

Evaluating reservoir passage and survival of juvenile Chinook Salmon to support reintroduction upstream of Shasta Dam, California

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Abstract

Objective: Juvenile Chinook Salmon *Oncorhynchus tshawytscha* that are released upstream of Shasta Reservoir migrate more than 35 km to reach Shasta Dam, although survival through this system is poorly understood. We conducted a reservoir-scale acoustic telemetry study to quantify downstream movement and survival under seasonally variable environmental conditions to inform decisions about juvenile collection strategies for Chinook Salmon reintroduction above Shasta Dam.

Methods: A total of 656 hatchery-origin juvenile Chinook Salmon were acoustic-tagged, released near the mouth of the McCloud River, and monitored in Shasta Reservoir and the Sacramento River from September 2024 through March 2025 using an array of telemetry receivers.

Results: Most tagged fish failed to move downstream through the McCloud River Arm of Shasta Reservoir and arrive at Shasta Dam. Survival probabilities were estimated at 0.268 to the downstream end of the McCloud River Arm and 0.119 to Shasta Dam. For fish that did reach the dam, elapsed time from release to arrival was 66.4 d, and fish typically arrived and departed during daylight hours. Nine tagged juveniles were detected downstream of the dam, and three were later detected more than 500 km downstream.

Conclusions: The consistently low survival and restricted downstream movement provide important information indicating that downstream collection of juvenile Chinook Salmon should be focused in the lower McCloud River and the upper portion of the McCloud River Arm of Shasta Reservoir rather than at Shasta Dam.

Keywords: acoustic telemetry, Chinook Salmon, fish behavior, high-head dams, juvenile salmon, Shasta Reservoir

Lay summary

Most tagged juvenile Chinook Salmon did not reach Shasta Dam, and survival through the system was low. These results inform whether collection upstream or dam passage approaches better support reintroduction efforts for winter-run Chinook Salmon.

Introduction

Shasta Dam was completed in 1945, blocking passage for migratory fish to approximately 306 km of historical spawning and rearing habitat in the Upper Sacramento River (including the McCloud and Pit rivers), California, USA (National Marine Fisheries Service [NMFS], 2009; Yoshiyama et al., 1998). In the Upper Sacramento River basin (SRB), four distinct populations of Chinook Salmon *Oncorhynchus tshawytscha* were historically present, including the spring run, winter run, fall run, and late-fall run (Yoshiyama et al., 1998). Among these, winter-run Chinook Salmon migrated far upstream into cold, high-elevation tributaries, such as the McCloud and Pit rivers, to spawn during summer months, taking advantage of snowmelt-fed flows and cool water temperatures (NMFS, 2009; Yoshiyama et al., 1998). Restricted access to high-quality habitat has been identified as a major factor in population declines for Chinook Salmon and steelhead *O. mykiss* (anadromous Rainbow Trout) in the SRB, ultimately leading to the listing of Sacramento River winter-run Chinook Salmon (SRWRCS), Central Valley spring-run Chinook Salmon, and Central Valley steelhead under the Endangered Species Act (Good et al., 2005; NMFS, 2014, 2024b). Increasing water temperatures in the SRB, prolonged drought conditions, and a unique Chinook Salmon life history strategy of summer spawning (compared with most fall spawning) have created a high extinction risk for SRWRCS (Lindley et al., 2007; NMFS, 2014). Therefore, reestablishing SRWRCS populations into cool, high-elevation tributaries has been identified as a priority action for the freshwater portion of the species' life history (NMFS, 2024a).

Research to support reintroduction of SRWRCS into previous habitat is ongoing, and in 2022 a partnership of tribal, state, and federal resource managers initiated an experimental outplanting of SRWRCS eggs into the McCloud River (Krempasky & Johnson, 2023; Krempasky et al., 2024; NMFS, 2023; Townsend, 2024). The McCloud River (located approximately 24 km upstream of Shasta Dam) is one of only two rivers in the world, along with Battle Creek, known to support SRWRCS (NMFS, 2023). For the experimental reintroduction, embryos were placed into streamside rearing containers for incubation; after emergence, the fish were able to enter the McCloud River for rearing and eventually moved downstream. Resource managers anticipated low survival and out-migration success for juvenile salmon (rearing and migratory [smolt] life stages) in Shasta Reservoir due to seasonally elevated water temperature, abundant predator populations, and insufficient downstream fish passage at Shasta Dam (Clancey et al., 2017; Krempasky & Johnson, 2023; Plumb et al., 2019; U.S. Bureau of Reclamation [USBR], 2016). Therefore, collection systems were developed and operated in the upper portion of the McCloud River Arm of Shasta Reservoir (Figure 1) in an attempt to capture juvenile SRWRCS before they entered the reservoir and were exposed to these factors. The collection systems included rotary screw traps, an inclined-plane trap, and an experimental head-of-reservoir collector (termed “the Juvenile Salmonid Collection System”; Claire et al., 2023, 2025). Juvenile SRWRCS that were collected in these systems were transported downstream

of Shasta and Keswick dams (Figure 1) and released into the main-stem Sacramento River near Redding, California. Collection and transport activities were implemented as interim measures to facilitate early reintroduction efforts. However, juvenile SRWRCS reservoir transit and survival remain critical uncertainties in determining whether collection should continue to occur upstream of Shasta Reservoir or shift to Shasta Dam, where dedicated fish passage infrastructure would need to be developed.

Acoustic telemetry studies conducted in 2017 provided insights into downstream migration survival and behavior in Shasta Reservoir (Adams et al., 2018; Plumb et al., 2019). During those studies, juvenile (hatchery) Chinook Salmon were tagged and released into the McCloud River in February ($n = 262$) and November ($n = 355$) of 2017, and movement was monitored for approximately 3 months following each release. Survival results differed markedly between the two studies; the February release group experienced elevated streamflows in the study area during which a high percentage of tagged fish migrated through the McCloud River Arm of Shasta Reservoir (77%) and were detected at Shasta Dam (69%). The median travel time from release to first detection at Shasta Dam was 54 d. In total, 41 fish (16%) were detected passing Shasta Dam, and three fish (1%) were detected 550 km downstream of Shasta Dam. In contrast, only 18 fish (5%) from the November release group were detected migrating out of the McCloud River Arm, four fish (1%) were detected at Shasta Dam (Plumb et al., 2019), and no fish were detected downstream of the dam. The two fish releases conducted in 2017 provide limited snapshots of fish survival and migration through Shasta Reservoir. Because results from the two studies were so disparate, additional research was needed to assess reservoir migration behavior and survival to inform decisions related to juvenile passage limitations upstream of Shasta Dam.

