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Outmigration Behavior and Survival of Juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) in Response to Deep Drawdown of the Lookout Point Project, Middle Fork Willamette River, Oregon

Open-File Report 2024–1069

U.S. Department of the Interior
U.S. Geological Survey

Cover. Lookout Point Reservoir, October 5, 2023. Photograph by Jake Kelley, U.S. Geological Survey.

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
feet (ft)	0.3048	meter (m)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
acre-foot (acre-ft)	43,559.0	cubic foot (ft^3)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F = (1.8 × °C) + 32.

Datums

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 1929).

Reservoir elevation, as used in this report, refers to distance above the vertical datum.

Supplemental Information

Data used for analysis in the study are publicly available in the U.S. Geological Survey ScienceBase Catalog (Hansen and others, 2024).

Abbreviations

HOR	head of reservoir
LOP	Lookout Point
NMFS	National Marine Fisheries Service
PIT	passive integrated transponder
RO	regulating outlet
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

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By Dalton J. Hance,[1] Tobias J. Kock,[1] Jake R. Kelley,[1] Amy C. Hansen,[1] Russell W. Perry,[1] and Scott D. Fielding[2]

Abstract

An acoustic telemetry study was conducted during August 2023–February 2024 to evaluate outmigration behavior and survival of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) in the Middle Fork Willamette River, Oregon, during an experimental operation that was designed to facilitate downstream passage through two reservoirs and two dams. The experimental operation consisted of lowering the water surface elevation of Lookout Point Reservoir by nearly 100 feet between August and December 2023, and passing water through regulating outlets at Lookout Point Dam. This operation was intended to reduce residence time for juvenile Chinook salmon in Lookout Point Reservoir so that these fish would enter the free-flowing Willamette River as quickly as possible. During our study, acoustic-tagged juvenile Chinook salmon were released weekly during late August to late October to determine how fish responded to the drawdown. Data collected during the study were analyzed using a temporally stratified multistate mark-recapture model. We found that Lookout Point Reservoir became isothermic during the drawdown and water temperature exceeded 18 degrees Celsius during most of September 2023. This appeared to adversely affect juvenile Chinook salmon because the proportion of tagged fish that were subsequently detected in the forebay of Lookout Point Dam following release at the head of Lookout Point Reservoir during August 30–September 29 ranged from 0.01 to 0.05 for weekly release groups. Detections increased to 0.44–0.52 for fish released later in the year when water temperatures decreased. We found that fish size was a significant predictor of survival as fork length was positively related to survival probability in reservoir and free-flowing river reaches of our study area, but negatively related to survival probability for fish passing Lookout Point Dam. We also found that increased regulating outlet flow at Lookout Point Dam resulted in increased survival probability for juvenile Chinook salmon and water temperature was inversely related to survival. Results from this study suggest that the drawdown failed to create conditions that facilitated downstream passage and survival of juvenile Chinook salmon through the Lookout Point Project. Our analysis provides insights into several key factors that influence survival. This information can be used by resource managers when considering revised operations that may lead to improved outmigration survival in the future.

Introduction

In the western United States, high head dams provide numerous societal benefits including flood control, hydropower, irrigation, and recreation, but these structures and their large storage reservoirs have affected Pacific salmon (*Oncorhynchus* spp.) populations by limiting access to historical spawning habitat and creating conditions where fish are subject to increased mortality due to factors such as migration delay, passage mortality, predation, and parasitism (Keefer and others, 2012, 2013; Murphy and others, 2021, 2023). In many rivers, assisted passage has been implemented to collect juvenile and adult salmon and transport them around dams and reservoirs, but these “trap-and-haul” programs are costly and have experienced a varied range of successes (Kock and others, 2019a, 2021).

In the Willamette River Basin, the U.S. Army Corps of Engineers (USACE) owns and operates the Willamette Valley Project, a series of 13 dams and reservoirs which are operated for several authorized purposes including flood control. The Willamette Valley Project was identified (National Marine Fisheries Service [NMFS], 2008a) as a significant cause of severely depressed populations of spring-run Chinook salmon (*O. tshawytscha*) and winter steelhead (*O. mykiss*) in the basin, which were listed under the U.S. Endangered Species Act in 2008 (NMFS, 2008b). A court-imposed interim

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[2]U.S. Army Corps of Engineers.

injunction has required the U.S. Army Corps of Engineers to undertake a suite of measures aimed at improving fish passage and water quality at several Willamette Valley Project dams since 2021. In 2023, one injunction measure required initiation of novel operations at Lookout Point Dam during summer and fall to draw down Lookout Point Reservoir from a maximum elevation of 888 feet (ft) to a minimum elevation of 750 ft by November 15, 2023, a drawdown target elevation approximately 100 ft lower than during normal operations. The biological goal of the deeper drawdown was "to provide improved volitional downstream passage and survival for juvenile spring Chinook salmon through Lookout Point Reservoir and past Lookout Point Dam in the fall." (USACE, 2023b, p. 2). The target life histories for the drawdown were "salmon fry and subyearlings that entered the reservoir in the previous winter–spring and reared through summer in the reservoir, and subyearlings that enter the reservoir in summer and fall" (USACE, 2023b, p. 2). The drawdown was intended to allow fish to access and volitionally pass through the regulating outlets (RO) of Lookout Point Dam with "high passage efficiency and survival anticipated" (USACE, 2023b, p. 2).

Previous studies have shown that juvenile Chinook salmon primarily exhibit three life history patterns upstream of Lookout Point Dam, two of which were the target of the drawdown operations. Many juvenile Chinook salmon move downstream and enter Lookout Point Reservoir from March through May as fry and spend several months rearing in the reservoir, which thermally stratifies under normal conditions (Kock and others 2019b, 2019c). Spring fry migrants experience high growth rates in the reservoir but are exposed to increased predation risk (by non-native fish species including Smallmouth Bass [*Micropterus dolomieu*] and walleye [*Sander vitreus*]) (Murphy and others, 2021) and experience high rates of infection by parasitic copepods (*Salmincola californiensis*; Monzyk and others, 2015; Murphy and others, 2023). Fall subyearling migrants rear in streams upstream of Lookout Point Reservoir during their first spring and summer, then move downstream into the reservoir during September–November. These fish do not experience the same growth rates as their spring migrant counterparts. Under pre-injunction operations, downstream passage of juvenile salmon at Lookout Point Dam during summer months was limited (Keefer and others, 2012) because fish must sound a significant distance (greater than [>] 40 meters [m]) to reach turbine and RO intakes. Downstream passage has been shown to increase substantially at the dam during fall as reservoir elevations decrease and turbine and (or) RO passage routes become more accessible. However, results from previous studies also suggest that fish passing Lookout Point Dam in fall experienced substantial injury or mortality. These factors are important to understand because of the potential for management actions (such as reservoir drawdown) to differentially affect spring and fall migrants in terms of reservoir survival, passage timing, and passage survival. The third life history, spring yearling migrants, are targeted by another injunction operation strategy (spring spill) that is not addressed by this study.

We conducted an acoustic telemetry study during August 2023–February 2024 to evaluate outmigration behavior and survival of juvenile Chinook salmon in the Middle Fork Willamette and main stem Willamette Rivers. We designed the study to be partly representative of both target life histories: reservoir rearing fry and fall migrants. Tagged fish were released at the head of Lookout Point Reservoir from late August through late October 2023 with earlier releases intended to represent reservoir rearing spring migrants that survived to fall, and later releases intended to represent fall migrants entering from upstream tributaries. We monitored fish as they migrated through the Lookout Point Project (two reservoirs and two dams) and the Willamette River. We fit a temporally stratified release-recapture model to acoustic telemetry detections to evaluate the effect of changing environmental conditions on the survival and travel time of fish through the Willamette Valley Project. Our results show that the cumulative effects of the 2023 drawdown on reservoir survival, dam passage, and downstream survival were likely to result in very low reservoir survival and passage for reservoir rearing fish and relatively higher survival and passage for fall migrants.

Methods

Study Area

The Lookout Point Project, located on the Middle Fork Willamette River in western Oregon, is comprised of two dams and two reservoirs that are operated by USACE as part of the Willamette Valley Project. Lookout Point Dam is a large, high-head dam (84 m tall) that stores water in Lookout Point Reservoir; at full capacity the reservoir stores 477,700 acre-feet of water. Dexter Dam is a 27 m tall re-regulating dam that is located 1.6 kilometer (km) downstream of Lookout Point Dam. The re-regulating purpose of Dexter Dam produces consistent flows in downstream reaches while allowing for fluctuating flows at Lookout Point Dam that are designed to meet peak hydropower demands within the region.

The Lookout Point Project does not allow for upstream passage of adult salmon that return to the Middle Fork Willamette River for spawning, so fish are collected in the tailrace of Dexter Dam and transported by truck to upstream reaches where they are released to spawn naturally. Progeny of transported adults emerge and move downstream, eventually entering Lookout Point Reservoir. Downstream passage through Lookout Point Reservoir and Lookout Point Dam typically requires several months so juvenile Chinook salmon rear in Lookout Point Reservoir where they experience rapid growth but are susceptible to mortality from predation and parasites (Monzyk and others, 2015; Kock and others, 2019b, 2019c; Murphy and others, 2021). Downstream passage at Lookout Point Dam typically occurs when reservoir elevations decline during fall and early winter, but injury and mortality rates can be high (>50 percent; Keefer and others, 2012, 2013; Fischer and others, 2018, 2019). The goal of the 2023 deep drawdown was to facilitate improvements to downstream passage and survival through the Lookout Point Project.

Acoustic Receiver Locations

A total of 14 acoustic telemetry receivers were deployed at five locations in the Willamette River Basin to detect tagged Chinook salmon moving downstream (fig. 1). These five locations define the downstream borders of study reaches (fig. 1). Three receivers were deployed in the forebay immediately upstream of Lookout Point Dam with the area between these receivers and the head of reservoir release location at Hampton Landing being defined as the Lookout Point Reservoir reach (reach 0). Two additional receivers were deployed in the tailrace approximately 400 m downstream of the dam with the area upstream of these receivers to the forebay receivers defined as the Lookout Point Dam reach (reach 1). The tailrace release site was located immediately upstream of these two receivers. Two receivers were mounted on the face of Dexter Dam in the forebay with the area upstream of these receivers to the tailrace defined as the Dexter Reservoir reach (reach 2). Three receivers were deployed near Eugene, Oregon, in the Middle Fork Willamette River about 1 km upstream of the convergence with the Coast Fork Willamette River with the area upstream defined as the lower Middle Fork Willamette River reach (reach 3). Four receivers were deployed in the mainstem Willamette River just upstream of Willamette Falls: two each on each side of the river and spaced approximately 500 m apart. The area upstream of the uppermost pair of these receivers was defined as the mainstem Willamette River reach (reach 4). The area between uppermost pair and the lowermost pair was defined at the Willamette Falls dual array reach (reach 5).

