Technical Report 2015-6

EVALUATION OF SALMON PASSAGE BEHAVIOR IN RELATION TO FISHWAY MODIFICATIONS AT BONNEVILLE DAM – 2013-2014

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

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Department of Fish and Wildlife Sciences
University of Idaho, Moscow, Idaho 83844-1136

And

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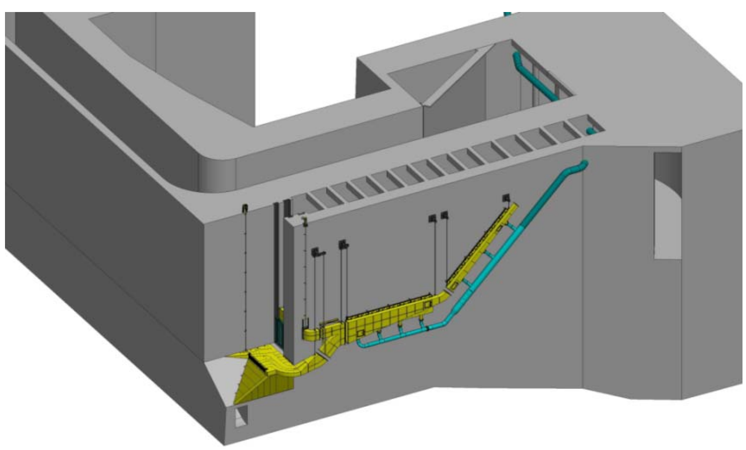
Northwest Fisheries Science Center
National Marine Fisheries Service
2725 Montlake Blvd. East, Seattle, Washington 98112



For

U.S. Army Corps of Engineers
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Acknowledgements

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Executive Summary

In 2013 and 2014, we evaluated the passage and migration behavior of radio-tagged spring and summer Chinook salmon (*Oncorhynchus tshawytscha*) and sockeye salmon (*O. nerka*) in relation to the installation of the Lamprey Flume System (LFS) at the north downstream entrance (NDE) of the powerhouse 2 (PH2) fishway at Bonneville Dam. We also conducted a fourth year of radiotelemetry studies of spring–summer Chinook salmon at Bonneville Dam to evaluate if modifications made at the Cascades Island (CI) fishway in winter 2008-2009 to facilitate passage of adult Pacific lamprey (*Entosphenus tridentatus*) and improve hydraulics at the entrance for salmon adversely affected passage of adult salmon. Our primary study objective was to compare passage times and behaviors from pre-modification years to those from post-modification years using a set of 5-7 quantitative passage metrics while considering inter-annual variation in environmental, operational, and ecological conditions. The metrics included: entrance efficiency, exit ratio, approach-to-entry time, entry-to-ladder base time, and proportion of adults requiring > 1 hour to pass these segments. We also compared behaviors at NDE and CI to similar sites: the PH2 south downstream entrance (SDE) and Bradford-Island B-Branch entrance, respectively.

A total of 1,200 adult spring-summer Chinook salmon, 600 jack spring-summer Chinook salmon, and 799 adult sockeye salmon were collected and radio-tagged at the adult fish facility at Bonneville Dam in 2013 and 2014. All tagged fish were released below Bonneville Dam near Dodson, OR, or Skamania, WA. Movements of radio-tagged salmon were monitored with aerial and underwater antennas attached to fixed-site radio receivers in the tailrace and at the dam. Data were compared to results from 1996-1998, 2000-2004, 2005 (summer Chinook salmon only), 2006-2007 (spring Chinook salmon only), and 2009- 2010. No pre-modification data were available for jack Chinook salmon. Sockeye salmon data from a single year (1997) were deemed unsuitable for comparison to 2013-2014 results for sockeye salmon due to extreme high water conditions in 1997.

Inter-annual variation in passage metrics collected at the NDE of Bonneville Dam PH2 was high in pre-modification years. Some variation was attributable to differences in environmental factors and operations among years. For instance, 1996-1998 were relatively high flow, cool years and 2000-2001 were low flow years with warm temperatures. Slightly below average discharge and spill levels, and above average temperatures were observed in 2013-2014.

For adult lamprey, mean NDE entrance efficiencies were significantly lower ($P< 0.001$) in 2013 (0.26) and 2014 (0.23) compared to pre-modification years (1996-2010 *mean* = 0.37). Spring Chinook salmon NDE entrance times were slightly slower in 2013 and slightly faster in 2014 than in pre-modification years; collectively, there was not a statistical difference in entrance times between pre- and post-modification years ($P = 0.927$). In contrast, mean entrance efficiencies for adult summer Chinook salmon were significantly higher ($P < 0.001$) and entrance times were faster ($P = 0.005$) than values from pre-modifications years. Differing results in the same passage metrics among runs and species suggest that the observed values were not directly related to the newly-constructed LFS. Adult Chinook salmon exit ratios, times from the PH2 NDE entrance to the base of the ladder, and the ratio of fish approaching and entering the NDE versus the SDE were within the range of values observed in pre-modification years. Observed

differences in passage metrics between pre- and post-modification years suggested that any effects of the LFS were small relative to environmental factors and other unmeasured factors.

The CI entrance efficiency for adult spring and summer Chinook salmon in 2013-2014 were significantly lower than in the average across pre-modification years. Pairwise comparisons among years were mixed with some higher and some lower between pre- and post-modification entrance efficiencies. Lower entrance efficiencies were observed after the modifications for spring Chinook salmon in 2009 (58%) and for summer Chinook salmon in 2013 (47%) vs. pre-modification years (*means* of 73% and 76%, respectively). Sockeye salmon entrance efficiency was 61% in 2013 and 65% in 2014. Jack spring Chinook salmon entrance efficiencies ranged from 50-74% and jack summer Chinook salmon entrance efficiencies ranged from 67-77%. Times to enter the CI fishway opening for adult spring and summer Chinook salmon in post-modification years were collectively higher than those from pre-modification years. Similar patterns of lower entrance efficiencies and longer entrance times were also observed for spring Chinook salmon at Bradford Island from 2009 to 2014. At the CI fishway opening, spring and summer Chinook salmon exit ratios and times from entry to the base of the ladder did not appear to be adversely affected by the modifications made in 2008-2009.

Introduction

Adult Pacific salmonids (*Oncorhynchus* spp) migrating to their natal streams in tributaries of the Columbia River must pass up to nine main stem dams, four in the lower Columbia and Snake rivers and five in the mid-Columbia 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). This study address priority research areas related to improving passage and survival of adult salmonids identified by the U. S. Army Corps of Engineers (USACE), fish agencies, and NOAA in the Columbia River Federal Power System (FCRPS) Biological Opinion released in 2008 related to recovery of threatened and endangered Columbia and Snake River salmon and steelhead.

Major and minor fishway modifications intended to improve passage of adult Pacific lamprey (*Entosphenus tridentatus*) and/or adult salmonids have recently been completed and as with any significant changes to the passage facilities, the modifications must be evaluated for effectiveness and to ensure that salmonid passage is not adversely affected. This study provides information relevant to implementation of the USACE Pacific Lamprey Passage Improvements Draft Implementation Plan 2008-2018 because many recent and planned modifications to fishways must also be suitable for ESA-listed adult salmonid passage. Increases in passage delay are of concern because salmon migrate upstream using fixed energetic reserves and relatively long passage time has been associated with lower survival to tributaries (Caudill et al. 2007). At Bonneville Dam, slowed passage into the fishways may also increase the probability of predation by sea lions (*Zalophus californianus* and *Eumetopias jubatus*) in the tailrace (Keefer et al. 2012; Stansell et al. 2014) or harvest by anglers for spring and early summer Chinook salmon.

In 2010, a prototype lamprey flume system (LFS) was designed for the Washington-shore fishway North Downstream Entrance (NDE) at Powerhouse 2 (PH2) of Bonneville Dam (Figure 1). Design elements for this structure were drawn from experience with the Bonneville Dam Lamprey Passage Structure (LPS) collectors (Moser et al. 2011) and from behavioral observations in the experimental lamprey fishway (Keefer et al. 2010, 2011). The flume system included two alternative entrances with lower entrance velocities and a duct system leading to a LPS collector that terminated on the tailrace deck. A primary research objective at PH2 in 2013-2014 was to assess adult salmonid movements at the NDE after the LFS was installed.

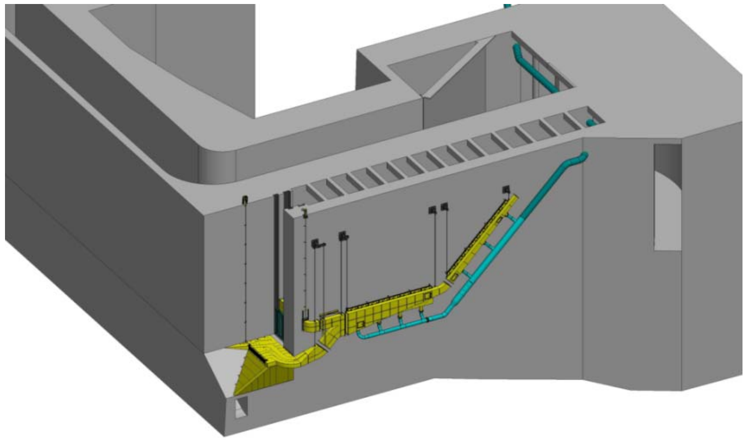

Figure 1. Lamprey flume system (LFS) designed for the Washington-shore NDE.

A variable-width entrance weir and bollards were installed at the Cascades Island (CI) entrance at Bonneville Dam in 2008-2009 (Figure 2; also see Clabough et al. 2010) to improve the passage of both salmonids and Pacific lamprey. The variable-width weir is thought to improve attraction flows for salmonids while providing a wider opening at the bottom of the weir with reduced entrance velocities for lamprey. This design also eliminated lower bulkheads that may have interfered with adult lamprey entering the fishway and reduced operation and maintenace costs. Monitoring radio-tagged, adult Chinook salmon at the site provided evidence of slowed passage in the first year post-construction (Jepson et al. 2010). Specifically, a low percentage of spring Chinook salmon that approached the CI fishway opening subsequently entered it and those that did enter took a relatively long time to do so in 2009. While river conditions explained some of the differences, there was also evidence that the modified CI opening was associated with a decline in entrance efficiency. Data from 2010 indicated that salmon passage metrics were more like pre-modification passages at Cascades Island (Jepson et al. 2011), though the mechanism(s) creating the differences between pre- and post- modification years was unclear. Variation in CI passage metrics from 2009 to 2010 may have been related to short-term effects of construction and "seasoning" of the structure, interannual variation in overall environmental conditions, and/or hydraulic effects of the new weir design. Monitoring in 2013-2014 provided additional post-modification data on passage behavior at the location.

Our primary objective at both NDE PH2 and CI entrances was to compare fish performance metrics from pre-modification years to those from post-modification years while simultaneously considering interannual variation in environmental, operational, and ecological conditions. Below we describe variation in environmental parameters, general fishway use patterns of adult salmon at Bonneville Dam, and then we present the detailed results of passage behavior at the modified PH2 NDE and CI fishways.

Figure 2. Variable-width entrance weir (line drawing, left) and Bonneville Dam Cascades Island entrance during installation of bollards, Lamprey Passage System (LPS, ascending wall to right in photo), and Half-Duplex PIT antennas (white bars spanning opening near entrance bulk head). The variable-width weir was installed to the entrance slot in spring 2009.

Methods

Radio-tagging and monitoring

We collected and radio-tagged adult and jack Chinook and adult sockeye salmon at the Adult Fish Facility (AFF), located adjacent to the Washington-shore ladder. Sockeye salmon were collected and tagged in approximate proportion to the 10-year average run timing. Fish were selected haphazardly in the order they entered the trap each day, though the sample cannot be considered a 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 three types of digitally-encoded radio transmitters developed by Lotek Wireless (Newmarket, Ontario) in 2014. The transmitter model used to tag adult Chinook salmon was a 7-volt MCFT-7F (16mm × 83mm; 29 g in air). Jack Chinook and adult sockeye salmon were tagged with either a 3-volt MCFT2-3BM transmitter (11mm × 43mm; 7.7 g in air) or a MST-930 transmitter (9.5 mm × 26 mm; 4.0 g in air). Taggers distinguished between jack and adult males using a combination of length, jaw and head morphology, and body shape rather than using a strict size criterion in an effort to minimize the potential to bias either sample when operating the flume, with the greatest uncertainty for individuals 60-65 cm. For example, when selecting for a jack, there was potential for taggers to unintentionally select against larger jacks. Individuals classified as jacks were < ~ 64 cm, had longer jaws and snouts, and were generally thinner in overall body shape than individuals classified as adults.

All jacks and 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 transmitter loss rates, detection efficiencies, and conversion rates using both radio- and PIT-detections (see Keefer et al. 2015 for a summary of reach conversion estimates). Fish that were radio-tagged were scanned for the presence of a PIT-tag, weighed, measured for fork length, and had scale (for aging) and caudal fin punches (for genetic evaluation) collected. Lipid content was also estimated using a Distell Fatmeter (Distell Industries Ltd., West Lothian, Scotland). 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.