To address these needs, we conducted an acoustic telemetry study in Shasta Reservoir and the Sacramento River during 2024–2025 that spanned multiple seasons and included a range of reservoir environmental conditions. The purposes of the study were to (1) evaluate the survival and behavior of juvenile Chinook Salmon in Shasta Reservoir, (2) describe behavior and passage patterns at Shasta Dam, and (3) relate these metrics to environmental covariates (e.g., flows and reservoir stratification) and dam operations (e.g., intake alternatives).

Methods

Study site

The McCloud River originates 137 km northeast of Redding, California, as a series of spring-fed streams on the southeastern slope of Mount Shasta and flows south, eventually forming a set of waterfalls known as the McCloud River Falls. The river is impounded (Lake McCloud) by McCloud Dam and then flows through a deep canyon and joins Shasta Reservoir approximately 80 km from its origin. The McCloud River is one of three major tributaries, including the Upper Sacramento River and the Pit River, that flow into Shasta Reservoir (Figure 1), and together they form the Sacramento River

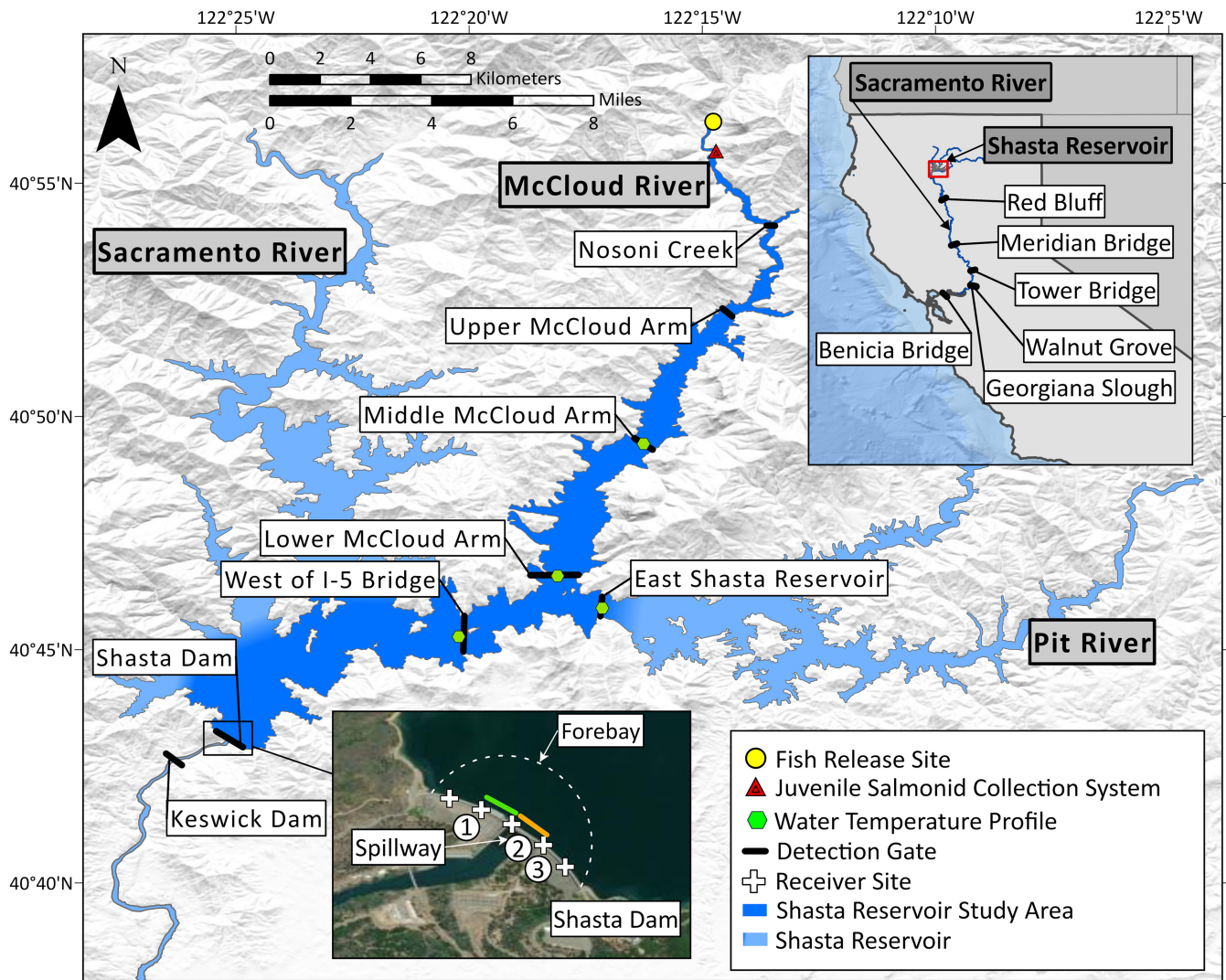


Figure 1 Map of Shasta Reservoir and Shasta Dam (lower inset), California, showing the location where acoustic-tagged juvenile Chinook Salmon were released (yellow circle) and the locations of acoustic telemetry receivers (black lines in main map and upper inset; white crosses in dam aerial view). The location of the Juvenile Salmonid Collection System is shown with a red triangle, and water temperature profile locations are denoted by green hexagons. In the lower inset, passage routes are delineated for the temperature control device (green) and river outlets (orange), with numbered receivers used for classification. (Base map: U.S. Geological Survey, The National Map-3DEP, GMTED2010 [April 2025]; inset: Maxar HD [July 2024].)

(California's largest river). Shasta Reservoir, formed by Shasta Dam, is the largest reservoir in California, with a surface area of 11,940 ha and 644 km of shoreline (USBR, 2016). The dam is located 14 km north of Redding and is situated at approximately river kilometer 550 upstream from the Pacific Ocean (i.e., river kilometer 0). Shasta Dam is a high-head hydroelectric facility that functions to store water in the reservoir, with withdrawals made through a multilevel temperature control device (TCD) connected to penstocks that supply five Francis turbines, allowing operators to select withdrawal depths and manipulate water temperature downstream in the Sacramento River (USBR, 2016). The dam is also equipped with multiple river outlets that are used for high-flow release operations (see [Supplementary Material A](#) for more details). A second dam, Keswick Dam, regulates outflow from Shasta Dam and is located 14 km downstream of Shasta Dam.

