Technical Report 2014-3

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Study Code: **ADS-W-13-1**

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L. Martinez-Rocha, J. Renner, C. Erdman
Department of Fish and Wildlife Sciences
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and

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Ellensburg, WA 98926

For

U.S. Army Corps of Engineers
Walla Walla District, Walla Walla WA

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Executive Summary

The Biological Opinion (BiOP) for the operation of the Federal Columbia River Power System specifies management goals for survival rates of adult salmon and steelhead during upstream migration. Recent data from PIT-telemetry monitoring indicates survival rates are lower than BiOp targets. We conducted a multiple objective study in 2013 using radiotelemetry and environmental monitoring to: 1) characterize general adult migration behavior and passage metrics at lower Snake River dams and reservoirs upstream of Ice Harbor Dam forebay, 2) test for associations between behavior of adult spring–summer Chinook salmon during passage of Little Goose Dam and dam operations and river environmental conditions; and 3) monitor adult salmonid passage in relation to temperature conditions in the Lower Granite Dam fishway and forebay near the fishway exit.

We radio-tagged and monitored movements of three samples of Chinook salmon: 600 adult spring–summer Chinook collected and trapped at Bonneville Dam, 300 jack Chinook salmon collected and tagged at Bonneville Dam, and 300 adult Chinook salmon collected and tagged at a new trap in the Ice Harbor Dam south fishway. Inclusion of adults tagged at Bonneville Dam increased sample size and allowed tests for short-term tagging effects in the Ice Harbor-tagged sample, though we note that differences in tagging schedules between the locations complicated direct comparison between the two adult samples. The primary sources of environmental data were from strings of temperature loggers deployed in the forebay of Lower Granite Dam and operational and river environmental data collected at dams by USACE. Prior to estimation of passage metrics, we assessed the potential for operation of the new trap at Ice Harbor Dam to affect passage of adults in the fishway downstream of the trap. These analyses revealed no strong or consistent evidence the operation of the trap delayed adults downstream, though we note that most comparisons had small sample sizes that prevented statistical comparison.

We estimated conversion rates of radio-tagged adults for seven reaches between the base of Lower Monumental Dam and the top of Lower Granite Dam. Comparisons among release groups differed ($P < 0.05$, $\chi 2$ tests) for two reaches: Ice Harbor-tagged adults had lower conversion from the base of Lower Monumental dam past Lower Monumental Dam (0.901 versus 0.982 for Bonneville adults and 1.000 for Bonneville jacks) and from the base of Lower Monumental Dam past Lower Granite Dam (0.860 versus 0.969 for Bonneville adults and 0.974 for Bonneville jacks). These results suggest a likely short-term handling effect for Ice Harbor-tagged fish prior to passage of Lower Monumental Dam. There were no statistically meaningful differences among tag groups in any reach upstream from Lower Monumental Dam. When the combined radiotelemetry and PIT detection data were considered, 95.2% of Bonneville adults, 97.4% of Bonneville jacks, and 84.0% of Ice Harbor adults were considered to have passed Lower Granite Dam. The groups of fish that did not pass Lower Granite Dam were last detected at a variety of Snake River sites, but primarily in dam tailraces and fishways.

Evaluation of passage behavior at Lower Monumental, Little Goose and Lower Granite dams provided estimates of the distribution of adults approaching and entering different fishways, the number of approaches, entries, and exits, and estimates of entry and passage efficiency. Excluding the apparent tag effects in the Ice Harbor-tagged adult group, these analyses revealed relatively high entrance and passage efficiency (> ~95%). Median tailrace-fishway exit passage times were more rapid at Lower Monumental (12.1-18.6 h) and Little Goose (11.1-19.7 h) dams than at Lower Granite Dam (19.8-24.1). Fallback percentages ranged from 2.9-7.9% among the dams and three sample groups.

We used Cox proportional hazards regression to test for associations between Chinook salmon passage time and operational conditions at Little Goose Dam, while statistically controlling for several time-varying factors such as time of day and temperature. The models indicated increases in the rate of passage during periods of increased discharge from turbine units 1 and 3 and decreased passage rate with increased discharge through spillbays 1 and 6.

Temperature monitoring at Lower Granite Dam revealed forebay surface waters within 122 m of the fishway exit were above 20 ºC in the upper water column (< 6.1 m) from 1 July through 25 September, whereas temperatures remained near 18 ºC at depths >18 m. The warmer surface water resulted in warmer temperatures in the ladder from the transition pool to the exit than in the forebay and fishway entrance, and the difference in temperature was > 2 ºC from mid-July to mid-September. Relative few radio-tagged salmon passed during this period, preventing statistical evaluations, but the results were qualitatively consistent with previous observations showing longer passage times during periods with high fish ladder water temperature differences.

Introduction

Adult salmon and steelhead migrating to their natal streams in tributaries of the Columbia River must pass up to nine dams and their reservoirs, including four in the lower Columbia River and four in the lower Snake River. Losses and delays in migration at each hydroelectric project must be minimized to maintain the native fish runs and achieve the recovery goals outlined by the Northwest Power Planning Council (NWPPC) and by NOAA Fisheries (NOAA). Adequate upstream passage conditions and continued high survival through the FCRPS Hydrosystem are primary requirements of the 2008 BiOp, 2010 Supplemental BiOp and 2014 Supplemental BiOp (hereafter collectively referred to as "the BiOp").

Recently, some conversion rates between Bonneville-McNary dams and between McNary-Ice Harbor dams using PIT-detection of adults tagged as juveniles have fallen below standards established in the BiOp for three ESUs: Snake River (SNR) spring-summer Chinook salmon, Upper Columbia (UCR) Chinook salmon, and SNR steelhead (Keefer et al. 2014a). Further, RPA 52 identifies a need to identify factors such as run timing, spatial effects, and predators that might explain the conversion rates for the under-performing ESUs and develop monitoring plans based on the findings. Several other factors may be contributing to sub-standard passage. Structural and operational changes have been undertaken at lower Snake River dams to improve passage of juveniles during downstream outmigration. However, there is concern that specific operations may impede adult upstream migration (e.g., Caudill et al. 2006; Jepson et al. 2009). In recent years, ladder counts of adults and data from a single radiotelemetry study (Jepson et al. 2009) indicated that hydraulic effects in the Little Goose tailrace can strongly impede adult passage. Spill operations at Little Goose attempt to optimize use of a surface spillway weir by juveniles migrating downstream, but some spill patterns are associated with sharp declines in adult ladder counts. Shifts in spill pattern have periodically resulted in large surges of adults through the ladder. While the adult delay appears related to eddy formation in the tailrace, the specific mechanisms and set of operational parameters that successfully balance adult and juvenile passage requirements remains elusive.

Many adult salmonids currently experience marginal temperature conditions as they migrate through the FCRPS, and show behavioral and mortality responses to high temperature conditions (e.g., Naughton et al. 2005; Goneia et al. 2006; Keefer et al. 2009, 2014b). In particular, thermal gradients in fishways, with higher temperatures at fishway exits compared to lower ladder sections, have been implicated in reduced passage rate at Lower Granite and other lower Snake River dams (Caudill et al. 2006, 2013). The specific details of how thermal gradients are generated, how they might be ameliorated, and their short- and long-term effects on migrating adult salmonids remain unknown. Here, we report on monitoring similar to past studies and also provide additional information on the thermal environmental in the forebay of Lower Granite Dam near the fishway exit.

This study used three samples of radio-tagged adult salmon: adult spring–summer Chinook salmon tagged at Bonneville Dam, jack spring–summer Chinook salmon tagged at Bonneville Dam, and a sample of adult spring Chinook salmon tagged at Ice Harbor Dam. The adults tagged at Ice Harbor Dam were collected using a new facility installed by USACE during winter 2012-2013 near the exit of the south fishway at Ice Harbor Dam to provide research access to adult salmonids near the beginning of their upstream migration through the Snake River. This study was the first to use the facility and thus also evaluated whether operating the adult fish trap impeded the upstream passage of adult salmonids in the south fishway by comparing behavior and passage times for Bonneville-tagged adults entering the ladder during periods when the trap was or was not in operation.

The work reported here primarily used samples of adult salmon radio-tagged at Ice Harbor and Bonneville dams to monitor upstream migration behavior and success through the lower Snake River to address the follow primary objectives:

1. Evaluate the behavior and success of adult spring–summer Chinook salmon migrating through the lower Snake River FCRPS including:

i) Characterization of general migration behavior and passage metrics for lower Snake River dams and reservoirs upstream of Ice Harbor Dam forebay.

ii) Test for associations between behavior of adult spring–summer Chinook salmon during passage of Little Goose Dam and dam operations and river environmental conditions.

2. Monitor adult salmonid passage in relation to temperature conditions in the Lower Granite Dam fishway and forebay near the fishway exit.

The focal sample for these objectives was composed of adult Chinook salmon collected and radio-tagged at Ice Harbor Dam in the new adult fish trap. Results for this sample were also compared to adult spring–summer Chinook salmon collected and radio-tagged at Bonneville Dam as part of other study objectives funded by the Portland District USACE. The latter sample increased sample size and allowed tests for short-term tagging effects in the Ice Harbor-tagged sample, though we note that differences in tagging schedules between the locations complicated direct comparison between the two samples. The primary sources of environmental data were from strings of temperature loggers deployed in the forebay of Lower Granite Dam and operational and river environmental data collected at dams by USACE.

We note that this report presents components of a larger study with two additional objectives reported elsewhere: 1) estimation of adult conversion and survival by ESU between McNary (MCN) and Lower Granite (LGR) dams based on PIT-tag detections using records from ~80,000 PIT tag histories (Keefer et al. 2014a); and 2) determination of movements and fate of Tucannon River origin steelhead collected and radio-tagged at Lower Granite Dam. Few steelhead (four) were collected at Lower Granite Dam and radio-tagged for the latter objective due to a prolonged period of warm temperatures that prevented trapping (Keefer et al. 2014c).

Methods

Collection and radio-tagging at Bonneville Dam

We collected and radio-tagged adult and jack Chinook salmon and adult steelhead at the Adult Fish Facility (AFF), located adjacent to the Washington-shore ladder. The early portion of the spring Chinook salmon run was not sampled at Bonneville Dam in 2013 due to delayed receipt of radio transmitters. Fish were selected haphazardly in the order they entered the trap each day, though the sample cannot be considered a true random sample of the run at large because only adults passing the Washington-shore ladder were sampled and no known-origin (i.e., previously PIT-tagged) fish were radio tagged. Protocols for collection and outfitting salmon and steelhead with transmitters at Bonneville Dam, downloading of data from receivers, coding of the data, and data analysis were similar to those developed in prior years (e.g., Keefer et al. 2004, 2005; Jepson et al. 2011). Fish receiving a radio transmitter were anesthetized in a ~18 mL/L solution of AQUI-S 20E (Aquatactics, Kirkland, WA). We used several types of digitally-encoded radio transmitters developed by Lotek Wireless (Newmarket, Ontario). The transmitter models used to tag adult Chinook salmon were the 7-volt MCFT-7F (16mm × 88mm; 31 g in air) and the MCFT-7A (16mm × 83mm; 29 g in air). Jack spring and summer Chinook salmon, defined as having a fork length < 60 cm, were tagged with a nano transmitter (NTC-4-2L; 8mm × 18mm; 2 g in air) and adult steelhead were tagged with a 3-volt MCFT2-3A transmitter (16mm × 46mm; 16.0 g in air). All adults were also tagged with a full duplex PIT-tag inserted to the abdominal cavity as a secondary tag (e.g., Keefer et al. 2005) that allowed estimation of tag loss / failure rates, detection efficiencies and conversion rates using both radio- and PIT-detections. Fish that were radio-tagged were weighed, measured for fork length, and had scale and caudal fin punches for DNA samples collected. After recovery from anesthesia, all radio-tagged fish were transported by truck and released ~ 8 km downstream from Bonneville Dam. Fish were supplied with continuous oxygen until their release.

Collection and radio-tagging at Ice Harbor Dam

The Ice Harbor south fishway was retrofitted with a new trap (Figure 1) and was operated in a similar manner to the old trap, with one exception – the trap was promptly removed from the fish ladder on a daily basis as required by the 2013 USACE Fish Passage Plan (FPP). Each day adult Chinook salmon were collected for radio-tagging, an overhead pendant crane was used to lower the trap and picket screens into the fishway near the top of the south-shore ladder. Picket screens were used to guide salmon to the main trap. Pneumatically-controlled gates, operated by an individual in a floating booth adjacent to the trap, were used to capture fish and transport them up towards the deck of the dam. Initial operation of the new trap was conducted in close coordination with the USACE TPOC and Ice Harbor Project Biologists to ensure the new trap was operating as specified.

All trapping was conducted in accordance with the 2013 USACE FPP including a maximum trap operation duration of four hours per day between 06:00 and 14:00, with further daily tagging restrictions of no more than four days a week related to temperature (>70° F, 21° C) and time of day (06:00 and 10:00). During the 2013 trapping operations, the fish ladder water temperatures did not reach 70° F, but if they had and exceeded 72° F, then the guidelines were to cease all trapping operations.

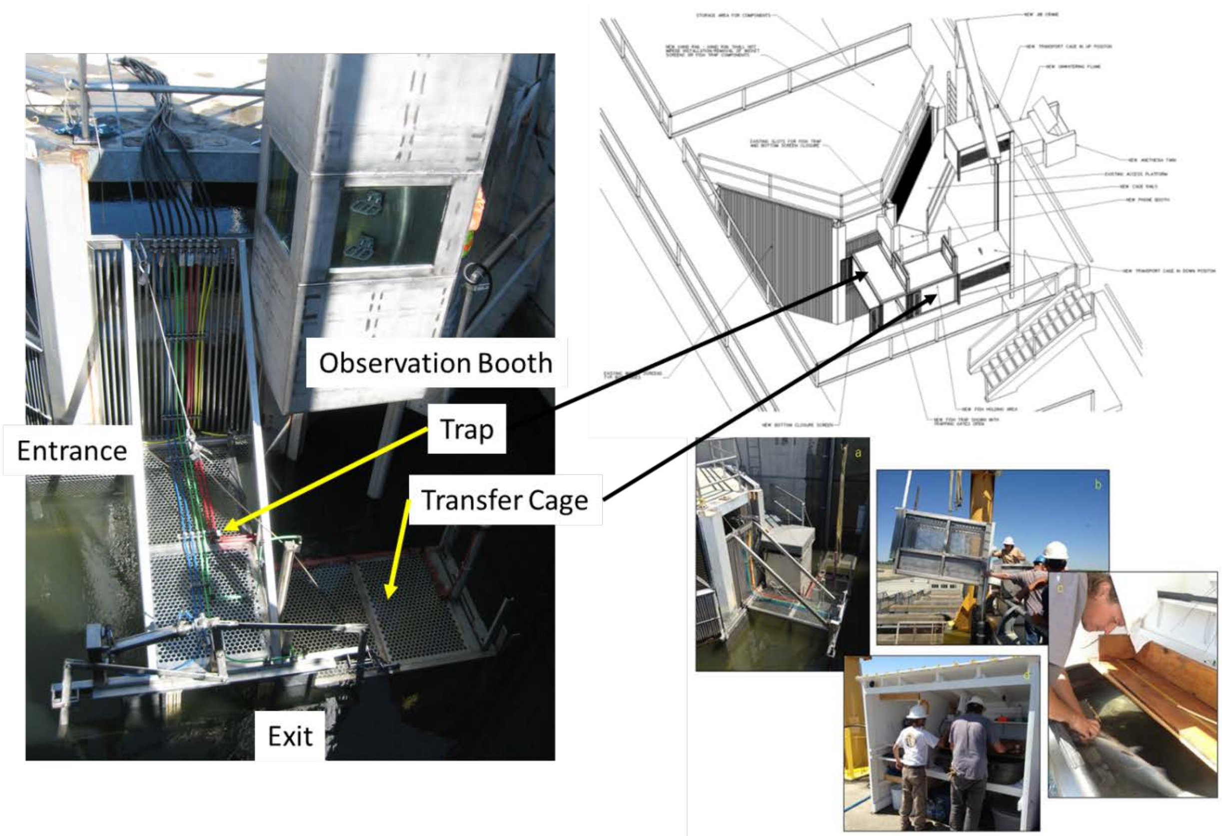

Figure 1. Images showing: the Ice Harbor adult fish trap installed and operating (left photo and conceptual drawing from 30% design review [source: USACE], right photo), the transfer cage during a lift to the deckside tank, and operation of the tagging station (lower right). Fish are crowded through picketed leads where they can pass through the trap. An operator sitting in the observation booth may actuate pneumatic gates to close the trap and open the transfer cage. Once a selected fish is in the transfer cage, gates close the transfer cage and open the trap, after which the transfer cage can be lifted to a deck-side tank for tagging.

The trap was operated a total of 24 days from 6 May through 24 June 2013, with a mean start time of 0832 hrs and a mean end time of 1306 hrs (Figure 2). These times included the initiation of installation and the termination of trap removal procedures, which typically lasted approximately 30 minutes on either end of the formal trapping effort. Trapping effort for adult Chinook salmon (not including the installation and removal time) did not exceeded a total duration of four hours per day during the study.

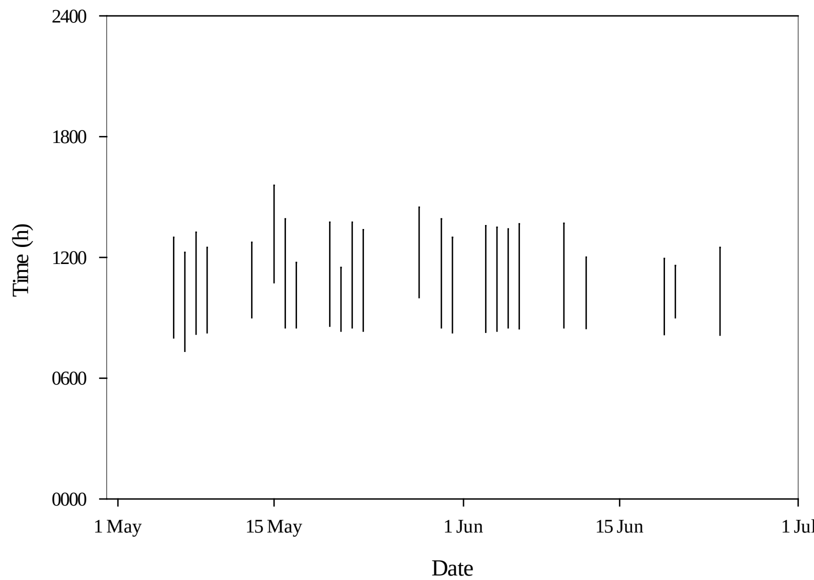

Figure 2. Dates and hours of fish trap operation in the south fishway of Ice Harbor Dam, 2013.

As noted above, this study was the first to use the new trap and consequently several in-season modifications to the trap and operational protocols were implemented to improve effectiveness and fish safety in collaboration with USACE biologists and NOAA-Fisheries. Briefly, these included adjustments to the pneumatic doors and trap opening, some changes to the rubber lining, and transition gate between the trap and anesthetic holding tank; further details were provided to the USACE in biweekly in-season reports (Hatch and Sullivan 2013).

Salmon collection began each tagging date between 07:00 and 09:00 and was completed before 14:00. Once trapped, fish were transferred (water to water) to a tank with AQUI-S 20E anesthetic at 20 ppm (175-220 ml of AQUI-S 20E solution was added to the tank when filled). Induction target times were typically 3-5 min. Water temperatures in the anesthetic tank were difficult to manage and remain within 2ºC from the 'base' temperature recorded at the Ice Harbor fishway exit thermometer. Containers of frozen river water were used as needed. Modifications were made to the tank to minimize any increase in water temperatures (i.e., the tank was painted white, the lid remained closed unless fish were being removed, and damp towels were installed on the tank back to keep warm air from influencing the water temperatures.

After salmon were anesthetized, they were moved to an examination tank and scanned for the presence of a PIT tag. Previously PIT-tagged fish were not included in the study (with a single permitted exception), and previously PIT-tagged fish were immediately transferred to an aerated 650 gallon, insulated recovery tank filled with river water until release at Levey Park (Figure 3). If there was no existing PIT tag, one was inserted (Biomark 8.4 mm full-duplex tag) and a 7-V radio transmitter (Lotek Wireless, Inc.) MCFT-7F (16mm × 88mm; 31 g in air) or MCFT-7A (16mm × 83mm; 29 g in air) was gastrically implanted. Fish size and condition data were collected as described above for the Bonneville sample. Radio-tagged fish were transferred to the recovery tank and trucked to the release site ~3.7 km upstream from Ice Harbor Dam at Levey Park typically twice a day. No mortalities were observed during transport or release.

Figure 3. Aerial photo showing the lower Snake River, Ice Harbor Dam and Levey Park, the site where radio-tagged Chinook salmon were released (~3.7 km upstream from Ice Harbor Dam).

Telemetry monitoring at Snake River dams

Tailraces and fishways at the four Snake River dams and several reservoir sites were monitored in 2013 (Table 1; Figures 4-7). The general locations of antennas at each dam were similar and included one or two aerial antennas in the tailrace below the dam to monitor entry to the tailrace, antennas at fishway openings used to detect approaches to fishway openings (within ~10 m), a series of antennas in the lower fishway and transition area used to confirm entrance to the fishway and passage of the transition area into the fish ladder, and one or more antennas at the fishway exits used to detect passage events.