We used an array of fixed-site radio receivers to monitor locations of tagged fish. Receivers were installed to intensively monitor movements at the modified areas: the BON PH2/ Washington Shore NDE and the CI fishways. It is important to note that the PH2 NDE and CI entrances were monitored using an aerial Yagi antenna in 2013 and 2014 (due to limited access to underwater locations in winter 2012-2013) whereas these sites were monitored using underwater antenna arrays historically (Figure 3). Data collected in 2013 and 2014 were compared to passage performance metrics collected during previous passage evaluations (1996-2007, 2009-2010). Powerhouse priority has changed through the evaluation years. In 1996 powerhouse priority was PH2, from 1997 until 2000 it was PH1, and from 2001 until 2014 it has been PH2.

Data Analyses

A variety of passage time and passage efficiency metrics were examined as defined below to evaluate whether the fishway modifications may have affected Chinook and sockeye salmon behavoirs. For this evaluation, we report metrics that are consistent across the previous 12 study years which inluded 1996-1998, 2000-2004, 2005 (summer Chinook only), 2006-2007 (spring Chinook only), and 2009- 2010. No previous data were available for jack Chinook salmon and data for sockeye salmon from a single year (1997) were deemed unsuitable for comparison to 2013 and 2014 results due to near-record high flow conditions in 1997. We compared 2013 and 2014 passage metrics from locations with major modifications at Bonneville Dam to corresponding values for Chinook salmon from previous years. Note spring Chinook salmon in 2013 did not include any April records because the early portion of the spring Chinook salmon run was not sampled due to delayed receipt of radio transmitters.

We performed several statistical analyses to test for differences in passage metrics across study years. A chi square (χ^2) statistic was used to investigate whether salmon entrance efficiencies and exit ratios differred between pre- and post- modification years. Statistical tests of between-year effects in entrance and lower ladder passage times were performed using a General Linear Model (GLM) and contrast statements to specifically test hypotheses that entrance and lower ladder passage times were not different after modification to the fishway compared to premodification years (Zar 1999). Predictor variables used in the model included year, fishway approach date, and flow on that date. Due to collinearity between flow, spill, water temperature, and tailwater elevations, we chose to use date as a proxy for water temperature and flow as a proxy for spill and tailwater elevation because these variable were highly correlated. Tukey HSD tests were performed to compare the difference in annual mean passage times. We evaluated the degree of association between PH2 and CI entry and lower ladder passage times between years, approach date, and associated flow conditions. Passage time data were consistently right-skewed because some fish had unusually long passage times; data were log-transformed to improve normality. For fish with extended passage times, we used a Logistic regression model to evalute if longer passage times (> 60 min) were associated with the modifications. We used correlation techniques to evaluate the degree of association between PH2 NDE and CI approach-to-entry times and four enviromental factors: total discharge (flow), spillway discharge, water temperature, and tailwater elevation. Potentially confounding factors in our multi-year comparisons were the deployment of sea lion exclusion devices (SLEDs) in all years after 2005, variations in spill patterns, orifice gate closures, reduced nightime flows for lamprey, and the powerhouse priority shift from PH1 to PH2 in 2001. Across study years, the spill pattern also shifted toward proportionately more spill through end spillbays. In addition, the abundance of marine mammal predators increased over the study period (Stansell et al. 2009; Keefer et al. 2012).

Passage metrics

We estimated several passage time and passage efficiency metrics to evaluate potential effects of the PH2 NDE and CI entrance modifications on adult spring-summer Chinook salmon behavior. The metrics estimate different elements of fishway approach and entry behaviors and passage times. The same suite of metrics was calculated for jack Chinook and sockeye salmon.

1) ***Entrance efficiency***. The ratio of the total number of fishway entry events at a site divided by the total number of fishway approaches at the same site. Each event was reviewed manually and multiple events by individuals were included. A drop in entrance efficiency would suggest that the environment near the entrance became less attractive to salmon.

2) ***Exit ratio***. The number of exit events (fish recorded exiting the fishway after entrance into the tailrace) divided by the number of entrance events (fish recorded entering the fishway). Each event was reviewed manually and multiple events by individuals were included. An increase in the exit ratio would suggest that conditions inside the fishway entrance became less favorable.

3) ***Entrance time***. The passage time from first approach to first entrance. An increase in entrance time would suggest that passage conditions at the entrance have degraded.

4) ***Entrance to base of ladder time***. The passage time from the entrance antenna to the antenna located in the transition pool at the base of the ladder. An increase in passage time through this section would suggest that the modifications had a negative effect on adult salmon behavior inside the fishway at or near the lamprey modifications. Vibration

related to pumps at the LFS is of concern at NDE and the bollards may have affected hydraulics inside the entrance at CI.

5) ***Extended passage times***. Salmon passage times are strongly right-skewed. We used the percentage of fish that require > 1 h to pass through the lower fishway (entrance to base of ladder) as a standardized metric of slowed passage. Increases in this metric would suggest that passage became more difficult.

6) ***PH2 entry locations of successful dam passages (PH2 NDE only)***. Salmon that successfully passed Bonneville Dam via the Washington-shore fishway received an LP ("last pool") code when they exited the transition area and entered the overflow section of the ladder for the final time (i.e., before they passed the dam). We calculated the percentage of LP events that were preceded by an entry at NDE. A decrease in this metric could indicate reduced use or reduced effectiveness of NDE.

7) ***Proportion of PH2 NDE approaches and entries in relation to SDE***. Among-year differences in the proportions of fish approaching and entering the PH2 north downstream entrance compared to the PH2 south downstream entrance may help explain among-year differences at PH2 or a shift in fishway use if adults avoided PH2 NDE.

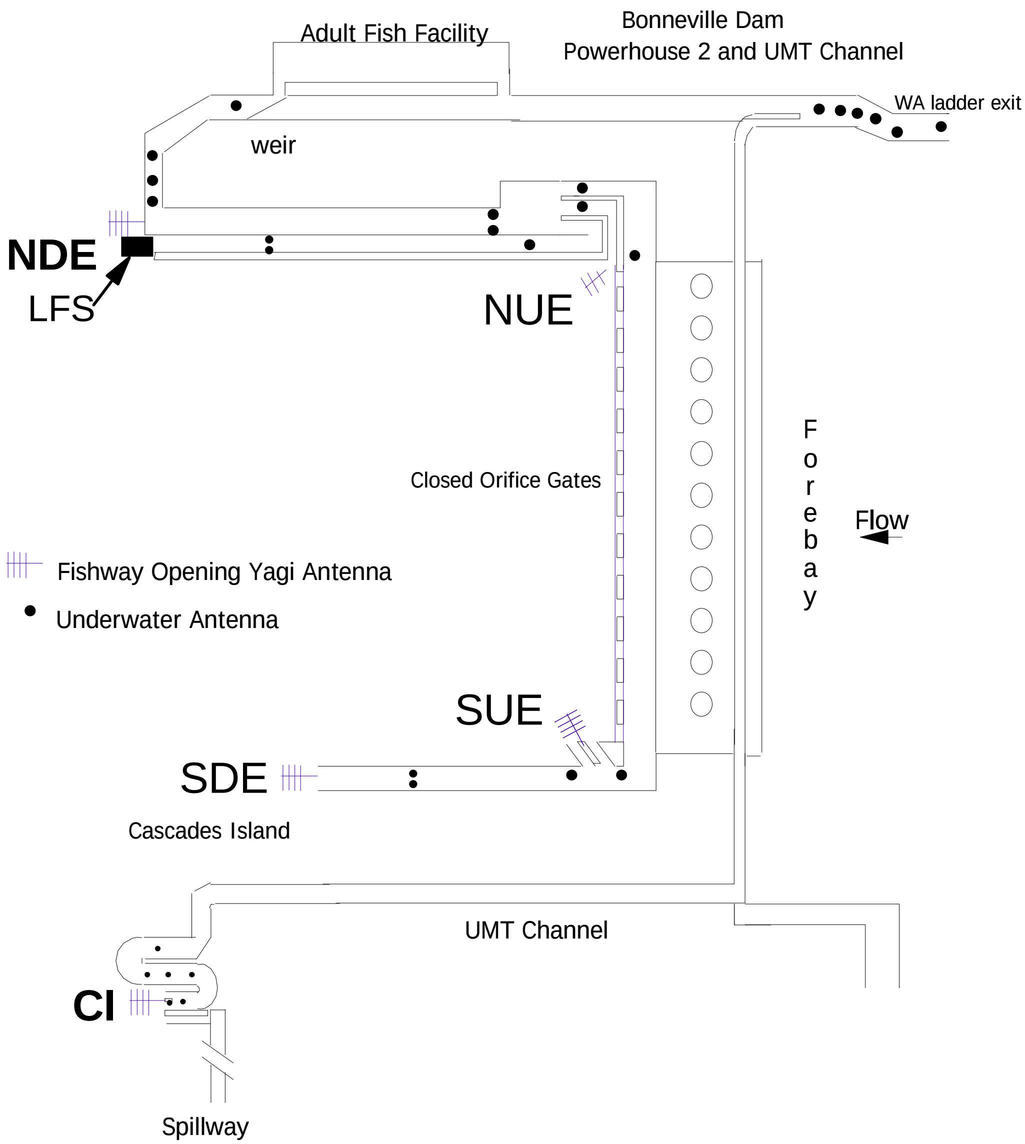

Figure 3. Dam diagram of underwater and aerial antennas used at Bonneville Dam to monitor movements of radio-tagged Chinook and sockeye salmon in 2013 and 2014. Solid square indicates the location of the modified north downstream entrance (NDE) and lamprey flume system (LFS). Note that the Bradford Island fishway is not shown.

Results

Radio-tagging

During 2014, we collected and intragastrically radio-tagged 384 adult spring (April 8-May 31) and 216 adult summer (June 1-July 17) Chinook salmon at the AFF (Figure 4). We also collected and tagged 300 jack Chinook salmon (168 spring and 132 summer) and 399 adult sockeye salmon (June 6-July 15). A total of 186,609 adult spring Chinook salmon, 100,036 adult summer Chinook salmon, and 586,046 adult sockeye salmon were counted passing the dam during the tagging period. Radio-tagged salmon represented ~0.2% of the Chinook and ~0.06% of the sockeye salmon counted at the dam during the tagging period.

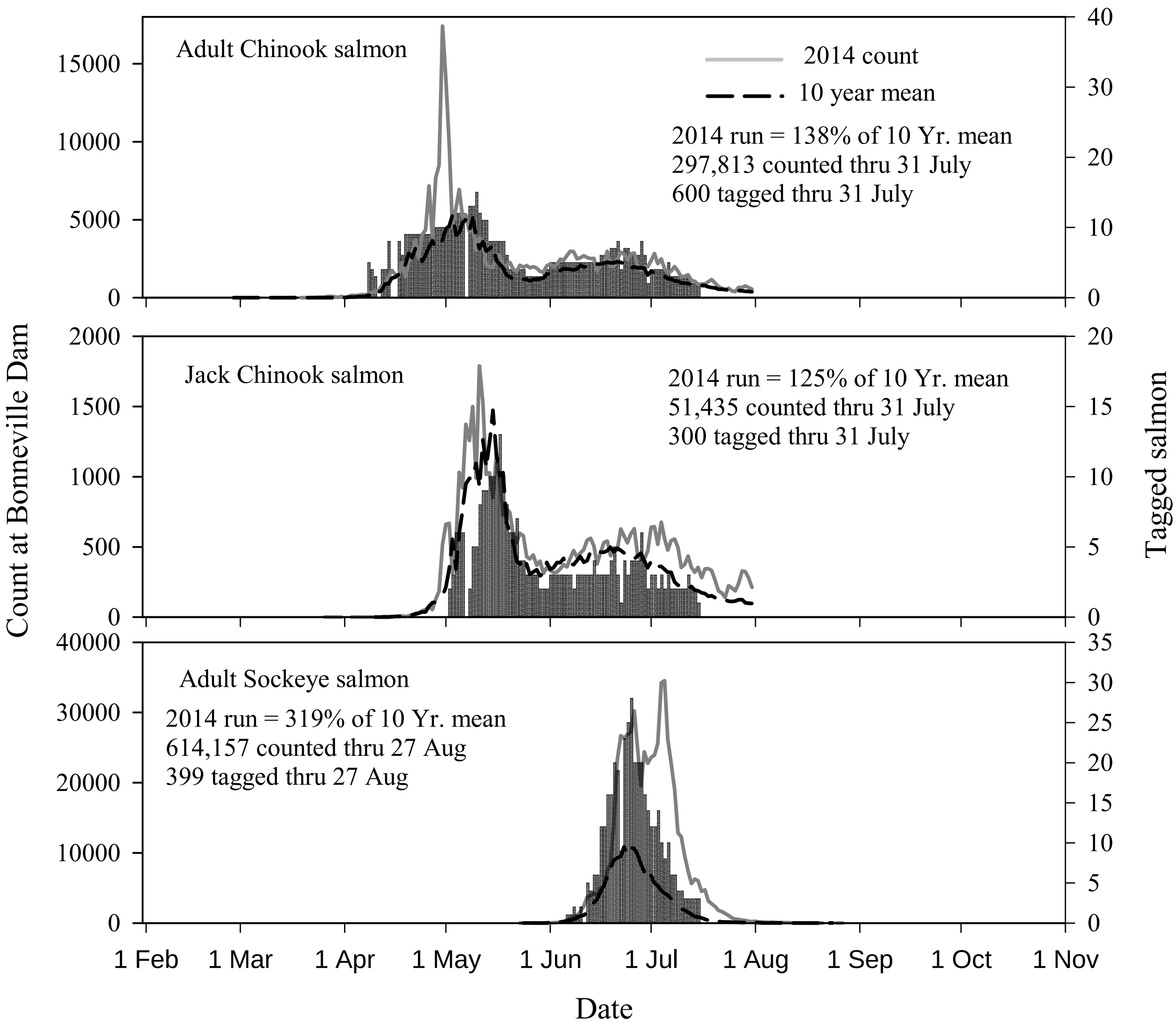

Figure 4. The number of adult and jack Chinook salmon and sockeye salmon radio-tagged and released downstream from Bonneville Dam and the count of salmon passing the dam in 2014.