Environmental conditions

Environmental data (McCloud River streamflow and water temperature; Shasta Reservoir elevation) and Shasta Dam operations data were acquired for the period spanning September 2024–April 2025. These data were downloaded from a California Department of Water Resources website (California Data Exchange Center, 2024) and were summarized to daily averages for analysis. McCloud River streamflow and temperature data (station ID = MSS; 38.2 km upstream of Shasta Dam) were used to characterize riverine and reservoir environmental conditions that potentially influenced fish movement. Inflow, outflow, and reservoir elevation data at Shasta Dam (station ID = SHA) were used to assess operational conditions that may have affected fish behavior and passage in the reservoir and near the dam. Additional operations data, including TCD gate configurations (USBR, 2024, 2025) and

river-outlet-specific outflow (Stockwell et al., 2025), were provided by USBR.

We also collected vertical water temperature profile data in the McCloud River and in Shasta Reservoir (at 21–46-d intervals) during September 2024–January 2025 (Stockwell et al., 2025). Sampling was conducted near acoustic telemetry sites (described below) at two locations in the McCloud River Arm of Shasta Reservoir and at one location in Shasta Reservoir (Figure 1). Data were collected from a boat by using a conductivity–temperature–depth (CTD) sampling device (SonTek CastAway-CTD; YSI, Inc., Yellow Springs, Ohio). The Middle McCloud River Arm location was sampled six times (September 10, October 1, October 22, November 19, and December 18, 2024; and January 23, 2025); the Lower McCloud River Arm location and the West of I-5 Bridge location were sampled five times (October 1, October 22, November 19, and December 18, 2024, and January 23, 2025). Raw data were processed using the SonTek CastAway-CTD software (YSI, Inc.). The CTD profiles were processed to a vertical resolution of 1 m and interpolated to generate daily temperature estimates between sampling dates. Additionally, water temperature profiles for the Shasta Dam forebay were obtained from USBR. These profiles, which were collected at a higher temporal resolution (weekly), were also interpolated to daily values. The original 5-m vertical resolution was interpolated to 1-m intervals to align with the CTD data set.

Fish tagging and release

We used the Juvenile Salmon Acoustic Telemetry System (McMichael et al., 2010) to evaluate migration behavior and survival of juvenile Chinook Salmon during our study. A total of 656 juvenile Chinook Salmon were tagged and released from September to December 2024 (Supplementary Material B Table 1). Study fish were late-fall-run Chinook Salmon produced by Coleman National Fish Hatchery (Anderson, California), which is where fish tagging occurred. These fish were the only option available for evaluating migration behavior and survival in Shasta Reservoir. Late-fall-run Chinook Salmon from Coleman National Fish Hatchery were also used by Plumb et al. (2019). These fish were larger than naturally produced SRWRCS in the McCloud River based on collection data (Claire et al., 2025), but the SRWRCS were too small for acoustic tagging. Fish were held in outdoor concrete raceways supplied with continuously flowing water until 2 d prior to tagging, at which time they were transferred into indoor metal tanks, where food was withheld to ensure stomach evacuation prior to surgery. Following the protocols described by Liedtke et al. (2012), juvenile Chinook Salmon were surgically tagged with an acoustic transmitter (Model SS400; Advanced Telemetry Systems, Isanti, Minnesota; 216 mg; 15.00 × 3.38 mm; pulse rate interval [PRI] = 5 or 7 s) and a PIT tag (Model APT12; Biomark, Boise, Idaho; 106 mg; 12.50 × 2.03 mm). The 5-s PRI transmitters operated for a median lifespan of 110 d, and the 7-s PRI tags operated for a median lifespan of 141 d.

After tagging, fish were held overnight in indoor metal tanks before being transported 1.5 h (90 km) to the release location. Water temperature and oxygen concentration were

Table 1 Summary statistics for acoustic-tagged juvenile Chinook Salmon that were released into the McCloud River, California, in 2024. The table includes detection percentages and fish counts (in parentheses) at the Nosoni Creek, Lower McCloud River Arm, and Shasta Dam detection sites for each release group. Data are from Stockwell et al. (2025).

Release group	<i>n</i>	Nosoni Creek	Lower River McCloud Arm	Shasta Dam
Sep 24	65	61.5 (40)	24.6 (16)	3.1 (2)
Oct 15	100	55.0 (55)	4.0 (4)	1.0 (1)
Oct 22	100	65.0 (65)	16.0 (16)	5.0 (5)
Oct 29	104	79.8 (83)	20.2 (21)	3.8 (4)
Nov 5	106	91.5 (97)	10.4 (11)	7.5 (8)
Nov 19	104	95.2 (99)	54.8 (57)	33.7 (35)
Dec 3	77	83.1 (64)	18.2 (14)	16.9 (13)

measured in holding tanks prior to transportation (Supplementary Material B Table 1). Fish were then transported in 113.6-L coolers equipped with aerators. Prior to release, water temperature was measured in the coolers at the release location, and gradual water tempering occurred if the temperature difference between the cooler and the river was greater than 2°C (Supplementary Material B Table 1). Fish were removed with sanctuary nets and released into the river at the McCloud River Bridge (~34.4 km upstream of Shasta Dam; Figure 1) on seven release days between September and December 2024 (Table 1).

Fish monitoring array

A total of 55 acoustic telemetry receivers (Models SR3017 and SR3001, Advanced Telemetry Systems; Model WHS4350L, Lotek Wireless, Inc., Newmarket, Ontario, Canada) were used to monitor fish movement from the McCloud River release site to San Francisco Bay (Benicia-Martinez Bridge) on the lower Sacramento River. Telemetry receivers were deployed at 14 different locations (Figure 1; Table 2).

Receivers located in Shasta Reservoir and at Shasta and Keswick dams were deployed specifically for this study. Receivers located downstream of Keswick Dam were an existing array of acoustic receivers maintained by the U.S. Fish and Wildlife Service, U.S. Geological Survey, and University of California–Santa Cruz for various studies within the SRB (CalFishTrack, 2024).

Data analysis

Telemetry records were compiled and automatically proofed before being integrated with fish tagging and release, environmental, and dam operations data to create a comprehensive final data set for analysis. Raw acoustic detection data were filtered using an automated program to remove false positive detections following procedures outlined by Beeman and Perry (2012). This data processing was carried out using SAS software (SAS Institute, Inc., 2013). All other data analyses

Table 2 Locations of acoustic receiver arrays in Shasta Reservoir and the Sacramento River, California. The table includes site names, associated water bodies, river kilometers (rkm) upstream of the Pacific Ocean (rkm 0), and the number of receivers installed at each site. Data are from [Stockwell et al. \(2025\)](#).