We also performed more detailed monitoring of passage behavior at Little Goose Dam. Two aerial antennas were deployed in the Little Goose Dam tailrace, one on each side of the river (Figure 6). Underwater antennas were used to monitor the Little Goose fishway, including the north powerhouse entrance and north collection channel, the south entrance, transition area, and top-of-ladder exit. Importantly, (and unfortunately) no antennas monitored the north end of the spillway because conditions, including erosion in this area, were considered too dangerous for installation.

Table 1. Radiotelemetry monitoring sites in the Snake River in 2013.

Site	Antenna type	# Receivers
Ice Harbor Dam Tailrace	Aerial	1
South fishway opening	Underwater	2
South fishway transition area	Underwater	6
South fishway top-of-ladder exit	Underwater	1
North powerhouse openings	Underwater	3
North fishway opening and transition area	Underwater	7
North fishway top-of-ladder exit	Underwater	1
Lower Monumental Dam Tailrace	Aerial	2
South fishway opening and transition area	Underwater	6
South fishway top-of-ladder exit	Underwater	1
South powerhouse openings	Underwater	5
North fishway opening	Underwater	4
North transition area	Underwater	4
North fishway top-of-ladder exit	Underwater	1
Lower Monumental Reservoir – Lyons Ferry Hatchery	Aerial	1
Lower Monumental Reservoir – Downstream of Tucannon River	Aerial	1
Lower Monumental Tributary – Tucannon River	Aerial	1
Little Goose Dam Tailrace	Aerial	2
South fishway opening	Underwater	4
North powerhouse openings	Underwater	6
South fishway transition area	Underwater	4
South fishway top-of-ladder exit	Underwater	1
Lower Granite Dam Tailrace	Aerial	2
South fishway opening	Underwater	7
South fishway transition area	Underwater	5
North powerhouse openings	Underwater	6
North spillway opening	Underwater	2
South fishway top-of-ladder exit	Underwater	1
Clearwater River near Potlatch Mill	Aerial	1
Snake River upstream of 3 Mile Island	Aerial	1

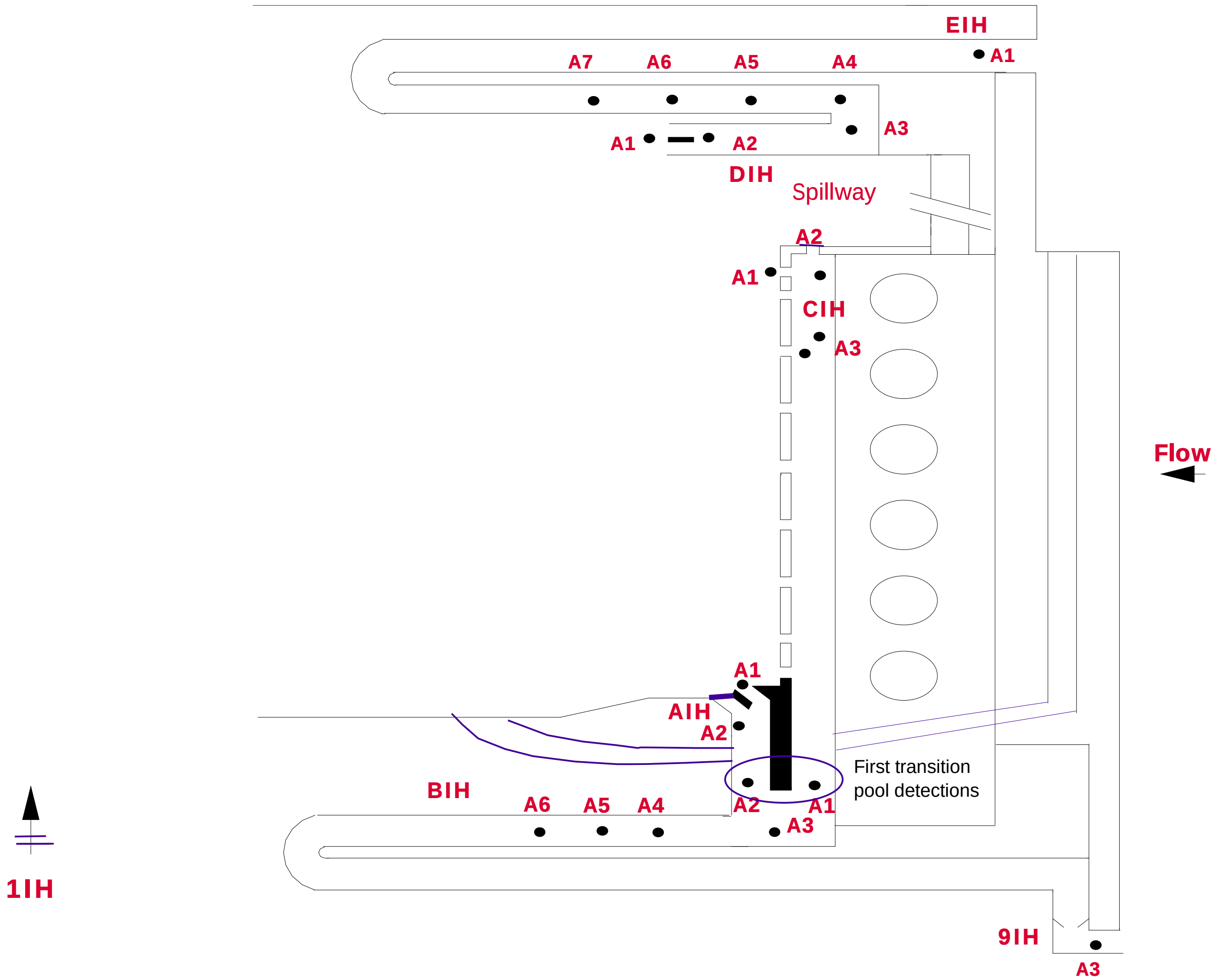

Figure 4. Locations that water temperature loggers and radiotelemetry antennas were deployed inside the Ice Harbor Dam fishway in 2013. (Not to scale.)

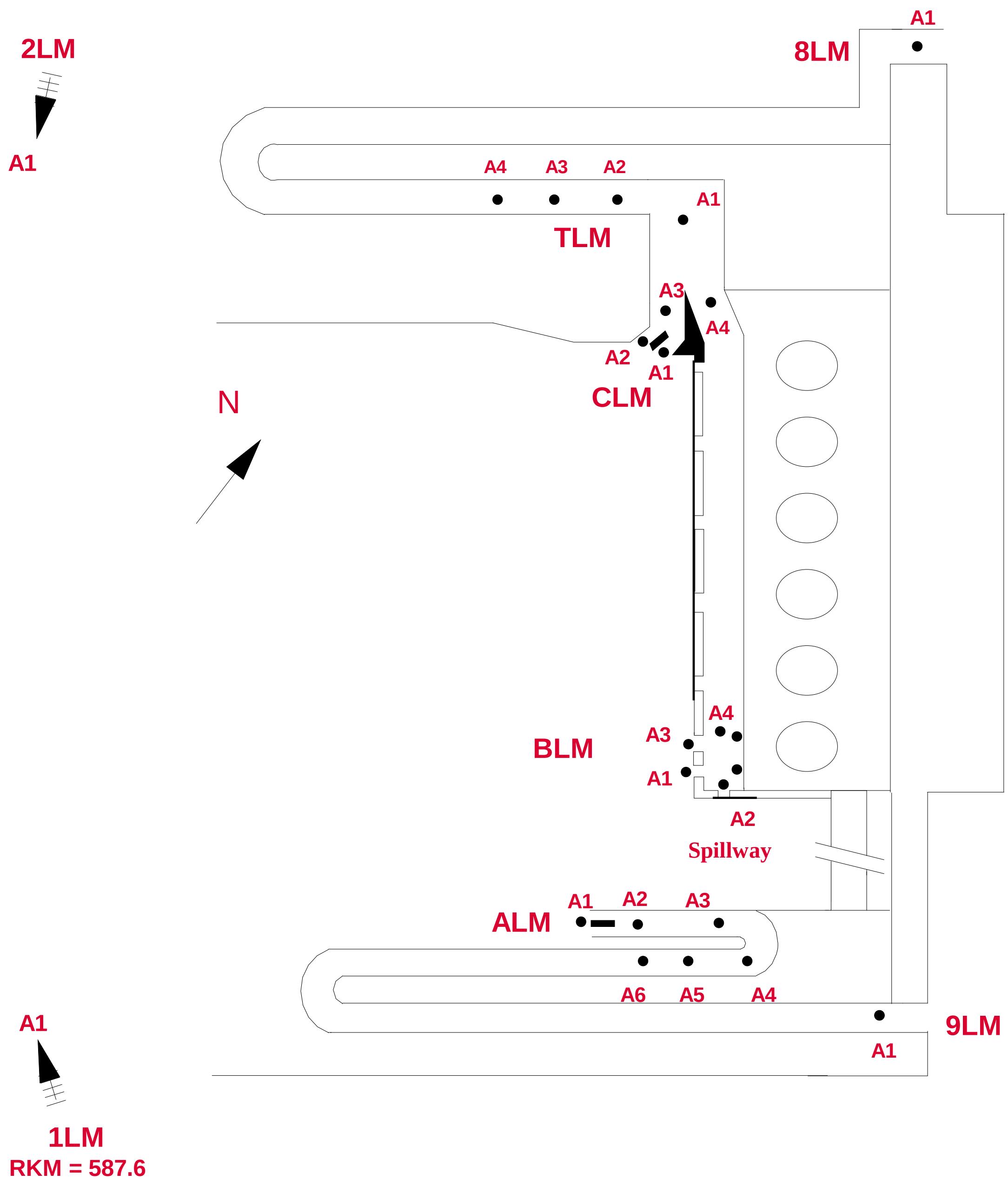

Figure 5. Locations that radiotelemetry antennas were deployed inside the Lower Monumental Dam fishway in 2013. (Not to scale.)

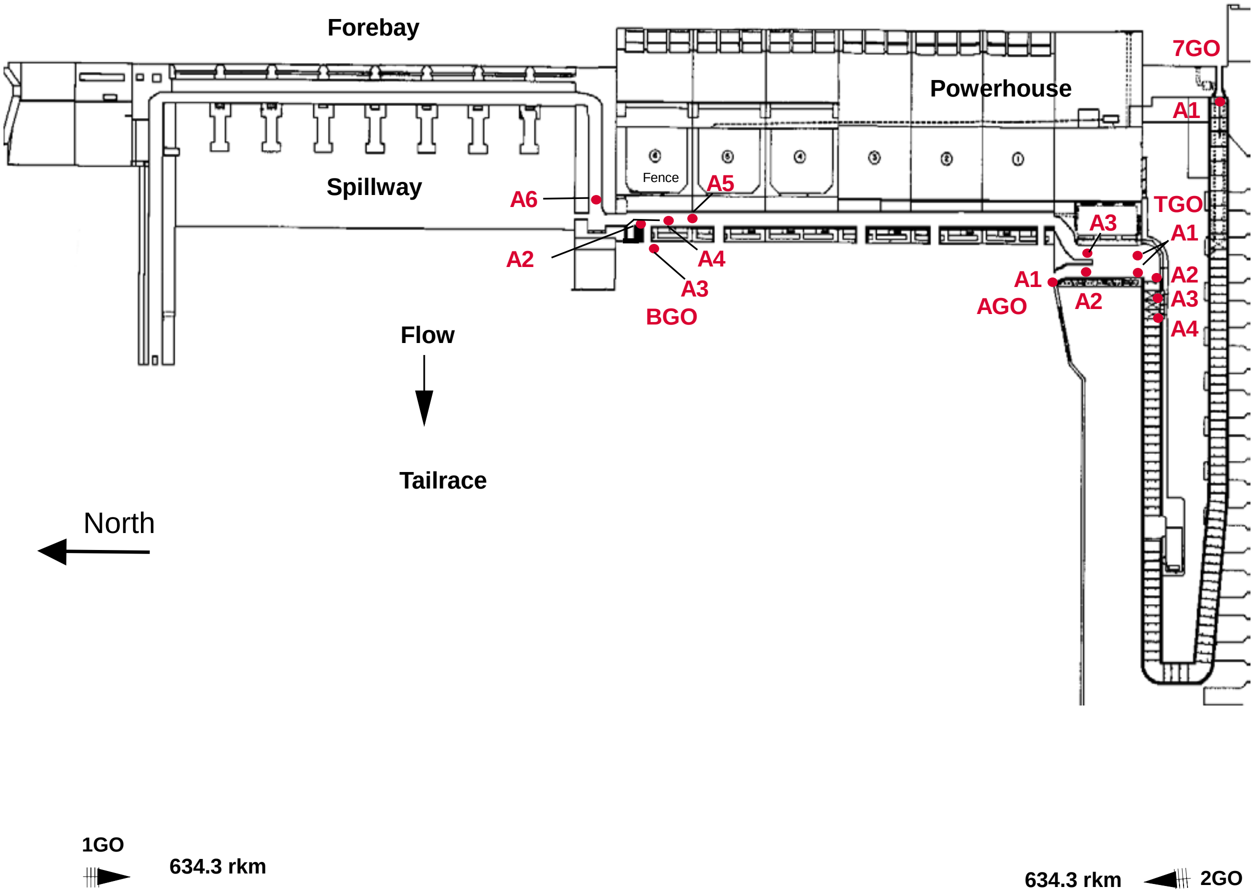

Figure 6. Locations that radiotelemetry antennas were deployed in the Little Goose tailrace (aerial 1GO and 2GO) and inside the Little Goose Dam fishway (underwater) in 2013. (Not to scale.) Note that the north spillway fishway entrance was open but not monitored due to safety concerns. Turbines numbered 1-6 and spillbays numbered 1-8 from right to left.

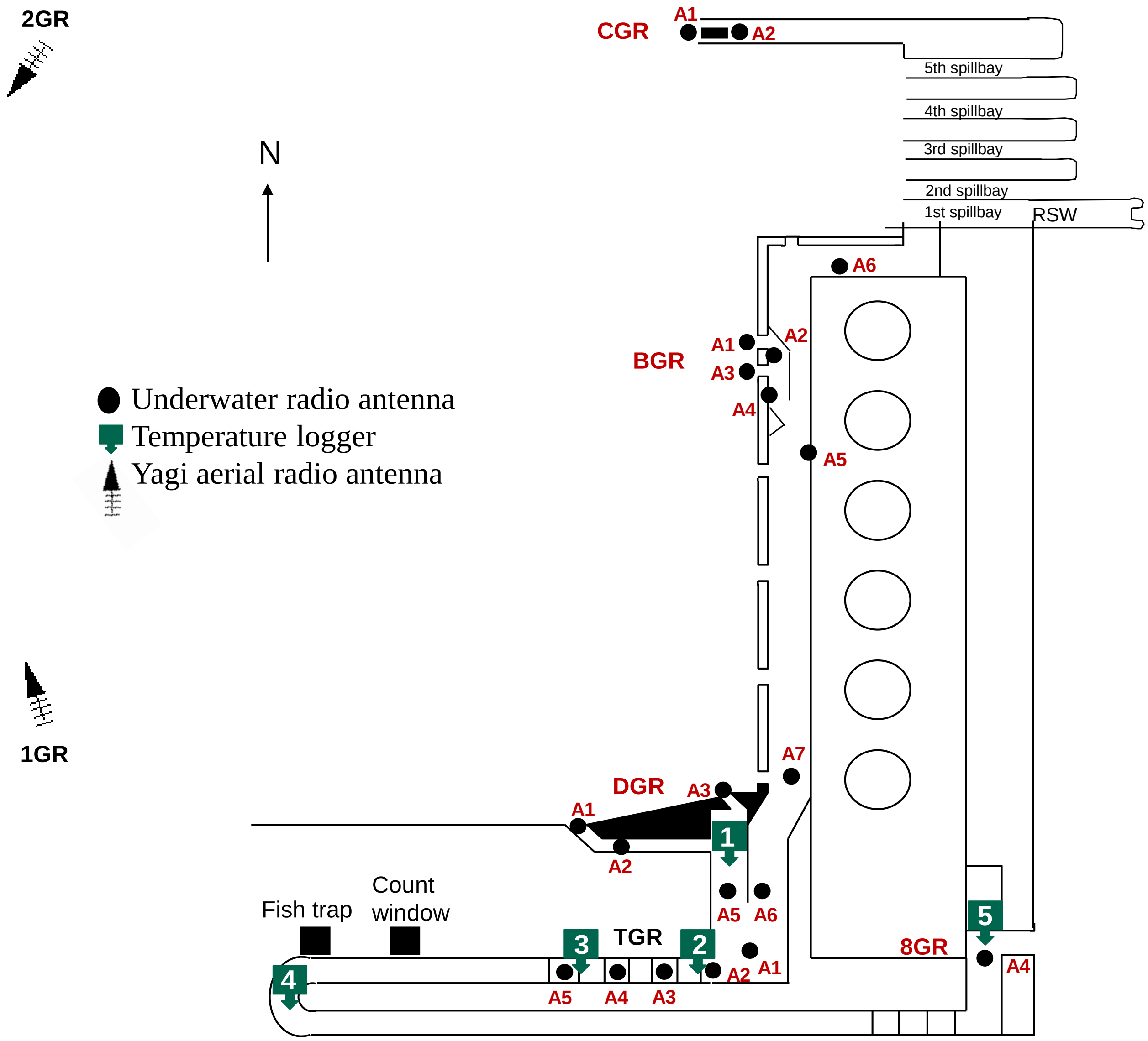

Figure 7. Locations that water temperature loggers and radiotelemetry antennas were deployed at Lower Granite Dam in 2013. (Not to scale.) Temperature loggers: (1) south shore entrance, (2) lower transition pool, (3) upper transition pool, (4) above adult fish trap and (5) fish ladder exit.

Lower Granite water temperature monitoring

Water temperatures in the Lower Granite fish ladder were collected from 4 June through 30 September and forebay temperatures were collected from 16 July through 23 October. Five loggers (Onset Hobo ProV2) recorded hourly temperatures and were deployed approximately 0.3 meters from the bottom of the fish ladder at five locations: 1) near the south entrance, 2) lower transition pool area, 3) upper transition pool area, 4) upstream of fish trap, and 5) at exit fish ladder exit (Figure 7). Three strings of temperature loggers were deployed in the forebay: 1) 15 m upstream from the ladder exit, 2) 61 m upstream from the ladder exit, and 3) 122 m upstream from the ladder exit (Figure 8). Each string had an Onset Hobo U20 water level and temperature logger deployed at 3 m and Onset Hobo ProV2 loggers at approximately 6, 12, 18, and 24 m. The furthest upstream string had an additional logger at 27 m.

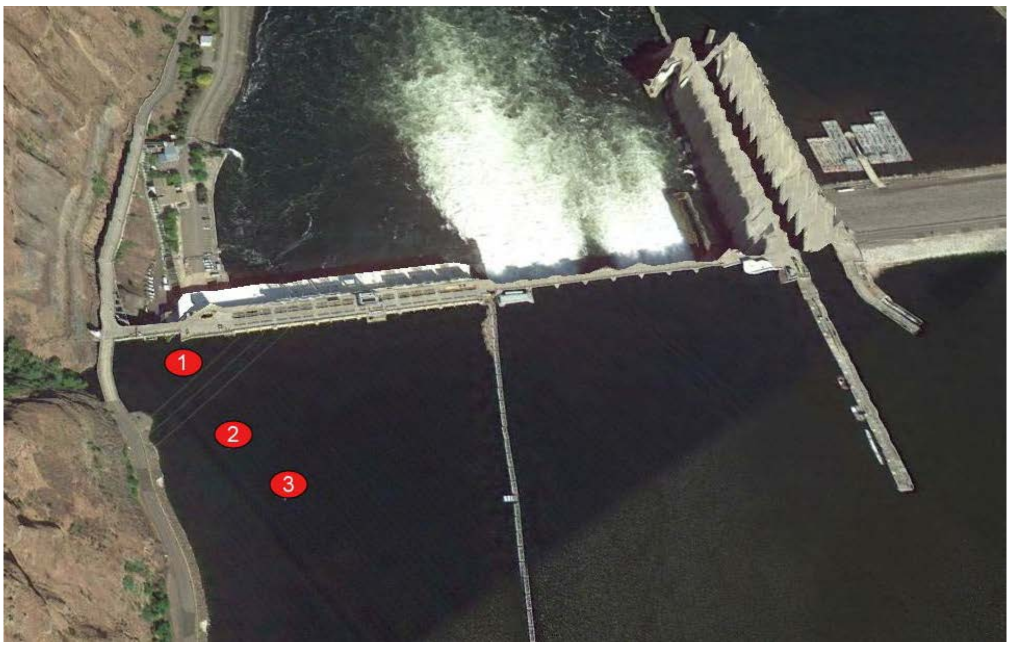

Figure 8. Location of temperature logger strings deployed in Lower Granite forebay in 2013.