Environmental Data

Flow, spillway discharge, and river temperatures in the Bonneville Dam tailrace varied considerably during the Chinook salmon runs over the fourteen study years (Figure 5-7). This contributed to the large inter-annual variation in salmon passage behavior. For example, total river discharge ('flow') and spill ranged from near-record low levels in 2001 (flow mostly < 200 kcfs [5,663 cms]) to near-record high levels (flow ~500 kcfs [14,158 cms]) in 1997. Environmental conditions at Bonneville Dam during 2013 and 2014 salmon tagging were characterized by higher than average flows, near average spill (< 170 kcfs [4,813 cms]), and above average temperatures (Figures 5-7). (Note: flow and spill hereafter reported in English units.)

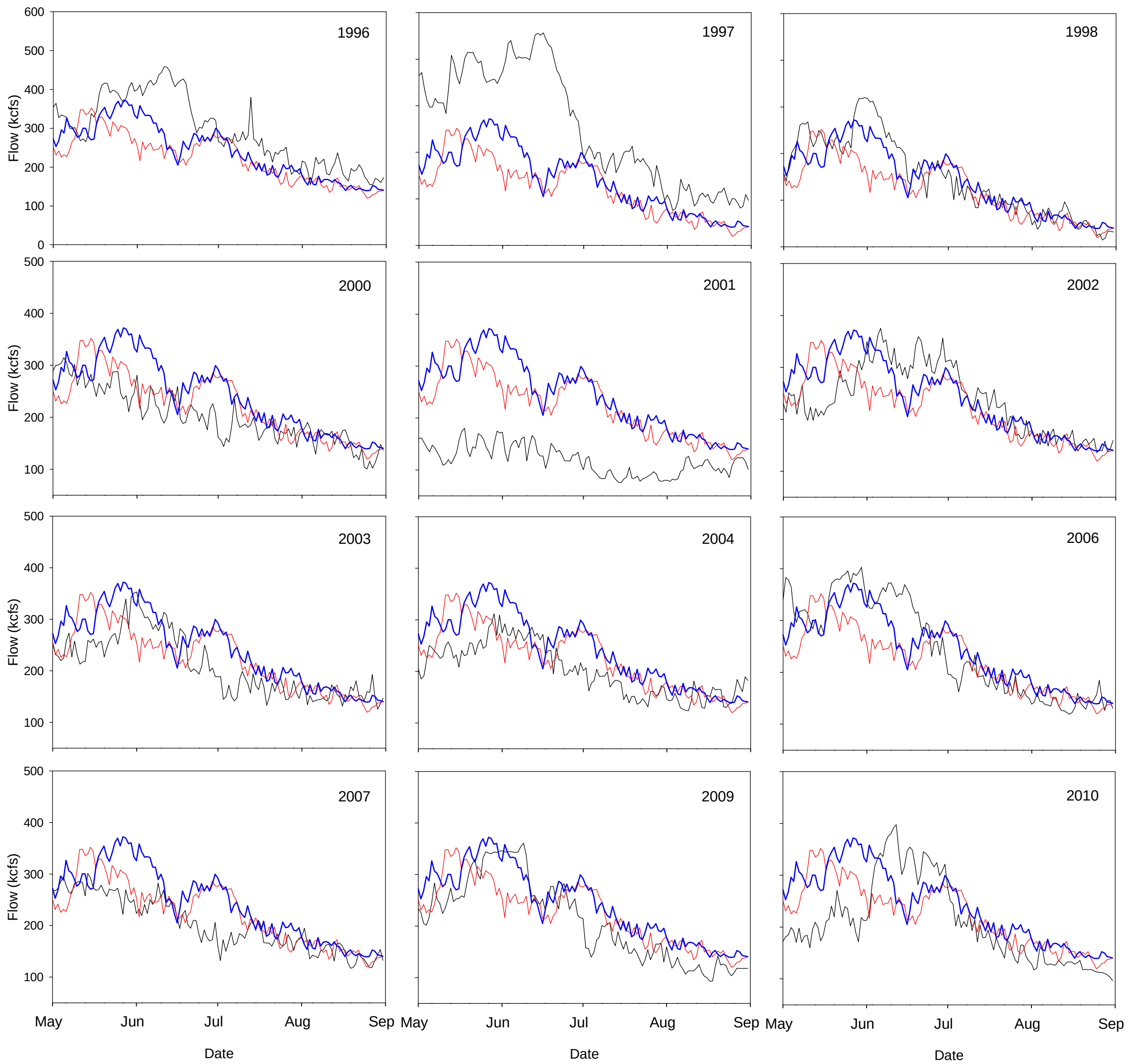

Figure 5. Mean daily flow at Bonneville Dam from May through August in 1996-1998, 2000-2004, 2006-2007, and 2009-2010 (black line) versus 2013 (red line) and 2014 (blue line). Note y-axes differ.

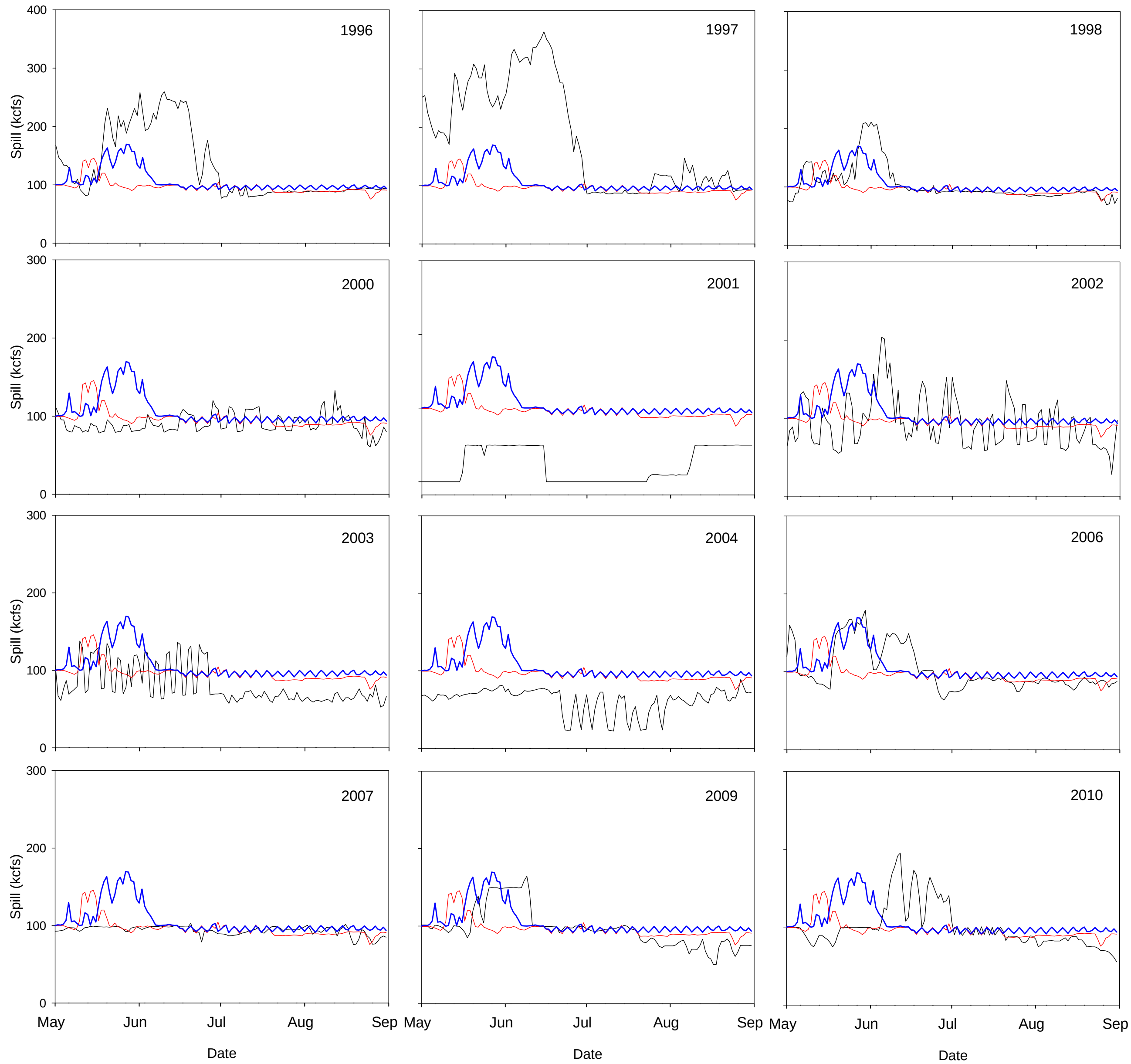

Figure 6. Mean daily spill volume at Bonneville Dam from May through August in 1996-1998, 2000-2004, 2006-2007, and 2009-2010 (black line) versus 2013 (red line) and 2014 (blue line). Note y-axes differ.

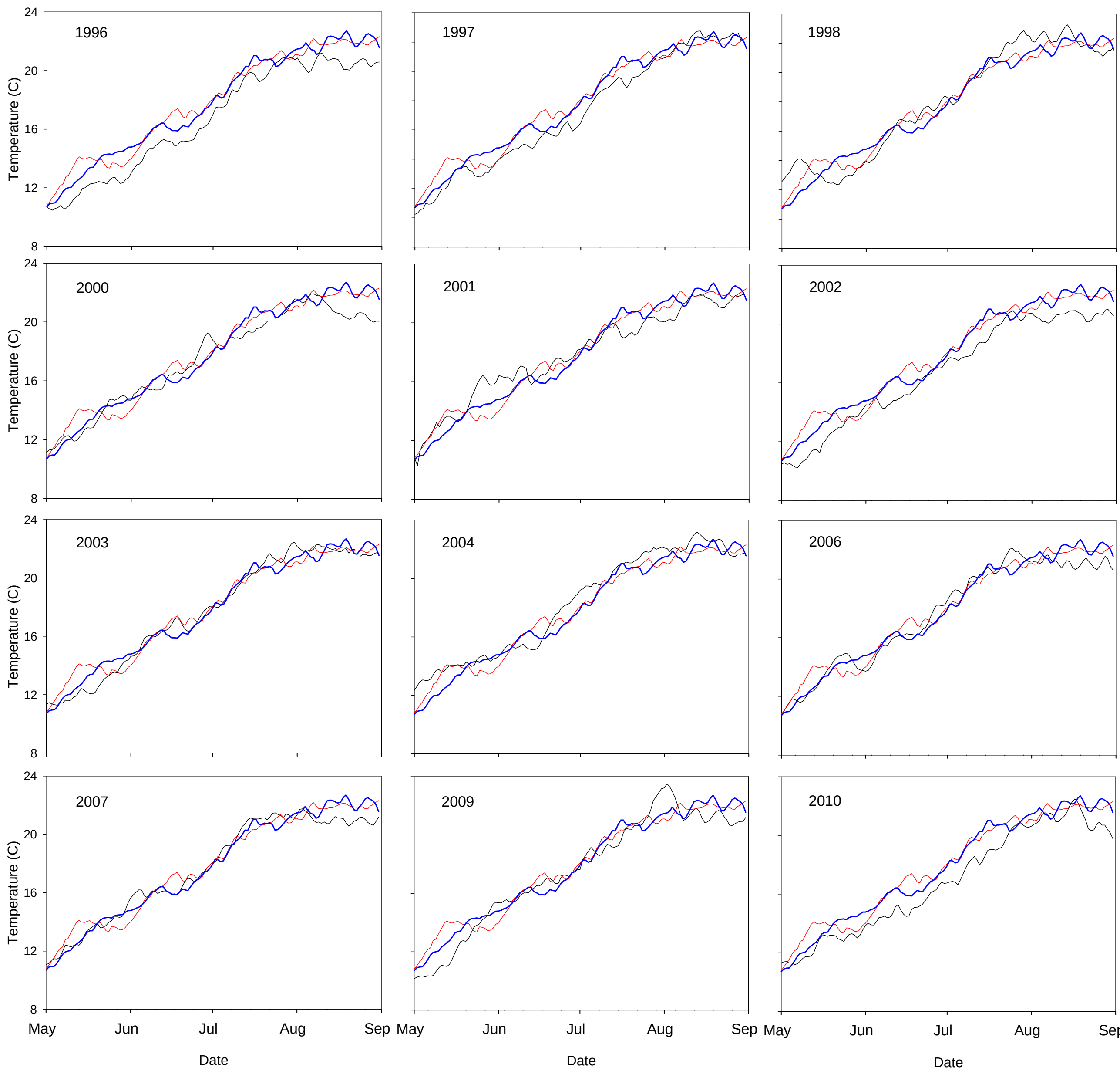

Figure 7. Mean daily tailrace water temperature at Bonneville Dam from May through August in 1996-1998, 2000-2004, 2006-2007, and 2009-2010 (black line) versus 2013 (red line) and 2014 (blue line).