Site name	Water body	Location (rkm)	Number of receivers
Nosoni Creek	Shasta Reservoir	583.4	4
Upper McCloud River Arm	Shasta Reservoir	579.3	2
Middle River McCloud Arm	Shasta Reservoir	573.5	3
Lower River McCloud Arm	Shasta Reservoir	567.5	4
East Shasta Reservoir ^a	Shasta Reservoir	564.8	3
West of the I-5 Bridge	Shasta Reservoir	563.3	4
Shasta Dam	Shasta Reservoir	554.5	5
Keswick Dam	Sacramento River	553.1	1
Red Bluff	Sacramento River	457.0	2
Meridian Bridge	Sacramento River	290.8	2
Tower Bridge	Sacramento River	172.0	3
Walnut Grove	Sacramento River	120.3	2
Below the Georgiana Slough	Sacramento River	118.4	4
Benicia-Martinez Bridge	Sacramento River	52.2	16

^aUpstream of the McCloud River Arm–Shasta Reservoir confluence in the adjacent Pit River Arm.

were conducted using Python Spyder version 3.8.10 ([Raybaut, 2009](#)) and R version 4.4.1 ([R Core Team, 2024](#)). Figures were produced using Matplotlib version 3.10.5 ([Hunter, 2007](#)) in Python and using ggplot2 version 3.5.1 ([Wickham, 2009](#)) in R. Maps were created using ArcGIS Pro version 3.3.1 ([Esri, 2024](#)).

To estimate release-group-specific survival of juvenile Chinook Salmon, we conducted an analysis using Cormack–Jolly–Seber mark–recapture models ([Cormack, 1964](#); [Jolly, 1965](#); [Seber, 1965](#)). For this analysis, a capture history for each individual fish was created to summarize fish detection histories in the study area. The five-digit capture history included a 1, indicating release for the first character, and the remaining characters were either a 1 (detected) or a 0 (not detected) based on each fish's detection history. The reach between the release location and the Nosoni Creek site was treated as an acclimation reach ([Perry et al., 2018, 2019](#)) to (1) allow hatchery fish to acclimate to the natural setting and recover from potential handling effects associated with tagging, transport, and release and (2) eliminate potential bias associated with the Juvenile Salmonid Collection System, which was located in the reach ([Chen et al., 2025](#); [Sturrock et al., 2019](#)). We estimated survival in study area segments to Shasta Dam, and we estimated a single value of λ , the joint probability of surviving and migrating downstream ([Perry et al., 2010](#)), for all sites downstream of the dam. Survival probabilities were allowed to vary by reach and release group, and we used RMark version 3.0.0 ([Laake, 2013](#)). This structure allowed estimation of survival probabilities for each release group in two discrete segments (from the Nosoni

Creek site to the Lower McCloud River Arm site and from the Lower McCloud River Arm site to Shasta Dam) and the cumulative survival probability from the Nosoni Creek site to Shasta Dam ([Supplementary Material B Table 3](#)). Confidence intervals for the cumulative survival estimates by release group were calculated using the delta method ([Seber, 1982](#)).

Residence time and travel time were calculated to characterize movement dynamics. Residence time (the amount of time that an individual spent within a reach) was defined as the time between the first and last detections at a given detection gate during a fish visit, where a fish visit was defined as a sequence of one or more detections of an individual at a gate. Travel time (defined as the duration that an individual spent moving between locations) to Shasta Dam was calculated as the elapsed time from release to the first detection at Shasta Dam, while reservoir transit time was calculated from the last detection at the Lower McCloud River Arm site to the first detection at Shasta Dam. Total residence time in the Shasta Dam forebay was determined by summing all residence periods at that site and grouping individuals by the month of their first arrival. To visualize spatial patterns in total fish detections in the Shasta Dam forebay, detection percentages at each receiver in the forebay were calculated by dividing the number of detections at a given receiver by the total number of detections in the forebay. Diel patterns in fish movement at Shasta Dam were assessed by binning the time stamps of first and last detections at the dam forebay by hour of day and summarizing the detection counts across the 24-h cycle.