Telemetry data analyses

The raw radiotelemetry data were screened for likely 'noise' records using filters that identified signal collisions (i.e., two or more codes at the same receiver at the same time). A detection history for each radio-tagged fish was generated using an automated coding program that assigned activity codes (e.g., tailrace entry and exit, fishway entry and exit, ladder passage, tributary entry, etc.) to the time-stamped detections at each antenna using a set of coding rules followed with review by experienced technicians who identified records that did not have corroborating support from detections at nearby antennas. We used coded records to summarize when and where fish approached, entered, and exited the fishway, to calculate entrance and passage efficiency estimates, and to estimate passage times through the tailrace, through various fishway segments at Lower Monumental, Little Goose and Lower Granite dams. Telemetry data for the three tag groups (Bonneville adult, Bonneville jack, Ice Harbor adult) was summarized separately.

Each fish received a full-duplex PIT tag as a secondary marker, and we supplemented the radiotelemetry histories using PIT detections inside dam fishways (Bonneville, The Dalles, McNary, Ice Harbor, Lower Granite, and upper Columbia River dams), inside tributaries, and at fish collection facilities. The PIT detection data were downloaded from the Pacific States Marine Fisheries Commission PIT Tag Information System database (PTAGIS). PIT detections were also used to identify passage by salmon that lost transmitters or that had transmitters that were not working. Both radio and PIT data were used to assign dam passage events and to assign final detection locations.

Fish detection efficiencies were >95% at most sites, and antenna redundancy in most fishways increased dam-wide detection efficiency to near 100%. We used top-of-ladder sites and upstream detections to determine whether fish passed dams and to estimate dam-to-dam reach conversion rates (see methods below). Missed radio detections at top-of-ladder antennas mostly occurred during power outages.

Ice Harbor Dam trap effects - We used radiotelemetry records at Ice Harbor Dam of adults tagged at Bonneville Dam to test for effects of trap operation on passage behavior. We determined when any tagged salmon was first detected on a transition pool antenna in the south fishway and assigned each fish a treatment based on whether the trap was operating or not. We determined whether each fish passed the dam after pool entry or exited the dam to the tailrace. If trap operations impeded the passage of Chinook salmon, we expected to see a higher frequency of fish exit the dam to the tailrace (after pool entry) when the trap was used. For any fish that exited the dam to the tailrace, we determined whether that fish spent the ensuing night in the fishway or downstream from the dam. For all fish that passed the dam with known ladder top detections, we calculated the time fish used to migrate from their initial south pool entry to their exit at a ladder top.

Conversion rate estimation-We estimated reach-specific upstream conversion rates for seven reaches in the lower Snake River: (1) Lower Monumental Dam tailrace to pass dam; (2) top of Lower Monumental to Little Goose; (3) at Little Goose to pass dam; (4) top of Little Goose to Lower Granite; (5) at Lower Granite to pass dam; (6) at Lower Monumental to pass Lower

Granite; and (7) top of Lower Monumental to pass Lower Granite. Lower Monumental Dam was used as a starting point because it was upstream from the release site for the Ice Harbor-tagged fish.

Separate estimates were calculated for each of the tag groups (Bonneville adults, Bonneville jacks, Ice Harbor adults). We used a combination of radiotelemetry and PIT-tag detections to estimate the number of fish that passed each reach. Some fish passed top-of-ladder radio antennas undetected but were subsequently identified as passing either by PIT detections at the same dam or by upstream detections at radiotelemetry or PIT antennas at dams and in tributaries. These fish were therefore in the 'passed reach' category for conversion estimates. The generally high detection efficiency of both radio- and PIT-tagged fish in the adult fishways allowed for calculation of relatively precise, unbiased estimates of adult reach conversion.

Potential tag group effects on reach-specific conversion estimates were assessed using Pearson's χ^2 tests. We also used logistic regression models (Agresti 2012) to evaluate the effects of migration date on reach conversion and to estimate seasonally-varying 95% confidence intervals. The final detection locations for all radio-tagged fish that entered the study area (i.e., those detected at Lower Monumental Dam) were summarized to describe the final distribution of adults for each sample and to help assess the fates of those that did not pass Lower Granite Dam.

Time-to-event analysis at Little Goose Dam – It is challenging to assess the effects of continuously changing covariates on fish passage. Such "time-varying covariates" include total river discharge, water temperature, turbine discharge, spill, and daylight (among others). Consequently, we have used proportional hazards regression (PHReg), a form of time-to-event analysis (Caudill et al. 2007; Jepson et al. 2009; Castro-Santos and Perry 2012), to explicitly incorporate the temporal changes in environmental and operational covariates on Chinook salmon passage. PHReg estimates the probability or 'hazard' that an event such as dam passage by an individual salmon occurs within a small time interval. The probabilities of passage are expressed as a hazard ratio. The method does not estimate the time to passage, but rather the effect of the time-varying covariate(s) on the risk of the event occurring with a one unit increase in the predictor variable (e.g., temperature, a continuous variable) or under one condition compared to another for class variables (e.g., tag group).

We used PHReg to evaluate the effects of daylight, water temperature, river discharge, TSW operation, and individual turbine and spillbay discharge on Chinook salmon passage at Little Goose Dam. These analyses were largely exploratory because no experimental operations were conducted at the dam in 2013. There were some low- and high-crest TSW operations in May and early June that we compared, although other covariates were continuously changing during this time. All covariates were mean hourly values, as provided by USACE.

Data for the three tag groups (Bonneville adult, Bonneville jack, Ice Harbor adult) were summarized separately and in combination to improve inferential power. 'Tag group' was included as a categorical covariate in the combined analyses. $P < 0.05$ for individual predictors was considered statistically significant.

Lower Granite passage times and overnighting - Passage times of Chinook salmon and steelhead tagged at Bonneville Dam and chinook salmon tagged at Ice Harbor dam were calculated from a fish's first pool record in the transition area to the last record at the top of the ladder (exit). Ladder temperature differences (ΔT) were calculated by subtracting the temperature logger data at the south ladder entrance from the temperature logger data at the top of the ladder. Hourly temperatures values from south ladder entrance logger were matched to first pool fish records. A fish overnighted if it did not pass the dam on the same day (date) it entered the lower ladder (i.e., first pool record).

Results and Discussion

Tagging summary: Bonneville

The adult tagging effort at Bonneville Dam ran from 2 May through 15 July (Figure 9). The early portion of the adult spring Chinook salmon run was not represented in the sample due to availability of transmitters. The jack run was later than the adult run, but similar under-sampling of the early run occurred. Sampling effort from May through mid-July included the tagging of a relatively higher proportion of spring than summer Chinook salmon in an effort to meet total spring Chinook sample targets. We radio-tagged 328 adult spring and 272 adult summer Chinook salmon, 300 jack Chinook salmon (178 spring and 122 summer) and 400 adult sockeye salmon. A total of 52,128 adult spring Chinook salmon, 82,460 adult summer Chinook salmon and 172,140 adult sockeye salmon were counted passing the dam during the tagging period (Figure 9). Radio-tagged salmon represented ~0.4% of the Chinook and ~0.2% of the sockeye salmon counted at the dam during the tagging period.

Tagging summary: Ice Harbor

The adult tagging effort at Ice Harbor Dam began on 6 May and continued through 24 June (Figure 10). No tagging occurred during the early portion of the spring Chinook salmon run due to delays in the installation of the tagging facility and protocol development at the new trap. We radio-tagged 253 adult spring and 47 summer Chinook salmon in 2013. A total of 27,614 adult spring Chinook salmon, and 5,911 adult summer Chinook salmon were counted passing the dam during the tagging period (Figure 10). Radio-tagged salmon represented ~0.9% of the Chinook salmon counted at the dam during the tagging period.

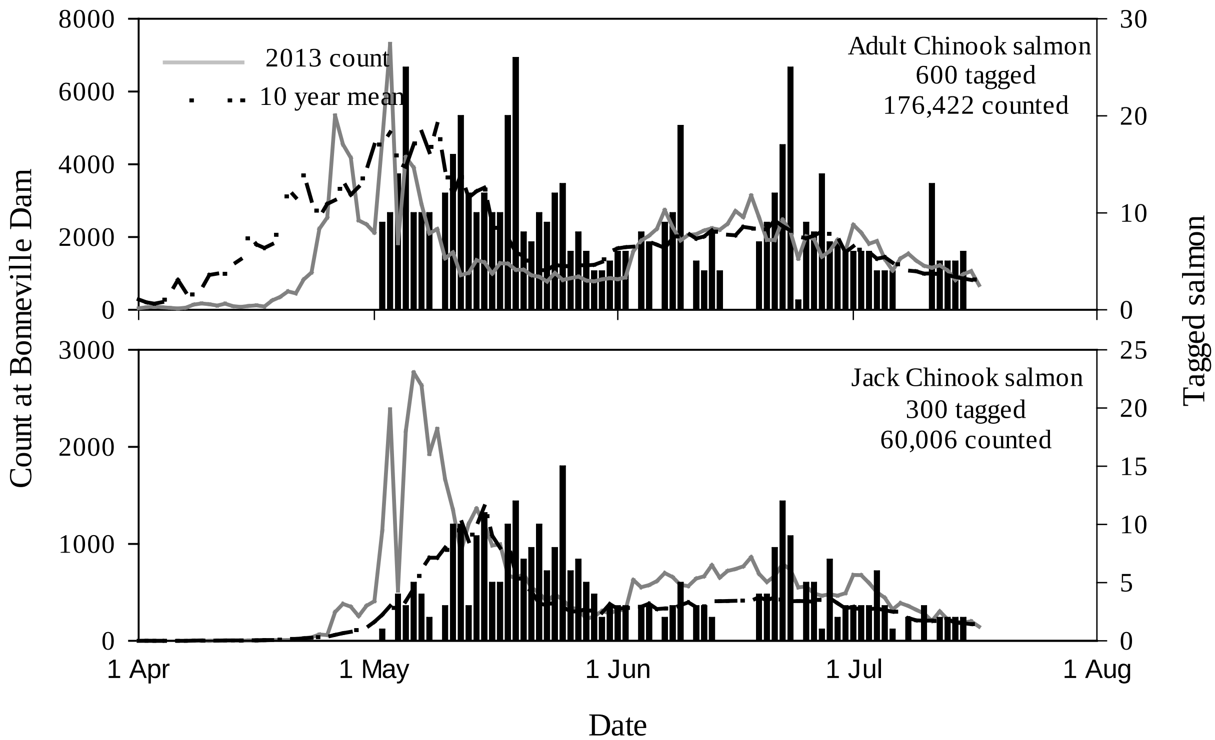

Figure 9. Number of adult and jack spring–summer Chinook salmon collected and radio-tagged at Bonneville Dam and released downstream in 2013. Lines show the 2013 and 10-year daily mean adult and jack Chinook salmon counts at the dam.

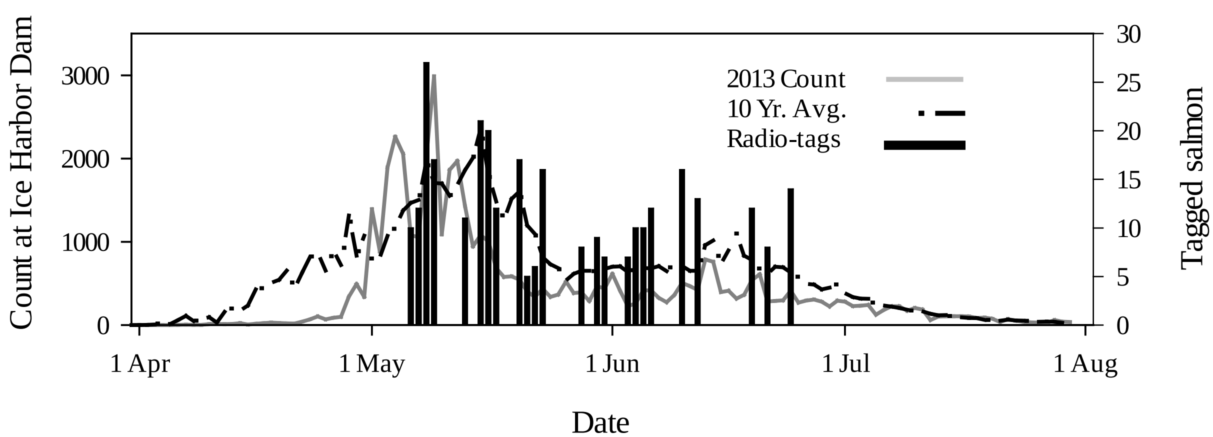

Figure 10. Number of spring Chinook salmon collected and radio-tagged at the Ice Harbor south fishway trap (bars) and released at Levey Park upstream from Ice Harbor Dam in 2013. Lines show the 2013 and 10-year daily mean adult Chinook salmon counts at the dam.

Ice Harbor Dam trap effects

We compared passage behavior between Bonneville-tagged salmon first approaching the south fishway on days when the Ice Harbor south ladder trap was or was not operated during the trapping period (6 May through 24 June). During this time, a total of 224 unique, radio-tagged Chinook salmon were detected in the south transition pool, including 132 adults and 92 jacks (Figure 11). Of the 132 adults detected in the south pool, 114 entered the pool when the trap was not operated and 18 entered when the trap was operated (Figure 11). Forty-eight of the 114 adults (42%) that entered the pool when the trap was off moved back to the tailrace whereas 9 of the 18 adults (50%) that entered the pool when the trap was on exited to the tailrace (Table 2). There was no significant difference between these two ratios (χ^2 test, $P = 0.53$). Of the 48 adults from the 'Trap Off' treatment that passed the dam, 20 (42%) passed Ice Harbor Dam on their south pool entry date, 26 (54%) passed the dam at least one day after their south pool entry date, and two failed to pass the dam at all (Table 3; low sample size prevented statistical tests for this and other comparisons in Table 2 and 3). Of the nine adults in the 'Trap On' group that exited the dam after south pool entry, five (56%) passed the dam on their south pool entry date and four (44%) passed the dam at least one day after their south pool entry date.

Of the 92 jacks detected in the south pool, 86 entered the pool when the trap was not operated and six entered when the trap was operated (Figure 11). Twenty of the 86 jacks (23%) that entered the south pool when the trap was off exited the dam to the tailrace compared to zero of the six jacks (0%) that entered the pool when the trap was on (Table 2). Of the 20 jack salmon in the 'Trap Off' group that exited the dam after south pool entry, 7 (35%) passed the dam on their south pool entry date and 13 (65%) passed the dam at least one day after their south pool entry date (Table 3). No jack salmon from the 'Trap On' group exited the dam to the tailrace.

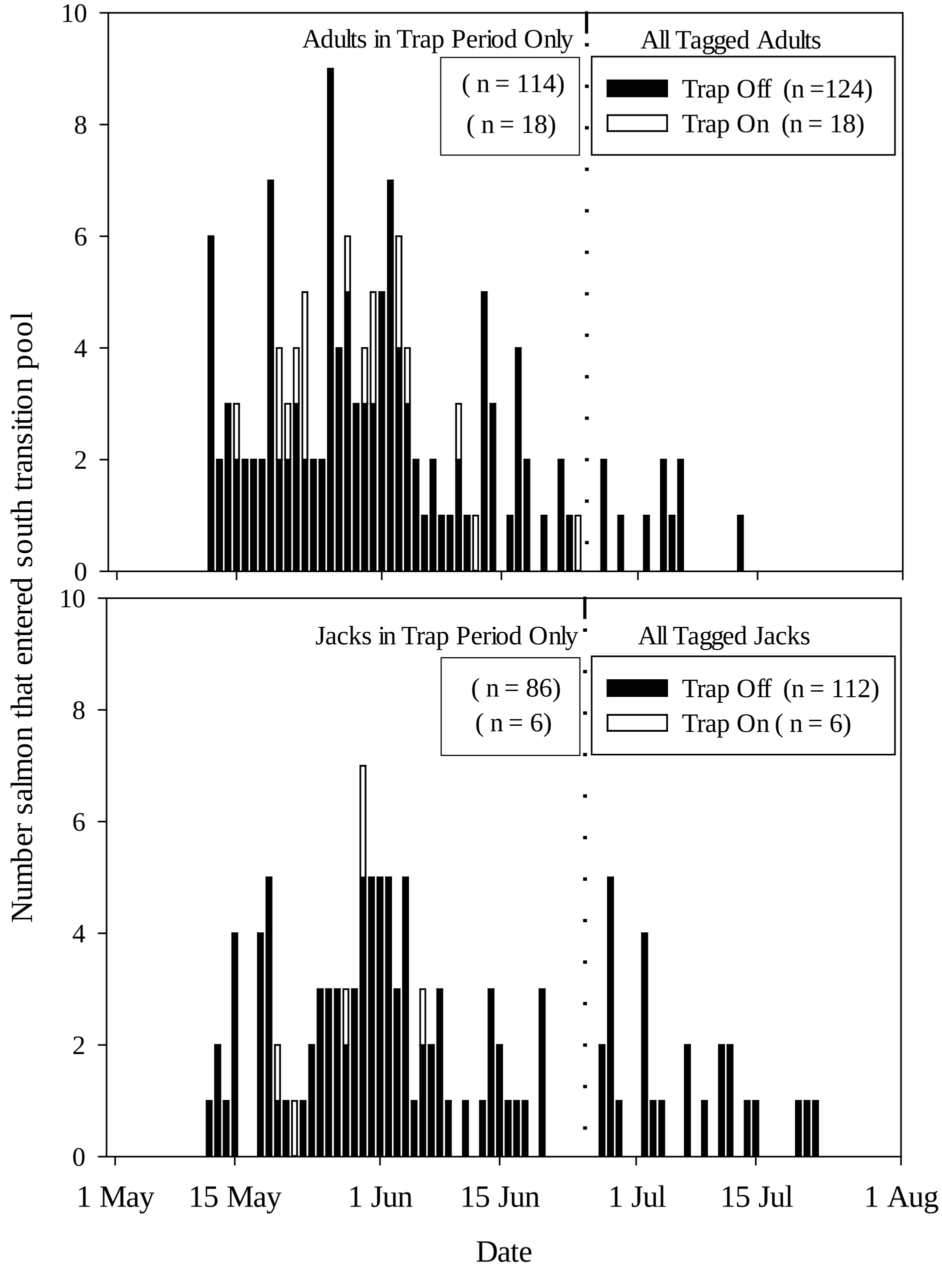

Figure 11. Histograms of arrival date at the south transition pool of Ice Harbor Dam by adult (upper panel) and jack (lower panel) Chinook salmon radio-tagged at Bonneville Dam in 2013.

Table 2. Frequencies and percentages (in parentheses) of radio-tagged adult and jack Chinook salmon that entered the south transition pool at Ice Harbor Dam, the fish trap status at the time of pool entry, and the frequencies of tagged salmon that returned to the tailrace one or more times after entering the fishway.

Life Stage	Trap Treatment	Exit? No	Exit? Yes	χ^2 (*P value*)
Adult	Off	66 (58)	48 (42)	0.42
	On	9 (50)	9 (50)	
Jack	Off	66 (77)	20 (23)	n/a
	On	6 (100)	0	

Table 3. Frequencies and percentages (in parentheses) of radio-tagged adult and jack Chinook salmon that exited the dam to the tailrace after being detected in the Ice Harbor south transition pool, the fish trap status at the time of pool entry, and the frequencies of tagged salmon that failed to pass the dam, passed the dam the same day as that of their south pool entry, or passed the dam at least one day after their south pool entry.

Life Stage	Trap Treatment	Overnight? (No pass)	Overnight? No	Overnight? Yes	χ^2 *(P value)*
Adult	Off	2 (4)	20 (42)	26 (54)	n/a
	On	0	5 (55)	4 (45)	
Jack	Off	0	7 (35)	13 (65)	n/a
	On	0	0	0	

Trap operation and passage times

We compared the passage times of adults that approached the ladder during periods when the trap was and was not operated. Of the 260 radio-tagged Chinook salmon recorded entering the south fishway transition pool at Ice Harbor Dam in 2013, 256 (98.5%) ultimately passed the dam. Those that passed included 140 adult salmon and 116 jack salmon. Two jacks and two adults that entered the south pool failed to pass the dam. Of the 140 adults that passed, 123 (88%) passed via the south fishway and 17 (12%) passed via the north fishway. Similarly, 84% (97/116) of the jack salmon passed via the south fishway compared to 16% (19/116) that passed via the north fishway. Of the 256 tagged salmon known to have passed the dam, 164 (64%) were recorded on ladder top antennas, including 92 adults and 72 jacks.

Adult salmon that entered the south pool when the trap was off and did not return to the tailrace prior to passage had the lowest median time (1.9 h) from first south pool detection to the last detection at a ladder top among treatment/behavior groups (Table 4). In comparison, tagged adults that entered the pool when the trap was on and did not exit to the tailrace had a modestly higher median passage time (3.5 h), although the sample size was low (n = 7). The median passage times for adults that exited to the tailrace and passed on the same date as their pool entry was 4.5 h for the ‘Trap Off’ group and 3.3 h for the ‘Trap On’ group. Adults that exited the south pool to the tailrace and passed the dam on a different date than their pool entry date had the highest median passage times, independent of trap treatment or ladder passed (*range* = 18.4 –

27.1 h for south migrants and 25.1 – 53.9 h for north migrants). The relatively high percentage of adults in the 'Trap On' group that passed via the south ladder after trap operations switched to off may circumstantially reflect a modest inhibitory effect to adult fish passage by trap operations. Alternately, this result probably reflects the fact that only adults approaching and passing rapidly (< 4 hours) could be assigned the "on" group *and* pass during the treatment period.