PH2 NDE Results

Of the 384 adult spring Chinook salmon tagged through May 31, 2014, 184 (48%) were recorded approaching and 43 (11%) were recorded entering the NDE (Figure 8). The 2013 and 2014 approach and entrance percentages were lower than the means from pre-modification years, which were 51% and 21%, respectively. The adult entrance percentages in 2013-2014 were similar to those in 2009 (~10%) and to those for jack Chinook salmon (13%) in 2013 and 2014.

Of the 216 adult summer Chinook salmon tagged in 2014, 83 (39%) were recorded approaching and 50 (23%) were recorded entering the NDE (Figure 9). Approach percentages for adult summer and jack Chinook in 2013 and 2014 were less than mean values from pre-modification years but were within the ranges of values from those years. Adult tagged sockeye salmon had similar NDE approach (27-35%) and entry (23%) percentages as summer Chinook salmon.

The annual percentage of fish detected approaching the NDE increased slightly with increasing river discharge (Figure 10). The 2013 and 2014 detection rates were in line with rates from previous years given discharge conditions. No relationship was found with the annual percentage of fish detected approaching the SDE and river discharge.

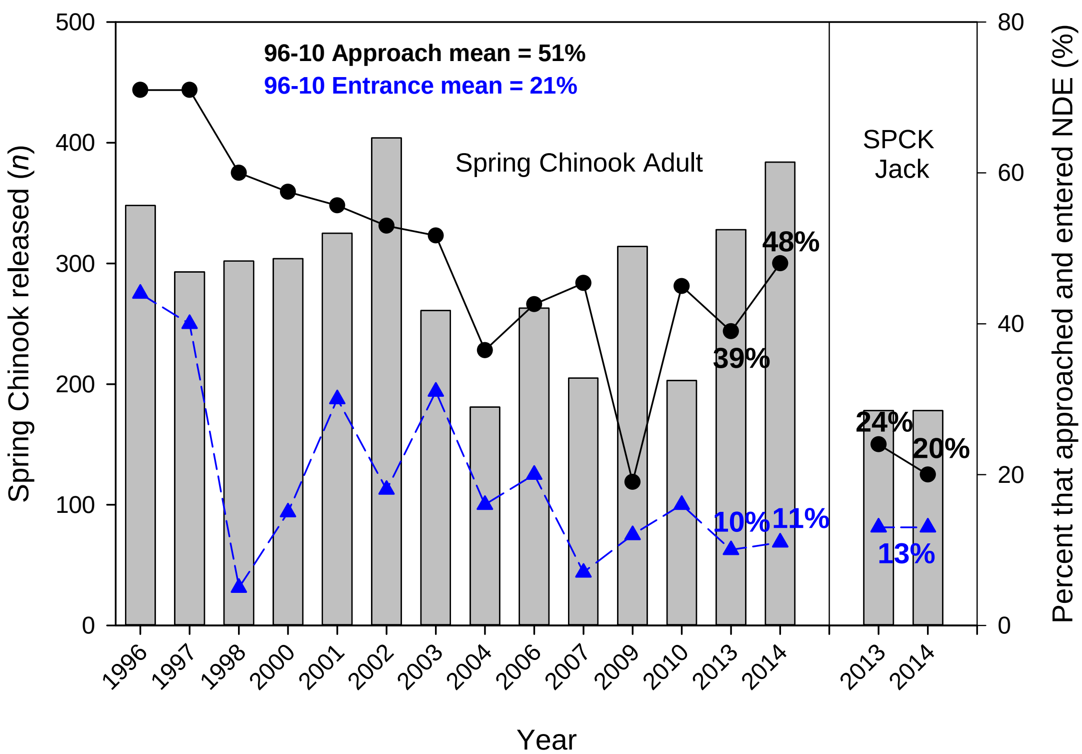

Figure 8. Number of spring Chinook salmon radio-tagged (bars) and the percentages that were recorded approaching (circles and solid line) and entering (triangles and dashed line) the PH2 NDE.

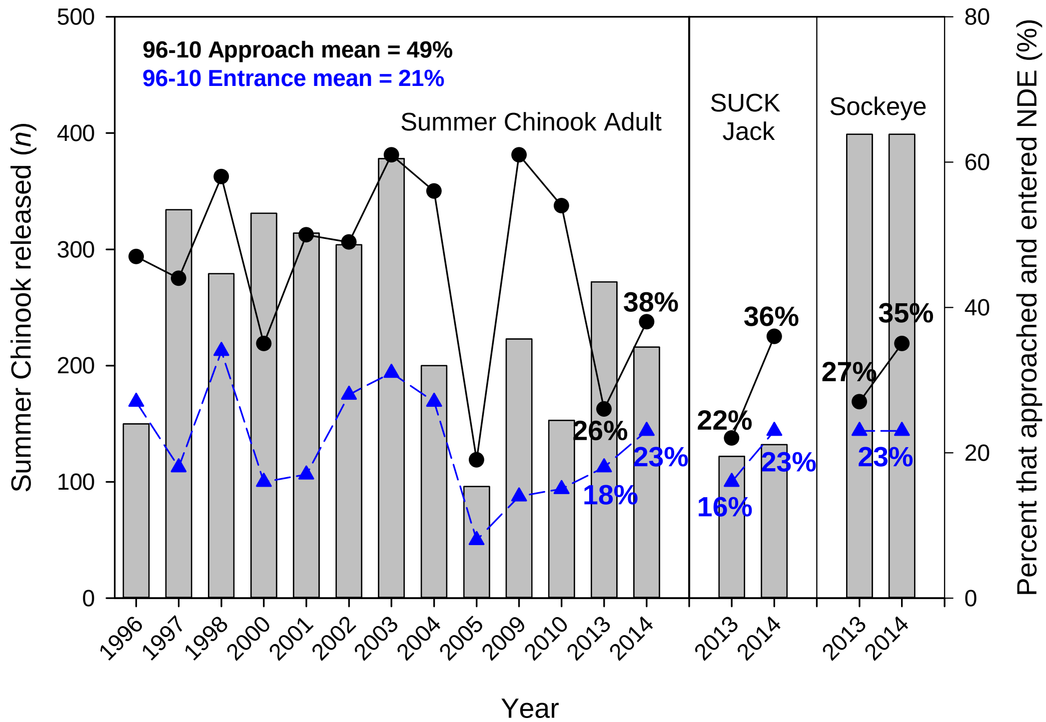

Figure 9. Number of summer Chinook and sockeye salmon radio-tagged (bars) and the percentages that were recorded approaching (circles and solid line) and entering (triangles and dashed line) the PH2 NDE.

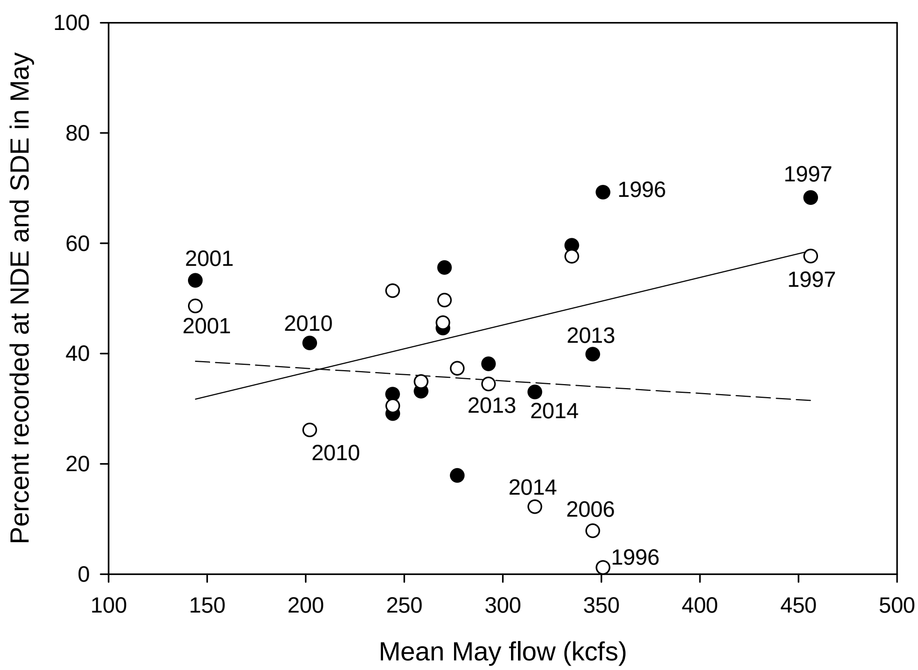

Figure 10. Linear relationship between mean May discharge at Bonneville Dam and the percentage of spring Chinook salmon recorded at NDE (solid circles; $r^2 = 0.18$, $P = 0.751$) and SDE (open circles; $r^2 = 0.008$, $P = 0.133$).

Metric 1: Entrance efficiency. The NDE entrance efficiency estimates for radio-tagged adult spring Chinook salmon in 2013 (0.26) and 2014 (0.23) were lower than the mean across pre-modification years (0.37) but were higher than entrance efficiencies from 1998 and 2000 (Figure 11). In a χ^2 test, entrance efficiency during post-modification years was significantly lower than in pre-modification years ($\chi^2 = 18.87$, $P < 0.001$). In pairwise χ^2 tests among years, results were mixed, with some higher and some lower between pre- and post-modification years (Appendix Table 1). Entrance efficiency estimates at SDE in post-modification years for spring Chinook salmon (0.22-0.25) were also lower than the mean across pre-modification years (0.30). In contrast, the spring jack Chinook NDE efficiency in 2013 (0.64) was higher than the adult mean from pre-modification years (Figure 11). Adult and jack summer Chinook NDE post-modification mean entrance efficiencies (0.65 and 0.68; Figure 11) were also higher than the means from pre-modification years (0.44) at NDE, as was the post-modification NDE mean efficiency for sockeye salmon (0.75). Summer Chinook post-modification entrance efficiency was significantly higher than in pre-modification years ($\chi^2 = 23.73$, $P < 0.001$). In χ^2pairwise comparisons, post-modification years were significantly (P <0.05) higher in 2013 versus eight pre-modification years and in 2014 versus five pre-modification years (Appendix Table 2). Post-modification mean efficiencies at SDE for adult (0.38) and jack (0.41) summer Chinook and sockeye (0.41) salmon were also above the mean adult value (0.37) across pre-modification years.

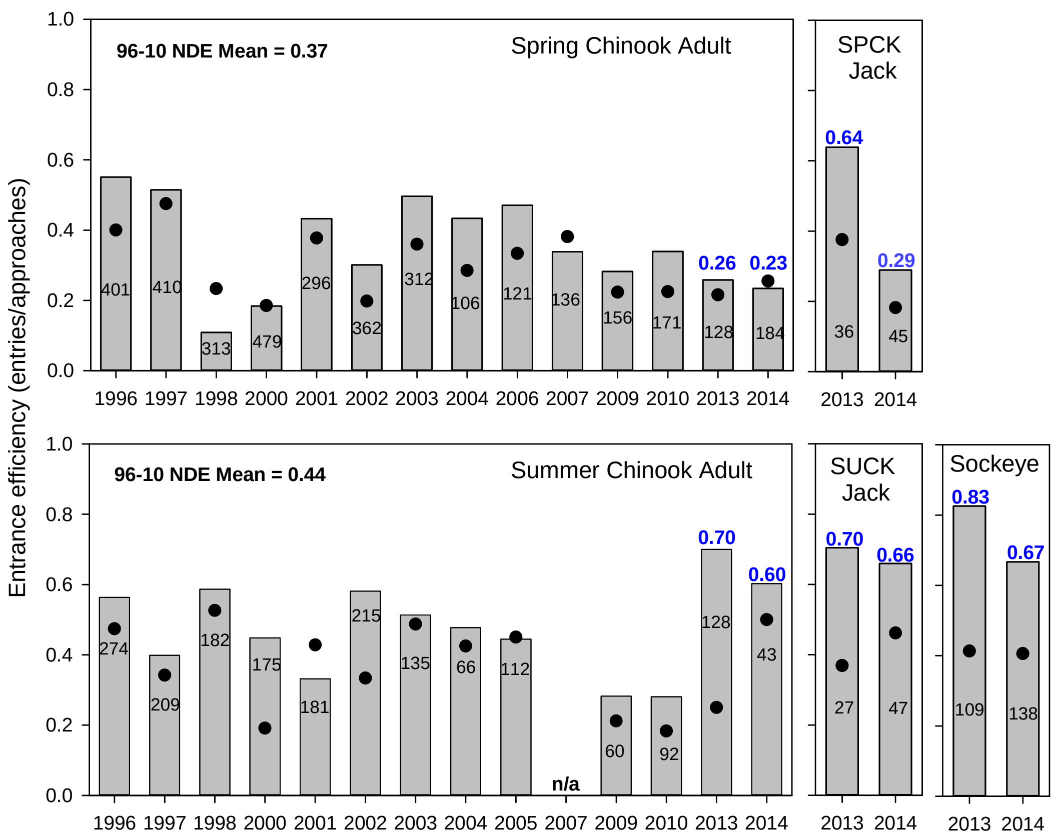

Figure 11. NDE (gray bars) and SDE (solid circles) entrance efficiency (unique entrances/unique approaches) for radio-tagged spring Chinook salmon (top panel) and summer Chinook and sockeye salmon (bottom panel). Years on x-axes are different. Samples sizes in each bar are NDE approaches.