Environmental Conditions

Several environmental variables were of interest in relation to juvenile Chinook salmon outmigration behavior and survival including water temperature, streamflow, forebay elevation at Lookout Point Dam, discharge through regulating

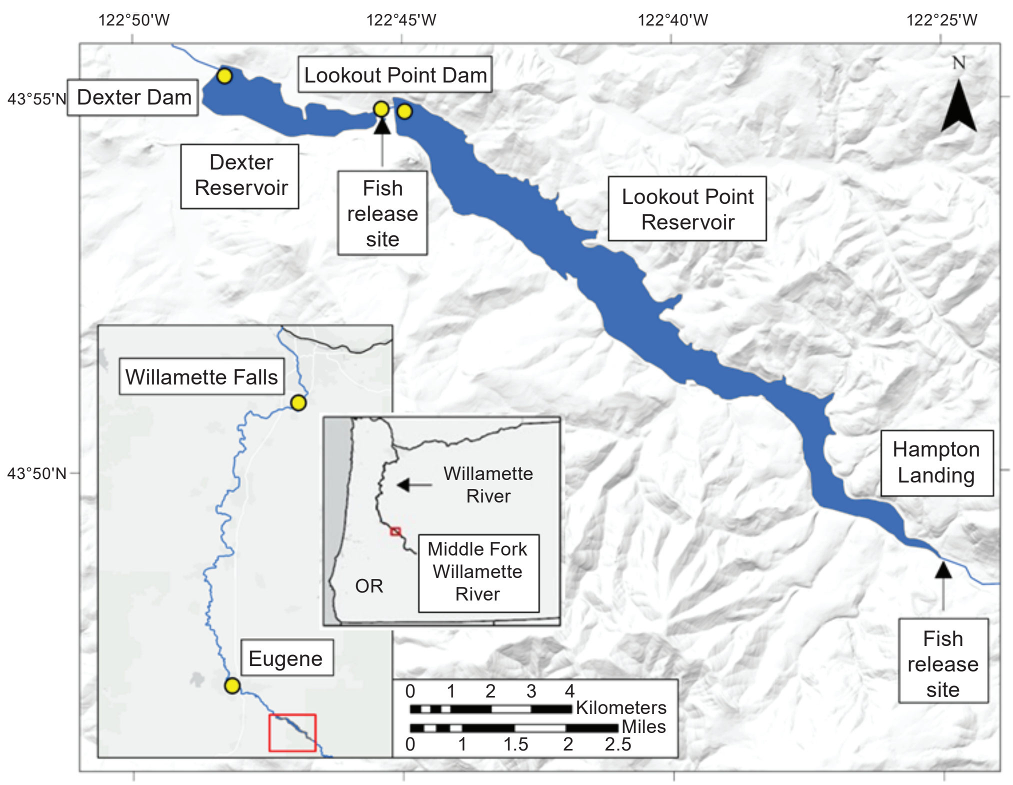

Figure 1. Locations of fish release sites, acoustic telemetry monitoring sites (circles), Lookout Point Dam, and Dexter Dam in the Willamette River Basin, Oregon. Fish release sites were located near Hampton Landing at the head of Lookout Point Reservoir and in the tailrace of Lookout Point Dam. Red outline boxes identify the location of Dexter Reservoir and Lookout Point Reservoir shown in the large, detailed schematic. [OR, Oregon.]

outlets at Lookout Point Dam, and total discharge at Dexter Dam. Most environmental data were queried and pulled from the U.S. Army Corps of Engineers DataQuery 2.0 website (USACE, 2023a; https://www.nwd-wc.usace.army.mil/dd/common/web_service/) via program R (R Core Team, 2022), including water temperature (instantaneous) and flow (hourly) near the Hampton Landing release location (U.S. Geological Survey, 2022, Lookout Point forebay elevation (instantaneous), forebay temperature string data (hourly at depths of 10, 20, 30, 40, 60, 80, and 100 ft), total outflow (hourly), and regulating outlet flow (hourly), Dexter forebay elevation (instantaneous), total outflow (hourly) and spill flow (hourly), and flow in the Willamette River at Eugene (instantaneous; USGS streamgage 14158050). Instantaneous and hourly data were summarized to daily mean values. Additionally, temperature loggers (HOBO Data Loggers, Bourne, Massachusetts, Model TidbiT MX2203) were attached to the hydrophone mounts of acoustic receivers to collect local temperature data. Temperatures used for Lookout Point tailrace were averages of temperatures recorded from the two loggers at acoustic receivers positioned in the tailrace. Lookout Point Dam regulating outlet hourly gate opening data were compiled from monthly dam operations spreadsheets provided by the U.S. Army Corps of Engineers, and data were quality checked and updated as appropriate based on comparisons of reported outflows to outflows calculated from rating tables using the regulating outlet opening data and forebay elevation.

Fish Tagging and Release

Juvenile Chinook salmon were produced for this study by Oregon State University's Wild Fish Surrogate Program (WFSP; Cogliati and others, 2023) from adult spring Chinook salmon that were spawned at the Willamette Hatchery (operated by the Oregon Department of Fish and Wildlife) in Oakridge, Oregon. The WFSP transferred eyed eggs from the Willamette Hatchery to their facility in Corvallis, Oregon in October 2022. Juvenile Chinook salmon were reared to achieve size-at-tagging that approximated fish size from Lookout Point Reservoir during fall months in previous studies (Romer and others, 2016; Kock and others, 2019b). These prior studies show a size disparity in the fall between the two life histories targeted in this study. In September and October, fork lengths for reservoir rearing fry are typically between 150 millimeters (mm) and 200 mm (Kock and others, 2019b) while fork lengths for fall migrants are typically between 80 and 120 mm (Romer and others, 2016). Mean fork length of juvenile Chinook salmon tagged and released during the study was 134.2 mm (standard deviation [SD] = 12.2 mm) with most fish between 100 mm and 160 mm (fig. 2).

Fish tagging and release occurred from late August to late October 2023 (table 1) (methods described in Liedtke and others, 2012) to target operating conditions at Lookout Point Dam when water was only passed through regulating outlets. Juvenile Chinook salmon were surgically tagged with an acoustic transmitter (Model SS400, Advanced Telemetry Systems, Isanti, Minnesota) and a passive integrated transponder (hereafter "PIT tag"; Model APT12, Biomark, Boise, Idaho). Mean weight was 25.3 grams (g) (SD = 7.1 g),

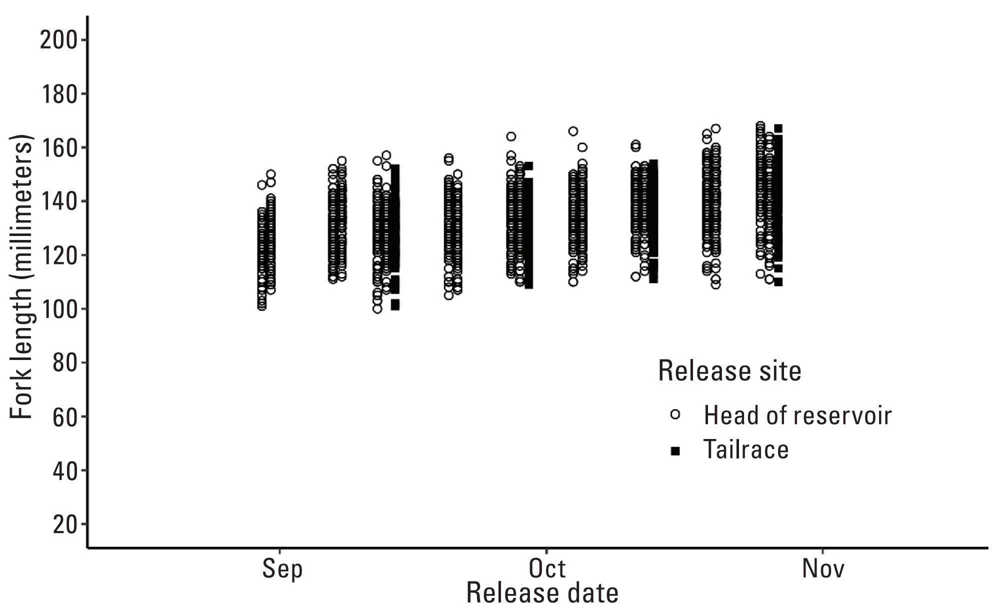

Figure 2. Fork lengths by release date for surrogate upper Willamette Chinook salmon (*Oncorhynchus tshawytscha*) used in this study.

Table 1. Number of acoustic-tagged juvenile Chinook salmon (*Oncorhynchus tshawytscha*) released weekly at two locations near Lookout Point Dam, Oregon, to evaluate experimental operations at the dam in Lookout Point Reservoir in 2023.

[—, no data]

Release period	Number of fish at release site	
	Head of reservoir	Tailrace
August 30–31	175	—
September 7–8	176	—
September 12–14	180	100
September 20–21	177	—
September 27–29	180	100
October 4–5	177	—
October 11–13	180	100
October 19–20	190	—
October 25–27	189	102
Total =	1,624	**402**

and mean tag burden (total weight of acoustic transmitter and PIT tag divided by fish weight) was 1.4 percent (SD = 0.4 percent). After tagging, fish were held at the WFSP facility overnight and then transported to release sites located near the head of Lookout Point Reservoir (hereafter "head of reservoir") and in the tailrace of Lookout Point Dam (hereafter "tailrace"). Fish releases at the head of reservoir were conducted weekly (175–190 fish released during each release week) and, in total, 1,624 tagged Chinook salmon were released at the site (table 1). Fish releases in the tailrace were conducted four times during the study (100–102 fish released during each release week) and in total, 402 tagged Chinook salmon were released at the site (table 1)

Seventy-five additional acoustic tags from the same manufacturing lot as study tags were randomly sampled, activated, and monitored with an acoustic receiver in 10-degree Celsius (°C) river water. Monitoring continued until no tags were detected on the receiver for 24 hours. The time of failure of each tag, x_h, was recorded as difference between the activation time of the tag and the timestamp of the final detection for test tag h.