Table 4. Life stage, trap status at time of first south pool entry, exit behavior, overnighting behavior, median passage times from first south pool entry to a ladder top (south and north), frequencies of treatment switchers, and sample sizes for radio-tagged Chinook salmon with known detections at an Ice Harbor Dam ladder top in 2013.

Life Stage	Trap At S. pool entry	Exit ?	Overnight?	Median S. fishway entry to S. fishway exit (h)	n	Freq. of S. fishway passers that switched treatments	Median S. fishway entry to N. fishway exit (h)	n
Adult	Off	No	-	1.9	41	2 of 41 passed when trap was On.	-	-
	Off	Yes	No	4.5	12	1 of 12 passed when trap was On.	6.6	5
	Off	Yes	Yes	18.4	10	2 of 10 passed when trap was On	25.1	10
	On	No	-	3.5	7	5 of 7 passed when trap was Off	-	-
	On	Yes	No	3.3	3	3 of 3 passed when trap was Off	-	-
	On	Yes	Yes	27.1	3	3 of 3 passed when trap was Off	53.9	1
Jacks	Off	No	-	2.5	39	5 of 39 passed when trap was On	-	-
	Off	Yes	No	4.2	6	0 of 6 passed when trap was On	11.0	6
	Off	Yes	Yes	15.9	4	1 of 4 passed when trap was On	24.2	13
	On	No	-	2.4	4	2 of 4 passed when trap was Off	-	-
	On	Yes	No	-	-	-	-	-
	On	Yes	Yes	-	-	-	-	-

Median passage times for jack Chinook salmon showed a similar pattern to those of adults based on trap treatment and behaviors. The most notable difference between adults and jacks, however, was the lack of difference between median passage times for the group that entered the south pool when the trap was off and did not exit the dam to the tailrace (i.e., 2.5 h for the 'Trap Off' group and 2.4 h for the 'Trap On' group). Like the adults, there was a low sample size for the 'Trap On' jack group (n = 4). There was a modest increase in median passage times for jacks in the ‘Trap Off’ group that exited the dam to the tailrace (4.2 h) and a more substantial increase for those that passed the dam on a different date than their initial south pool entry (15.9 h).

Overall, there was not consistent evidence that operation of the adult trap at Ice Harbor Dam caused large changes in migratory behavior of non-trapped adult in downstream areas of the ladder. However, we note that relatively few adults passed the south fishway during trapping operations and subtle behavioral effects may have been missed due to low sample size and the relatively coarse resolution of the radio antennas used in the analyses. Based on frequencies of tagged salmon that exited the south transition pool, trap operations appeared to have little effect on adult or jack Chinook salmon passage at Ice Harbor Dam in 2013. Passage times associated with different behaviors after south pool entry suggested that if trap operations can be directly associated with post-entry behaviors, there may have been a modest inhibitory effect on Chinook salmon passage associated with trap operations. This effect, if truly present, was small (~2 hours increase in passage time among those passing without exiting to the tailrace). In the future, deploying antennas in the fishway upstream from the south transition pool and downstream from the trap could provide increased resolution to monitoring for any potentially inhibitory effects associated with trap operations.

Reach conversion estimates

We estimated conversion rates for seven reaches between the base of Lower Monumental Dam and the top of Lower Granite Dam (Table 5). Comparisons among release groups differed ($P < 0.05$, χ^2 tests) for two reaches: Ice Harbor-tagged adults had lower conversion from the base of Lower Monumental dam past Lower Monumental Dam (0.901 versus 0.982 for Bonneville adults and 1.000 for Bonneville jacks) and from the base of Lower Monumental Dam past Lower Granite Dam (0.860 versus 0.969 for Bonneville adults and 0.974 for Bonneville jacks). This results suggests a likely short-term handling effect for Ice Harbor-tagged fish, with ~10% of the sample moving upstream from the Levey Park release site and being detected at Lower Monumental Dam, but then failing to pass the dam. There were no statistically meaningful differences among tag groups in any reach upstream from Lower Monumental Dam (Table 5). Conversion estimates from the top of Lower Monumental Dam past Lower Granite Dam were 0.969 (Bonneville adults), 0.974 (Bonneville jacks), and 0.955 (Ice Harbor adults).

The lower conversion at Lower Monumental Dam for Ice Harbor-tagged adults was strongly associated with reduced passage by the later tag groups (Figure 12). In a logistic regression model with date at Lower Monumental Dam as the predictor variable, late-timed fish tagged at Ice Harbor Dam were much less likely to pass Lower Granite Dam than earlier migrants (χ^2 = 33.3, $P < 0.001$). A similar, but less pronounced, seasonal effect was identified for the Bonneville-tagged adult sample (χ^2 = 10.4, P = 0.001) but not for the jack group (χ^2 = 1.0, P = 0.322). When the models were restricted to fish that passed Lower Monumental Dam, date was not influential for any group ($0.124 \leq P \leq 0.384$). Importantly, this seasonal effect on conversion was also evident in the much larger, multi-year samples of PIT-tagged sockeye and wild spring–summer Chinook salmon recently summarized by Keefer et al. (2014a). Lower conversion through various Snake and Columbia rivers during warm water periods has been attributed to increased straying and increased mortality in several studies (e.g., Naughton et al. 2005; Keefer et al. 2008).

When the combined radiotelemetry and PIT detection data were considered, 95.2% of Bonneville adults, 97.4% of Bonneville jacks, and 84.0% of Ice Harbor adults were considered to have passed Lower Granite Dam (Table 6). The groups of fish that did not pass Lower Granite Dam were last detected at a variety of Snake River sites, but primarily in dam tailraces and fishways. The largest numbers of 'unsuccessful' Ice Harbor-tagged fish were the 4.3% of the total sample last detected in the Ice Harbor tailrace (i.e., they moved downstream from the release site 3.7 km upstream from Ice Harbor Dam), and 6.7% detected in the Lower Monumental tailrace. Several of the fish that did not pass Lower Granite Dam may have been successful migrants: one Bonneville adult (0.6%) and two Ice Harbor adults (2.0%) were last detected in the Tucannon River and one Bonneville jack (0.7%) was near Lyons Ferry Hatchery. Relatively more jack salmon had only PIT detections at Lower Granite Dam, probably related to the lower transmission power of the smaller tags.

Table 5. Detection numbers and reach conversion estimates for radio-tagged adult and jack Chinook salmon that were detected at Lower Monumental, Little Goose, and Lower Granite dams in 2013. Includes fish with PIT-tag detections only (i.e., fish that lost or had non-functional radio transmitters). BON = tagged at Bonneville Dam; ICE = tagged at Ice Harbor Dam. Paired estimates with the same superscript letter differed ($P < 0.05$, Pearson χ^2 tests).

	BON adult (*n*)	BON jack (*n*)	ICE adult (*n*)
Released above ICE[1]	166	153	300
At Lower Monumental	166	153	293
Passed Lower Monumental	163	153	264
At Little Goose	161	151	261
Passed Little Goose	160	151	256
At Lower Granite	160	150	252
Passed Lower Granite	158	149	252
Reach conversion estimates			
Passed L. Monumental / At L. Monumental	[a]0.982	[b]1.000	[ab]0.901
At L. Goose / Passed L. Monumental	0.988	0.987	0.989
Passed L. Goose / At L. Goose	0.994	1.000	0.981
At L. Granite / Passed L. Goose	1.000	0.993	0.984
Passed L. Granite / At L. Granite	0.988	0.993	1.000
Passed L. Granite / At L. Monumental	[a]0.952	[b]0.974	[ab]0.860
Passed L. Granite / Passed L. Monumental	0.969	0.974	0.955

[1] detected upstream from ICE for Bonneville-tagged groups

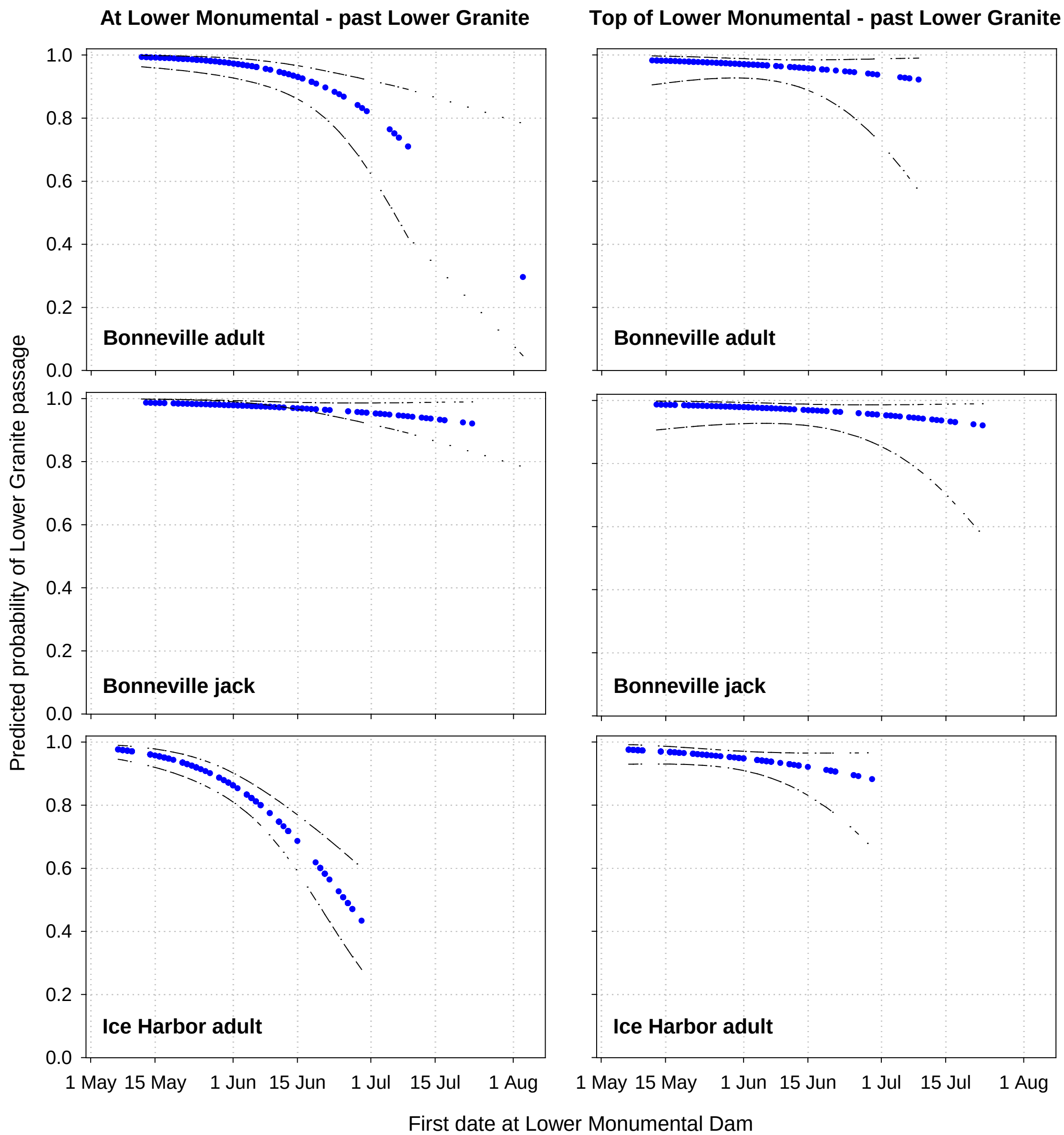

Figure 12. Estimated probabilities, with 95% confidence intervals, that radio-tagged Chinook salmon would pass Lower Granite Dam relative to their first detection date at Lower Monumental Dam. Relationships were estimated using logistic regression. Left panels show the probability from the base of Lower Monumental Dam past Lower Granite Dam; right panels show the probability from the top-of-ladder sites at Lower Monumental Dam past Lower Granite Dam.

Table 6. Last recorded locations of radio-tagged Chinook salmon derived from the combination of radiotelemetry and PIT detections. Note that some fish were recorded upstream from their final location (i.e., they fell back downstream).

	BON adult		BON jack		ICE adult	
	n	%	*n*	%	*n*	%
Released above ICE[1]	166		153		300	
Release site	n/a		n/a		1	0.3%
ICE tailrace (ds from release site)					13	4.3%
LMD tailrace	2	1.2%			20	6.7%
LMD fishway	2	1.2%			6	2.0%
Lyons Ferry Hatchery			1	0.7%		
LGO tailrace	1	0.6%	2	1.3%	6	2.0%
LGO fishway						
Tucannon River	1	0.6%			2	0.7%
LGR tailrace	1	0.6%	1	0.7%		
LGR fishway	1	0.6%				
Passed LGR (radio)	152	91.6%	132	86.3%	248	82.7%
Passed LGR (PIT detection only)	6	3.6%	17	11.1%	4	1.3%
Total past LGR	**158**	**95.2%**	**149**	**97.4%**	**252**	**84.0%**

[1] detected upstream from ICE for Bonneville-tagged groups

Lower Monumental

Fishway use

A majority of first approaches (51-52%) were at the north fishway opening for Bonneville adult and jack groups (Table 7). First approaches by Ice Harbor-tagged adults were split between the north (41%) and north powerhouse (36%) openings. Across all approach events (total approaches), adults were distributed more evenly between the north and north powerhouse openings. All tag groups approached (first and total) the south opening least often.

Salmon from the three tag groups used all of the openings to enter the Lower Monumental fishways, where first and total entries were similar among groups (Table 7). All three tag groups entered the north and south powerhouse openings approximately a third or more of the time and entered the south opening least often.

Of the radio-tagged salmon that entered Lower Monumental fishways, minimums of 22% (Bonneville adults), 18% (Bonneville jacks), and 24% (Ice Harbor adults) subsequently exited into the tailrace one or more times. First exits were somewhat evenly distributed across fishway openings and total exits most frequently occurred at the south powerhouse opening (Table 7.)

Table 7. Distributions of first and total fishway approaches, entries and tailrace exits by radio-tagged Chinook salmon at Lower Monumental Dam in 2013. Numbers in parentheses are percentages within tag group and category.

	Approach		Entry		Exit to Tailrace	
	First	Total	First	Total	First	Total
Bonneville adults						
North	83 (52)	717 (41)	60 (38)	146 (35)	17 (28)	79 (30)
S. Powerhouse	42 (26)	769 (44)	59 (37)	176 (42)	18 (30)	111 (42)
South	35 (22)	242 (14)	36 (23)	83 (20)	23 (38)	58 (22)
Unknown	0	16 (1)	4 (3)	16 (4)	2 (3)	16 (6)
Bonneville jacks						
North	71 (51)	353 (40)	60 (43)	105 (32)	8 (18)	37 (20)
S. Powerhouse	44 (32)	347 (40)	40 (29)	100 (31)	19 (42)	80 (42)
South	19 (14)	142 (16)	24 (17)	81 (25)	15 (33)	52 (28)
Unknown	5 (4)	34 (4)	14 (10)	40 (12)	3 (7)	20 (11)
Ice Harbor adults						
North	118 (41)	1,184 (40)	87 (32)	193 (31)	34 (26)	110 (31)
S. Powerhouse	106 (36)	1,307 (44)	82 (30)	220 (36)	43 (33)	129 (36)
South	65 (22)	425 (14)	67 (25)	132 (21)	40 (31)	85 (24)
Unknown	2 (1)	67 (2)	36 (13)	69 (11)	12 (9)	35 (10)

Passage efficiency estimates

Almost all radio-tagged Chinook salmon detected approaching Lower Monumental Dam entered the fishway at least once in 2013. Dam-wide entrance efficiency estimates were 0.948-1.000 for the three tag groups (Table 8). All but two of the 159 Bonneville and 14 of the 275 Ice Harbor adult salmon entered the fishway eventually passed the dam. The last radiotelemetry detections for fish that did not pass the dam were 7 in the Lower Monumental fishway, 8 in the Lower Monumental tailrace, and 1 in the Ice Harbor tailrace.

Table 8. Dam-wide efficiency (Eff) metrics estimated for unique radio-tagged Chinook salmon at Lower Monumental Dam in 2013. Fish with lost or non-functioning radio transmitters excluded.

	Fishway entrance efficiency			Fishway passage efficiency			Dam passage Efficiency		
Group	App	Enter	Eff	Enter	Pass	Eff	App	Pass	Eff
BON adult	160	159	0.994	159	157	0.987	160	157	0.981
BON jack	137	137	1.000	137	137	1.000	137	137	1.000
ICE adult	290	275	0.948	275	261	0.949	290	261	0.900

Passage times

Chinook salmon passage times differed among the three study groups and were longer in the Ice-Harbor tagged sample for every metric except median tailrace-to-approach time (Table 9). Median passage times from first tailrace detection to first approach at a Lower Monumental fishway antenna were 1.7 h (Bonneville adults), 2.0 h (Bonneville jacks), and 1.8 h (Ice Harbor adults). Medians from first tailrace to first fishway entry were 5.0 h, 5.9 h, and 7.7 h, respectively. The largest difference was for full-dam passage times, from first tailrace to exit into the Lower Monumental forebay: medians were 12.3 h (Bonneville adults), 12.1 h (Bonneville jacks), and 18.6 h (Ice Harbor adults). Passage times were right-skewed for all groups, resulting in higher mean times (Table 9). This was because some fish spent one or more nights in the tailrace or fishway or exited from the fishway into the tailrace one or more times. Slower passage by the Ice Harbor group was attributable, in part, to earlier migration timing and associated cooler water temperature and higher discharge.

Table 9. Median and mean passage times (hours) of radio-tagged Chinook salmon at Lower Monumental Dam in 2013.

	BON adult			BON jack			ICE adult		
Segment	*n*	Median	Mean	*n*	Median	Mean	*n*	Median	Mean
Tailrace – Approach	146	1.7	2.9	72	2.0	4.3	230	1.8	12.6
Tailrace – Entry	141	5.0	9.9	69	5.9	10.7	182	7.7	36.1
Tailrace – Pass dam	143	12.3	19.2	74	12.1	17.0	210	18.6	38.7
Approach – Entry	155	2.2	6.8	124	1.4	6.0	236	4.1	21.0

Fallback

Fallback percentages and rates were the same for each tag group because no fish fell back multiple times (Table 10). Fallback rate and percentage was 5.7% for both Bonneville and Ice Harbor adults and was 2.9% for Bonneville jacks. All but one of the Bonneville adults, one of the Bonneville jacks, and four of the Ice Harbor adults that fell back reascended and passed Lower Monumental Dam. The one Bonneville adult that did not reascend the dam was last recorded in the tailrace of Lower Monumental Dam. The one Bonneville jack that did not reascend was recaptured in the Umatilla River. Three of the four Ice Harbor adults that did not pass the dam a second time were last recorded in the tailrace of Lower Monumental Dam and the fourth was last detected in Ice Harbor tailrace.

Table 10. Fallback percentages (unique fish that fell back/unique fish past dam) and rates (fallback events/unique fish past dam) for radio-tagged Chinook salmon at Lower Monumental Dam in 2013. Note: passage determined by PIT tag only were excluded.

Group	Unique fish past dam (*n*)	Unique fallback fish	Total fallback events	Fallback percent (%)	Fallback rate (%)
BON adult	157	9	9	5.7%	5.7%
BON jack	138	4	4	2.9%	2.9%
ICE adult	262	15	15	5.7%	5.7%

Little Goose

Environmental and operations data

Total river discharge throughout most of May-August was comprised of approximately 70% turbine discharge and 30% spill. The contribution of each turbine varied considerably throughout the study period. T1 and T2 were run more consistently than T3-T6 (Figures 13 and 14). The highest spill volume was typically through S1, where the TSW was operated in either low-crest (early May, most of June, all of July) or high-crest (mid- to late May only). Spill was also relatively consistent through S8 (~20% of total spill) to provide attraction flow for the north fishway.

Snake River water temperature measured at the Little Goose WQM site increased from ~10 °C in early May to >20 °C through most of July (Figure 15). Warming rates were variable. There was a cooling period in the second half of May that coincided with peak discharge, rapid warming in early June and early July, and periods of little change in late June and late July.