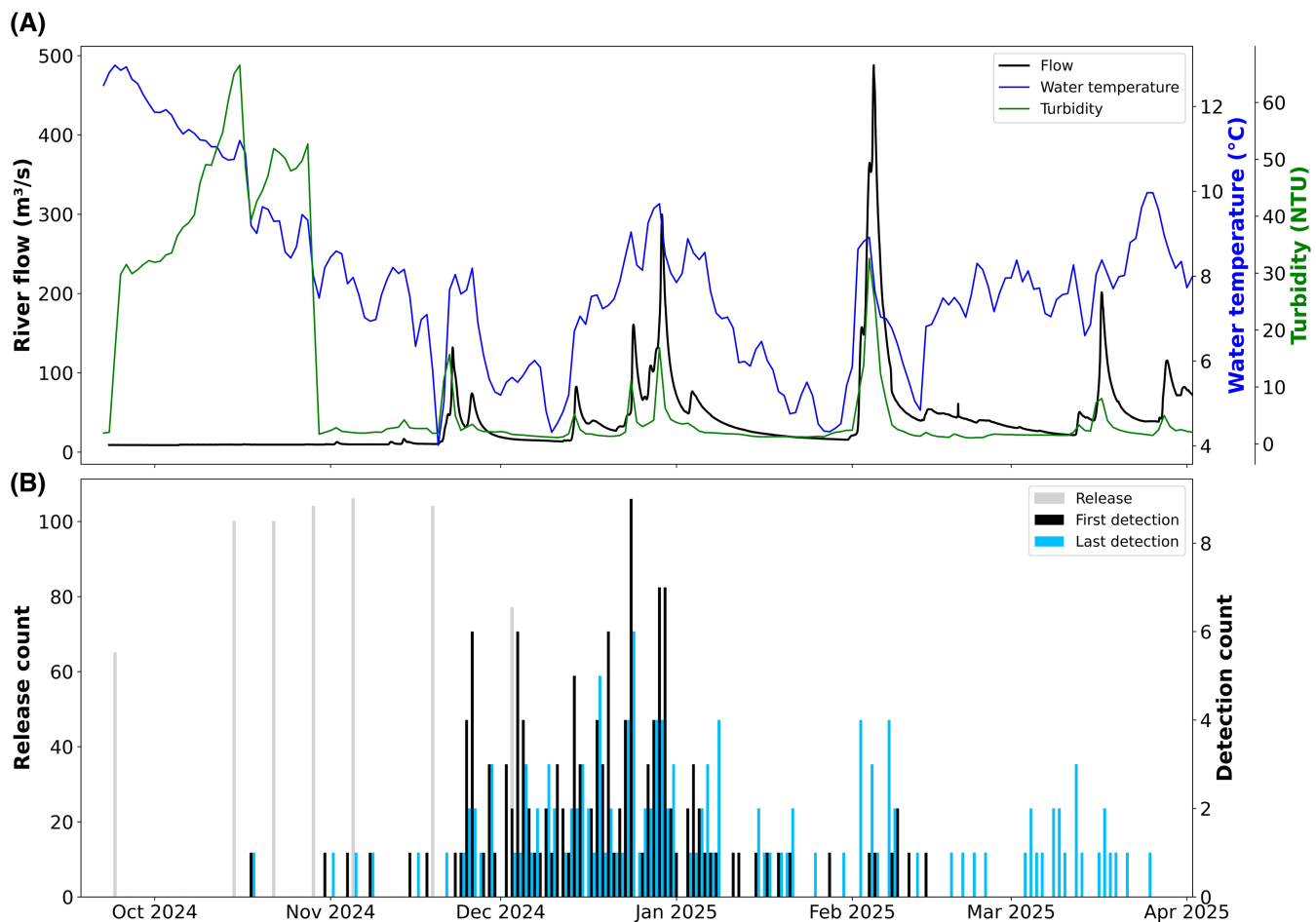


Figure 2 Environmental conditions in the McCloud River, California, from September 2024 to April 2025 (Stockwell et al., 2025): (A) daily mean river flow (black line), daily mean water temperature (blue line), and daily mean turbidity (green line) and (B) days of juvenile Chinook Salmon release (gray bars), first detection at the Lower McCloud River Arm gate (black bars), and last detection at the Lower McCloud River Arm gate (blue bars).

Results

Environmental conditions and dam operations

We observed substantial variability in environmental conditions during the study. Several large rain events affected factors such as streamflow, reservoir elevation, and inflow/outflow at Shasta Dam during the study. McCloud River streamflows were very low (<10 m³/s) during most of the study period but peaked repeatedly (e.g., 91–402 m³/s between November and February; Figure 2A). Water temperature ranged from 4°C to 13°C during the study period, declining from 13°C in September to 4°C in November and then fluctuating between 4°C and 9°C through March (Figure 2A). Turbidity ranged from 1 to 68 NTU and generally increased during periods of higher flow. A sustained period of elevated turbidity (29–68 NTU) occurred between September 24 and October 29, 2024, with a peak on October 16, 2024 (Figure 2A).

Vertical water temperature profiles indicated stratification in the McCloud River Arm and in the main body of Shasta Reservoir during fall 2024 (Supplementary Material B Figure 1). At all three locations, surface temperatures averaged 25°C from September to October 2024 and subsequently cooled, ranging from 10.0°C to 12.5°C from late December 2024

through January 2025. The Middle McCloud River Arm was stratified from September until late November 2024, followed by mixing, when thermal stratification weakened and temperature differences in the water column decreased (Supplementary Material B Figure 1). Temperature profiles for the Lower McCloud River Arm were not collected in September; profiles from October through late November showed stratification, after which the water column became isothermal and continued cooling through January 2025. The Shasta Dam forebay displayed strong stratification from September through October 2024, with a cold deepwater layer present (Supplementary Material B Figure 1). Mixing began in November 2024, and the coldwater layer became progressively shallower from December 2024 through April 2025. Reservoir operations and hydrologic conditions varied throughout the study period. Shasta Reservoir surface elevation ranged from 300 to 320 m, with peak elevation, inflow, and outflow occurring in February 2025 (Figure 3C).

Reservoir passage and arrival at Shasta Dam

We detected 503 (76.7%) of the 656 tagged juvenile Chinook Salmon released for this study, but relatively few fish (68 fish [10.4%]) migrated through Shasta Reservoir and were