Metric 2: Exit ratio. Exit ratios varied considerably among years and Chinook salmon runs. Adult and jack spring Chinook salmon post-modification exit ratios (0.03-0.18) were low compared to pre-modification years (*mean* = 0.29; Figure 12). In a χ^2 test, adult spring Chinook salmon exit ratios were significantly lower in post-modification years than in pre-modification years ($\chi^2 = 21.81$, $P < 0.001$). In χ^2 pairwise comparisons, post-modification years were significantly ($P < 0.05$) lower in 2013 versus seven pre-modification years and in 2014 versus five pre-modification years (Appendix Table 3). Adult and jack summer Chinook exit ratios in post-modification years (*mean* = 0.46 and 0.42, respectively) were also less than the mean from pre-modification years (0.49). No significant differences were found in χ^2 comparisons between pre and post-modification years for adult summer Chinook exit ratios ($\chi^2 = 3.78$, $P = 0.052$). The sockeye salmon mean post-modification exit ratio (0.44) was similar to that for adult summer Chinook (*mean* = 0.46).

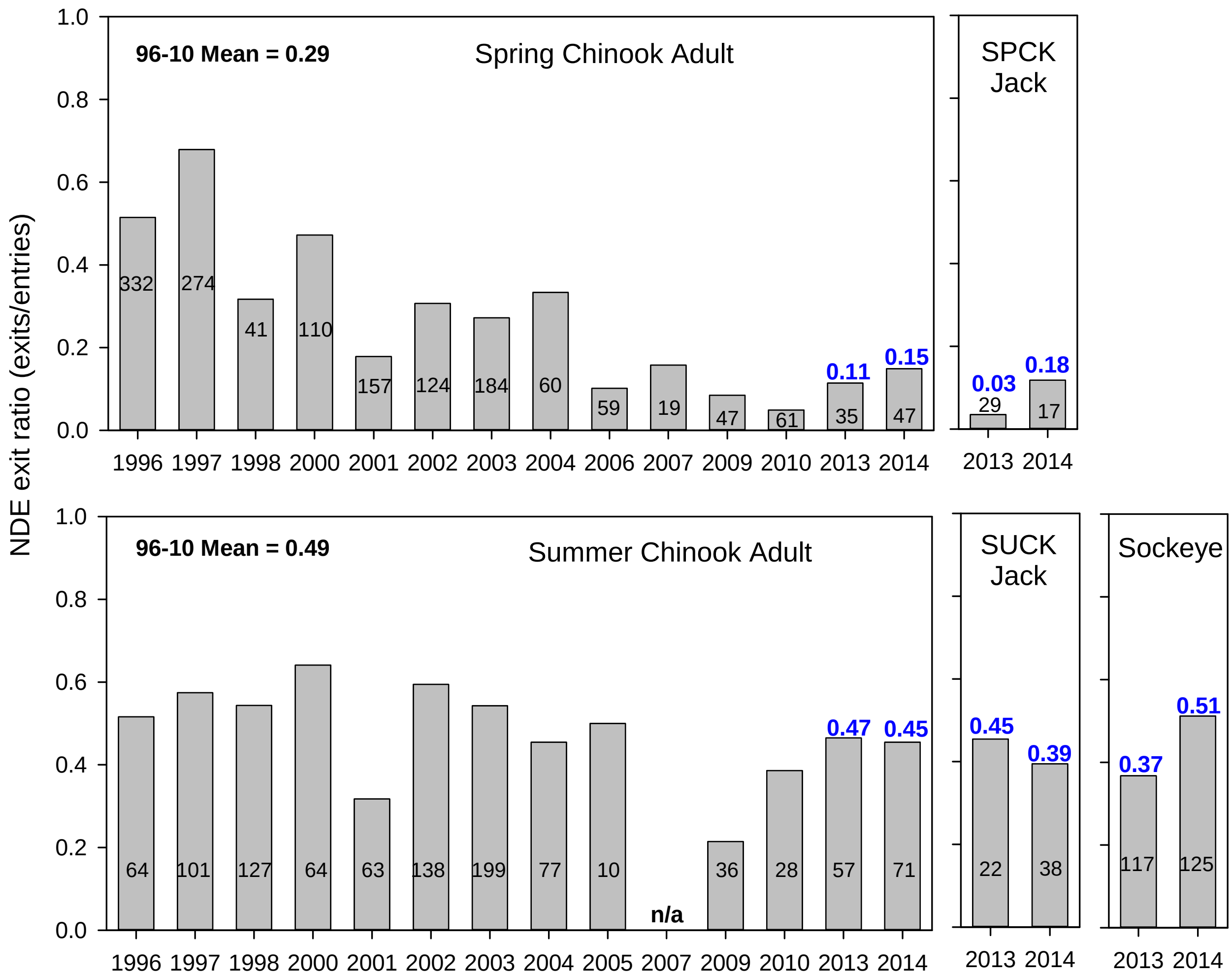

Figure 12. NDE exit ratios (exits/entries) for radio-tagged spring Chinook salmon (top panel) and summer Chinook and sockeye salmon (bottom panel). Years on x-axes are different. Sample sizes (number of entries) are inside each bar.

Metric 3: Entrance time. Generally, radio-tagged fish moved rapidly into the NDE in most years, but a few had long passage times when they repeatedly approached the fishway without entering, or moved to the tailrace, or to other fishways, and then returned to enter NDE. For spring Chinook salmon in 2013 and 2014, approach-entrance times ranged from less than a minute to 6.2 d with a median of 2 h and 0.5 h, respectively (Figure 13). In comparison, the median passage times for other pre-modification years ranged from <1 min in 2010 to 9.6 h in 2009. Collectively, there was not a significant difference in entrance times between pre- and post- modification years for adult spring Chinook salmon (ANOVA df =1, F = 0.01, P = 0.927); however, significant among-year differences were identified (ANOVA df =13, F = 5.57, P < 0.001). Pairwise comparisons using the Tukey test indicated differences in annual means occurred only among pre-modification years, with the exception of the 2013 mean being longer than the 2010 mean. Pairwise comparisons with the 2014 mean were not significantly different from any of the pre-modification years or 2013. Jack spring Chinook salmon passage times in 2013 and 2014 were consistently faster than for the larger adult fish.

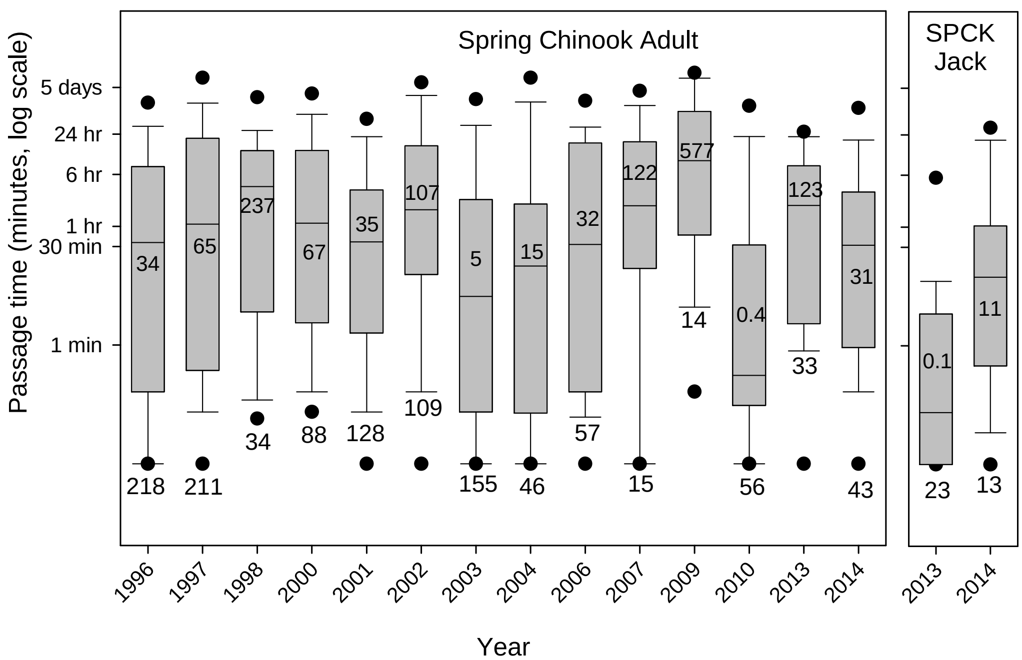

Figure 13. Spring Chinook salmon passage time distributions (log scale) from approach to entry at the NDE. Values inside boxes are median times. Distributions show 5th, 10th, 25th, 50th, 75th, 90th and 95th percentiles; sample sizes are shown at bottom.

Summer Chinook salmon passage times overall were faster than adult spring Chinook salmon times at NDE in 2013 and 2014 (Figure 14) and the 2014 median was the fastest in the time series. The median times for summer Chinook salmon in post-modification years were 6 and 2 min; respectively (ranged from < 1 min to 35 h). General linear model results for log-transformed passage times indicated entrance times were significantly faster post fishway entrance modificaton (df = 1, F = 8.04, P = 0.005). Tukey's pairwise comparisons indicated no differences in mean passage times between 2013 or 2014 and any of the previous 11 individual years. Jack summer Chinook and sockeye salmon entry times in 2013 and 2014 were similar to adults (*medians* = 1-2 min).

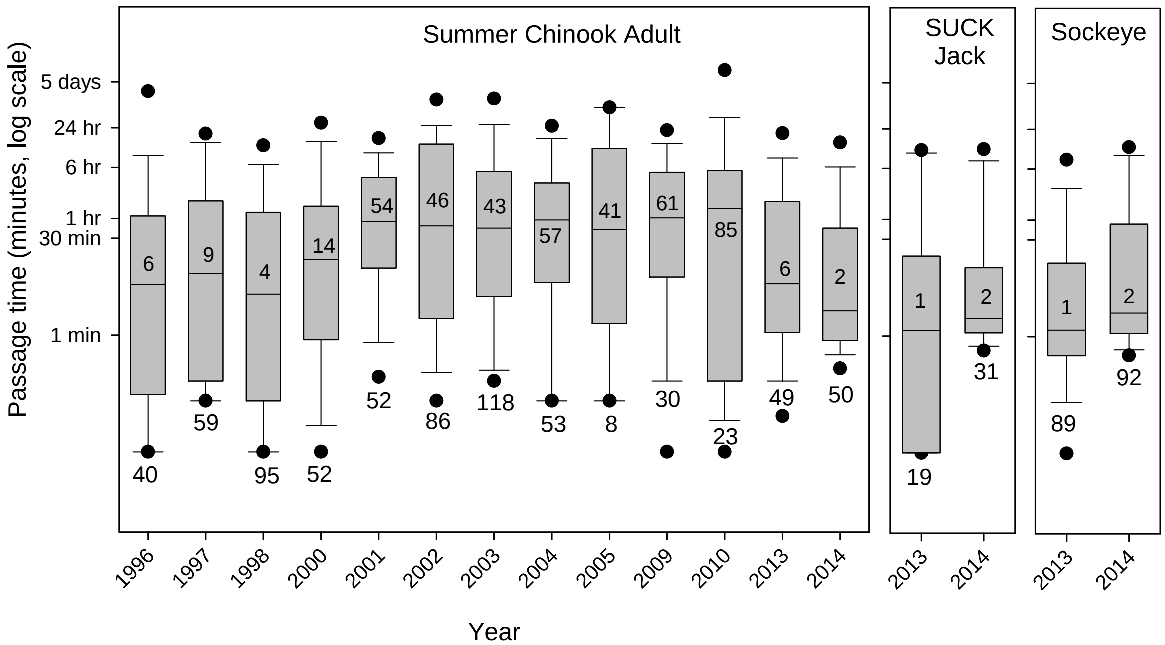

Figure 14. Summer Chinook and sockeye salmon passage time distributions (plotted on log scale) from approach to entry at the NDE. Values inside boxes are median times. Distributions show 5th, 10th, 25th, 50th, 75th, 90th and 95th percentiles; sample sizes are shown at bottom.