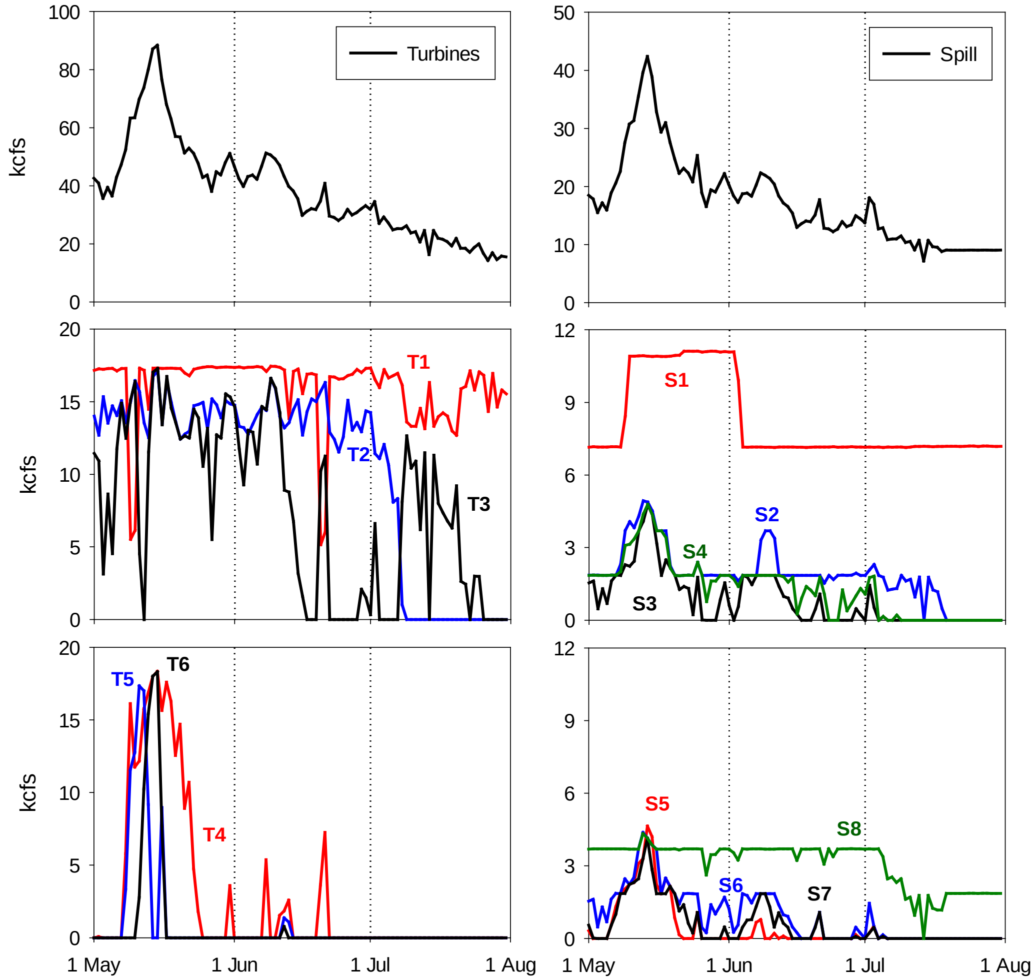

Figure 13. Mean daily turbine (T1-T6) and spillbay (S1-S8) discharge data (kcfs) from Little Goose Dam during the spring–summer Chinook salmon run in 2013. Note different y-axis scales.

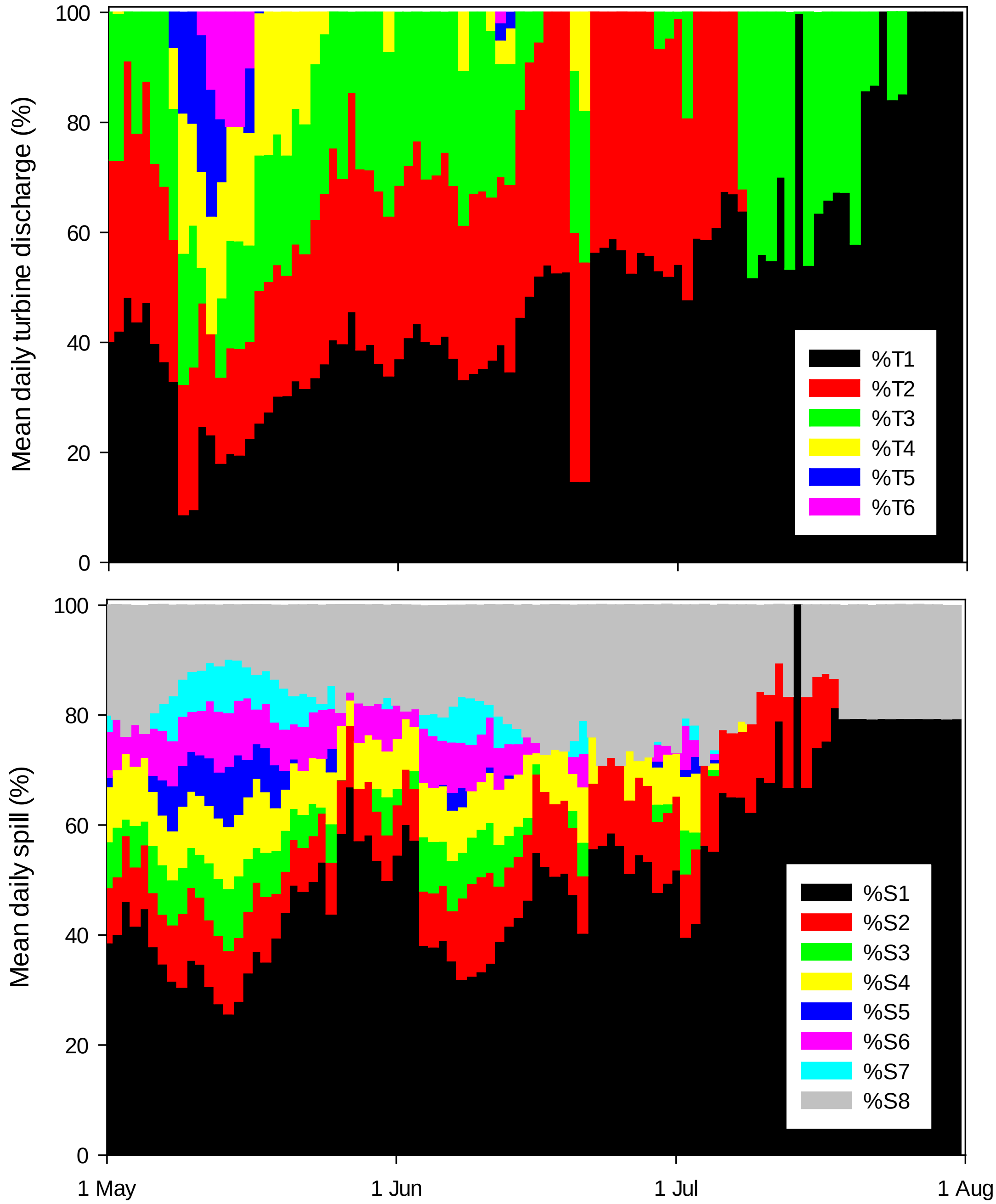

Figure 14. Mean daily turbine discharge and spill at Little Goose Dam during the spring–summer Chinook salmon run in 2013, expressed as percentages of daily totals.

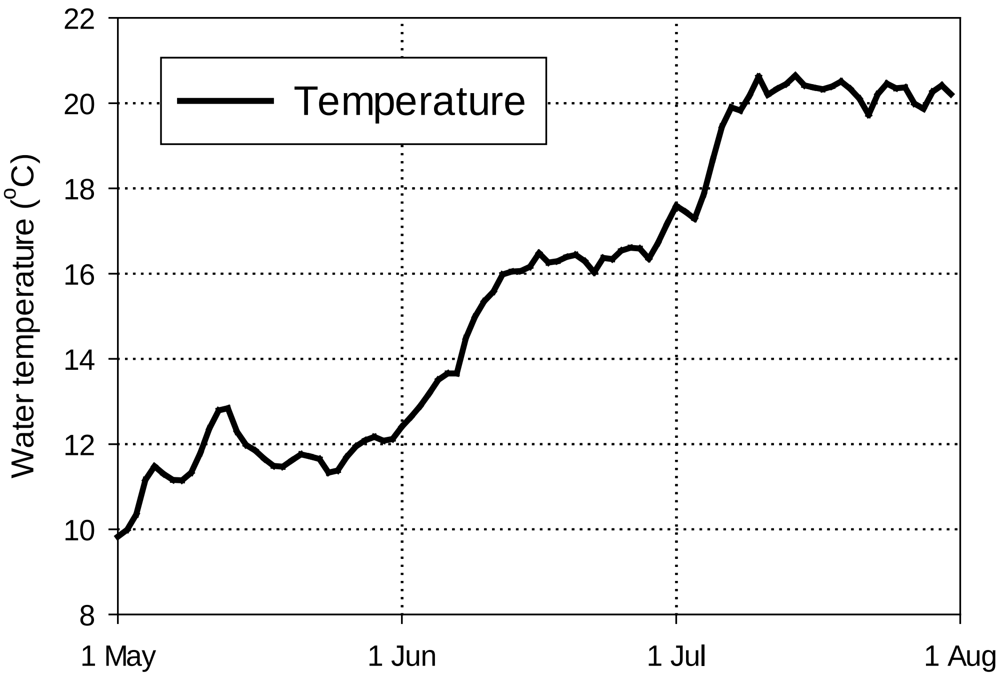

Figure 15. Mean daily water temperature (°C) recorded at the Little Goose tailrace water quality monitoring (WQM) site during the spring–summer Chinook salmon migration in 2013.

Sample summary

In total, 117 jacks tagged at Bonneville, 153 adults tagged at Bonneville, and 242 adults tagged at Ice Harbor were detected at Little Goose tailrace antennas (Figure 16). The arrival timing of these samples at Little Goose was later than the jack and adult run timing at large, reflecting the relatively late collection and tagging effort at both Ice Harbor and Bonneville dams (see Figures 9 and 10). Median arrival dates at Little Goose tailrace ranged from 23 May for Ice Harbor adults to 4 June for Bonneville jacks (spring and summer fish). The temporal mismatch between tagged and untagged salmon and the temporal differences among sample groups need to be carefully considered when interpreting results.

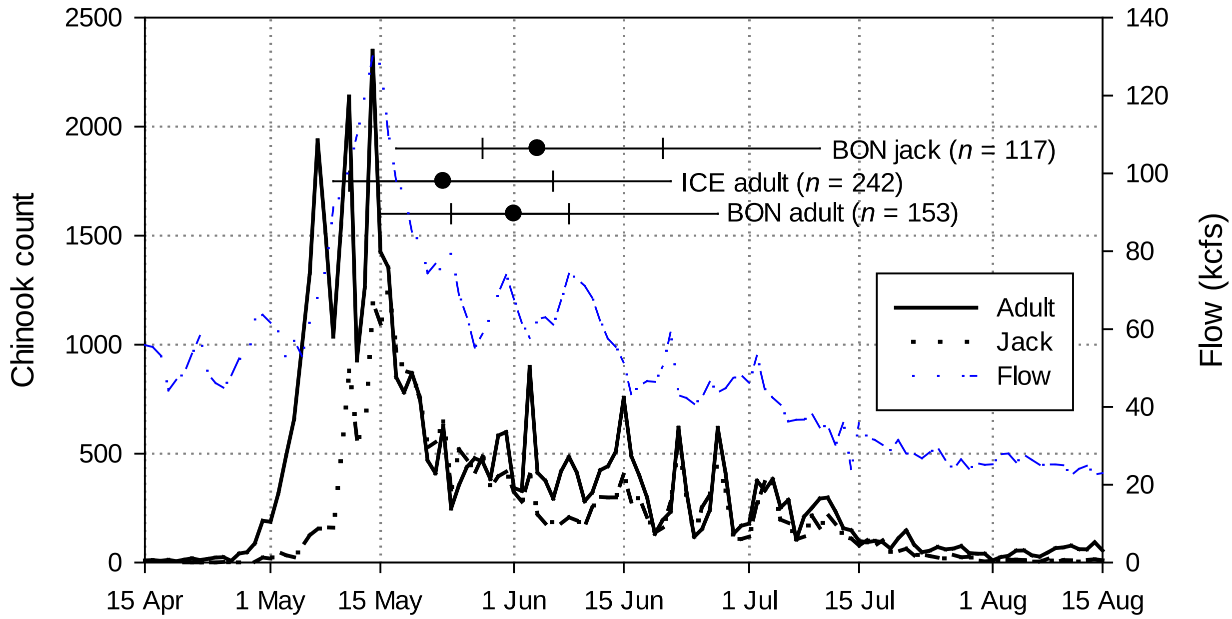

Figure 16. Daily counts of adult and jack Chinook salmon at Little Goose Dam in 2013, with the distributions (5, 25, 50, 75, and 95% percentiles) of first tailrace detection dates of radio-tagged Chinook salmon. The Bonneville-tagged samples included spring- and summer-run fish whereas the Ice Harbor-tagged sample was spring-run only. Blue dashed line is total daily discharge (kcfs).

Fishway use

A majority of first and total fishway approaches were at the south fishway openings for all three tag groups, and the north spillway opening was approached least often (Table S). With all three groups combined, 68% of first approaches and 57% of total approaches were at the south openings. Importantly, however, the estimates for the unmonitored north opening were inferred from records at other antennas and were almost certainly underestimates. Estimated approach percentages at the north entrance were comparable to results from the 2000-2004 radiotelemetry studies of Chinook salmon tagged at Bonneville Dam (Figure 17). Proportionately more adult Chinook salmon approached the north spillway opening in the radio-tagged sample from 2008, the year when spill was experimentally manipulated at the dam (Jepson et al. 2009).

Salmon from the three tag groups used all of the openings to enter the Little Goose fishways, but the distributions of first and total entries differed somewhat among groups (Table 11, Figure 17). Adults from the Ice Harbor and Bonneville groups used the south openings most often, followed by the north spillway opening, and the north powerhouse opening. Fishway entries by the jack sample were distributed somewhat more evenly among the south and north powerhouse openings; the north spillway opening was used least (but note previous comments about likely underestimation).

Of the radio-tagged salmon that entered Little Goose fishways, minimums of 25% (Bonneville adults), 19% (Bonneville jacks), and 31% (Ice Harbor adults) subsequently exited into the tailrace one or more times. First and total exits were most frequent for all groups via the north powerhouse opening and were least frequent via the north spillway opening (Table 11).

Table 11. Distributions of first and total fishway approaches, entries and tailrace exits by radio-tagged Chinook salmon at Little Goose Dam in 2013. Numbers in parentheses are percentages within tag group and category.

	Approach		Entry		Exit to Tailrace	
	First	Total	First	Total	First	Total
Bonneville adults						
N. Powerhouse	26 (16)	381 (41)	28 (18)	42 (18)	25 (57)	40 (50)
South	112 (70)	483 (52)	74 (47)	126 (53)	19 (43)	39 (49)
Unknown[1]	21 (13)	71 (8)	57 (36)	72 (30)	-	1 (1)
Bonneville jacks						
N. Powerhouse	48 (34)	205 (41)	54 (40)	89 (38)	22 (49)	43 (43)
South	77 (55)	259 (52)	51 (38)	110 (47)	18 (40)	43 (43)
Unknown[1]	15 (11)	36 (7)	31 (23)	36 (15)	5 (11)	14 (14)
Ice Harbor adults						
N. Powerhouse	42 (15)	442 (31)	44 (16)	85 (19)	59 (72)	107 (62)
South	201 (74)	901 (63)	170 (64)	270 (61)	23 (28)	64 (37)
Unknown[1]	29 (11)	85 (6)	53 (20)	85 (19)	-	1 (1)
All groups (%)						
N. Powerhouse	20%	36%	22%	24%	62%	54%
South	68%	57%	52%	55%	35%	41%
Unknown[1]	11%	7%	25%	21%	3%	5%

[1] many unknown were presumed to be via the unmonitored north opening; use of this site was underestimated

Passage efficiency estimates

Almost all radio-tagged Chinook salmon detected approaching Little Goose Dam entered the fishway at least once in 2013. Dam-wide entrance efficiency estimates were 0.984-1.000 for the three tag groups (Table 12). All but one of the 543 salmon that entered the fishway eventually passed the dam (fishway passage efficiency = 0.996-1.000). The only exception was an Ice Harbor-tagged adult that exited the fishway, moved downstream, and was last detected in the Lower Monumental tailrace.

The full-dam passage efficiency estimates (# past dam / # approached fishway) were 0.994 (Bonneville adults), 1.000 (Bonneville jacks), and 0.981 (Ice Harbor adults) (Table 12). These estimates did not statistically differ among groups ($P \geq 0.10$, Pearson χ^2 tests).

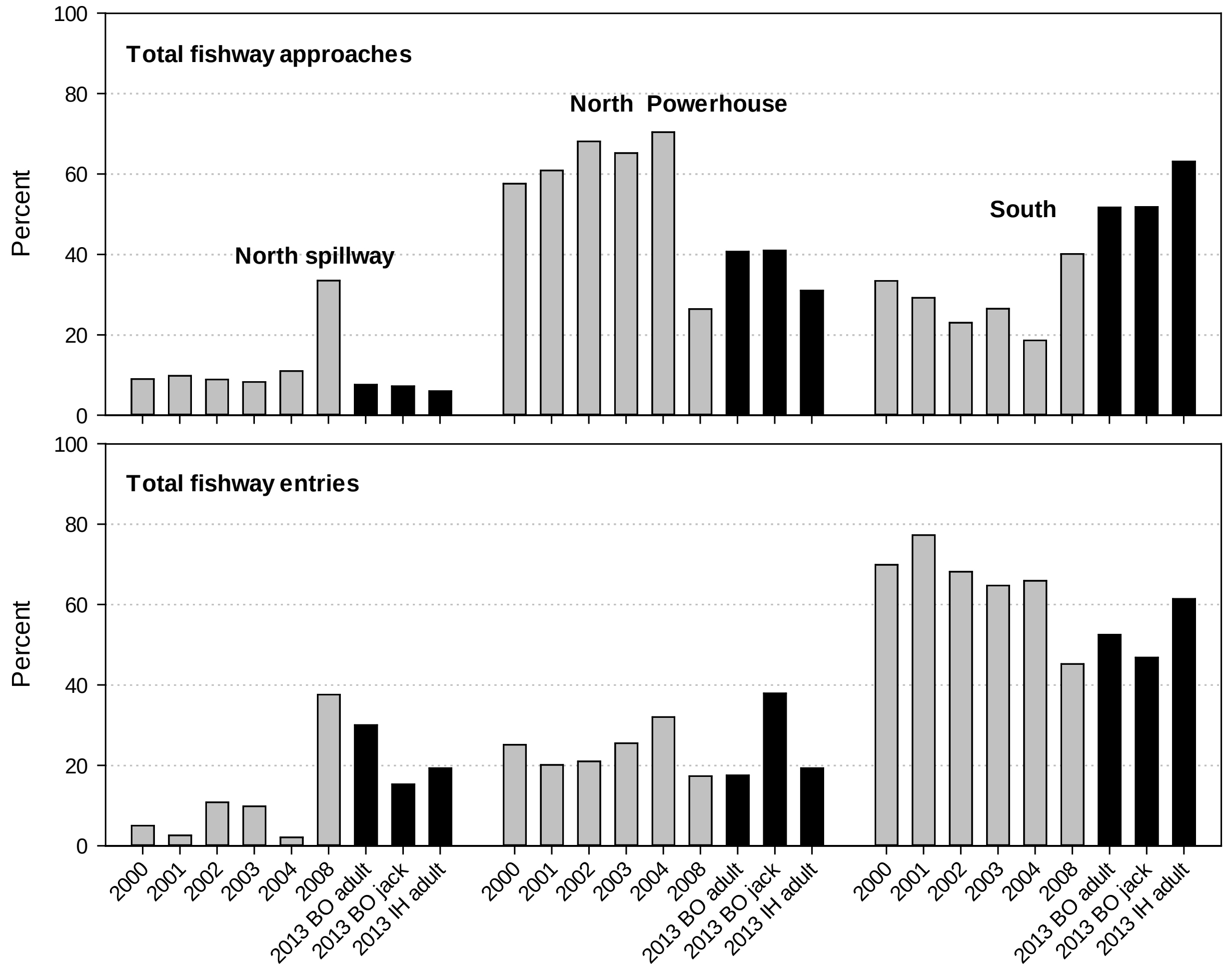

Figure 17. Percent of all fishway approaches (top) and fishway entries (bottom) of radio-tagged adult spring–summer Chinook salmon in 2000-2004 (tagged at Bonneville Dam), in 2008 (tagged at Ice Harbor Dam) and of the three study groups in 2013. Note that the north spillway opening was not monitored in 2013. The 'unknown' category is shown as the north spillway group because we assumed a majority of the unknown events were at this site in 2013. These were likely underestimated for both behaviors. *Note: the 2008 group encountered experimental spill treatments at Little Goose Dam (see Jepson et al. 2009).*

Table 12. Dam-wide efficiency (Eff) metrics estimated for unique radio-tagged Chinook salmon at Little Goose Dam in 2013. Fish with lost or non-functioning transmitters excluded.

	Fishway entrance efficiency			Fishway passage efficiency			Dam passage Efficiency		
Group	App	Enter	Eff	Enter	Pass	Eff	App	Pass	Eff
BON adult	155	154	0.994	154	154	1.000	155	154	0.994
BON jack	135	135	1.000	135	135	1.000	135	135	1.000
ICE adult	258	254	0.984	254	253	0.996	258	253	0.981

Passage times

The three tag groups showed similar diel behavior patterns at Little Goose Dam (Figure 18). Radio-tagged salmon were first detected in the tailrace at all hours of the day and night, with a peak in activity in mid-morning. In contrast, salmon were far more likely to first approach the fishway, first enter the fishway, and exit the fishway into the Little Goose forebay during daylight hours. This behavior is typical of upstream-migrating salmon at dams and affects overall dam passage times because fish that arrive in the tailrace late in the day are more likely to pass the dam the following day.