Acoustic Telemetry Data Processing and Summary Statistics

Acoustic telemetry data were processed and summarized in multiple steps. First, raw ping data were screened for false positives. This yielded a dataset consisting of single acoustic ping detections recording the timestamp, acoustic tag identifier (ID), and receiver ID of each detection. These ping-level data were summarized as detection events, where a detection event is defined as the set of sequential-in-time detections of an individual tag at any of the receivers within the array of receivers denoting a monitoring location (for example, any of the three forebay receivers) without an intervening detection at any other monitoring location. A new detection event was defined if the time differences between sequential detections exceeded 60 minutes. Detection event data consisted of the acoustic tag ID, monitoring location, first detection, last detection, and number of detections.

For each individual fish, we created "space-for-time" capture histories based on the detection event data and the study design to facilitate statistical modelling using the temporally stratified multistate (TSMS) mark-recapture framework described in Hance and others (2020, 2022). The TSMS capture histories summarize the sequential-in-space detections of individual fish as they migrated through each study reach over time. The TSMS can be used with any level of temporal stratification (for example, hourly, daily, weekly). For this study, we summarized the data using daily strata. Based on the 90-day estimated tag battery life and the release dates for all fish, we used August 30, 2023, as the first day of the study and January 31, 2024, as the final day of the study. This resulted in 155 total strata (T =155).

The capture history for each individual, y_i, was a six-element vector where each element, $y_{i,k}$, was either an integer representing the day on which the individual i was first detected (or released) at each location k or zero if the individual was not detected at that location. For individuals released at Hampton Landing, $y_{i,0}$ was the day of release with $y_{i,0}$ =1 for individuals released on August 30, 2023. Likewise for individuals released in the tailrace, $y_{i,2}$ was the day of release. In event of multiple detection events at a location, we used the timestamp of the first detection of the first detection event at each location. The TSMS framework does not allow for upstream transitions and so detection events at an upstream monitoring location that occurred after a detection at a downstream monitoring location were ignored. This only occurred within Dexter Reservoir where some individuals were detected on the tailrace receivers (at Lookout Point Dam) after having been detected on the Dexter forebay receivers. We also recorded the tag activation strata for each individual as q_i. In most cases, tags were activated 48 hours before release, but, for a small number of fish, tags were active 24 hours before releases.

Statistical Model

The TSMS framework describes a data generating process starting with an initial release of fish that survive, arrive over time, and are detected at monitoring stations that mark the transition between reaches. The TSMS allows for survival probability, travel (or residence) time, and detection probability to vary based on the time of entry to given reach. We adapted elements of models described in Hance and others (2020, 2022), but the model used for this study also contains elements novel to this study. The TSMS model for Lookout Point was defined in terms of the following parameters:

- $\phi_{i,j,s}$ is “apparent survival probability” or the probability that individual *i* having entered reach *j* on day *s* survived and migrated to reach *j* + 1. Because individuals may delay migration, this term includes the probability of an individual remaining alive but not passing to the next downstream reach prior to tag battery failure or the conclusion of the study.

- $\alpha_{i,j,s,t}$ is the probability that, having survived, individual *i* having entered reach *j* on day *s* entered reach *j* + 1 on day *t*, where $\alpha_{i,j,s,t} = 0$ for $s > t$, $\alpha_{i,j,s,t} > 0$ for $s \le t$ and $\sum_{t=s}^{T} \alpha_{i,j,s,t} = 1$ where *T* is the final day of the study.

- $\delta_{i,t}$ is the probability that the acoustic telemetry tag battery for individual *i* was still active on day *t*.

- $p_{i,k,t}$ is the probability that individual *i* entering reach *k* on day *t* was detected.

To account for non-detection and the passage time for undetected fish, the TSMS model framework makes use of two recursive intermediary parameters (Hance and others, 2020). The first recursive term defines the probability of each pair of detections with no other intervening detections. We define $\lambda_{i,j,k,s,t}$ as the probability that individual *i* having entered reach *j* on day *s* survived and entered reach *k* having on day *t* with an active tag having passed undetected by any monitoring stations between *j* and *k*:

$$\lambda_{i,j,k,s,t} = \phi_{i,j,s}\alpha_{i,j,s,t}\frac{\delta_{i,t}}{\delta_{i,s}} \tag{1}$$

for *k* = *j*+1 and

$$\lambda_{i,j,k,s,t} = \sum_{u=s}^{t}\begin{pmatrix}\lambda_{i,j,k-1,s,u}\\ (1-p_{i,k-1,u})\phi_{i,k-1,u}\alpha_{i,k-1,s,u}\end{pmatrix}\frac{\delta_{i,t}}{\delta_{i,s}} \tag{2}$$

for *k* > *j*+1.

The second recursive term, $\chi_{i,k,s}$ defines the probability of the final detection for individual *i* last detected entering reach *k* on day *s*. For fish last detected entering a reach above the downstream-most monitoring location, this term accounts for the various processes that could result in a fish not being detected at any downstream location. Those possibilities include that a fish died or experienced a delayed migration until either the tag battery failed or the end of the study. For individuals last detected at the downstream-most monitoring location, we set $\chi_{i,K,s} = 1$, and define the remaining terms for 0 less than or equal to [≤] $k \le K$ recursively as:

$$\chi_{i,k,s} = \left(1-\phi_{i,k,s}\right) + \phi_{i,k,s}\sum_{u=s}^{T}\left(\alpha_{i,k,t,u}\begin{bmatrix}\left(1-p_{i,k+1,u}\right)\chi_{i,k+1,u}\dfrac{\delta_{i,u}}{\delta_{i,s}}\\ +\left(1-\dfrac{\delta_{i,u}}{\delta_{i,s}}\right)\end{bmatrix}\right) \tag{3}$$

For mathematical convenience in expressing the likelihood, we define two sets of indicator variables based on the observed capture histories: $m_{i,j,k,s,t}$ and $l_{i,k,t}$. We let $m_{i,j,k,s,t} = 1$ if $y_{i,j} = s$, $y_{i,k} = t$, and $y_{i,g} = 0$ for $j < g < k$. Otherwise, we let $m_{i,j,k,s,t} = 0$. We let $l_{i,j,s} = 1$ if $y_{i,j} = s$ and $y_{i,k} = 0$ for all $k > j$. Otherwise, $l_{i,j,s} = 0$. Abbreviating the entire set of parameters as θ allows us to define the observed data likelihood for the capture histories as:

$$\Pr(y|\theta) \propto \prod_i \prod_{j=0}^{K-1} \prod_{k=j+1}^{K} \prod_{s=1}^{T} \prod_{t=s}^{T} \left(\lambda_{i,j,k,s,t}p_{i,k,t}\right)^{m_{i,j,k,s,t}} \times \prod_i \prod_{j=0}^{K-1} \prod_{s=1}^{T} \left(\chi_{i,j,s}\right)^{l_{i,j,s}} \tag{4}$$

We included an auxiliary likelihood to better inform estimates of acoustic tag battery failure by fitting a log-logistic distribution to the observed failure times in test tags:

$$x \sim LL(v, \psi) \tag{5}$$

This allowed us to set $\delta_{i,t} = 1 - F(t - q_i) = [1 + (^t/_v)^{\psi}]^{-1}$ in the terms above with the parameters for log median tag life, *v* and inverse scale, ψ, shared among the test tags and study tags.

Using this framework, we were able to investigate the effect of time-varying environmental conditions and individual covariates on the apparent survival and residence time of fish in each study reach. To model the effect of covariates on apparent survival in reach *k* we used a general logit-link regression form:

$$\mathrm{logit}(\phi_{i,k,s}) = \beta_{0,k} + \beta_{1,k}X_{i,k,1,s} + \ldots + \beta_{P,k}X_{i,k,P,s} \tag{6}$$

where $\beta_{p,k}$ are generic regression coefficients for the slope of the effect of $X_{i,k,p,s}$, the p^{th} generic individual and (or) time varying covariate for individual *i* entering reach *k* on day *s*. We used a log-logistic distribution to model the residence time probabilities for fish in each reach. That is, for $s \le t$:

$$\alpha_{i,k,s,t} = \left(\frac{\left(\left[1+\dfrac{t-s}{\mu_{k,s}}\right]^{-\sigma_k}\right)^{-1} - \left[1+\left(\dfrac{t-s-1}{\mu_{k,s}}\right)^{-\sigma_k}\right]^{-1}}{\left[1+\left(\dfrac{T-s}{\mu_{k,s}}\right)^{-\sigma_k}\right]^{-1}}\right) \tag{7}$$

where the log median of residence time in each reach, $\mu_{k,s}$, was estimated as a function of environmental conditions experienced on the day of entry, *s*, to reach *k*:

$$\mu_{k,s} = \gamma_{0,k} + \gamma_{1,k}Z_{i,k,1,t} + \ldots + \gamma_{P,k}Z_{i,k,P,t} \tag{8}$$

where $\gamma_{p,k}$ are generic regression coefficients for the slope of the effect of $Z_{i,k,p,s}$, the p^{th} generic individual and (or) time varying covariate for individual i entering reach k on day s. Separate inverse-scale parameters, σ_k, were estimated for each reach but shared among individuals and strata within reaches.

We chose different covariates for each study reach. For all reaches, we used individual fish length as a covariate on apparent survival, but not on median residence time. In both models, we assumed that detection probability at monitoring locations between reaches was constant for all individuals and across strata. That is, $p_{i,k,t} = p_k\ \forall i,t$. Time varying covariates used were as follows:

- For Reach 0, from head-of-reservoir release to the Lookout Point (LOP) forebay, we used daily mean forebay water temperature as a covariate for both $\phi_{i,0,s}$ and $\mu_{0,s}$. Daily mean forebay water temperature was measured as the arithmetic average of hourly water temperatures measured at 10-ft, 20-ft, 30-ft, 40-ft, 60-ft, and 80-ft depths. That is, forebay temperature strings were averaged over depth and hour for each day to arrive at a single daily measurement.
- For Reach 1, from LOP forebay to the LOP tailrace, we used daily mean reservoir elevation and daily mean outflow through the ROs as a covariate for both $\phi_{i,1,s}$ and $\mu_{1,s}$.
- For Reach 2, from the LOP tailrace to Dexter forebay, we used daily mean tailrace temperatures as a covariate for both $\phi_{i,2,s}$ and $\mu_{2,s}$.
- For Reach 3, from Dexter forebay to Eugene, we used daily mean outflow from Dexter Dam as a covariate for both $\phi_{i,3,s}$ and $\mu_{3,s}$.
- For Reach 4, from Eugene to Willamette Falls, we used daily mean Willamette River flow as a covariate for both $\phi_{i,4,s}$ and $\mu_{4,s}$.