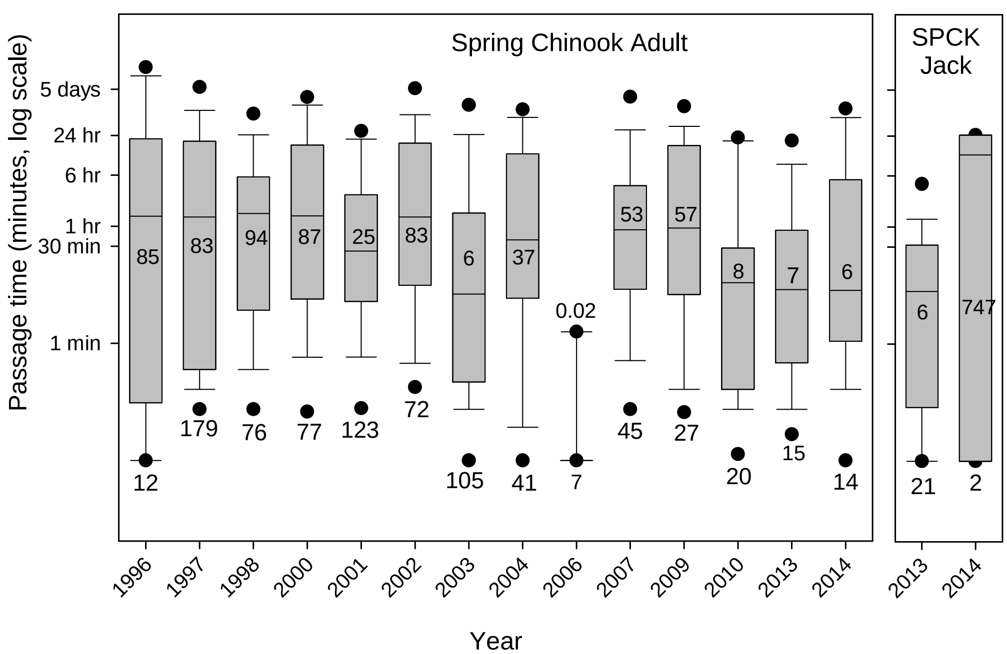

Figure 15. Spring Chinook salmon passage time distributions (plotted on log scale) from approach to entry at the SDE. Values inside boxes are median times. Distributions show 5th, 10th, 25th, 50th, 75th, 90th and 95th percentiles; sample sizes are shown at bottom.

Salmon passage times at SDE, a useful comparison site for NDE, were generally faster than those at NDE for spring and summer Chinook salmon (Figures 15 and 16). Median SDE approach-to-entry times for spring Chinook salmon ranged from <1 min (2006) to 1.6 h (1998). The medians in 2013 and 2014 were 7 and 6 minutes, respectively, for adult spring Chinook salmon. The median passage time (6 min) for 2013 jack Chinook was similar to the adults; the 2014 jack sample size was only two fish. Median summer Chinook salmon passage times at SDE ranged ~ 1 min (2013 and 2014) to 4.5 h (2009). Jack summer Chinook and sockeye salmon passage times were consistent with those of the adults (Figure 16).

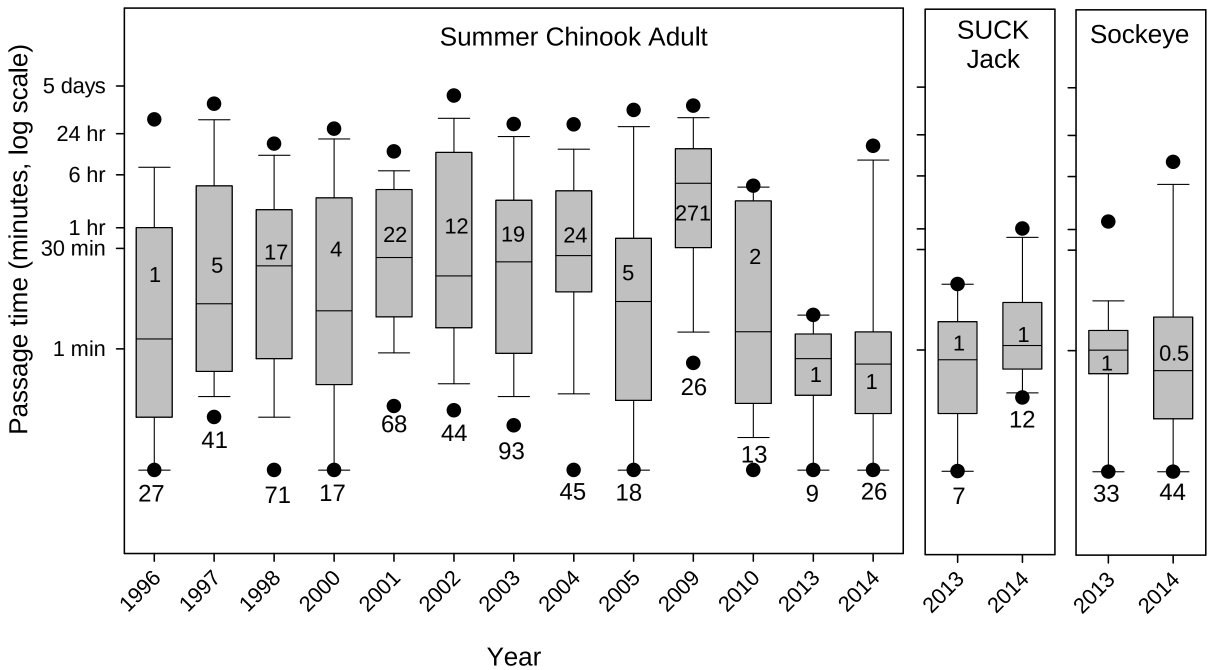

Figure 16. Summer Chinook and sockeye salmon passage time distributions (plotted on log scale) from approach to entry at the SDE. Values inside boxes are median times. Distributions show 5^{th}, 10^{th}, 25^{th}, 50^{th}, 75^{th}, 90^{th} and 95^{th} percentiles; sample sizes are shown at bottom.

The median NDE approach-to-entry time for adult spring Chinook salmon in 2009 was unexpectedly long compared to past approach-to-entry times at NDE and SDE (Figure 17). In contrast, the relationship between NDE and SDE entry times for spring and summer Chinook salmon was relatively constant in the 2000-2006 data. Both 1996 and 2009 were spring Chinook salmon outliers, with the small 1996 sample (*n* = 11) having relatively long SDE approach-to-entry times and the 2009 sample having long NDE approach-to-entry times. Median approach-to-entry times in 2013 and 2014 were faster for summer Chinook than spring Chinook salmon and both were similar to previous years.

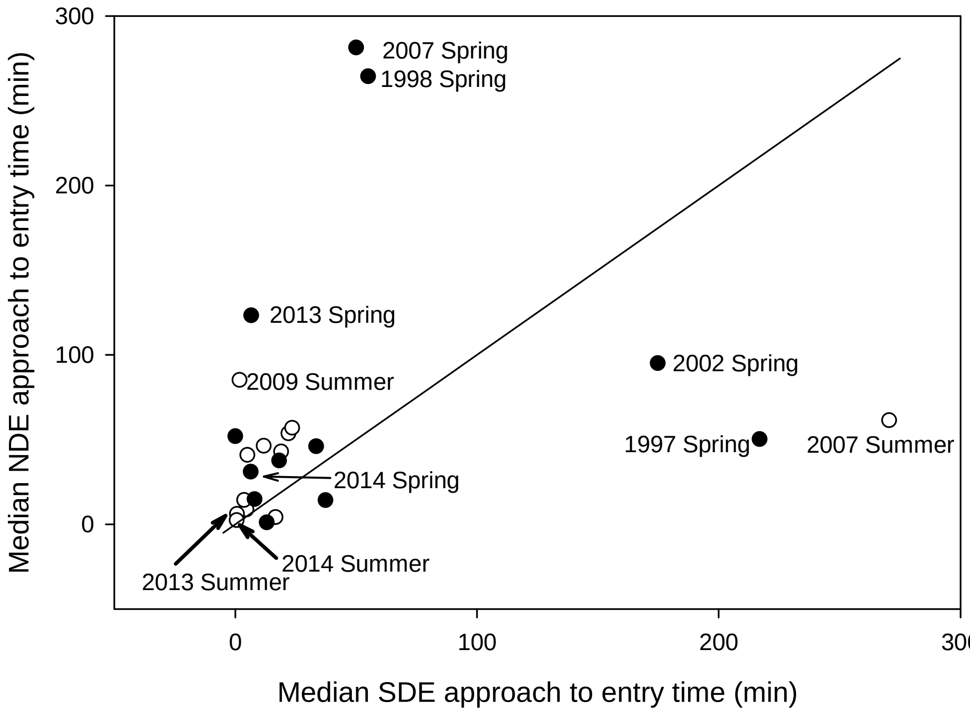

Figure 17. Scatterplot of annual median first approach to first entry times (min) at the NDE and SDE entrances for radio-tagged adult spring (solid circles) and summer (open circles) Chinook salmon. Note outliers not shown include 1996 spring Chinook (NDE = 10.1; SDE = 1283.9) and 2009 spring Chinook (NDE = 577.1; SDE = 56.7).

Within each post-modification year, associations between NDE approach-to-entry times and environmental factors were weak or absent (Tables 1 and 2). There tended to be stronger correlations between spring Chinook salmon NDE approach-to-entry times and environmental variables compared to pre-modification years (Table 1). Spill levels in 2013-2014 when tagged spring Chinook salmon approached PH2 NDE fluctuated around 100-130 kcfs, which was near average compared to previous years (Figure 18). Flows (2013 and 2014) and water temperatures (2013) were generally higher than in previous years and tailwater elevations were slightly higher when tagged salmon first approached the NDE (Figure 18). Higher temperature and lower tailwater elevations in 2013 may explain some of the variability in 2013 approach-to-entry times and have been associated with longer passage times in the past. Positive correlations indicated longer approach-to-entry times when temperature, flow, spill, and tailwater elevations were higher in 2014, however, negative correlations were observed among these same environmental variables with regard to passage time in 2013. General linear model results indicated a significant date effect for adult spring Chinook salmon, where passage times increased with date when considering all study years together ($df = 1$, $F = 4.20$, $P = 0.04$).

Table 1. Correlation coefficients (r) between environmental conditions that adult spring Chinook salmon encountered when they first approached the PH2 NDE opening and log-transformed approach-to-entry times, by year. Bold indicates $P < 0.05$.

Year	Flow	Spill	Temp	Tailwater elev.	Date
1996	0.07	0.11	0.06	0.06	0.03
1997	-0.12	-0.11	-0.09	-0.10	-0.09
1998	-0.09	0.01	-0.07	-0.08	-0.03
2000	0.05	0.02	-0.18	0.07	-0.17
2001	0.11	0.08	0.08	0.11	0.10
2002	0.13	0.18	0.04	0.12	0.05
2003	**0.16**	-0.04	**0.19**	**0.20**	**0.16**
2004	-0.07	-0.09	-0.13	-0.02	-0.08
2006	**0.32**	**0.35**	**0.33**	**0.32**	**0.35**
2007	0.25	-0.21	0.36	0.27	0.40
2009	-0.21	-0.14	-0.37	-0.19	-0.33
2010	0.11	0.03	**0.35**	0.11	**0.33**
2013	**-0.58**	**-0.77**	**0.35**	**-0.57**	**0.69**
2014	**0.52**	**0.44**	**0.51**	**0.54**	**0.55**

The degree of association between environmental factors and passage times within years was lower for adult summer Chinook salmon than adult spring Chinook salmon (Table 2). Water temperature and the date fish first approached PH2 NDE were the only significant factors associated with approach-to-entry times in 2013. Negative correlations indicated longer approach-to-entry times associated with lower water temperatures and earlier dates. These results were consistent with those from previous years where few environmental variables have shown a strong linear relationship with summer Chinook salmon approach-to-entry passage times. Collectively, across all study years model results indicated a significant date effect for adult summer Chinook salmon, where passage times decreased with increasing date (ANOVA df =1, F = 16.6, P < 0.001).

