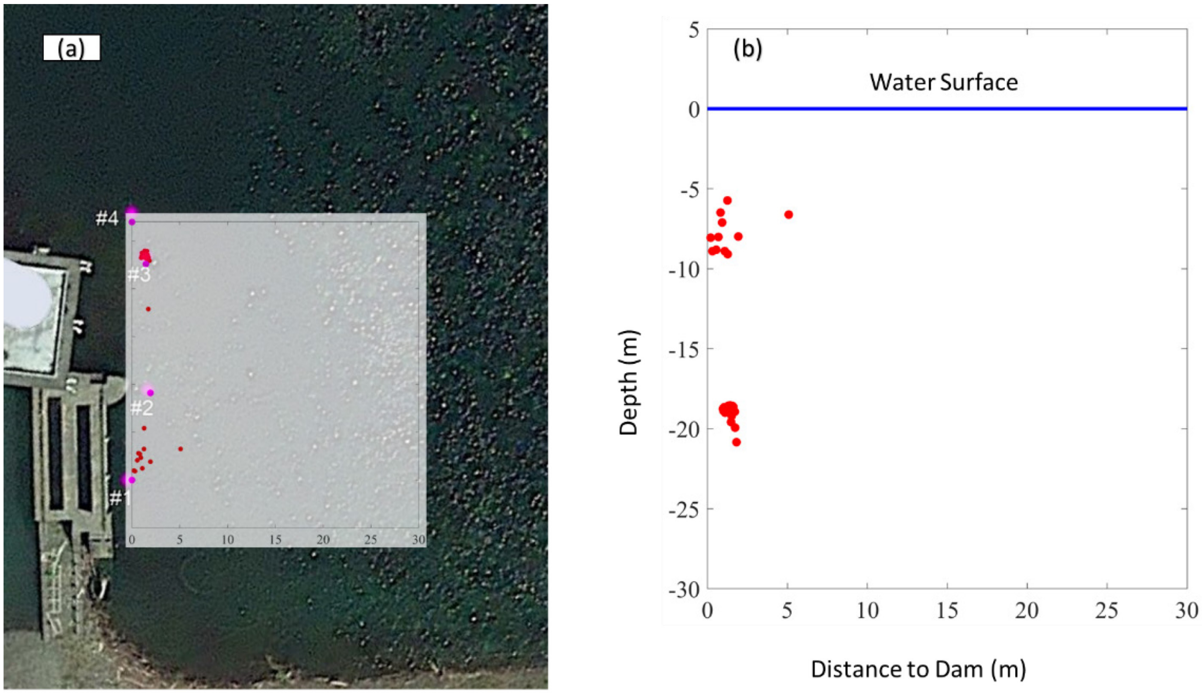

Figure 6-8. Detection of schools of fish (red dots) in the forebay on 6/17/2024 at 05:31:21. (a) Top-down view showing the spatial distribution of fish within the forebay. (b) Side view illustrating the vertical distribution of fish relative to the water surface (indicated by the blue line at 0 m depth).

Appendix B – Travel Times from Release to the Near Forebay

Appendix B provides travel times in days for acoustic-tagged fish from their release locations at the mid of reservoir (MOR), head of reservoir (HOR), or upper head of reservoir (UHOR) to the dam face array (near forebay array; NFB) at HAHD.

Table 6-1.Travel times from release locations to the near forebay array at the dam face of HAHD.

Release Location	Release Rkm	Array	Rkm	Release Time	Tag Count	5th Percentile (Days)	25th Percentile (Days)	Median (50th Percentile, Days)	75th Percentile (Days)	95th Percentile (Days)
MOR	106	NFB	105.34	Early March	288	0.001389	0.539583	0.839236	26.481424	50.038646
MOR	106	NFB	105.34	Late March	317	0.007222	0.473611	1.500694	27.533333	42.787777
MOR	106	NFB	105.34	Late April	306	0.050694	1.721528	18.991667	29.825521	35.562500
MOR	106	NFB	105.34	Early May	268	0.028715	0.522917	1.572569	17.733160	25.730451
MOR	**106**	**NFB**	**105.34**	**Combined**	**1179**	**0.025**	**0.544097**	**1.825**	**25.691319**	**39.847153**
HOR	108	NFB	105.34	Early March	284	0.602882	0.733507	1.670139	31.564931	52.250347
HOR	108	NFB	105.34	Late March	297	0.592917	1.626389	23.433333	37.160417	45.524167
HOR	**108**	**NFB**	**105.34**	**Combined**	**581**	**0.602778**	**0.820139**	**3.698611**	**34.697222**	**49.743750**
UHOR	110	NFB	105.34	Late April	274	1.465451	10.295833	23.746875	31.007986	41.294236
UHOR	110	NFB	105.34	Early May	226	0.947569	4.255729	18.003819	23.793750	29.240278
UHOR	**110**	**NFB**	**105.34**	**Combined**	**500**	**1.214097**	**7.030035**	**19.779514**	**28.083854**	**39.667014**

Rkm = river kilometer; NFB = near forebay array.
Release Locations: MOR = mid of reservoir; HOR = head of reservoir; UHOR = upper head of reservoir.
Individual travel times were computed by subtracting the release time from the first detection time at the NFB detection array.
Travel time percentile values were computed using all fish released live at the release point that were detected at the NFB detection array. Travel times are presented in days.

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