We fit the model using the Stan probabilistic programming language (Stan Development Team, 2024). Covariates were standardized by subtracting the mean and dividing by the standard deviation. We used weakly informative priors for most parameters with the exception of the parameters for v and ψ. For v, we used a normal prior with a mean of 4.5 and standard deviation of 0.5 and for ψ we use a half-normal prior with a standard deviation of 0.5. Priors for the terms of the logit-link functions were Student's t distributions with 7 degrees of freedom and standard deviation of 2 for intercept terms and 1 for slope terms. Normal priors were chosen for the terms of μ with mean 2 for the intercept and mean of 0 and standard deviation of 1. Half-normal priors with standard deviation of 1 were used for the inverse-scale terms of the residence time distribution. We ran 4 chains with a warmup of 1,000 iterations and a sampling of 1,000 iterations for a total of 4,000 posterior samples. Model chains were verified for convergence by checking diagnostic plots.

Results

Complete data and results from this study are available at Hansen and others (2024).

Detection Summary

A seasonal trend was observed for fish detections as the number of fish detected per release week was initially low but increased throughout the study. The number of fish that were detected in the study area from releases that occurred during September was very low and generally increased during October (fig. 3). Of the 1,624 Chinook salmon released at the head of reservoir a total of 335 (21 percent) were detected in the Lookout Point forebay, 155 in the Lookout Point tailrace (10 percent), 139 in the Dexter forebay (9 percent), 75 (5 percent) in Eugene and 51 (3 percent) at Willamette Falls. Passage at Lookout Point Dam occurred almost exclusively through the regulating outlets; only one tagged fish passed the dam when regulating outlets were closed and turbines were operating (fig. 3). All fish detected at Eugene and Willamette Falls were from October releases and, in particular, fish released in the last 2 weeks of the study accounted for 44 of the 51 head of reservoir fish detected at Willamette Falls (fig. 3). A similar trend was apparent in the tailrace releases where the September 14 release of 100 fish saw only 11 percent of fish detected in the Dexter forebay, 3 percent in Eugene, and 1 percent at Willamette Falls. For the remaining tailrace releases, greater than 75 percent were detected in the Dexter forebay, while the last two releases in the second half of October were responsible for most Willamette Falls detections (table 2).

Environmental Conditions

The pool elevation at Lookout Point forebay steadily lowered during the drawdown until early November, when it was held near 750 ft until early December when a series of high rainfall events led to a rapid rise in reservoir elevation and ended drawdown operations. Regulating outlet flows through Lookout Point Dam were held steady through September and October, increased in November when pool elevations were at the low point, and peaked in early December before being closed off by mid-December (fig. 3). Water was passed through the turbines during mid-December to early February when the study ended (fig. 3). Lookout Point forebay temperature string data show that the forebay went isothermic around late-August, with temperatures above 18 degrees Celsius (°C) until late September (fig. 3). Water temperatures cooled through October and November. Water temperatures in Dexter Reservoir followed a similar pattern, with temperatures above 18 °C from late-August to late-September, and then cooling temperatures thereafter. Flows at both Dexter Dam and Eugene were relatively stable through September and October and increased in November and December.

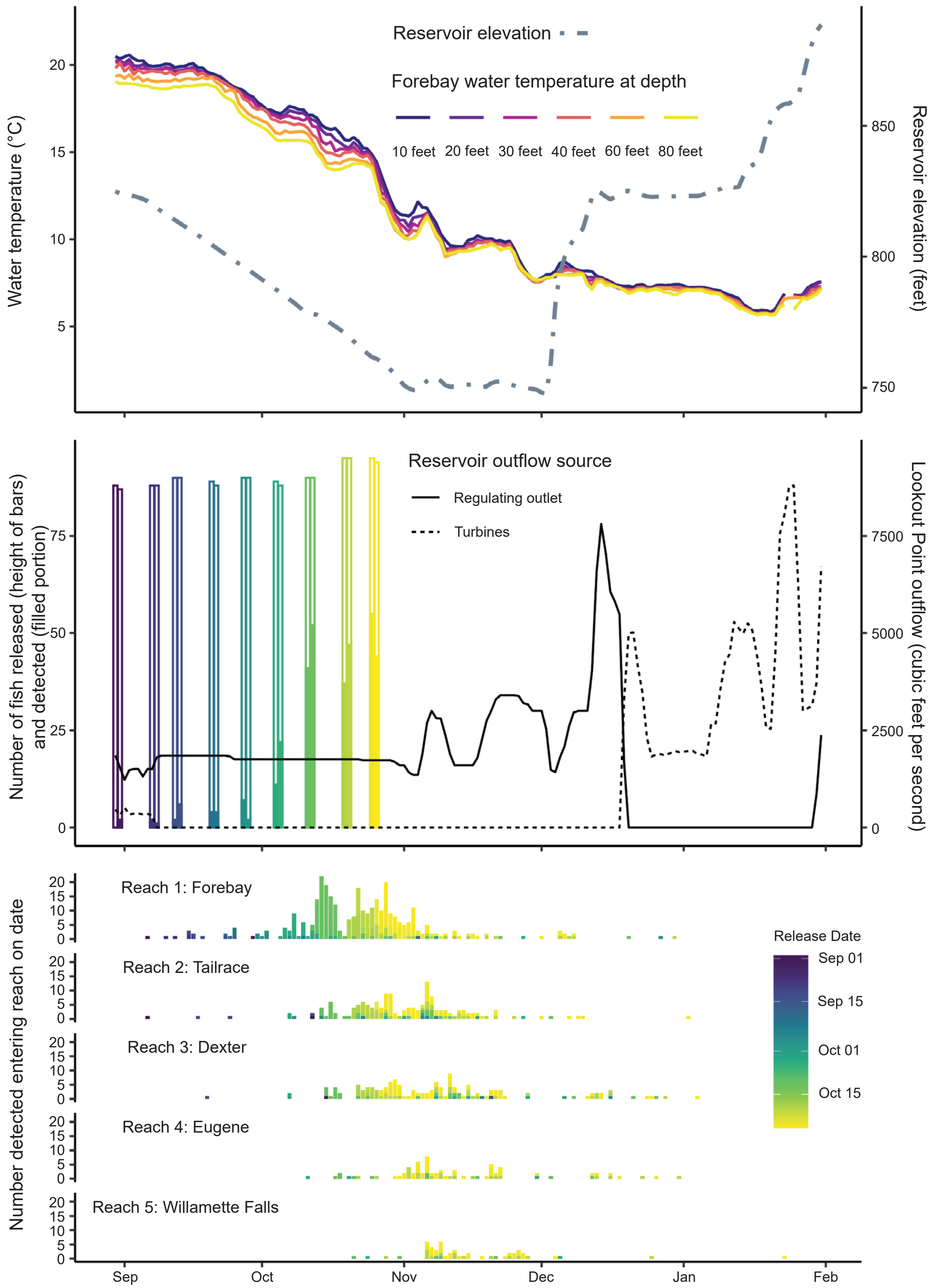

Figure 3. Summary of reservoir water temperature and elevation (top panel), fish release timing and dam operations (middle panel), and detection timing (bottom panel) of individual Chinook salmon (*Oncorhynchus tshawytscha*) at specific detection locations during an acoustic telemetry study in the Willamette River Basin, Oregon, August 2023–February 2024. [°C, degrees Celsius.]

Table 2. Proportion of acoustic-tagged juvenile Chinook salmon (*Oncorhynchus tshawytscha*) detected at each monitoring location from weekly releases at two locations near Lookout Point Dam, Oregon, to evaluate experimental operations at the dam in Lookout Point Reservoir in 2023.

[LOP, Lookout Point; HOR, head of reservoir; —, no data]

Release period	Release site	Proportion of fish detected at monitoring location				
		LOP forebay	LOP tailrace	Dexter forebay	Eugene	Willamette Falls
August 30–31	HOR	0.01	0.01	0.01	0.00	0.00
September 7–8	HOR	0.02	0.00	0.00	0.00	0.00
September 12–14	HOR	0.03	0.02	0.01	0.00	0.00
September 12–14	Tailrace	—	—	0.11	0.03	0.01
September 20–21	HOR	0.05	0.00	0.00	0.00	0.00
September 27–29	HOR	0.04	0.03	0.01	0.00	0.00
September 27–29	Tailrace	—	—	0.78	0.41	0.07
October 4–5	HOR	0.18	0.04	0.04	0.02	0.01
October 11–13	HOR	0.52	0.15	0.12	0.06	0.03
October 11–13	Tailrace	—	—	0.79	0.46	0.28
October 19–20	HOR	0.44	0.23	0.21	0.11	0.07
October 25–27	HOR	0.52	0.35	0.34	0.22	0.16
October 25–27	Tailrace	—	—	0.89	0.44	0.30

Covariate Effects

The direction and magnitude of the effect of fish length on apparent survival varied among reaches (fig. 4). For reach 0, from head of reservoir release to LOP forebay, apparent survival increased with length. At mean forebay water temperature (12.7 °C), apparent survival increased from an estimate of 0.50 (90-percent confidence interval [CI]: [0.39, 0.62]) at 110 mm to 0.83 [0.78, 0.87] at 160 mm. For reach 1, from LOP forebay to LOP tailrace, apparent survival decreased with length. At mean forebay elevation (798 ft) and mean RO outflow (1,661 cubic feet per second [ft^3/s]), apparent survival decreased from an estimate of 0.41 (90-percent CI: [0.26, 0.56]) at 110 mm to 0.17 [0.08, 0.28] at 160 mm. For reach 2, from the tailrace to Dexter forebay, apparent survival increased with length. At mean tailrace water temperature (11.6 °C), apparent survival increased from an estimate of 0.78 (90-percent CI: [0.66, 0.87]) at 110 mm to 0.96 [0.94, 0.98] at 160 mm. For reach 4, from Dexter forebay to Eugene, length did not have a statistically meaningful effect on apparent survival. At mean Dexter outflow (2,786 ft^3/s), apparent survival was estimated to be 0.47 (90-percent CI: [0.36, 0.59]) at 110 mm and 0.61 [0.51, 0.70] at 160 mm. For reach 5, from Eugene to Willamette Falls, apparent survival increased with length. At mean Willamette River flow (5,624 ft^3/s), apparent survival increased from an estimate of 0.22 (90-percent CI: [0.11, 0.36]) at 110 mm to 0.76 [0.66, 0.85] at 160 mm. In reporting the effect of time-varying environmental covariates, we use a length of 110 mm to represent the likely effect of the 2023 drawdown operations on fall migrants and 160 mm to represent reservoir rearing spring migrants.