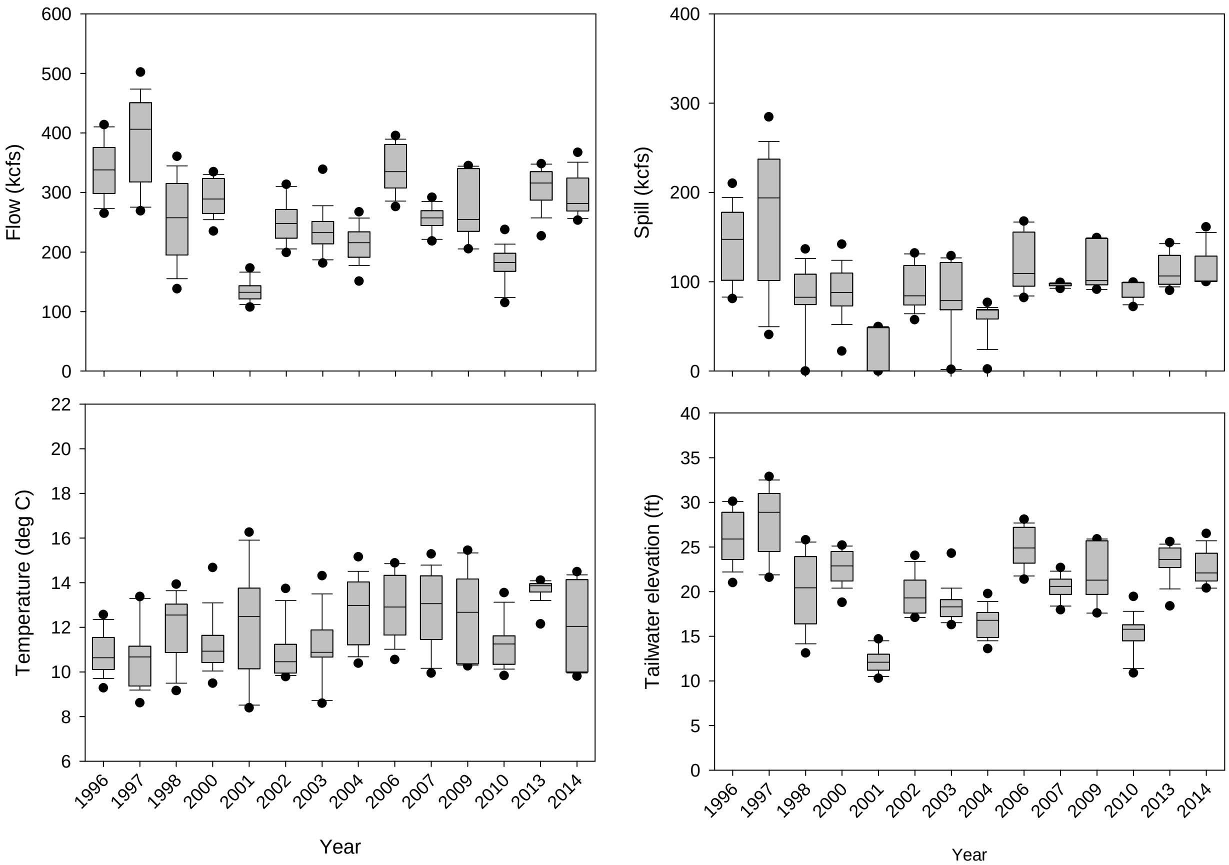

Figure 18. Box plots of the total discharge ('flow'), spill, tailwater elevation, and temperature on the days that radio-tagged adult spring Chinook salmon first approached the NDE. Distributions show 5th, 10th, 25th, 50th, 75th, 90th, and 95th percentiles.

Table 2. Correlation coefficients (*r*) between environmental conditions that adult summer Chinook salmon encountered when they first approached the PH2 NDE opening and log-transformed approach-to-entry times, by year. Bold indicates $P < 0.05$.

Year	Flow	Spill	Temp	Tailwater elev.	Date
1996	-0.12	-0.08	0.21	-0.16	0.18
1997	0.18	0.21	-0.22	0.20	-0.23
1998	-0.09	-0.10	0.01	-0.08	0.02
2000	0.04	0.14	-0.19	0.17	-0.13
2001	0.03	0.09	-0.05	0.03	-0.07
2002	-0.01	0.18	-0.17	-0.01	-0.17
2003	0.03	0.02	0.02	0.03	-0.02
2004	0.18	0.22	-0.18	0.18	-0.19
2005	-0.63	**0.81**	-0.31	**-0.75**	-0.32
2009	0.24	0.19	-0.31	0.24	**-0.39**
2010	-0.27	-0.40	-0.27	-0.16	-0.33
2013	-0.18	-0.03	**-0.44**	-0.18	**-0.49**
2014	-0.18	0.04	-0.10	-0.17	-0.14

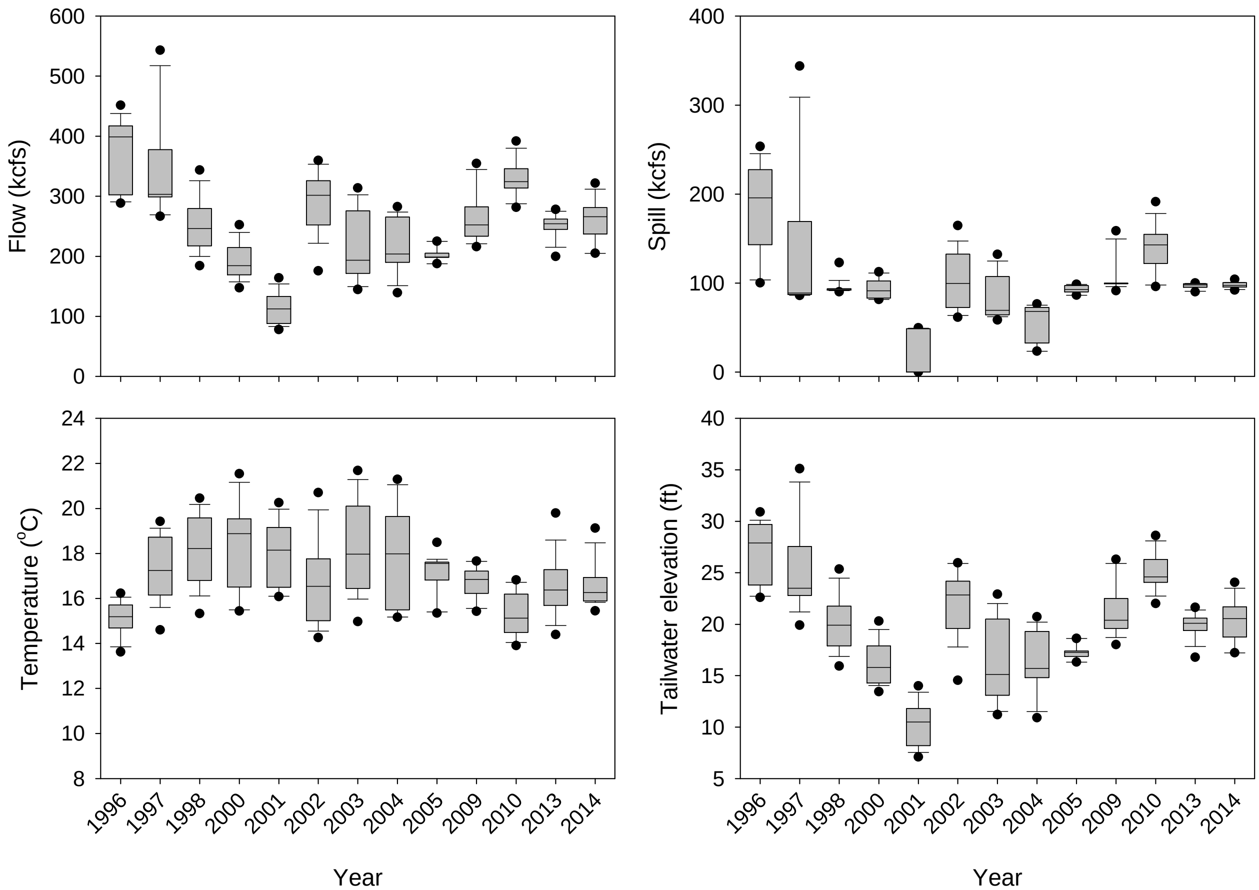

Figure 19. Box plots of the total discharge ('flow'), spill, water temperature, and tailwater elevation on the days that adult summer Chinook salmon first approached the NDE. Distributions show 5th, 10th, 25th, 50th, 75th, 90th, and 95th percentiles.

Metric 4: Entrance to base of ladder time. After tagged adult spring Chinook salmon entered NDE, the median time to reach the ladder base ranged from 4–41 min in pre-modification years (Figure 20). Median times for adult and jack spring Chinook salmon in 2013 and 2014 were at the lower end of that range with median times ranging from 4 to 9 min. General linear model results for log-transformed passage times indicated significantly faster passage times after the fishway modification (df =1, F =1 2.1, P < 0.001). Tukey pairwise comparisons indicated significantly faster passage times in 2013-2014 compared to 1996-1997. Summer Chinook salmon base of the ladder passage times were also significantly faster (df =1, F=21.1, P < 0.001) in post-modification years (*median* 4 min; Figure 21) than in pre-modification years (*median* range 7-20 min). Pairwise comparisons indicated salmon were significantly faster in 2013-2014 compared to 1996-1998 and 2000. Summer jack Chinook and sockeye salmon took slightly longer than adult summer Chinook salmon in 2013-2014 with median times ranging from 6-16 min.

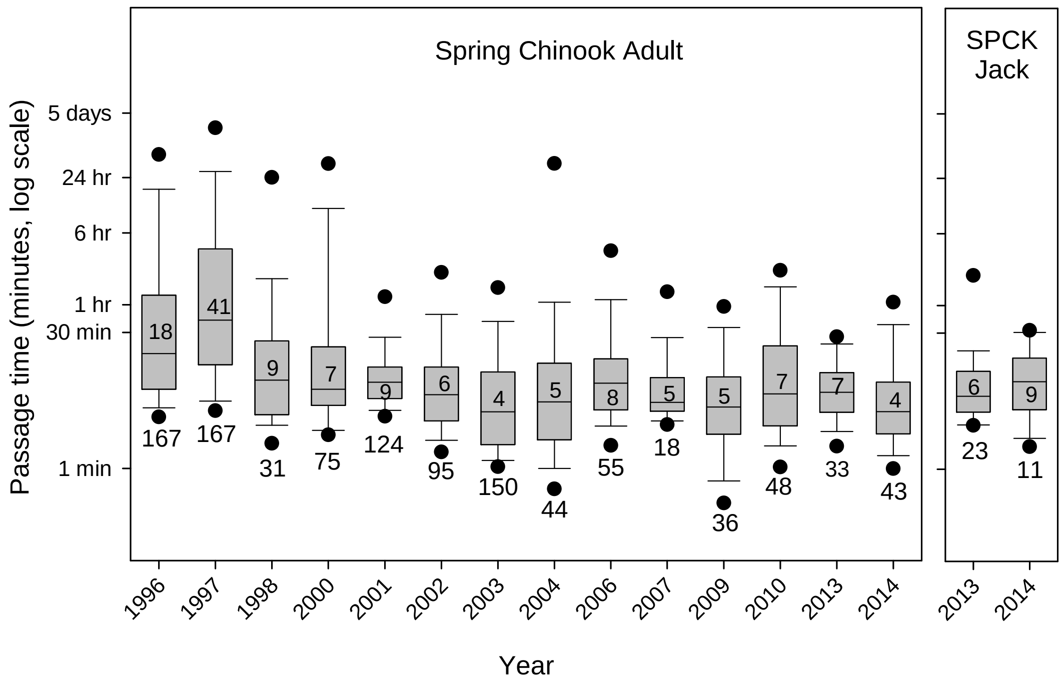

Figure 20. Spring Chinook salmon passage time distributions (plotted on log-scale) from NDE to the antenna at the base of the ladder. Numbers inside boxes are median times. Distributions show 5th, 10th, 25th, 50th, 75th, 90th, and 95th percentiles; sample sizes are below boxes.

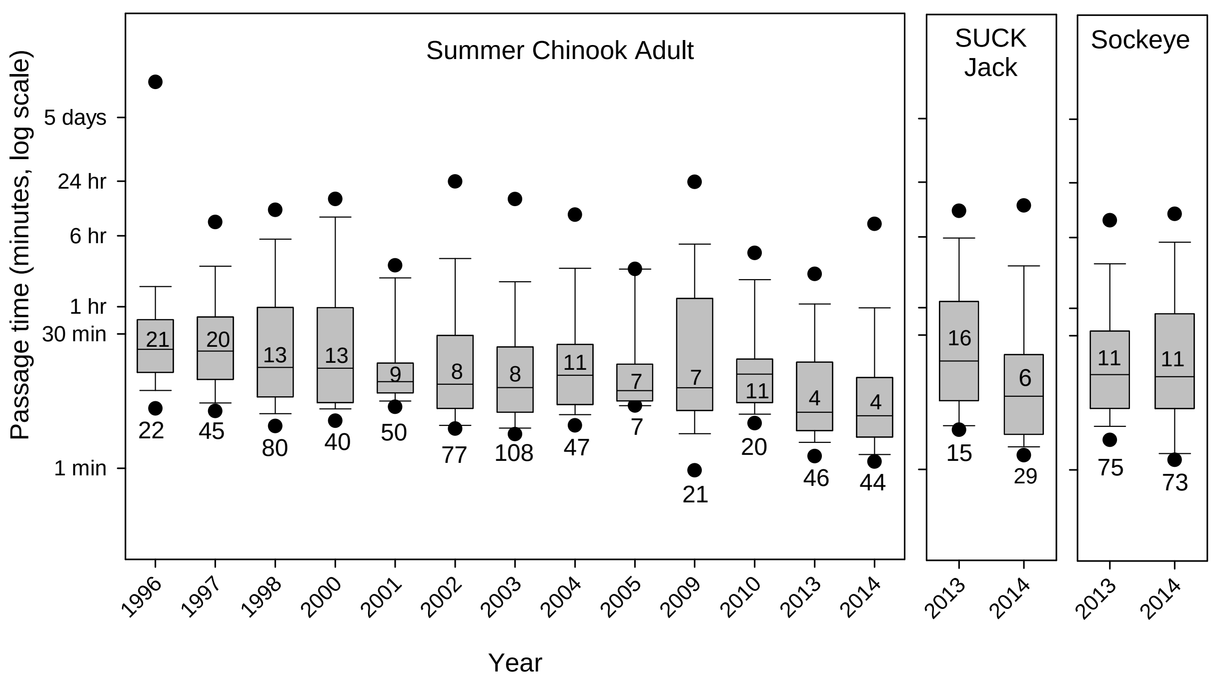

Figure 21. Summer Chinook and sockeye salmon passage time distributions (plotted on log-scale) from NDE to the antenna at the base of the ladder. Numbers inside boxes are median times. Distributions show 5th, 10th, 25th, 50th, 75th, 90th, and 95th percentiles; sample sizes are below boxes.