Chinook salmon passage times differed among the three study groups (Table 13). Median passage times from first tailrace detection to first approach at a Little Goose fishway antenna were 2.5 h (Bonneville adults), 1.4 h (Bonneville jacks), and 2.2 h (Ice Harbor adults). Medians from first tailrace to first fishway entry were 5.2 h, 3.0 h, and 7.4 h, respectively. The largest difference was for full-dam passage times, from first tailrace to exit into the Little Goose forebay: medians were 11.1 h (Bonneville adults), 11.2 h (Bonneville jacks), and 19.7 h (Ice Harbor adults). Passage times were right-skewed for all groups, resulting in higher mean times (Table 13). This was because some fish spent one or more nights in the tailrace or fishway or exited from the fishway into the tailrace one or more times. These patterns, and the median passage times, were generally within the ranges of times reported in previous radiotelemetry studies (Keefer et al. 2004; Jepson et al. 2009).

The longer full-dam passage times for the Ice Harbor group could be attributable to several factors. First, the Ice Harbor group migrated earlier than the Bonneville groups by an average of 8 d (Bonneville adults) and 13 d (Bonneville jacks). As a result, the Ice Harbor group encountered lower water temperatures and higher turbine discharge (6-10 kcfs, on average) and spill (3-5 kcfs, on average) compared to the Bonneville-tagged groups. These environmental factors are routinely associated with slower passage times (e.g., Keefer et al. 2004). Second, as noted above, the Ice Harbor group was slightly more likely to exit the fishway back to the Little Goose tailrace, a behavior that is associated with slower passage and higher incidence of overnight behavior. Third, the Ice Harbor sample arrived later and exited earlier in the day compared to Bonneville adults, suggesting some of the effect may be related to a carry-over effect of tagging, with release in afternoon that resulted in more Ice Harbor-tagged adults overnighting at Little Goose Dam.

Full-dam (tailrace to pass the dam) passage times varied seasonally for all three groups (Figure 19). The patterns suggest that common environmental or operational conditions affected some fish from all groups. In several weeks, however, the Ice Harbor-tagged adults had longer passage times than the fish tagged at Bonneville Dam. We used a generalized linear model (GLM) that included tag group (categorical covariate), date, total river discharge, and a quadratic term for time of tailrace entry (continuous covariates) to evaluate full-dam passage times (also see time-to-event analysis below). There was a significant tag group effect ($F = 7.1$, $P < 0.001$, $n = 494$, $df = 6$), with longer passage times for the Ice Harbor group after accounting for the other covariates. There was also a time of day effect, with slower passage for fish that entered the Little Goose tailrace late in the day ($F = 5.3$-6.1, $P < 0.05$ for the time and time^2 covariates).

Date and flow effects were non-significant ($P \geq 0.13$) in this model, but we note that the tag group effect included a date effect.

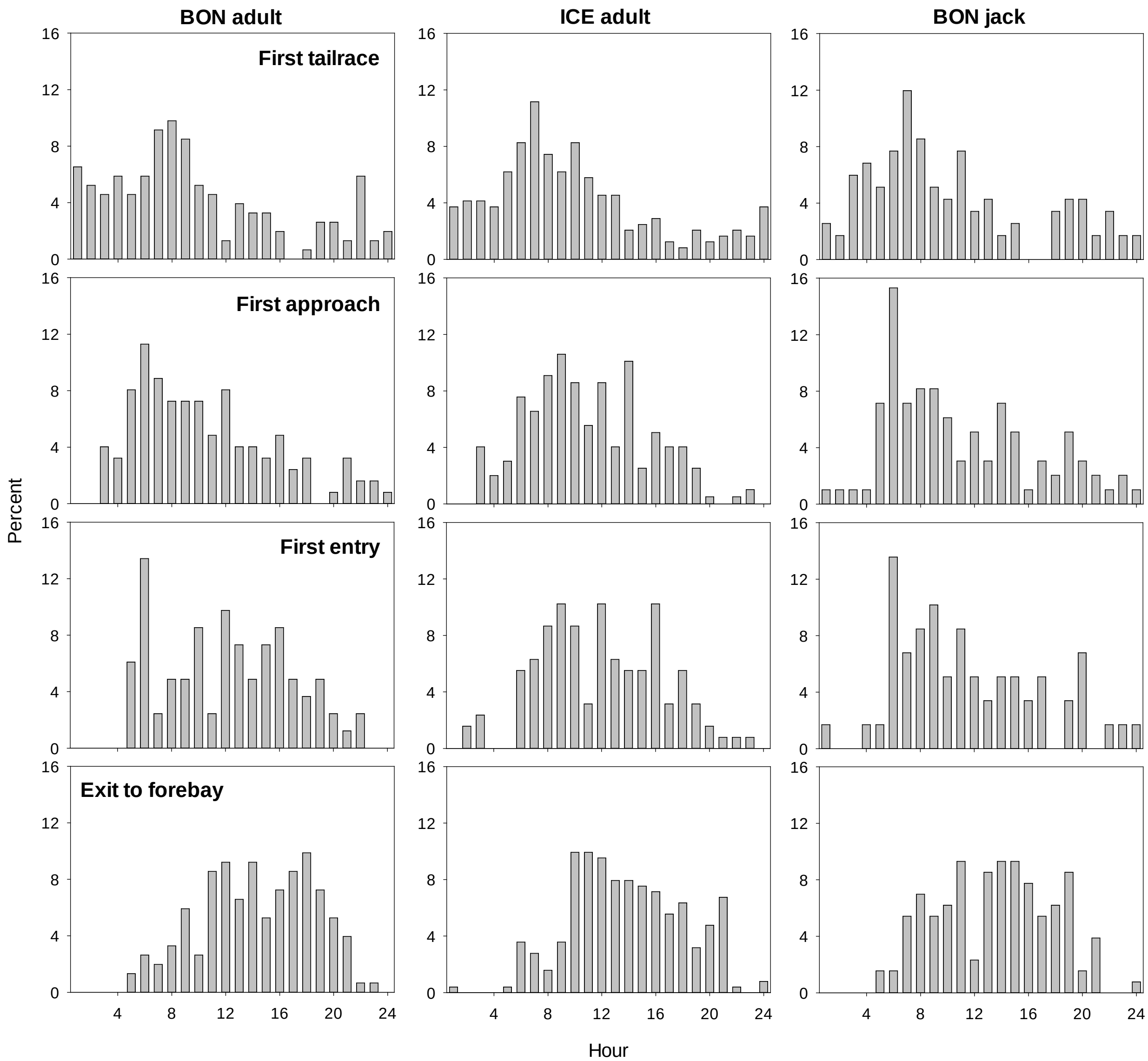

Figure 18. Diel distributions (%) of the times that radio-tagged Chinook salmon were first detected in the Little Goose tailrace, at their first known fishway approach and fishway entry, and as they exited from the fishway into the Little Goose forebay in 2013. Data from Bonneville-tagged adults, Ice Harbor-tagged adults, and Bonneville-tagged jacks are shown separately.

Table 13. Median and mean passage times (hours) of radio-tagged Chinook salmon at Little Goose Dam in 2013.

	BON adult			BON jack			ICE adult		
Segment	*n*	Median	Mean	*n*	Median	Mean	*n*	Median	Mean
Tailrace – Approach	120	2.5	7.4	86	1.4	2.9	185	2.2	6.3
Tailrace – Entry	79	5.2	14.1	50	3.0	5.8	117	7.4	27.9
Tailrace – Pass dam	149	11.1	27.8	110	11.2	20.1	235	19.7	46.4
Approach – Entry	82	1.0	8.8	59	0.4	2.7	127	1.5	21.5

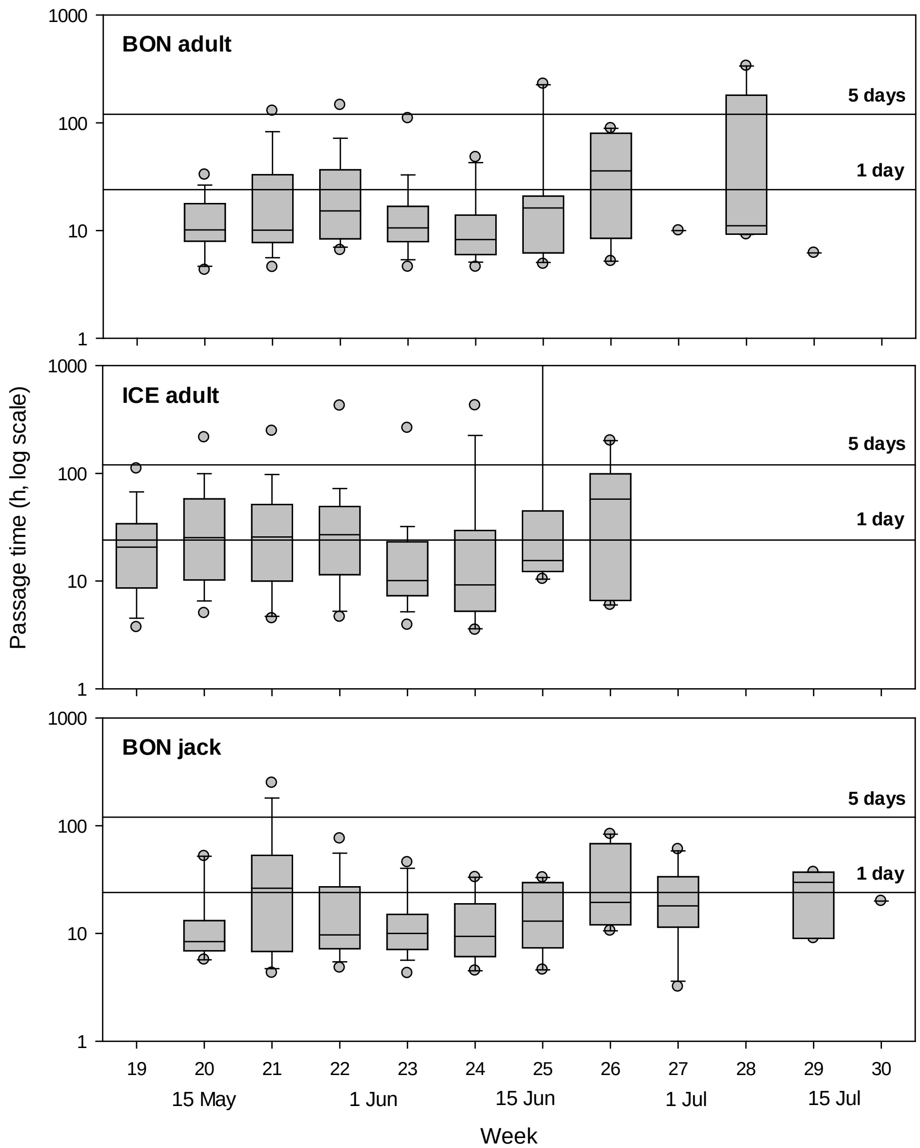

Figure 19. Passage times (h, log scale) of radio-tagged Chinook salmon from first detection in the Little Goose tailrace to exit from the fishway into the forebay in 2013. Data from Bonneville-tagged adults, Ice Harbor-tagged adults, and Bonneville-tagged jacks are shown separately.

Time-to-event analysis

We used time-to-event models to evaluate full-dam passage times (i.e., time from first tailrace record to exit into the Little Goose forebay). The first model (Model 1) included four time-varying covariates (daylight where night was from 21:00-06:00 h, water temperature, total turbine discharge, total spill) and four fixed covariates (tag group, date of first tailrace record, time of first tailrace record, number of fishway exits to tailrace). A second model (Model 2) included time-varying discharge from each turbine (n = 6) and each spillbay (n = 8) in place of total discharge from these sources. Note that total spill discharge + total turbine discharge ~ total river discharge.

In exploratory analyses, we ran separate models for the three tag groups (Bonneville adults, Ice Harbor adults, Bonneville jacks). Results with respect to the environmental and fixed covariates were generally consistent across tag groups. Therefore, we report results here only for the models that included all fish to maximize inferential power; tag group was a covariate in these models. The sample with complete data included 150 Bonneville-tagged adults, 110 Bonneville-tagged jacks, and 235 Ice Harbor-tagged adults.

Tag group – Both Bonneville-tagged groups had higher hazard ratios than the Ice Harbor-tagged adults, but only the Bonneville jack:Ice Harbor adult comparison was statistically significant in either Model 1 or Model 2 (Table 14). The Bonneville groups were ~20-40% more likely to pass Little Goose Dam (hazard ratios = 1.21-1.43) in any given time interval than the Ice Harbor adults.

Fishway exit to tailrace – Exit from the Little Goose fishway into the tailrace significantly reduced the probability of dam passage (hazard ratio ~ 0.72 in both Model 1 and Model 2). Each fishway exit was associated with a ~28% reduced instantaneous probability of dam passage. The delaying effect of fishway exit at FCRPS dams has often been reported previously.

Daylight – The most influential predictor of whether Chinook salmon passed Little Goose dam was daylight. The hazard ratio estimates for time of day in Model 1 (9.52) and Model 2 (9.35) indicated that salmon from all groups and the combined sample were more than nine times more likely to pass the dam during daytime hours than nighttime hours. This diel behavioral effect has been observed at many other dams, and likely reflects the reluctance of visually-oriented salmon to move through the turbulent, high velocity fishways at night (Keefer et al. 2013).

Tailrace date and time – Neither the date nor time that Chinook salmon entered the Little Goose tailrace was a statistically significant predictor in Model 1 or Model 2. This was likely because the time-varying daylight term accounted for most of the potential tailrace entry time-of-day effect and the other covariates, particularly water temperature, largely accounted for the date effect.

Water temperature – Water temperature had positive hazard ratios (1.102-1.138), indicating passage probabilities were higher at warmer temperatures. However, temperature was non-significant ($P > 0.05$) in both Model 1 and Model 2, suggesting a modest effect.

Table 14. Estimated passage hazard ratios (i.e., the probability of salmon passage during any given time interval) for radio-tagged Chinook salmon at Little Goose Dam in 2013. Hazards were estimated with proportional hazards regression (i.e., time-to-event) analysis. Hazards > 1.0 indicate a faster passage time. Hazards for categorical covariates (tag group) compare the first versus second group in the 'category' column. Hazards for continuous variables are for the change per unit increase in the covariate: 1 d, for tailrace (TR) date, 1 h for tailrace time of day, 1 °C for temperature, 1 kcfs (28 m^3/s) for turbine and spill discharge, and day:night for the daylight variable. Fishway exit and tailrace date and time are static covariates (i.e., not time-varying).

		Model 1			Model 2		
	Category	Hazard	χ^2	*P*	Hazard	χ^2	*P*
Tag group	BON adult:IH adult	1.237	3.4	0.064	1.211	2.7	0.103
	BON jack:IH adult	**1.428**	**7.6**	**0.006**	**1.431**	**7.6**	**0.006**
Fishwy exit		**0.723**	**44.5**	**<0.001**	**0.724**	**45.2**	**<0.001**
Daylight		**9.524**	**94.6**	**<0.001**	**9.354**	**92.8**	**<0.001**
TR date		1.008	0.4	0.525	0.996	0.1	0.807
TR time		1.072	0.1	0.712	1.148	0.5	0.469
Temperature		1.102	2.4	0.123	1.138	1.4	0.229
$Turbine_T$		**1.022**	**4.3**	**0.039**	-	-	-
$Spill_T$		0.977	1.2	0.284	-	-	-
T1		-	-	-	**1.039**	**4.4**	**0.036**
T2		-	-	-	0.992	0.2	0.690
T3		-	-	-	**1.051**	**10.7**	**0.001**
T4		-	-	-	1.009	0.4	0.533
T5		-	-	-	1.028	2.2	0.140
T6		-	-	-	1.020	1.4	0.236
S1		-	-	-	**0.897**	**4.8**	**0.028**
S2		-	-	-	0.947	0.3	0.587
S3		-	-	-	1.083	0.7	0.398
S4		-	-	-	0.983	0.0	0.856
S5		-	-	-	0.949	0.3	0.582
S6		-	-	-	**0.790**	**6.3**	**0.012**
S7		-	-	-	1.102	1.2	0.273
S8		-	-	-	1.349	3.6	0.058

Total turbine discharge (Model 1 only) – Total turbine discharge (included in Model 1 only) was positively associated with the instantaneous probability of dam passage (hazard ratio = 1.022). The probability increased by ~2.2% per 1 kcfs increase in turbine discharge. This may indicate that increasing turbine discharge provided increased attraction flow for salmon approaching and entering the fishway openings.

Total spill (Model 1 only) – Total spill was not associated with either increased or reduced passage probability (hazard ratio = 0.977, *P* = 0.28).

Individual turbine discharge (Model 2 only) – Discharge from individual turbines was positively associated with Chinook salmon passage at Little Goose Dam. However, only T1 discharge (hazard ratio = 1.039) and T3 discharge (hazard ratio = 1.051) were statistically significant. A 1 kcfs increase in discharge from these turbines was associated with a ~3.9 and

~5.1% increase in passage probability, respectively. Note that T4, T5, and T6 were only operated intermittently, and primarily in the first half of the 2013 Chinook salmon migration (Figure 14).

Individual spillbay discharge (Model 2 only) – The effects of individual spillbay discharge were mixed, with some hazard ratios greater than and others less than 1.0 (Table 14). The S1 discharge was significantly negatively associated with passage hazard (hazard ratio = 0.897, P = 0.028). This suggests that the high-crest TSW operation deterred passage for some fish because there were essentially two S1 discharge levels (see Figure 13), and the instantaneous probability of passage was ~10% lower during the high-crest operation. The S6 discharge was also negatively associated with passage (hazard ratio = 0.790, P = 0.012). Higher S6 discharge occurred during the high-crest TSW operation early in mid-May and again just after the TSW operation dropped to the low-crest in early June (see Figure 13). There was also a period late in the run when there was no discharge from S6. Across the full period, the instantaneous probability of passage was ~21% lower for each 1 kcfs increase in S6 discharge.

Hazard ratios were non-significantly positive for S3 (ratio = 1.083), S7 (ratio = 1.102), and S8 (ratio = 1.349). The S7 and S8 effect may indicate that discharge from these spillbays provides attraction flow. The proportion of spill via S8 was proportionately similar across the migration at approximately 20% of total spill, whereas discharge from S7 was limited to the high-flow conditions in May and early June (see Figure 14). Alternatively, increased at S8 may have affected flow condition the tailrace that improved guidance and attraction into fishways.

Fallback

All but one salmon that was recorded falling back at Little Goose Dam in 2013 had single fallback events, and therefore fallback percentages and rates were quite similar within tag group (Table 15). Percentages and rates were 2.9-3.9% for the Bonneville tag groups and 7.5-7.9% for the Ice Harbor group. The earlier timing of the Ice Harbor-tagged fish likely contributed somewhat to higher fallback, as these fish encountered higher river discharge and spill at the dam; on average, Ice Harbor-tagged salmon fell back 6 d earlier than the Bonneville-tagged fish.

There were 30 recorded fallback events across groups. In three events (10%), fish had moved upstream and were detected at Lower Granite Dam prior to the fallback at Little Goose Dam. The remainder (n = 27, 90%) were not detected upstream from the Little Goose ladder exit antenna prior to fallback.

Twenty-three of the 29 (79%) unique salmon that fell back at Little Goose Dam reascended the fishway and were last detected upstream from the dam. All but one of the 23 were last detected upstream from Lower Granite Dam. The six fish that did not reascend at Little Goose Dam were last detected in the Umatilla River (1), Tucannon River (1), Lower Monumental tailrace (1), or Little Goose tailrace (3).

Table 15. Fallback percentages (unique fish that fell back/unique fish past dam) and rates (fallback events/unique fish past dam) for radio-tagged Chinook salmon at Little Goose Dam in 2013. Note: passage determined by PIT tag only were excluded.

Group	Unique fish past dam (*n*)	Unique fallback fish	Total fallback events	Fallback percent (%)	Fallback rate (%)
BON adult	154	6	6	3.9%	3.9%
BON jack	138	4	4	2.9%	2.9%
ICE adult	254	19	20	7.5%	7.9%

Lower Granite

Temperature monitoring

Results from the water ladder temperature loggers indicate a temperature difference between the south ladder entrance and the rest of the fish ladder during the warm summer months. On average, temperatures near the south ladder entrance were 2.0 ºC cooler than the rest of the fish ladder (Figure 20). The logger data also differed, at times, from the temperatures recorded at the Lower Granite water quality monitoring (WQM) site. The WQM data spiked higher on several days in September. The maximum daily average temperature we recorded (23.8 ºC) was near the fish ladder exit at in July. Salmon counts at Lower Granite dam were highly variable during the warm weather period (Figure 21).