Apparent survival for Reach 0, from release to LOP forebay, was negatively associated with forebay water temperatures (fig. 5). Median residence time for reach 0 increased with decreasing water temperature (fig. 6). Daily mean forebay water temperatures, averaged over depths to 80 ft, were above 18 °C until September 23 and apparent survival was low for all sizes through most of September (fig. 7). Estimated apparent survival from release to the forebay at 18 °C was only 0.08 (90-percent CI: [0.07, 0.10]) at the mean fork length of 134 mm, about half of that for fish at fork lengths more typical of fall migrants (110 mm: 0.04 [0.03, 0.06]), and about twice that for fish at fork length more typical of reservoir rearing fish (160 mm: 0.17 [0.12, 0.22]). At the highest temperatures observed during our study (19.6 °C on August 31), reservoir rearing sized fish would be expected to have survival of around 0.08 [0.05, 0.11]. Temperatures moderated through October, dropping below 13.5 °C after October 26, the date of our final head of reservoir release. At 13.5 °C the apparent survival for fall migrant sized fish was estimated at 0.40 [0.30, 0.50].

Apparent survival for Reach 1, from LOP forebay to LOP tailrace, increased with decreasing reservoir elevation and with increased RO outflow (fig. 5). Median residence time moved in the opposite direction with the shortest residence times associated with lowest elevations and higher RO outflows (fig. 6). Reservoir elevations reached 755 ft by October 30 and remained below this level until December 3, when a series of atmospheric rivers led to a switch to flood control operations and a rapid rise in reservoir elevations. While at the target drawdown elevation, several smaller precipitation events led to temporary increases in RO outflows necessary

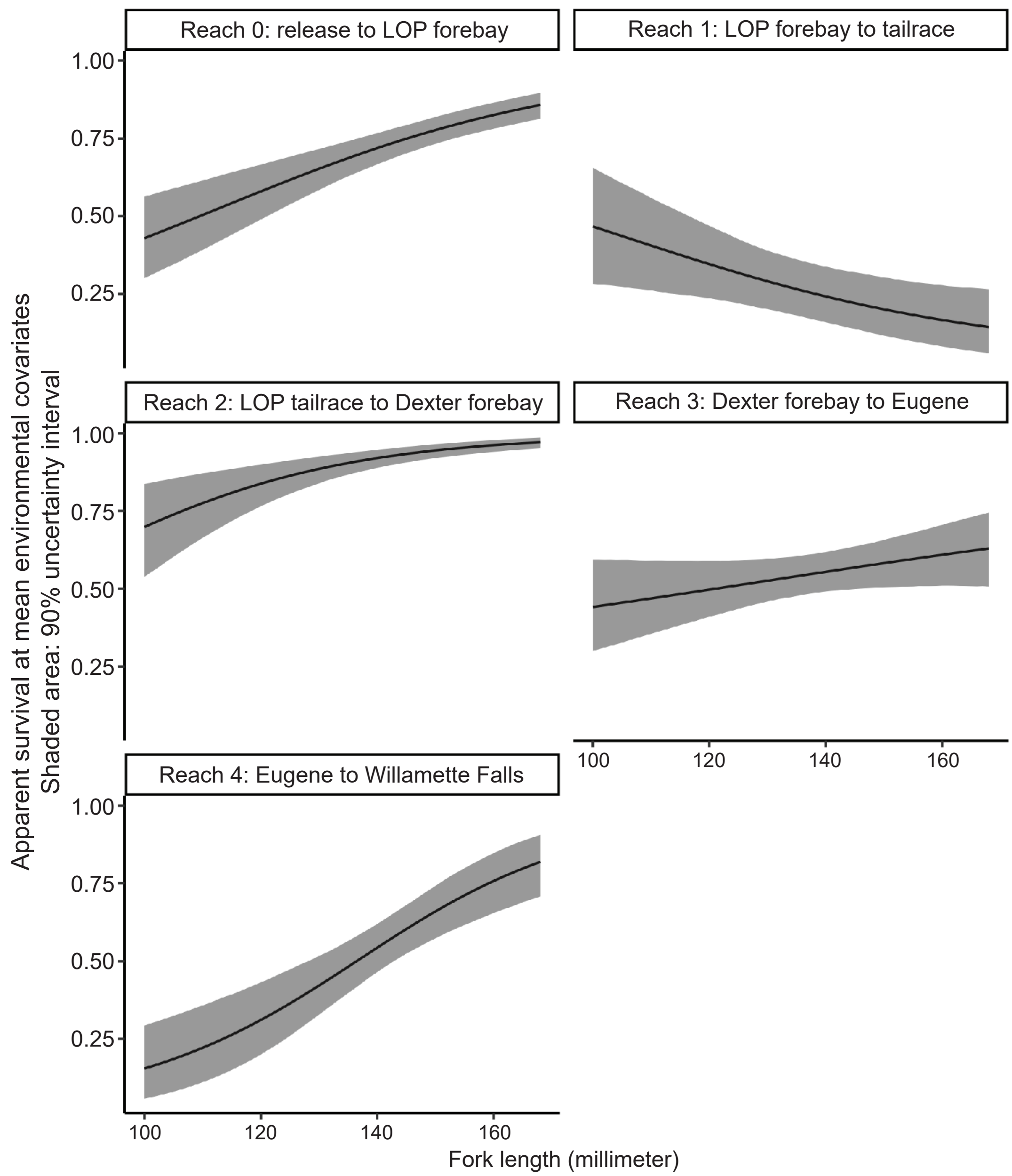

Figure 4. Effect of individual fish fork length on apparent survival by reach. Apparent survival is depicted by holding environmental covariates at their mean value. [%, percent; LOP, Lookout Point.]

to maintain the target drawdown elevation. The lowest RO outflow while at the target elevation was 1,600 ft^3/s. Estimated apparent survival for fish arriving in the forebay during these conditions of minimum RO outflow and minimum elevation was 0.70 [0.61, 0.79] at 134 mm fork length, 0.80 [0.66, 0.91] at 110 mm, and 0.55 [0.45, 0.65] at 160 mm (fig. 8). Median residence time was 1.7 days [1.13, 2.32] at these same conditions (fig. 9). Doubling RO outflow to 3,200 ft^3/s while holding elevations at 750 ft yielded estimates of apparent survival of 0.88 [0.73, 0.97], 0.92 [0.81, 0.99] and 0.79 [0.60, 0.95] for 134 mm, 110 mm, and 160 mm lengths respectively, while the estimate of median residence time decreased to 8 hours [2.5 hours, 18 hours]. On the other hand, at reservoir elevations of 825 ft and 0 RO outflow apparent survival was estimated to be as low as 0.05 [0.005, 0.13], 0.08 [0.01, 0.22] and 0.03 [0.002, 0.09] for 134 mm, 110 mm, and 160 mm lengths respectively, while the estimate of median residence time increased to 259 days [32.1 days, 800 days]. However, these estimates are based in part on an extrapolation for tag battery failure and residence time and should not be used for planning purposes.

Apparent survival for Reach 2, from LOP tailrace to Dexter forebay, was negatively associated with forebay water temperatures (fig. 5). Median residence time for reach 2

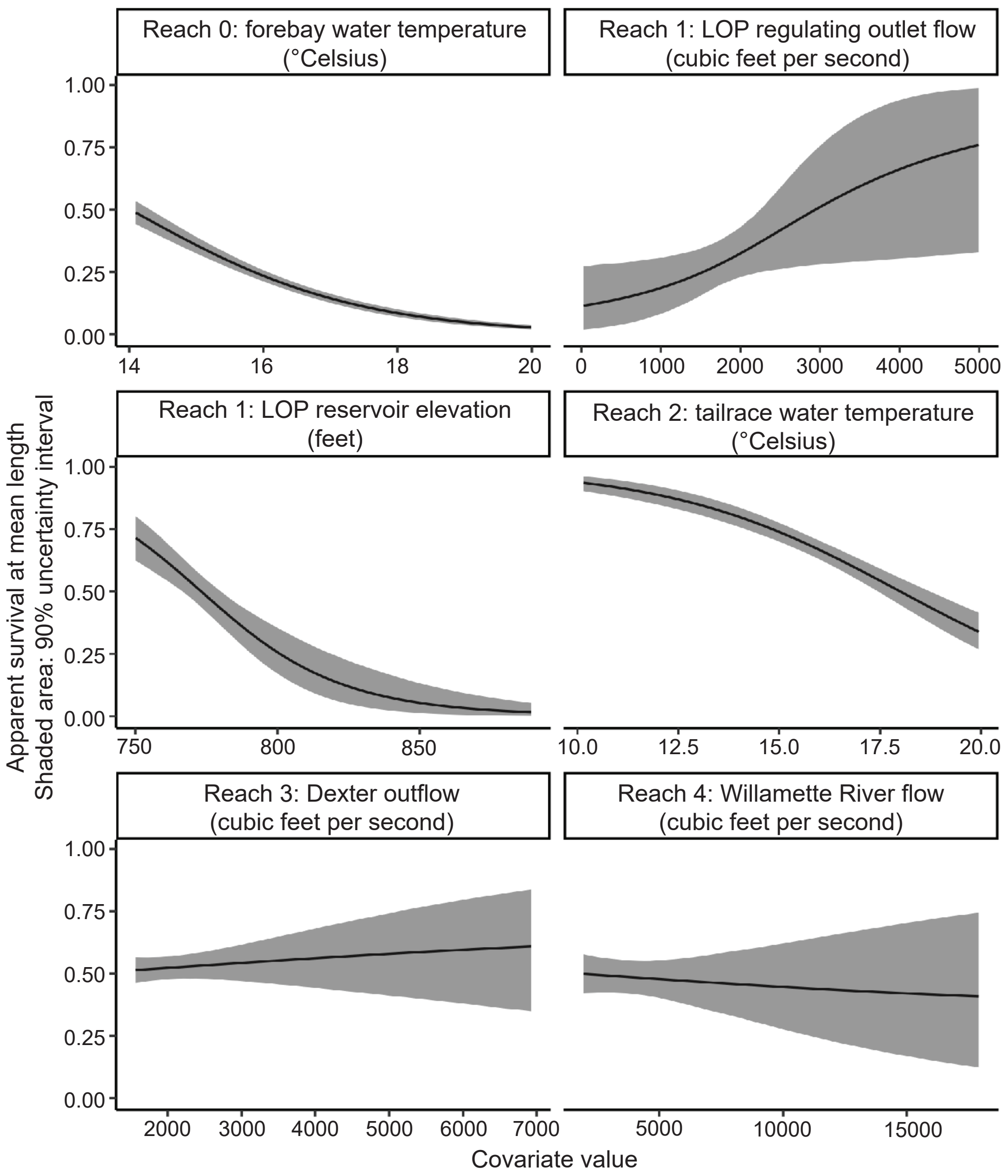

Figure 5. Effect of time-varying environmental covariates on apparent survival by reach. Apparent survival is depicted by holding fish length and, if applicable, other environmental covariates at the mean value. [%, percent; °, degrees; LOP, Lookout Point.]