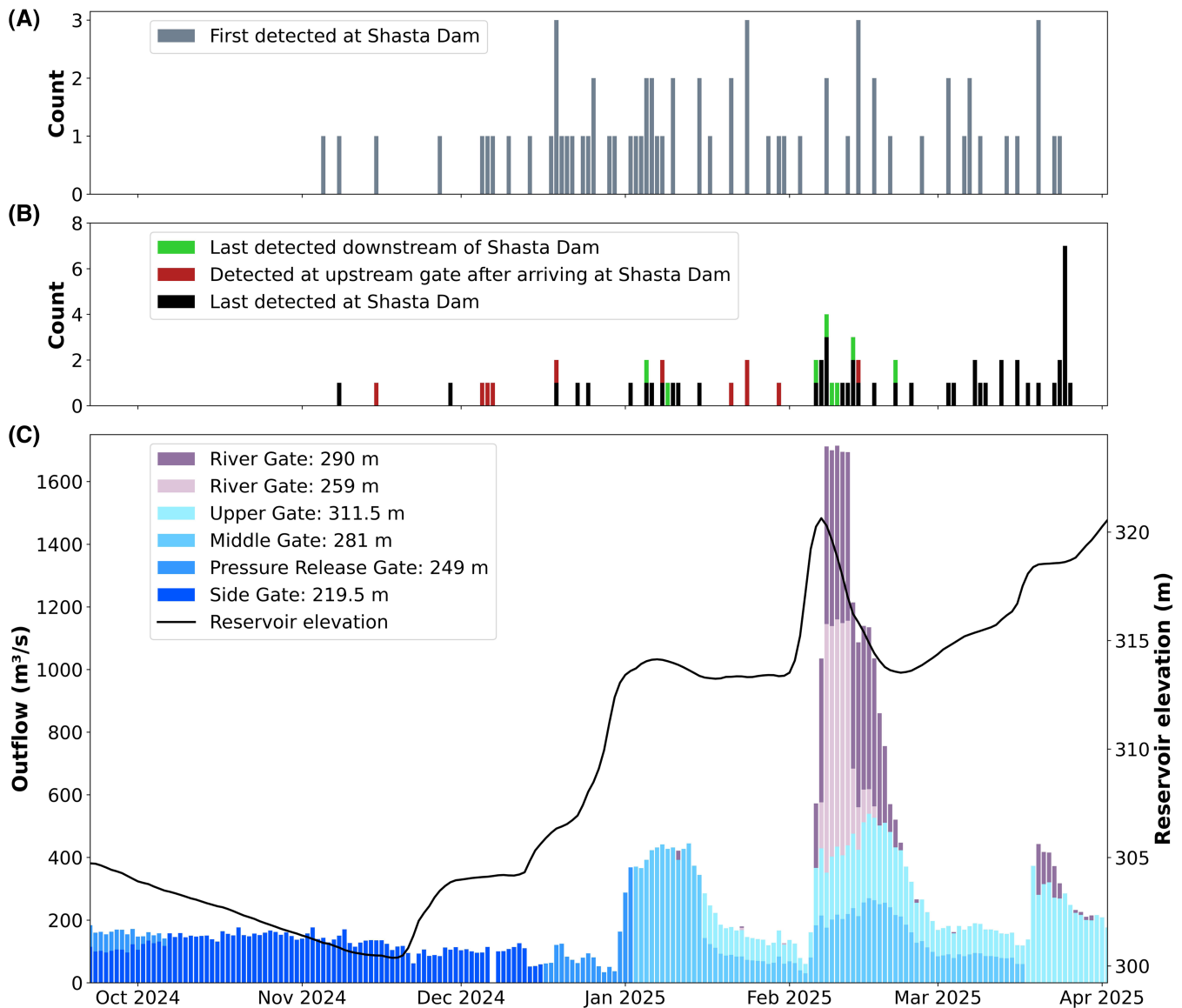


Figure 3 Fish detections and dam operations at Shasta Dam from September 2024 to April 2025 (Stockwell et al., 2025): (A) daily counts of tagged juvenile Chinook Salmon first detected at Shasta Dam; (B) daily counts of tagged fish last detected at Shasta Dam (black), individuals last detected at Shasta Dam before being detected downstream (green), and individuals first detected at Shasta Dam that were subsequently detected at an upstream gate (red); and (C) daily mean reservoir elevation (black line) and the gate location of daily mean outflow through the Temperature Control Device (blues) and the river outlets (purples). See [Supplementary Material A](#) for detailed descriptions of gate configurations and operating structures.

detected at Shasta Dam (Table 1). Detection percentages declined sharply as fish moved downstream through the McCloud River Arm—from 76.7% at the Nosoni Creek site to 21.2% at the Lower McCloud River Arm site. Fish moving out of the McCloud River Arm did so slowly, with a median travel time of 43.6 d from release to detection at the Lower McCloud River Arm site. Downstream movement primarily occurred after water temperatures in the upper 30 m of the water column cooled below 18°C (Supplementary Material B Figure 1), and most tagged fish reached the Lower McCloud River Arm site between late November 2024 and early January 2025 (Figure 2B). Apparent survival from the Nosoni Creek site to Shasta Dam was low (0.082 or less; Supplementary Material B Table 3) for most release groups (September 24–November 5; Figure 4; Supplementary Material B Table 3) but was higher

for fish released on November 19 (0.354) and December 3 (0.203; Supplementary Material B Table 3). Across all groups, fish that ultimately arrived at Shasta Dam did so between November 2024 and March 2025 (Figure 3A) and required a median of 66.4 d to travel from the release site to arrival at the dam, including approximately 34.5 d spent migrating through Shasta Reservoir.

Upstream trips

In addition to downstream movement, we observed upstream travel by tagged juvenile Chinook Salmon. At the East Shasta Reservoir gate (Pit River Arm), 60 fish were detected. These detections indicate that a portion of tagged fish traveled upstream into the Pit River Arm after exiting the McCloud River Arm, either directly or after first reaching Shasta Dam.

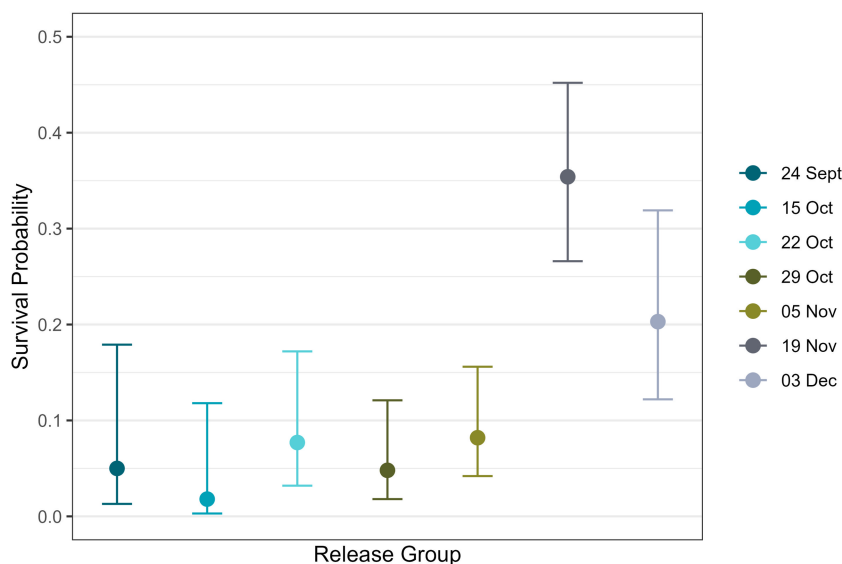


Figure 4 Apparent survival probability estimates from release to Shasta Dam for individual release groups of juvenile Chinook Salmon. Releases occurred in 2024. Points represent group-specific survival estimates, with 95% CIs shown as vertical error bars.

Of these individuals, 37% were later detected at Shasta Dam; however, 25% were not detected elsewhere in the study area after detection at the East Shasta Reservoir gate. Median residence time at the East Shasta Reservoir gate for the fish that were later detected downstream was 5.6 d, with individual residence times ranging from less than 1 h (0.03 h) to 93.6 d. Upstream trips were most common in the downstream reach of the McCloud River Arm (Lower McCloud River Arm to Middle McCloud River Arm: 43 fish) and decreased in upstream reaches (Middle McCloud River Arm to Upper McCloud River Arm: 34 fish; Upper McCloud River Arm to the Nosoni Creek site: 14 fish). Additionally, 20 fish moved upstream from the West of the I-5 Bridge site to the Lower McCloud River Arm site. Eleven fish arrived at Shasta Dam before traveling back upstream, and only three of those fish ever returned to the dam (Figure 3).

Shasta Dam forebay behavior and passage

For the 68 individuals that reached Shasta Dam, arrival primarily occurred during daylight between 0600 and 1800 hours, with a peak in both first detections and last detections at 1000 hours (Figure 5B). The greatest percentage of detections occurred near the center of the dam, and detection percentages were generally similar among remaining sites (Figure 5A). Median forebay residence time was 11.9 d (0.1–104.6 d; Figure 5C). Eight (11.8%) of 68 individuals were detected passing Shasta Dam (Supplementary Material B Table 4). Two fish passed the dam in January 2025, and six fish passed in February 2025. Of the eight fish, six passed on days when the river outlet gates were open, and passage assignments indicated that four individuals passed via the TCD and four fish passed via the river outlet gates (Supplementary Material A).