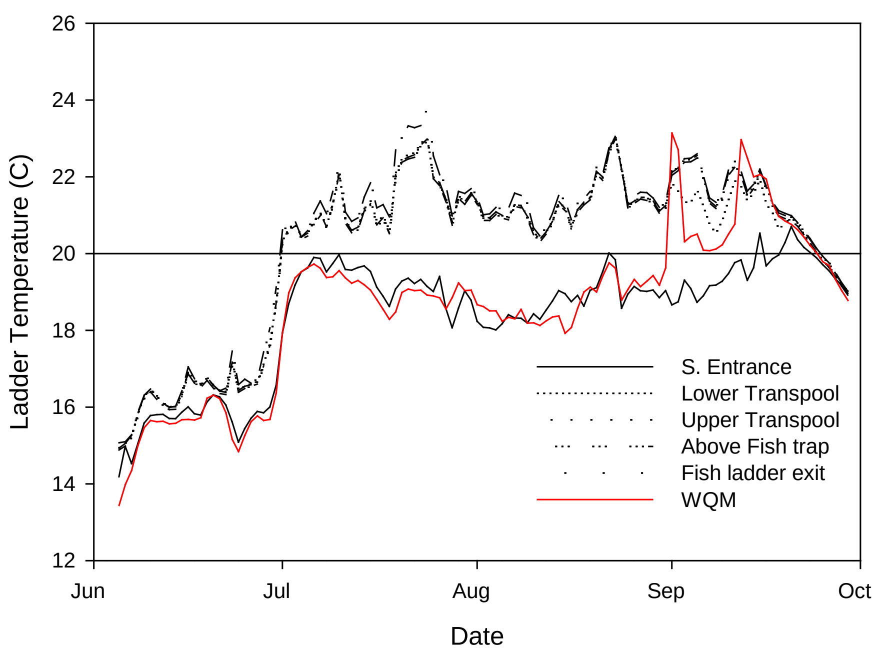

Figure 20. Daily average water temperatures at the five monitored locations in the Lower Granite Dam fish ladder in 2013 (black lines) and at the water quality monitoring site (red line).

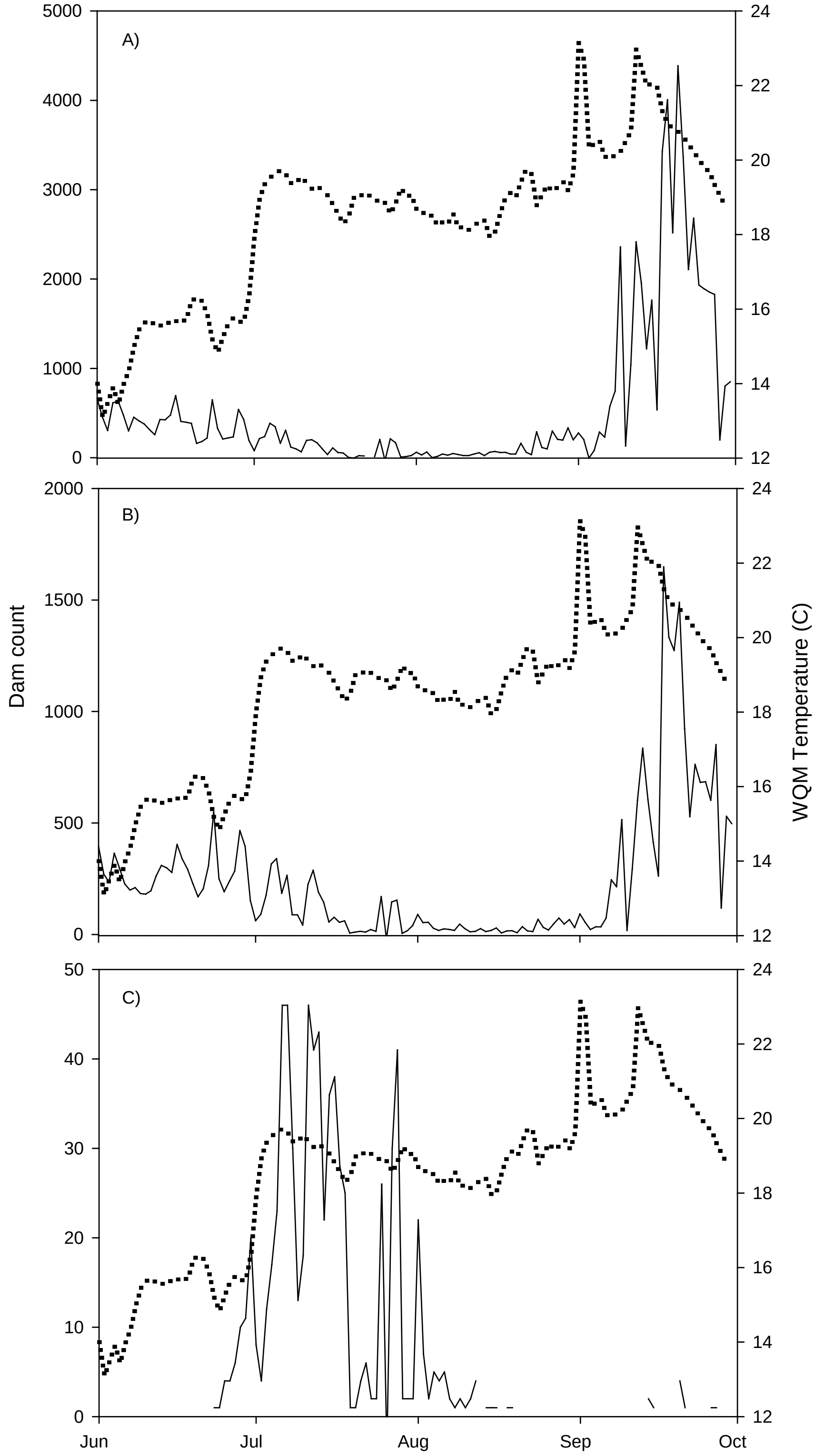

Figure 21. Daily counts of A) adult Chinook salmon, B) jack Chinook salmon, and C) adult sockeye salmon at Lower Granite Dam in 2013 (indicated by thin solid lines), with WQM water temperature (thick dashed lines).

Lower Granite forebay temperatures were consistently warm near the surface and upper water column with temperatures near or above 20ºC from July 1 until September 25 (Figure 22). Cooler water was recorded near the bottom of the water column (> ~18 m) in the 16-18ºC range. Forebay temperatures 122 m upstream of the exit peaked at 23.6ºC on 24 July and were similar near the dam (fish ladder exit; Figure 20) and upstream of the dam (Figure 22).

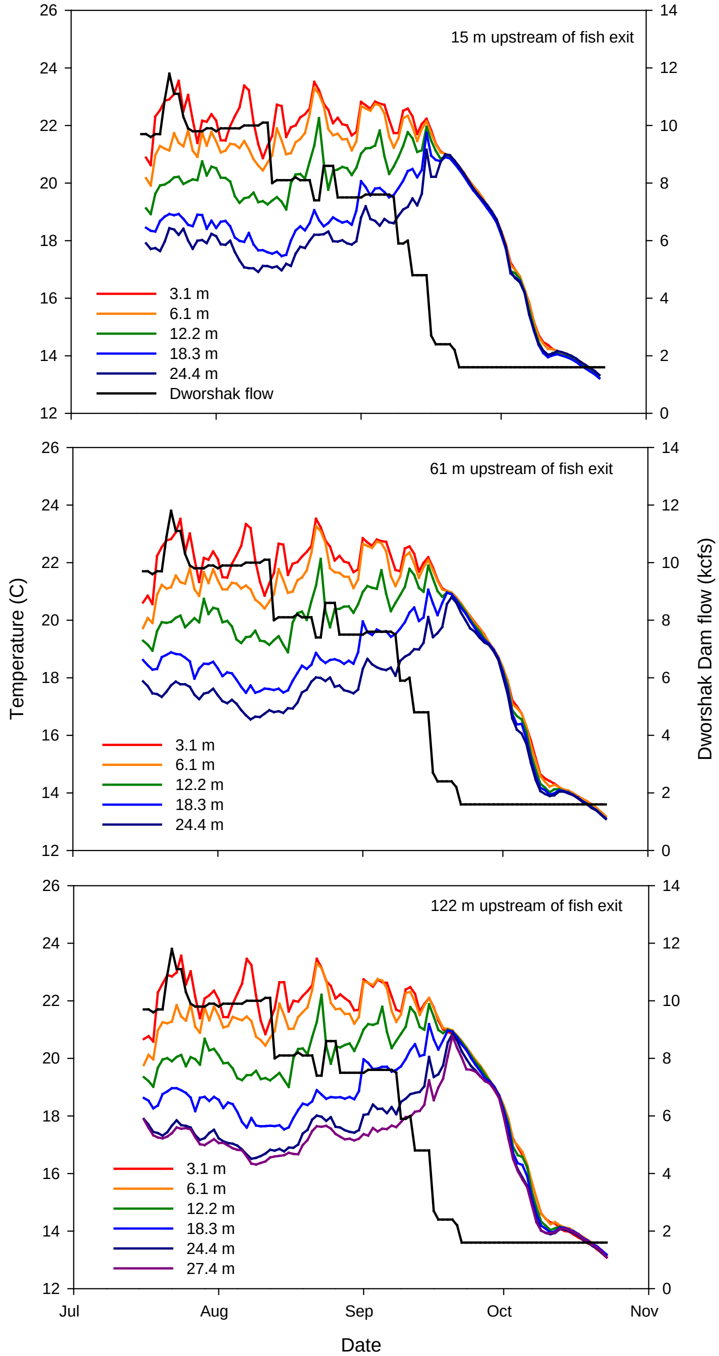

Figure 22. Lower Granite forebay temperature logger data collected upstream of the fish ladder exit (top panel 15 m upstream), middle panel (61 m upstream) and bottom panel (122 m upstream) and Dworshak Dam flow in 2013.

Radiotelemetry monitoring

In total, 544 radio-tagged Chinook salmon and one tagged sockeye salmon were detected at Lower Granite Dam (Figure 23). The Chinook total included 139 jack and 156 adults tagged at Bonneville Dam and 247 adults tagged at Ice Harbor Dam. Almost all of the Ice Harbor-tagged fish were first detected at Lower Granite Dam in May and June, before the onset of high water temperatures. The Bonneville-tagged sample included some summer-run Chinook salmon (*n* = 60) and 35 of these fish were first detected at Lower Granite Dam in July (Figure 23). A small sample (*n* = 9) of Bonneville tagged steelhead were also detected at Lower Granite Dam during the warm temperature period in September.

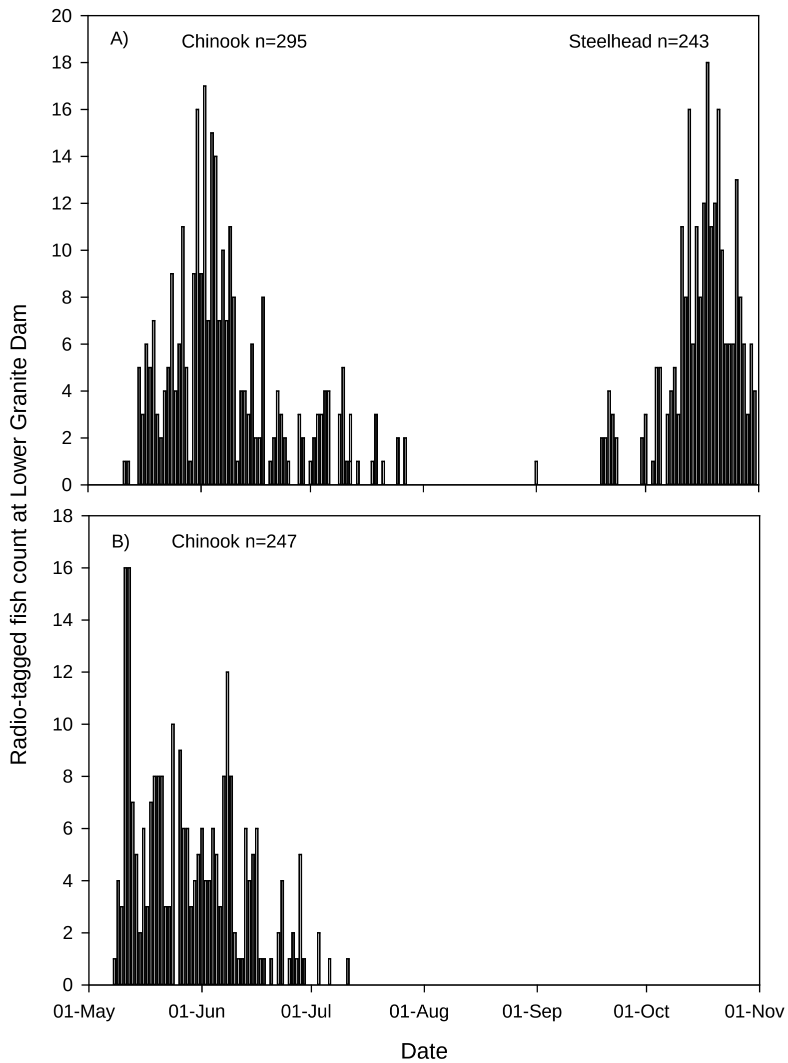

Figure 23. First detection dates of radio-tagged Chinook salmon and steelhead at Lower Granite Dam that were tagged at A) Bonneville Dam and B) Ice Harbor Dam. Note the majority of first detections were recorded on tailrace antennas (91.5 % of Chinook and 67% of steelhead tagged at Bonneville, and 83% of Ice Harbor-tagged Chinook). All other first detections were at the dam (at fishway entrance antennas).

Fishway use

The majority of first and total fishway approaches for each tag group were at the south fishway openings except for Bonneville-tagged jacks (first approaches), and the north powerhouse opening was approached least often (Table 16). With the two adult tags groups combined, 50% of first approaches and all three tags groups combined 60% of total approaches were at the south openings. Importantly, however, the estimates for the unmonitored north powerhouse openings and open orifice gates were recorded as unknown approaches, entries, and exits.

Overall the majority of salmon first and total entries of all three tag groups were unknown followed predominately by the north spillway entries (Table 16). Adults from all three tag groups used the north spillway openings most often, followed by the south opening, and the north powerhouse opening for first entries. Total fishway entries by tag groups were distributed somewhat more evenly among the south and north spillway openings; the north powerhouse opening was used least.

First exits to the tailrace of the radio-tagged salmon that entered Lower Granite fishways were split between south and north spillway entrances. Highest percentages of first exits occurred at south openings for Bonneville jacks (35%) and Ice Harbor adults (41%) and at north spillway openings for Bonneville adults (48%) that subsequently exited into the tailrace one or more times. Total exits were most frequent for all groups via south openings and were least frequent via the north powerhouse openings (Table 16).

Table 16. Distributions of first and total fishway approaches, entries and tailrace exits by radio-tagged Chinook salmon at Lower Granite Dam in 2013.

	Approach		Entry		Exit to Tailrace	
	First	Total	First	Total	First	Total
Bonneville adults						
North	43 (28)	242 (15)	49 (32)	145 (33)	31 (48)	97 (33)
N. Powerhouse	13 (8)	292 (18)	7 (5)	50 (11)	4 (6)	31 (11)
South	61 (40)	956 (59)	29 (19)	122 (28)	21 (32)	118 (41)
Unknown	37 (24)	126 (8)	69 (45)	126 (28)	9 (14)	45 (15)
Bonneville jacks						
North	51 (38)	143 (20)	55 (41)	104 (27)	17 (28)	39 (16)
N. Powerhouse	8 (6)	82 (11)	7 (5)	34 (9)	7 (12)	27 (11)
South	41 (30)	370 (51)	15 (11)	112 (29)	20 (33)	113 (45)
Unknown	36 (26)	135 (18)	58 (43)	135 (35)	16 (27)	71 (28)
Ice Harbor adults						
North	57 (23)	226 (9)	59 (24)	137 (26)	32 (33)	83 (29)
N. Powerhouse	16 (6)	403 (15)	17 (7)	64 (12)	11 (11)	43 (15)
South	139 (56)	1,774 (68)	47 (19)	132 (25)	40 (41)	117(40)
Unknown	37 (15)	204 (8)	128 (51)	204 (38)	14 (14)	46 (16)

Passage efficiency estimates

All Bonneville- and Ice Harbor-tagged Chinook salmon had 100% entrance efficiency at Lower Granite Dam (Table 17). Fishway and dam passage efficiency estimates for each group ranged from 0.987 for Bonneville adults to 1.000 for Ice Harbor adults. One of the two Bonneville adults that entered but did not pass the dam was last recorded in the Little Goose tailrace and the other was last recorded in the Tucannon River. The Bonneville jack that did not pass the dam was last detected in the Little Goose Tailrace.

Table 17. Dam-wide efficiency (Eff) metrics estimated for unique radio-tagged Chinook salmon at Lower Granite Dam in 2013. Fish with lost or non-functioning transmitters excluded.

	Fishway entrance efficiency			Fishway passage efficiency			Dam passage Efficiency		
Group	App	Enter	Eff	Enter	Pass	Eff	App	Pass	Eff
BON adult	154	154	1.000	154	152	0.987	154	152	0.987
BON jack	134	134	1.000	134	133	0.993	134	133	0.993
ICE adult	249	249	1.000	249	249	1.000	249	249	1.000

Passage times

Chinook salmon passage times were similar among the three study groups (Table 18). Median passage times from first tailrace detection to first approach at a Lower Granite fishway antenna were 1.2 h (Bonneville adults), 1.4 h (Bonneville jacks), and 1.5 h (Ice Harbor adults). Medians from first tailrace to first fishway entry were 3.3 h, 3.0 h, and 3.4 h, respectively. The largest difference was for full-dam passage times, from first tailrace to exit into the Lower Granite forebay: medians were 14.2 h (Bonneville adults), 15.8 h (Bonneville jacks), and 11.9 h (Ice Harbor adults). Passage times were right-skewed for all groups, resulting in higher mean times (Table 18). This was because some fish spent one or more nights in the tailrace or fishway or exited from the fishway into the tailrace one or more times. These patterns were similar to those reported for adult Chinook salmon in several previous studies (Keefer et al. 2004).

Table 18. Median and mean passage times (hours) of radio-tagged Chinook salmon at Lower Granite Dam in 2013.

	BON adult			BON jack			ICE adult		
Segment	*n*	Median	Mean	*n*	Median	Mean	*n*	Median	Mean
Tailrace – Approach	113	1.2	3.1	83	1.4	3.0	175	1.5	3.6
Tailrace – Entry	146	3.3	6.4	63	3.0	4.1	93	3.4	10.7
Tailrace – Pass dam	81	14.2	19.8	108	15.8	21.7	194	11.9	24.1
Approach – Entry	85	1.0	3.8	77	0.2	1.5	122	0.9	6.1

Fallback

Fallback percentages and rates were the same for each tag group since no fish fell back multiple times (Table 19). Fallback was similar between the groups with Ice Harbor adults having the lowest percentage and rate (4.8 %), followed by Bonneville adults (5.9%) and Bonneville Jacks (7.5%). All of the Bonneville (*n* = 9) and Ice Harbor (*n* = 10) adults that fell back over Lower Granite Dam reascended and passed the dam. Nine of the ten Bonneville jacks that fell back at Lower Granite Dam reascended the fishway and passed the dam. The one unique Bonneville tagged jack that did not reascend fell back over the three lower Snake River dams and McNary Dam and was ultimately recaptured in the Umatilla River (in a hatchery).

Table 19. Fallback percentages (unique fish that fell back/unique fish past dam) and rates (fallback events/unique fish past dam) for radio-tagged Chinook salmon at Lower Granite Dam in 2013. Note: passage determined by PIT tag only were excluded.

Group	Unique fish past dam (*n*)	Unique fallback fish	Total fallback events	Fallback percent (%)	Fallback rate (%)
BON adult	152	9	9	5.9%	5.9%
BON jack	133	10	10	7.5%	7.5%
ICE adult	251	12	12	4.8%	4.8%

Radiotelemetry and ladder temperatures

Ladder temperature differences in 2013 were similar to those recorded in 2002 with a mean ΔT (difference between top-of-ladder and base-of-ladder sites) of 2ºC from July until September (Figure 24). In 2001 and 2003, mean ladder temperature differences were 1.5ºC and in the coolest year that we monitored (2008) they were 0.5ºC.

Only a small number of radio-tagged Chinook salmon encountered a ΔT of 2 ºC or more during ladder passage when base of the ladder temperatures were ≥18ºC (Figure 25). However, 25 jack Bonneville-tagged summer Chinook encountered a ΔT of 1ºC or more when passing the Lower Granite fish ladder. Three Ice Harbor-tagged summer Chinook salmon passed when ΔT was 1.8-2.7 ºC. All nine Bonneville-tagged steelhead passed when ladder temperatures were ≥18ºC; however, ΔT was <1ºC due to a small temperature gradient between the base and top of the ladder in mid to late September.

Overall, Chinook salmon that passed during warmer temperatures had slightly longer passage times, however due to low samples sizes it was not possible to make meaningful direct statistical comparisons (Figure 26). Bonneville-tagged summer Chinook salmon that passed the fish ladder when temperatures were ≥18ºC had a median passage time of 1.0 d compared to 0.2 d when salmon passed during <18ºC. No differences were observed in median passage times between the two temperatures groups for jack Bonneville-tagged summer Chinook (0.2 d) and Ice Harbor-tagged summer Chinook salmon (0.1-0.2 d). Bonneville-tagged steelhead had the longest median passage time of all fish groups (0.4 d).