increased with decreasing water temperature (fig. 6). Daily mean tailrace water temperatures were above 18 °C until September 26, and apparent survival was low for all sizes through most of September (fig. 10). These results are similar to Reach 0, though apparent survival in the 4-km Reach 2 was not as low as the 20-km Reach 0 for similar water temperatures. Estimated apparent survival for Reach 2 at 18 °C was 0.51 [0.45, 0.56] for 134 mm fish, 0.29 [0.21, 0.37] for 110 mm fish, and 0.74 [0.64, 0.83] for 160 mm fish. By the time the drawdown operations reached their minimum elevation, water temperatures dropped to 11 °C or below. At 10 °C the apparent survival for fall migrant sized fish was estimated at 0.85 [0.75, 0.93] and 0.98 [0.96, 0.99] for reservoir rearing sized fish.

The covariates of Dexter outflow and Willamette River flow did not result in a statistically detectable effect on apparent survival for Reach 3 and 4 (fig. 5). However, these covariates did decrease residence time in these reaches (fig. 6). The mean estimate of apparent survival through Reach 3 (Dexter Dam to Eugene) during the month of November when the drawdown was at the target elevation was 0.57 [0.42, 0.70] for 134 mm fish, 0.50 [0.33, 0.67] for 110 mm fish, and 0.63 [0.46, 0.78] for 160 mm fish. For the same period in Reach 4, the mean estimate of survival was 0.44 [0.24, 0.66] for 134 mm fish, 0.21 [0.07, 0.43] for 110 mm fish, and 0.71 [0.48, 0.89] for 160 mm fish.

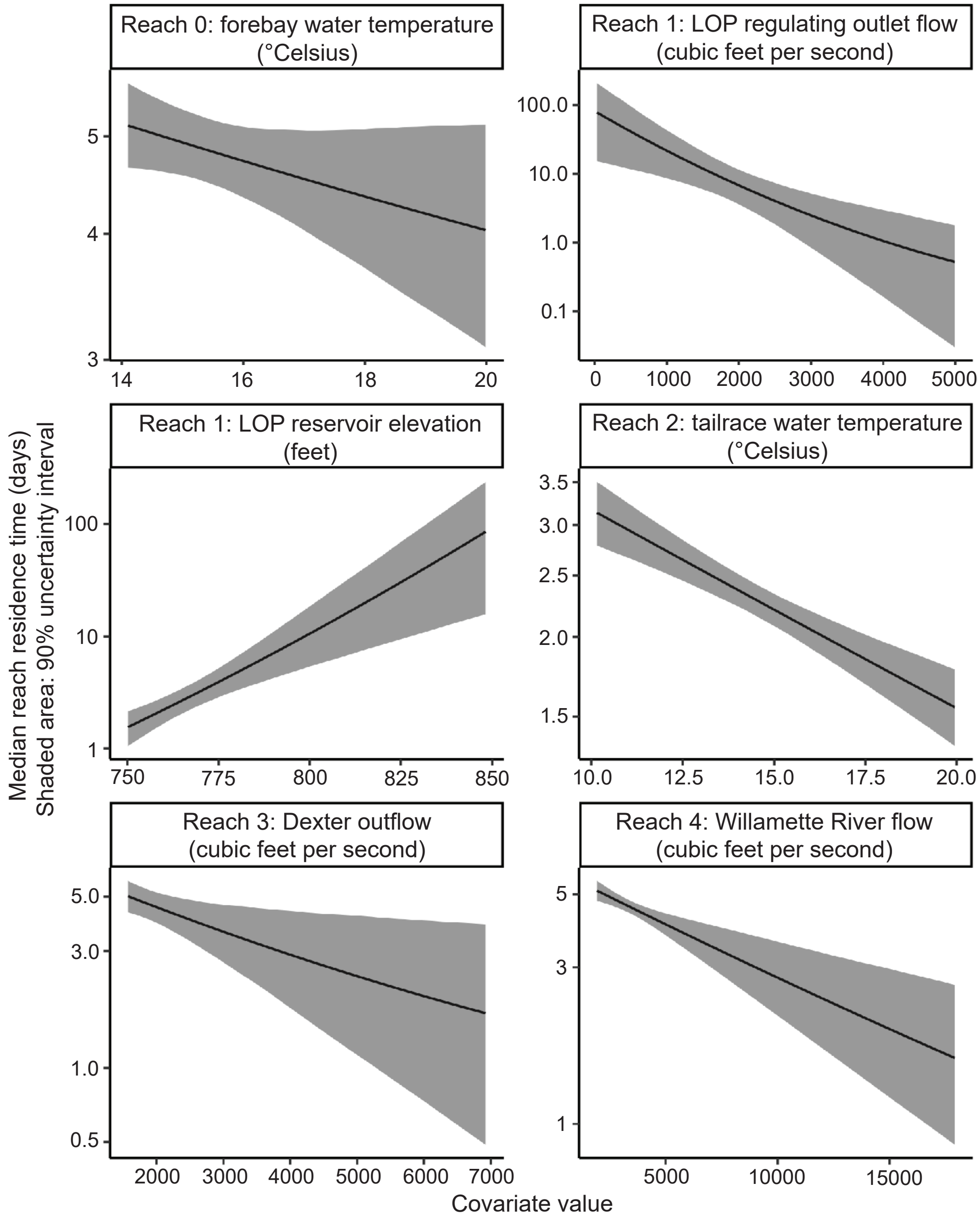

Figure 6. Effect of time-varying environmental covariates on median residence time by reach. If applicable (Reach 2 only), effects are depicted by holding other environmental covariates at the mean value. [%, percent; °, degrees; LOP, Lookout Point.]

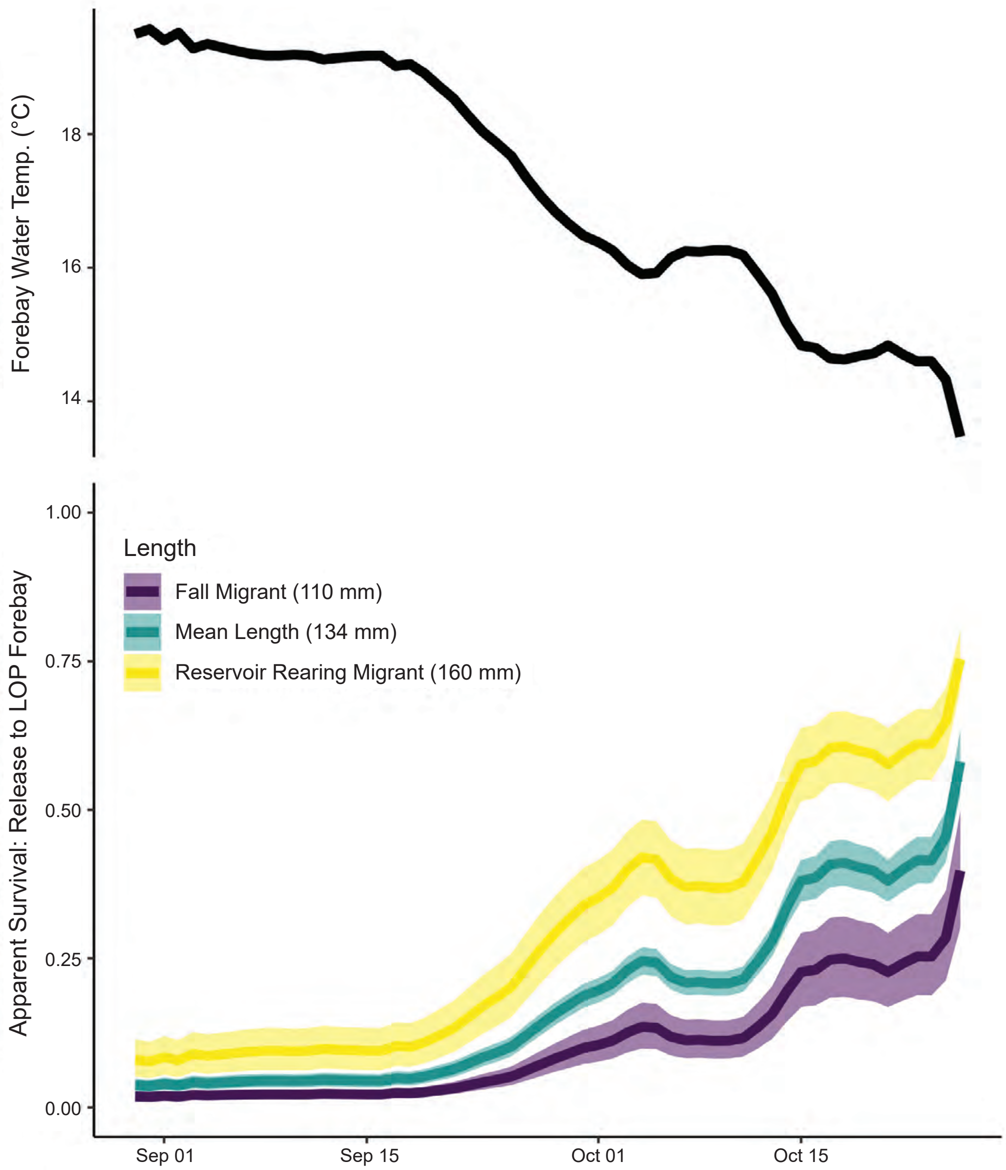

Figure 7. Effect of observed reservoir water temperatures on apparent survival over time for Reach 0, from release at the head of reservoir to Lookout Point forebay. Apparent survival is depicted at mean fish length (134 millimeters [mm]), at a fish length more representative of reservoir rearing migrants (160 mm), and at a fish length more representative of fall migrants (110 mm). [Temp, temperature; °C, degrees Celsius; LOP, Lookout Point; mm, millimeter.]