Sacramento River migration outcomes

In total, 10 fish were observed downstream of Shasta Dam (Supplementary Material B Table 4). Of these, two fish were captured in the Juvenile Salmonid Collection System in

October 2024, transported around Shasta and Keswick dams, and released into the Sacramento River near Redding, California (Supplementary Material B Table 4). Only one of the two fish was later detected (at Red Bluff; Supplementary Material B Table 4). The remaining eight fish passed Shasta Dam and were subsequently detected downstream. Three of the eight fish that passed Shasta Dam survived downstream passage through the lower Sacramento River and were last detected entering the San Francisco Bay at the Benicia-Martinez Bridge (Supplementary Material B Table 4).

Discussion

Downstream movement and survival

We found that most acoustic-tagged juvenile Chinook Salmon failed to move downstream through Shasta Reservoir and arrive at Shasta Dam, providing valuable information for reintroduction planning. The overall apparent survival estimate (from the upper portion of the McCloud River Arm of Shasta Reservoir to Shasta Dam) during our 7-month study was 0.119, indicating that about 1 in 10 juvenile Chinook Salmon survived and moved downstream through the reservoir. Downstream movement through the McCloud River Arm of Shasta Reservoir was generally poor as well, based on the apparent survival estimate of 0.268. These findings corroborate results from a previous study, which found that only four acoustic-tagged fish (of 355 released for the study; 1.1%) moved downstream from the McCloud River to Shasta Dam during fall 2017 (Plumb et al., 2019). Collectively, results from the two studies (Plumb et al., 2019) indicate that downstream migration and survival of juvenile Chinook Salmon through Shasta Reservoir during the fall and winter months are limited. This finding is important because SRWRCS collection in the McCloud River and the upper portion of the McCloud River Arm of Shasta Reservoir indicates that downstream migration is primarily occurring during September and October each year (Claire et al., 2023, 2025; Krempasky &

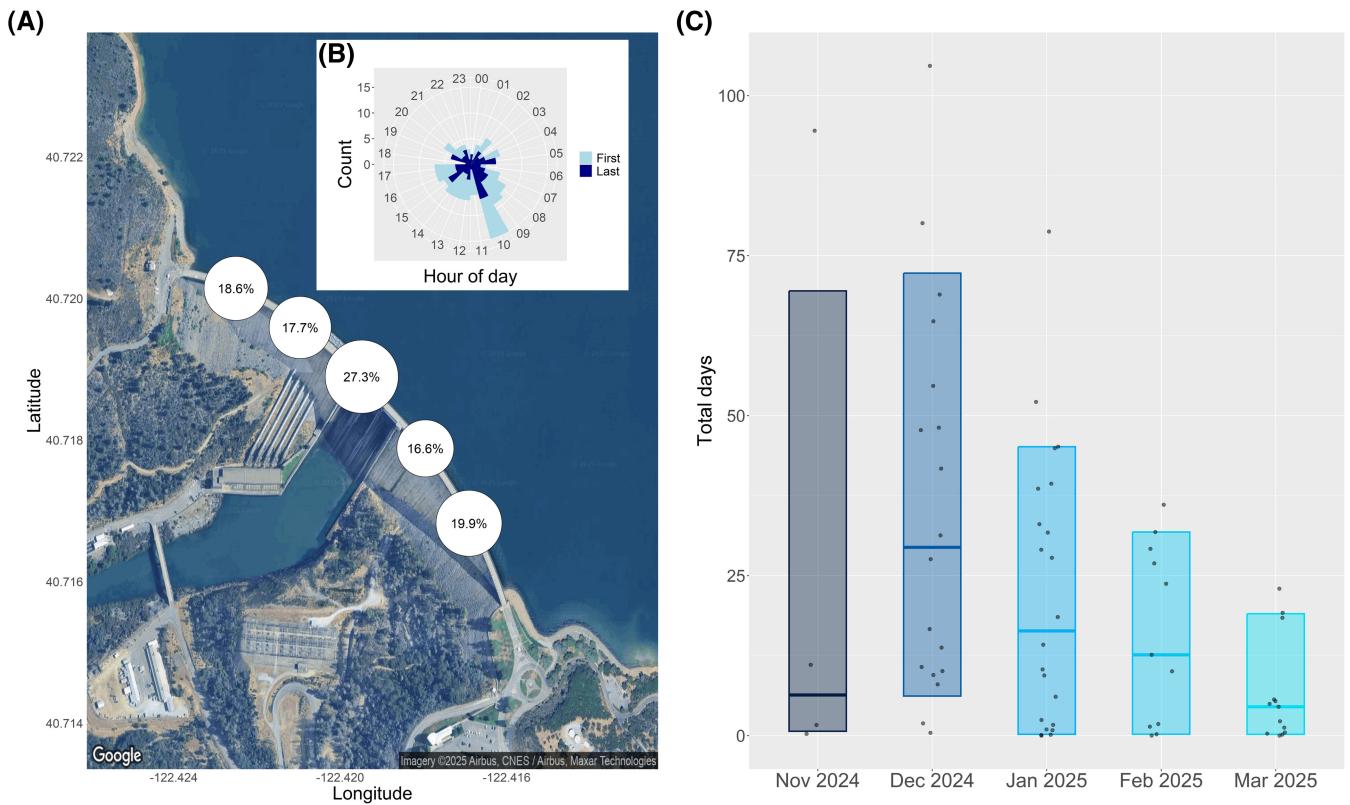


Figure 5 Detection behavior at the Shasta Dam forebay (Stockwell et al., 2025) represented by (A) a satellite image of the forebay, displaying percent detections for each receiver with bubble overlays illustrating total detections; (B) a rose plot showing first detection counts and last detection counts per hour of day; and (C) a box plot illustrating the total days spent in the forebay by arrival month, where each point represents an individual fish, horizontal bars indicate the median residence time, and boxes span the 10th–90th percentiles of the data. (Background imagery from Google Earth.)

Johnson, 2023). In a recent study, Anchor QEA and HDR Engineering, Inc. (2026), used a life cycle modeling approach to determine that at least 80% of the juvenile SRWRCS would need to survive and move downstream of Shasta Dam to support a steady or increasing reintroduced population upstream of the dam. Thus, it seems that collection efforts for juvenile SRWRCS should likely be focused on the lower McCloud River or the upper portion of the McCloud River Arm of Shasta Reservoir based on the low percentage of fish that successfully moved downstream to Shasta Dam during fall 2017 (Plumb et al., 2019) and during our study. This is especially true given that collection efficiency for some experimental trapping systems located in this area have exceeded 70% during specific operating periods (Michel et al., 2025; Townsend, 2024).