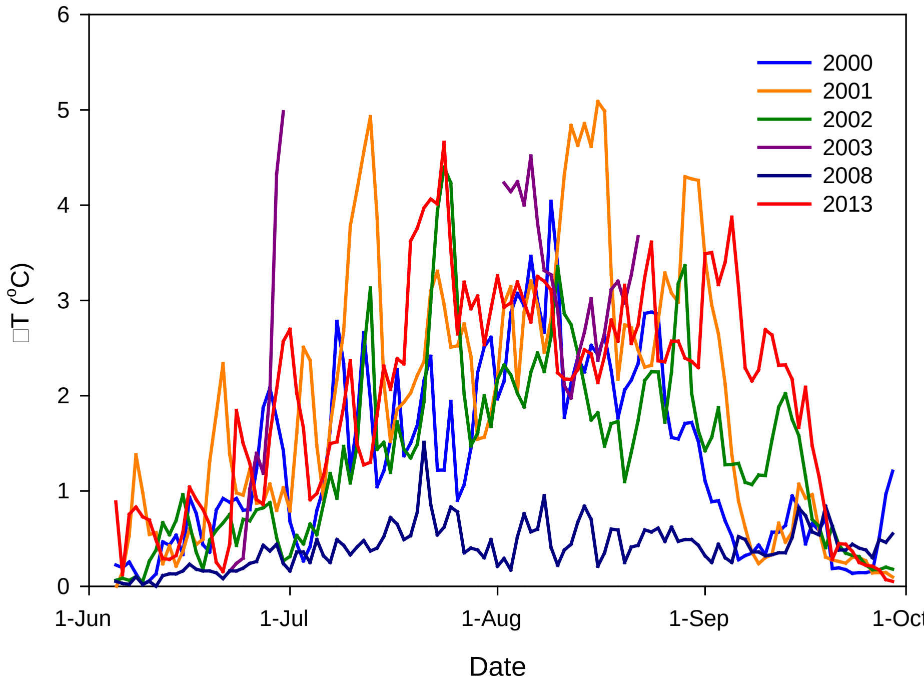

Figure 24. Mean daily ΔT estimates at Lower Granite Dam in 2000-2003, 2008, and 2013. ΔT was the water temperature difference between the top-of-ladder and base-of-ladder monitoring sites inside the fishway.

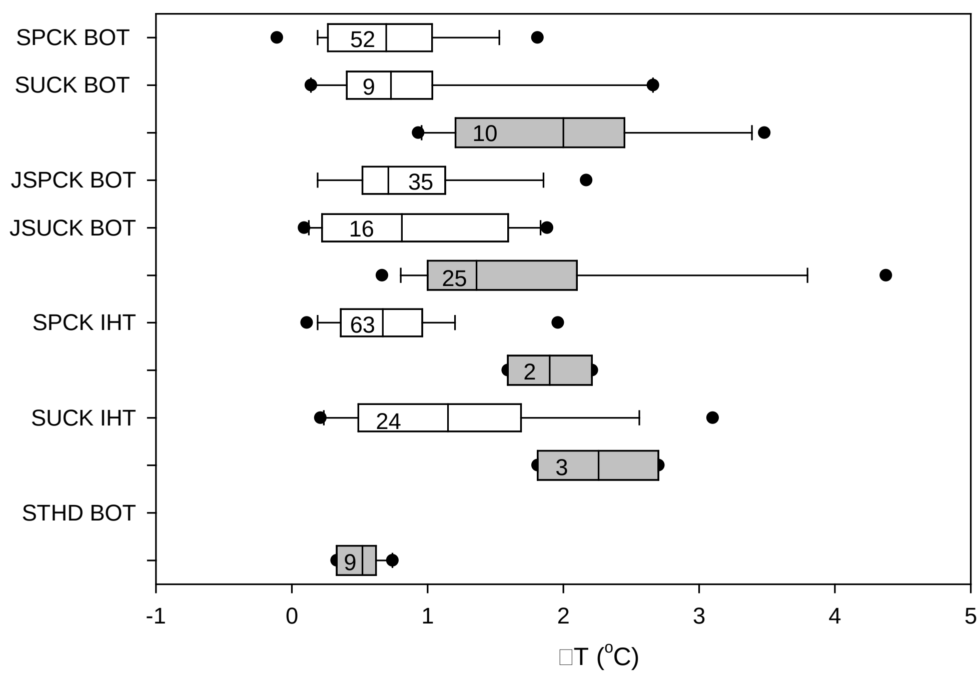

Figure 25. ΔT encountered by Chinook salmon and steelhead after entering the Lower Granite fish ladder. White boxes are ΔTs encountered when temperatures in the lower ladder were <18ºC and dark gray boxes are ΔTs encountered when temperatures in the lower ladder were ≥18ºC. Sample sizes are shown inside each box. Box plots show 5th, 10th, 25th, 50th, 75th, 90th and 95th percentiles.

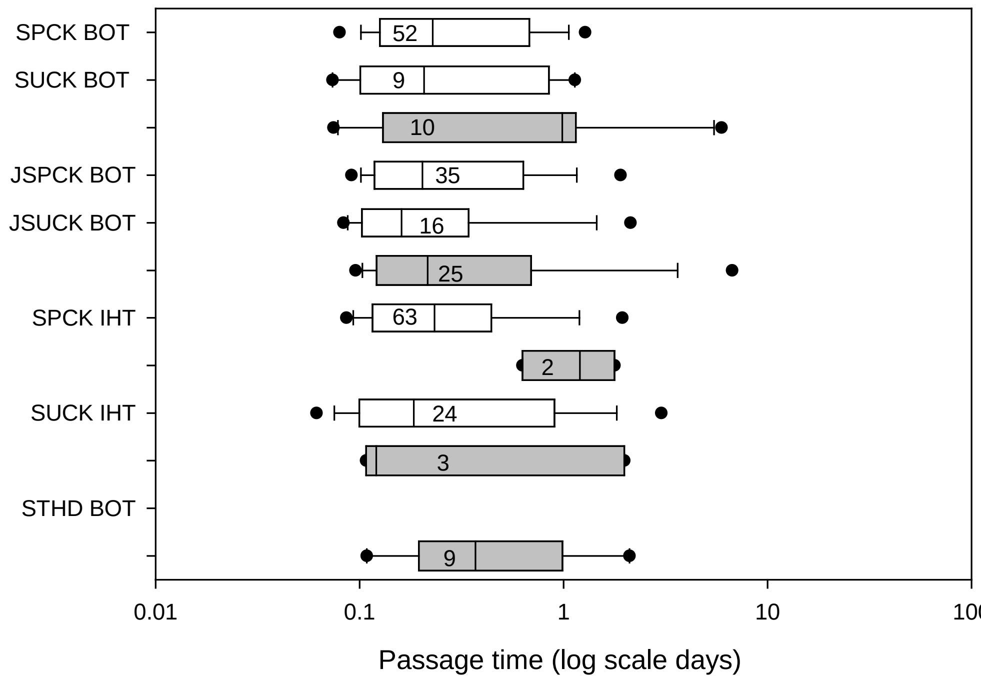

Figure 26. Passage times (plotted on log scale) of Chinook salmon and steelhead from first pool at base of ladder to exit at top of fish ladder. White boxes are passage times when temperatures in the lower ladder were <18ºC and dark gray boxes are passage times when temperatures in the lower ladder were ≥18ºC. Sample sizes are shown inside each box. Box plots show 5th, 10th, 25th, 50th, 75th, 90th and 95th percentiles.

Passage times of Chinook salmon to pass the Lower Granite fish ladder by ΔT had sample sizes that were too small to make statistical comparisons between groups, though the results were consistent with previous observations (Caudill et al. 2006, 2013). We did observe eight Bonneville-tagged summer Chinook salmon passing during temperatures ≥18ºC; four during a ΔT of 2 ºC with a median passage of 0.6 d and four during a ΔT of 3ºC with a passage time of 1.1 d (Figure 27). Bonneville-tagged jack summer Chinook were observed with the highest ΔT of 4 ºC with a median passage time of 3.7 d (Figure 28). Two Ice Harbor-tagged summer Chinook salmon during temperatures ≥18ºC with a ΔT of 3 ºC and a median passage time of 0.1 d (Figure 29).

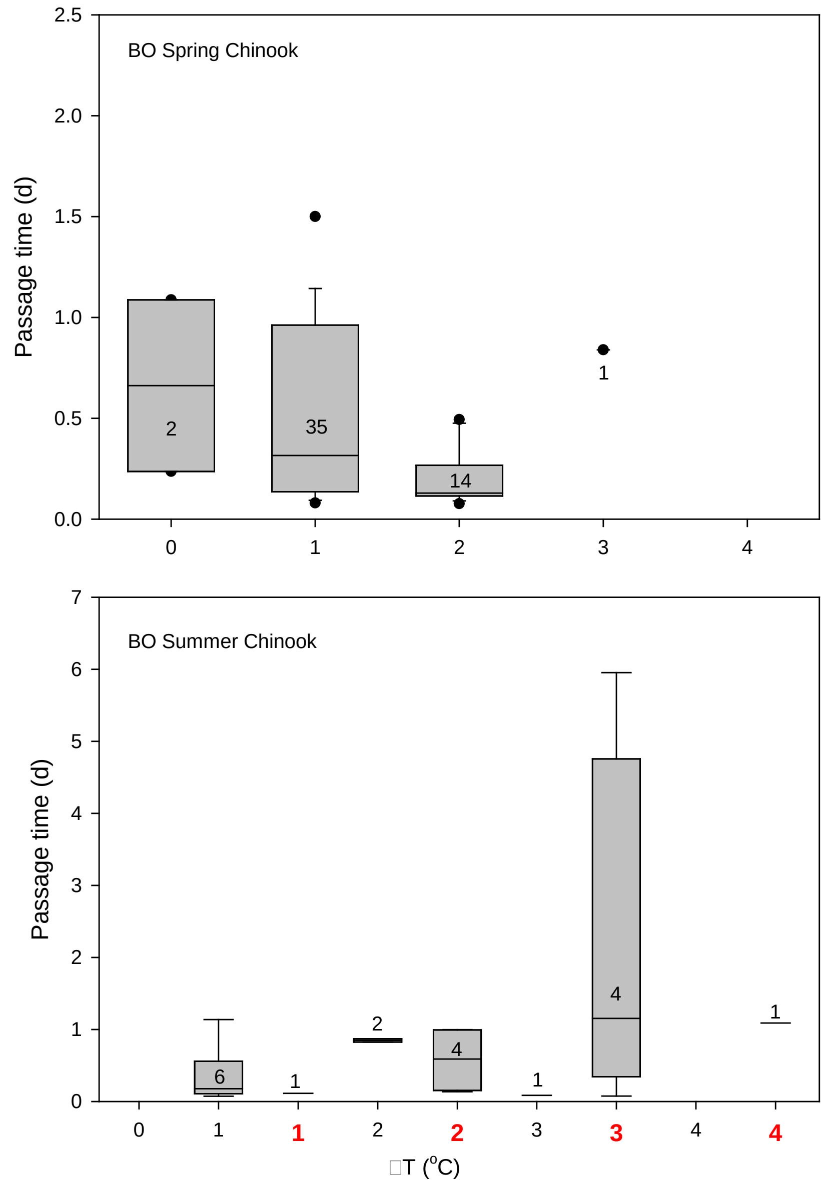

Figure 27. Passage times of Bonneville-tagged spring and summer Chinook salmon to pass Lower Granite ladder by ΔT. ΔT numbers in black are when water temperatures at the base-of-the ladder were <18ºC and numbers in red are when water temperatures were ≥18ºC. Sample sizes are shown in or near each box. Box plots show 5th, 10th, 25th, 50th, 75th, 90th and 95th percentiles.

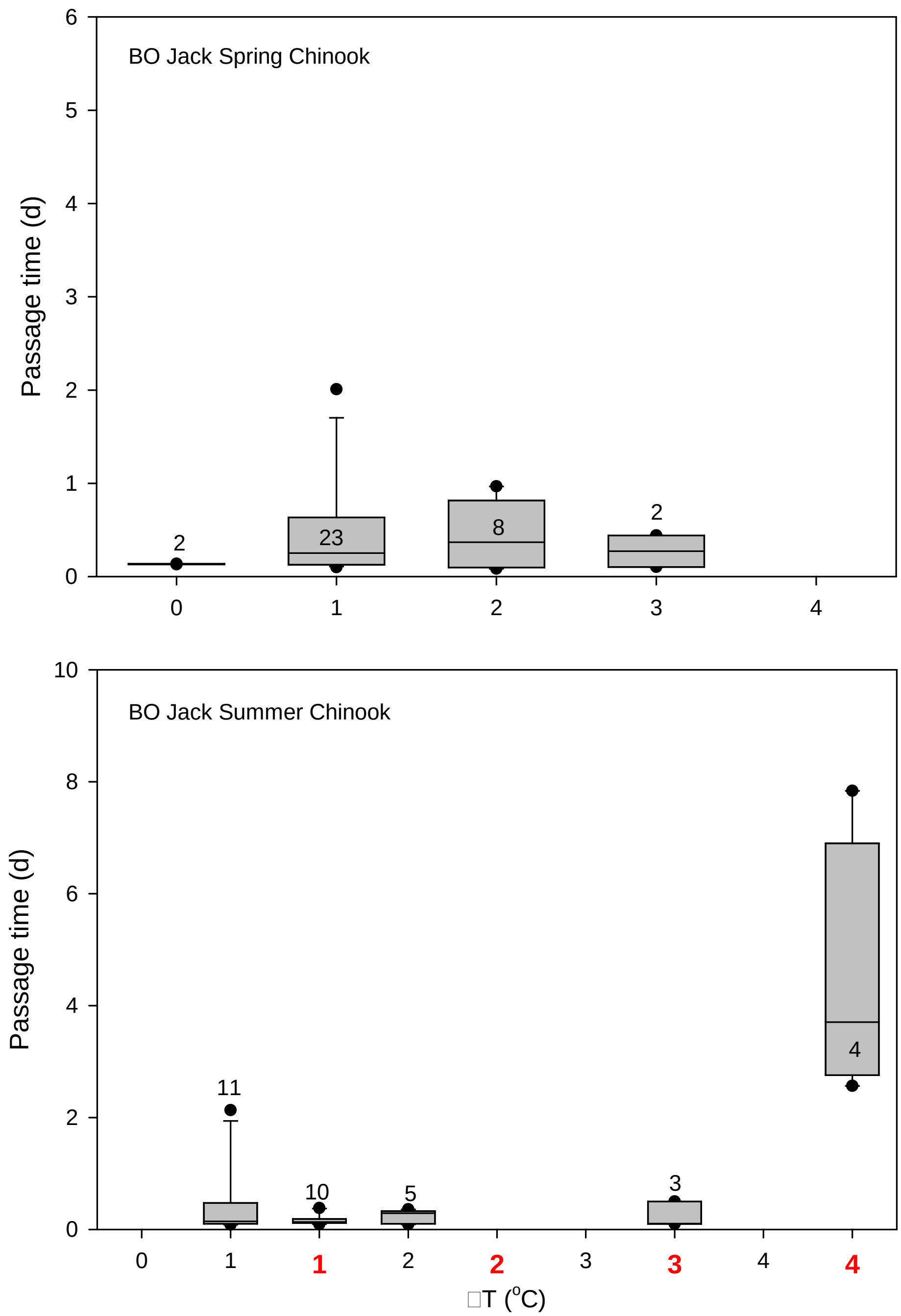

Figure 28. Passage times of Bonneville-tagged jack spring and summer Chinook salmon to pass Lower Granite ladder by ΔT. ΔT numbers in black are when water temperatures at the base-of-the ladder were <18ºC and numbers in red are when water temperatures were ≥18ºC. Sample sizes are shown in or near each box. Box plots show 5th, 10th, 25th, 50th, 75th, 90th and 95th percentiles.

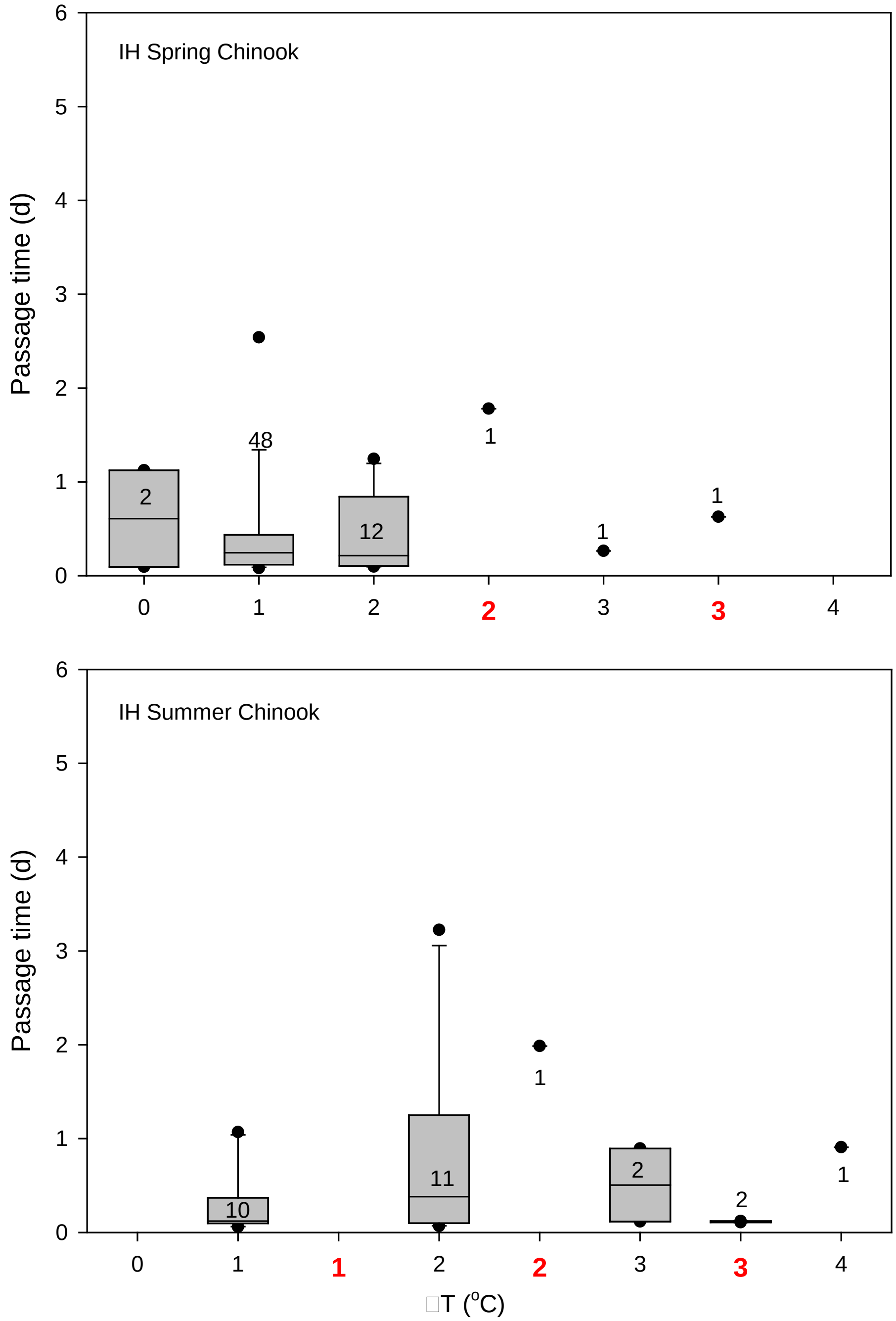

Figure 29. Passage times of Ice Harbor-tagged spring and summer Chinook salmon to pass Lower Granite ladder by ΔT. ΔT numbers in black are when water temperatures at the base-of-the ladder were <18ºC and numbers in red are when water temperatures were ≥18ºC. Sample sizes are shown in or near each box. Box plots show 5th, 10th, 25th, 50th, 75th, 90th and 95th percentiles.

The majority of all radio-tagged spring and summer Chinook salmon and steelhead that passed Lower Granite Dam did not overnight at the dam (Table 20). However, 58% (n = 11) of Bonneville-tagged summer Chinook salmon did overnight but only seven of those did so when ladder temperatures were ≥18°C. Four Bonneville-tagged steelhead also overnighted at the dam when temperatures were ≥18°C, though ΔT during passage was <1°C.

Table 20. Number and percent of adult spring–summer Chinook salmon and steelhead and jack spring-summer Chinook salmon that did or did not overnight at Lower Granite Dam when temperatures were less than or ≥18°C. SPCK=spring Chinook, SUCK=summer Chinook, and FP= first pool record at base of ladder.

						FP ≥18°C		
Tag location	Species	Overnight	n	FP temp <18°C	FP temp ≥18°C	ΔT <1°C	ΔT 1-2°C	ΔT >2°C
Bonneville	SPCK	Yes	16 (31%)	16	-	-	-	-
		No	36 (69%)	36	-	-	-	-
	SUCK	Yes	11(58%)	4	7	-	3	4
		No	8 (42%)	5	3	1	1	1
	Jack SPCK	Yes	11 (31%)	11	-	-	-	-
		No	24 (69%)	24	-	-	-	-
	Jack SUCK	Yes	9 (21%)	-	-	-	-	-
		No	33 (79%)	15	18	5	11	2
	Steelhead	Yes	4 (44%)	-	4	4	-	-
		No	5 (56%)	-	5	5	-	-
Ice Harbor	SPCK	Yes	19 (29%)	17	2	-	1	1
		No	46 (71%)	-	-	-	-	-
	SUCK	Yes	10 (27%)	9	1	-	1	-
		No	17 (63%)	15	2	-	-	2

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