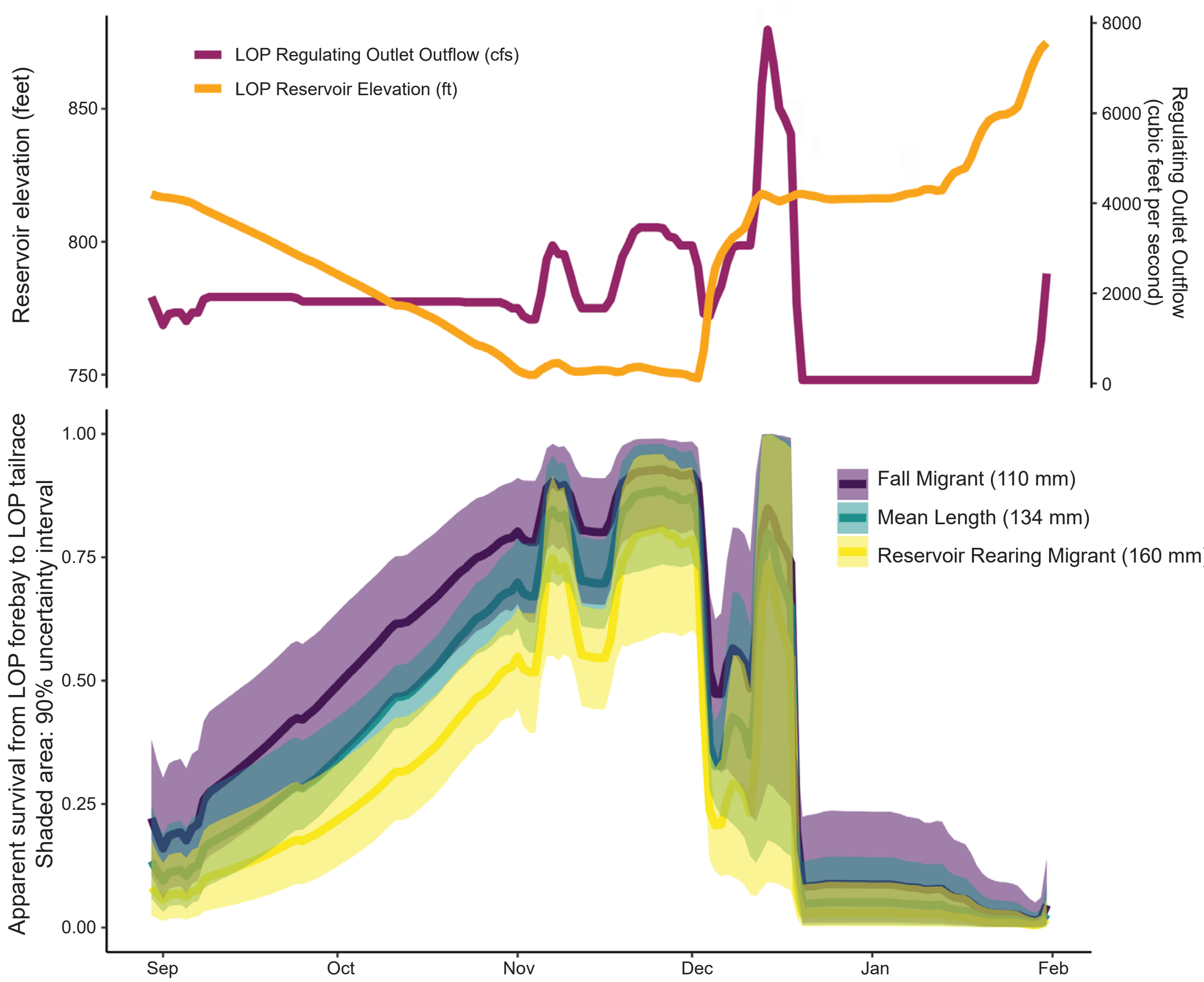

Figure 8. Effect of observed reservoir elevation and regulating outlet flow on apparent survival over time for Reach 1, from Lookout Point forebay to Lookout Point tailrace. Apparent survival is depicted at mean fish length (134 millimeters [mm]), at a fish length more representative of reservoir rearing migrants (160 mm), and at a fish length more representative of fall migrants (110 mm). [LOP, Lookout Point; cfs, cubic feet per second; ft, feet; %, percent; mm, millimeters.]

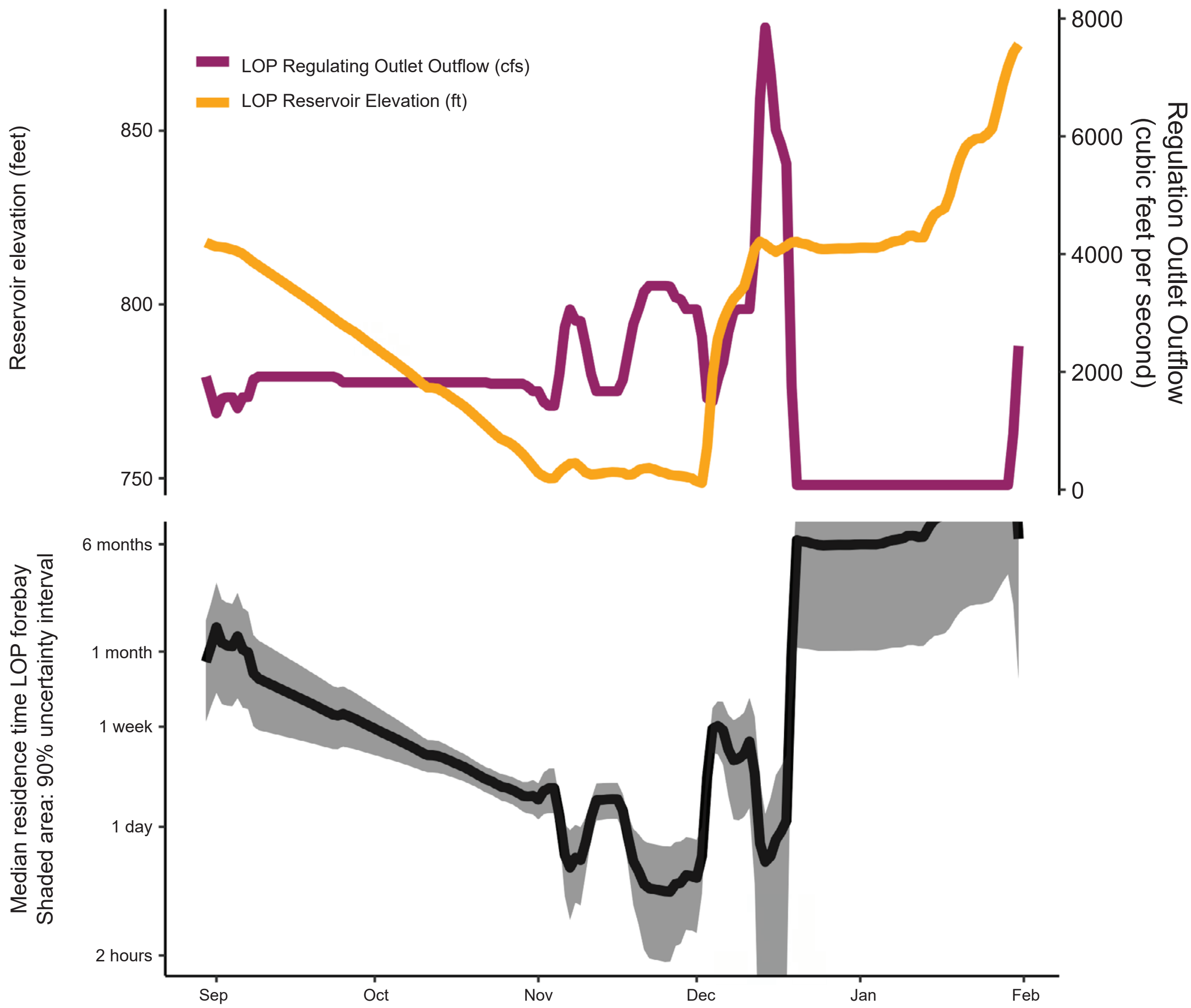

Figure 9. Effect of observed reservoir elevation and regulating outlet flow on median residence time in the forebay of Lookout Point Dam. [LOP, Lookout Point; cfs, cubic feet per second; ft, feet; %, percent.]