Factors affecting reservoir behavior and survival

Reservoir size and complexity, a lack of hydraulic cues, seasonal thermal stratification with warm water temperatures (>20°C) in the upper 20 m of the water column, and predation by piscivorous fish species have all been proposed as factors likely to limit successful downstream migration by SRWRCS through Shasta Reservoir (Clancey et al., 2017; USBR, 2016). Although our study was not designed to explicitly evaluate each of these factors, data collected during the study provide useful insights. For example, we found that many tagged fish made upstream trips between detection sites located in the McCloud River Arm of Shasta Reservoir, even though only

about one-fifth of the total tagged population eventually moved downstream through the entire length of the McCloud River Arm. Similar upstream movements occurred elsewhere in the reservoir: Some fish moved upstream after reaching Shasta Dam, while others shifted into the upper portion of Shasta Reservoir based on last detections at the East Shasta Reservoir site. These nondirected behaviors may reflect reduced hydraulic cues, particularly low water velocities and turbulence, which have been associated with migration limitations in other western U.S. reservoirs (Coutant, 2001; Tiffan et al., 2009). Thermal conditions also seem to have influenced movement. Downstream migration primarily occurred after surface temperatures declined below 16°C and thermal stratification weakened (Supplementary Material B Figure 1). Most tagged fish in our study were first detected moving downstream (Middle McCloud River Arm, Lower McCloud River Arm, and Shasta Dam forebay sites) after mid-November. Previous studies in large reservoirs have shown that juvenile Chinook Salmon tend to select cooler water (<16°C) during periods of stratification, typically residing in deeper, cooler layers through the fall months until mixing occurs (Beeman, Evans, Haner, Hansel, Hansen, Hansen, Hatton, Kofoot, & Sprando, 2016; Beeman, Evans, Haner, Hansel, Hansen, Hansen, Hatton, Sprando, et al., 2016; Kock, Perry, et al., 2019; Kock, Verretto, et al., 2019).

Finally, predation may also have been a factor in the limited downstream detections that occurred during our study.

Shasta Reservoir supports abundant populations of several piscivorous fish species, including Smallmouth Bass *Micropterus dolomieu*, Spotted Bass *M. punctulatus*, Largemouth Bass *M. nigricans*, Rainbow Trout, and Brown Trout *Salmo trutta* (Ratcliff et al., 2009; Saito et al., 2001). These species have been consistently collected at trapping sites located in the upper portion of the McCloud River Arm of Shasta Reservoir, where juvenile SRWRCS have been identified in stomach samples of predatory fish (Claire et al., 2025). Collectively, these examples highlight factors (hydraulic, thermal, and predation) that could limit successful downstream movement of juvenile Chinook Salmon through Shasta Reservoir.

Forebay behavior and passage

Although numerically limited, the tagged fish that arrived at Shasta Dam provided information about near-dam behavior, dam passage, and downstream survival. We found that fish primarily arrived and exited the dam forebay during daylight hours and that forebay residence time decreased from December to March. Tagged fish detections were highest near the center of the dam, where water is passed through the project, and we found that most passage (based on downstream detections in the Sacramento River) occurred during two periods of elevated discharge (early January and early February). Passage seemed to be evenly split between the TCD and the river outlet gates, and we observed that some fish survived passage and were able to move downstream through the Sacramento River. These observations were similar to those from the spring 2017 study in which 16% of study fish were detected downstream of Shasta Dam and 1% moved downstream to San Francisco Bay during a period of elevated streamflow (Plumb et al., 2019).

Limitations

Telemetry evaluations are commonly associated with limitations related to the size of fish that can be tagged, the operating life of the transmitters, and assumptions that are inherent in the survival modeling process. In this study, we used hatchery-produced late-fall-run Chinook Salmon that were larger than naturally produced SRWRCS juveniles in the system. Average fork length of study fish was 132 mm across all release groups compared to 46.9 mm fork length for SRWRCS that were collected at in-river collection systems during our study (Claire et al., 2025). Juvenile salmon migration rate and survival generally increase with increasing fish size (Claiborne et al., 2011; Johnson et al., 2017; Kock, Verretto, et al., 2019; Sogard, 1997); thus, we would expect our downstream detections and survival probabilities to overestimate these parameters for SRWRCS. Transmitter operating life (110–141 d) also constrained our ability to detect fish that survived and migrated downstream after transmitters expired; these individuals would have been assigned a “mortality” fate in our analysis. Additionally, the survival estimates presented here are generated using a spatial form of the Cormack–Jolly–Seber model, which assumes that tagged individuals are obligatory migrators, as is typically the case for juvenile salmon during their seaward migration. Under this framework, if a fish is detected at one receiver gate but not at the next, it is assumed

to have died between gates or to have been missed at the downstream gate. However, this assumption is problematic in Shasta Reservoir, where populations of stocked, landlocked Chinook Salmon are known to persist and grow to large sizes and where anecdotal evidence indicates that some newly reintroduced SRWRCS are adopting an adfluvial life history strategy (Bartlett, 2025; Kuta, 2025). As such, failure to detect a fish at a downstream gate may reflect residency within that reach rather than mortality. Therefore, reach mortality as estimated in this study is an amalgamation of true mortality as well as the propensity for fish to remain in specific reservoir reaches. Reaches with low apparent survival may thus reflect high mortality, high residency, or both, whereas reaches with high survival indicate low levels of both mortality and residency. Future telemetry studies incorporating sensor tags (e.g., predation-sensing or accelerometer tags) could help disentangle this discrepancy by providing direct information on individual fates.

Conclusions

This study provides a multiseason assessment of juvenile Chinook Salmon movement through Shasta Reservoir and at Shasta Dam, revealing substantial constraints on downstream migration during fall and winter. Survival and movement through the reservoir were low, with fish behavior likely affected by factors such as reservoir size and complexity, weak hydraulic cues, seasonal thermal structure, and predation. Based on these findings, reintroduction efforts may need to focus on collecting SRWRCS in the lower McCloud River or the upper portion of the McCloud River Arm of Shasta Reservoir to maximize juvenile survival rates. The few fish that reached Shasta Dam offered additional insight into forebay use, passage timing, and route selection, particularly during periods of elevated discharge. Together, these results illustrate the challenges that juvenile salmon face when migrating through large reservoirs.

Supplementary material

Supplementary material is available at *Transactions of the American Fisheries Society* online.

Data availability

Data from this study are publicly available online at Stockwell et al. (2025). Data for vertical water temperature profiles at Shasta Dam are available upon request from the USBR Northern California Area Office.

Ethics statement

All fish handling, tagging, and transport were conducted in accordance with Protocol PRF-2023-08 approved by the Institutional Animal Care and Use Committee at the U.S. Geological Survey Western Fisheries Research Center and Protocol Michc2207 approved by the Institutional Animal Care and Use Committee at the University of California–Santa Cruz.

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Conflicts of interest

The authors declare that there are no conflicts of interest.

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