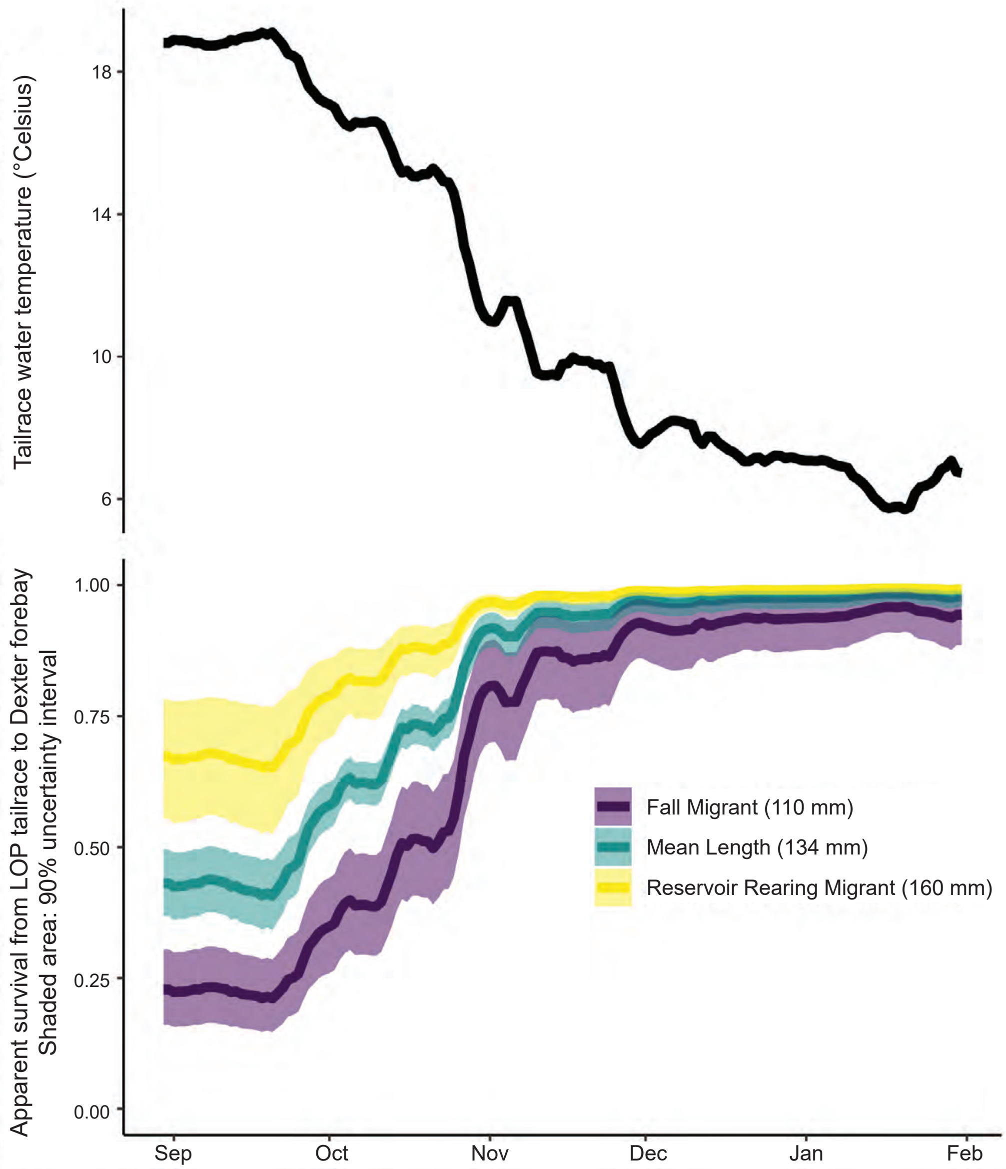

Figure 10. Effect of observed reservoir water temperatures on apparent survival over time for Reach 2, from Lookout Point tailrace to Dexter forebay. Apparent survival is depicted at mean fish length (134 millimeters [mm]), at a fish length more representative of reservoir rearing migrants (160 mm) and at a fish length more representative of fall migrants (110 mm). [°, degrees; LOP, Lookout Point; %, percent; mm, millimeters.]

Discussion

This study was designed to monitor and evaluate the effects of a 2023 deep drawdown at the Lookout Point Project with respect to the biological goals stipulated in the injunction measure ordering this experimental operation (USACE, 2023b). The drawdown was intended to improve reservoir survival for juvenile Chinook salmon through the Lookout Point Project and provide improved volitional downstream passage in the fall for two target populations: reservoir-rearing spring migrants that remained in the reservoir into the fall and fall migrants that entered the reservoir in the fall. The results for this study suggest that while there is evidence that the experimental drawdown during fall 2023 created conditions that facilitated dam passage during the month of November, environmental conditions throughout Lookout Point Project associated with the drawdown operations likely resulted in high mortality for juvenile Chinook salmon, particularly during September and early October. This study was designed to be representative of both target life histories and to be used to evaluate the likely impacts on each of them. Based on what is known about size and habitat, the results suggest that reservoir rearing fry were likely negatively impacted by the 2023 drawdown, perhaps quite substantially. On the other hand, the drawdown may have improved downstream passage conditions for fall migrants compared to historical (pre-injunction) operations.

The statistical model used in this analysis extended the family of mark-recapture models described in Hance and others (2020, 2022) that were developed to better link survival and migration timing to environmental covariates at management-relevant time scales. By using this time-integrated migration survival model framework we were able to identify differences in the effectiveness of the injunction measure in each reach through time that earlier methods based on single release point-estimates (for example Skalski and others, 1998) are unable to capture. Novel elements of the statistical model presented here included the addition of terms to account for the effect of acoustic tag battery life and terms to account for differences in apparent survival due to individual fish characteristics (for example, fish size). By including the former terms, we were able to eliminate bias from tag battery failure on estimates of apparent survival. The latter terms enabled us to identify differences in apparent survival in both the Lookout Point Reservoir and through Lookout Point Dam between the two target populations. However, one shortcoming of the model presented here is that estimates of apparent survival were based only on the covariate at the time of entry into a reach. Thus, we were not able to completely account for the conditions at the time of passage for fish that resided in the forebay for a period of time prior to passing Lookout Point Dam. This suggests one potential avenue for development in statistical methods for analyzing fish passage telemetry data by directly incorporating elements of exposure-time models to the existing time-integrated migration survival model framework.

Data collected in Lookout Point and Dexter Reservoirs showed that water temperature was 18°C or greater during September and early October and Lookout Point Reservoir became isothermic by late August thereby eliminating cool water refugia that typically exists when the reservoir has been managed using traditional (recent pre-injunction) operations (Kock and others, 2019b, 2019c). We found that survival was inversely related to water temperature in reaches that included Lookout Point Reservoir and Dexter Reservoir. This result was not surprising given that elevated water temperature has been shown to have significant consequences for juvenile Chinook salmon. Temperatures in the >17–20 °C range are known to impair metabolic activity, reduce swimming performance, and result in increased mortality for Chinook salmon, and temperatures in the 15–20 °C range have been shown to block the parr-to-smolt transformation (Adams and others, 1973). Marine and Cech (2004) found that juvenile Chinook salmon reared at 17–20 °C had similar growth, variable smoltification, and increased predation vulnerability compared to juvenile Chinook salmon reared at 13–16 °C. Elevated water temperature during our study likely resulted in increased predation rates by warmwater fish species (Fritts and Pearsons, 2004) such as Smallmouth Bass, Largemouth Bass (*Micropterus salmoides*), and walleye, which are pervasively present in reservoirs of the Middle Fork Willamette River (Murphy and others, 2021). Our results are consistent with these observations as the percent of tagged fish detected in the forebay of Lookout Point Reservoir was negatively related to water temperature: 2 percent of the tagged fish released during August 23–September 13 were detected in the forebay compared to 9 percent of the fish released during September 20–October 5 and 49 percent of the fish released during October 11–October 26 (fig. 3). This pattern was also observed for tagged fish released in the Lookout Point tailrace when examining detections at Dexter Dam as the percent of fish detected from the three release periods increased from 11 percent to 78 percent to 84 percent, respectively.

Many prior studies of juvenile Chinook salmon in the Lookout Point Project focused on the reservoir rearing life history which is thought to represent the most common life history. Reservoir rearing fry in Lookout Point Reservoir are afforded greater growth opportunities than stream rearing migrants and have been shown to obtain mean fork lengths between 160 mm and 200 mm by September (Larson and others, 2024). These fish are often located near the forebay of Lookout Point Dam by early August and at depths between 25 and 40 m where water temperatures were generally between 10–14 °C (Kock and others, 2019b). The fish used in this study were released at the head of the reservoir and had lengths that were on average smaller than reservoir rearing juveniles, but with some overlap in the length distributions. We found that larger fish had higher survival in Lookout Point Reservoir, but this effect was smaller than the effect of water temperature in Reach 0. Given what is known about the longitudinal distribution of reservoir rearing juvenile Chinook salmon in Lookout Point Reservoir and the fact the reservoir was isothermic by late August, it is likely that most naturally produced Middle Fork Willamette Chinook salmon that adopted a reservoir rearing life history in 2023 were exposed to even higher temperatures and attendant mortality than the tagged fish used in this study. While the benefits of larger size may have allowed some reservoir rearing fish to survive until the target drawdown elevation in November, we also found an inverse relationship between fish length and survival through Lookout Point Dam. In the absence of fall rain events, it is likely that regulating outlet flow would have to be held relatively low to maintain the target elevation. At the lowest RO flow and lowest reservoir elevations observed in our study, we found that only about half of 160 mm fish would have survived passage through the dam. However, most reservoir rearing fish would be larger than 160 mm in November, and extrapolating the length effect beyond the sizes of our study fish suggests that survival would be even lower. This comports with observations of Keefer and others, (2012, 2013) who found that the percentage of mortalities in rotary screw trap collections below Lookout Point Dam increased with fork length.

Comparatively less is known about the fall migrant life history in the Middle Fork Willamette River. In most Willamette Valley Project reservoirs, greater than 90 percent of fish produced migrate into the reservoirs as fry (Romer and others, 2016). However, Romer and others (2016) found that fall migrants represented 42 percent of the subyearling migrants from the North Fork Middle Fork Willamette River. In the McKenzie River, Oregon, this life history type produced the second highest total proportion of smolts passing Willamette Falls when averaged over the 2004–2013 brood years (Schroeder and others, 2016). In that study, spring fry migrants (the life history with closest correspondence to reservoir rearing fry) were the least common life history for McKenzie River origin smolts passing Willamette Falls. The results from this study suggest that, to the extent fall migrants represent a relatively large proportion of the population, the likely negative consequence of the 2023 drawdown on reservoir rearing fish may have been partially mitigated by improved opportunities for passage and survival for the smaller fall migrants. Despite fish size being negatively correlated with reservoir survival, the cooler temperatures in the fall would have led to higher survival for the smaller fall migrants entering in late October and November when compared to larger reservoir rearing migrants exposed to high temperatures in September. We found that smaller fish arriving in the Lookout Point Dam forebay at the lowest reservoir elevations and in conjunction with increased outflows from rain events in November would have had only minimal delay in the forebay and were likely to experience dam passage survival greater than 90 percent. However, the temporal window for passage was comparatively narrow. Romer and others (2016) observed the highest number of fall migrants exiting the North Fork Middle Fork Willamette River in December. By mid-December 2023, a series of atmospheric rivers led to rapidly increased reservoir elevations.

Pacific salmon evolved in highly variable environments and developed a wide variety of life histories strategies as an adaption to this variation. This diversity of behaviors serves to stabilize population numbers by spreading the risk across a wide portfolio of life histories (Schindler and others, 2010). However, environmental variability combined with uncertainty about the relative abundances and conditions fish encounter during other life stages makes it difficult to design one-size-fits-all management actions that benefit Pacific salmon. The results from our study suggest that the 2023 deep drawdown likely resulted in negative effects for the reservoir rearing life history, whereas fall migrants may have experienced positive effects, based on results from seasonal survival patterns. However, because the abundance of each life history type as well as the downstream survival and ocean survival for each life history is unknown, it is difficult to conclude whether the 2023 drawdown operation as a whole was either a net benefit or negative for the population.

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