***Metric 5:* Extended passage times.** In pre-modification years, the percentage of adult spring Chinook salmon with long passage times (> 1 h) for NDE approach to NDE entrance and from NDE entrance to the first ladder antenna ranged from 20–71% (*mean* = 48%) and from 3–40% (*mean* = 14%), respectively (Figure 22). The 2013 and 2014 percentages for adult spring Chinook salmon was 55% and 40%, respectively. Logistic regression models indicated no significant differences in fish taking > 60 min to enter the fishway between pre- and post-modification years ($df = 1$, $\chi^2 = 0.195$, $P = 0.659$). The percentages of spring jack Chinook salmon taking > 1 h to enter the fishway were lower than adults, ranging from 4-23% in 2013-2014. After entering at NDE, the nearly all or all (93-100%) of adult and jack spring Chinook salmon reached the antenna at the base of the ladder in less than 1 h in 2013 and 2014 (Figure 22).

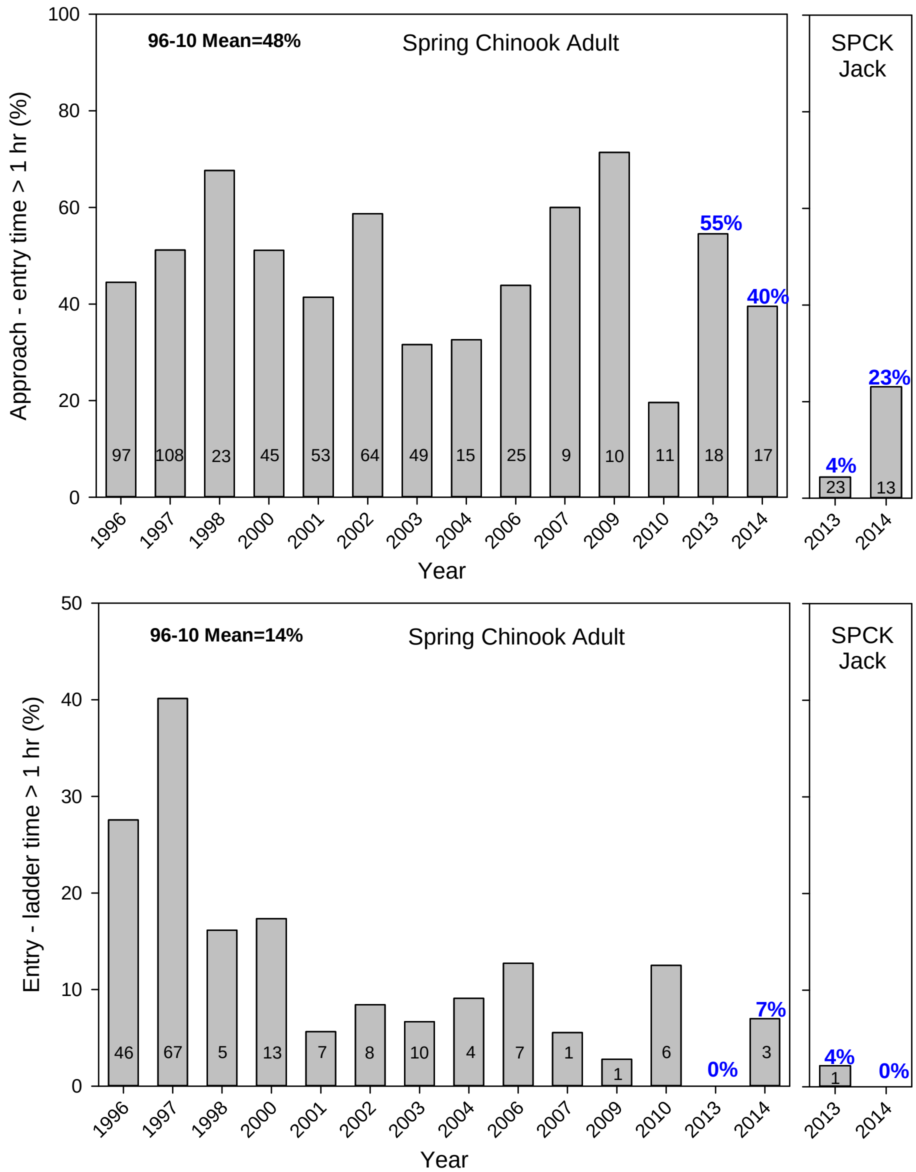

Figure 22. Percentages of radio-tagged spring Chinook salmon that took > 1 h to enter the north downstream fishway entrance (top panel) and the time to pass from the fishway opening to the base of the ladder (bottom panel). Sample sizes are inside each bar.

We observed fewer tagged adult summer Chinook salmon with long approach-to-enter passage times (> 1 h) at NDE in 2013-2014 (18-35%) than in the pre-modification year (*mean* = 41%), though logistic regresson models did not indicate a significant difference between pre- and post-modification groups ($df = 1$, $\chi^2 = 2.56$, $P = 0.11$). The percentage of fish that entered NDE and took longer that 1 h to reach the first ladder antenna post-modification was also lower (9-13%) in 2013-2014 than in the pre-modification years (*mean* = 18%) (Figure 23). The percentages for jack summer Chinook salmon with long approach-to-entry and base of ladder passage times ranged from 10-21% and 27-31%, respectively. Sockeye salmon with longer passage times through these segments were similar to adult summer Chinook at 19-22% and 17-22%, respectively.

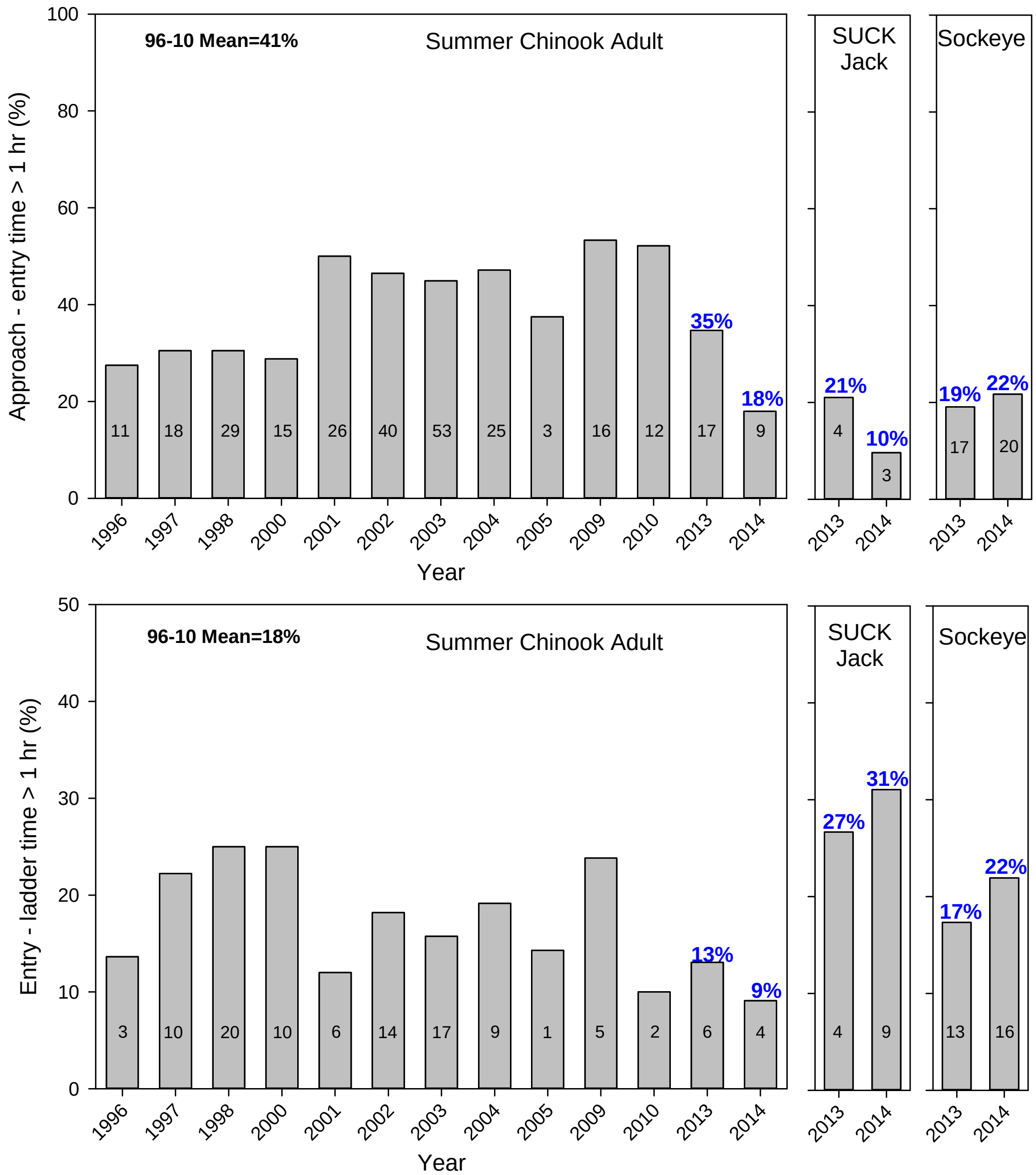

Figure 23. Percentages of radio-tagged summer Chinook and sockeye salmon that took > 1 h to pass from the north downstream approach to fishway entrance and from opening to the base of the ladder. Sample sizes are inside each bar.

Metric 6: PH2 entry locations of successful dam passages. In 2013 (27%) and 2014 (32%), of adult Chinook salmon that had an LP record (i.e., indicating a final passage through the WA shore transition pool specifically) and used one of the four main PH2 fishway openings had entered via NDE and the other 73% and 68%, respectively entered at NUE, SDE or SUE (Figure 24). In previous years, this NDE metric ranged from 22-68% (*mean* = 43%). The percentage of jack spring Chinook salmon that last entered NDE was 42% in 2013 and 23% in 2014.

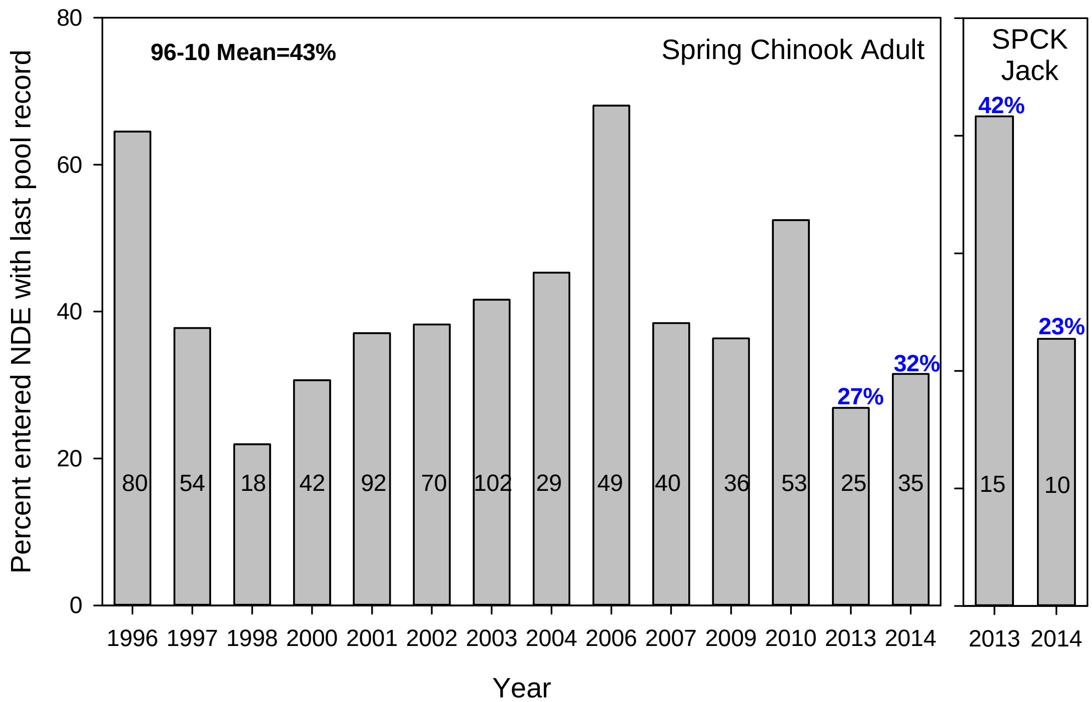

Figure 24. Percent of radio-tagged spring Chinook salmon that reached the upstream portion of the transition pool area (LP = last pool) and then passed Bonneville Dam after entering NDE. Sample sizes (number of NDE entries) are inside each bar.

In comparison to spring Chinook, more summer Chinook adult (56%) and jack summer Chinook (53%) had an LP record after entering NDE versus other main PH2 fishway openings in 2013 (Figure 25). However, in 2014 the summer adult (35%) and jack (30%) percentages were closer to spring adult post-modification numbers. Adult summer Chinook NDE entries were at or above the pre-modification mean (35%). The percentage of sockeye salmon reaching the transition pool after entering NDE (39-42%) was less variable between years and similar to the pre-modification mean for adult summer Chinook.

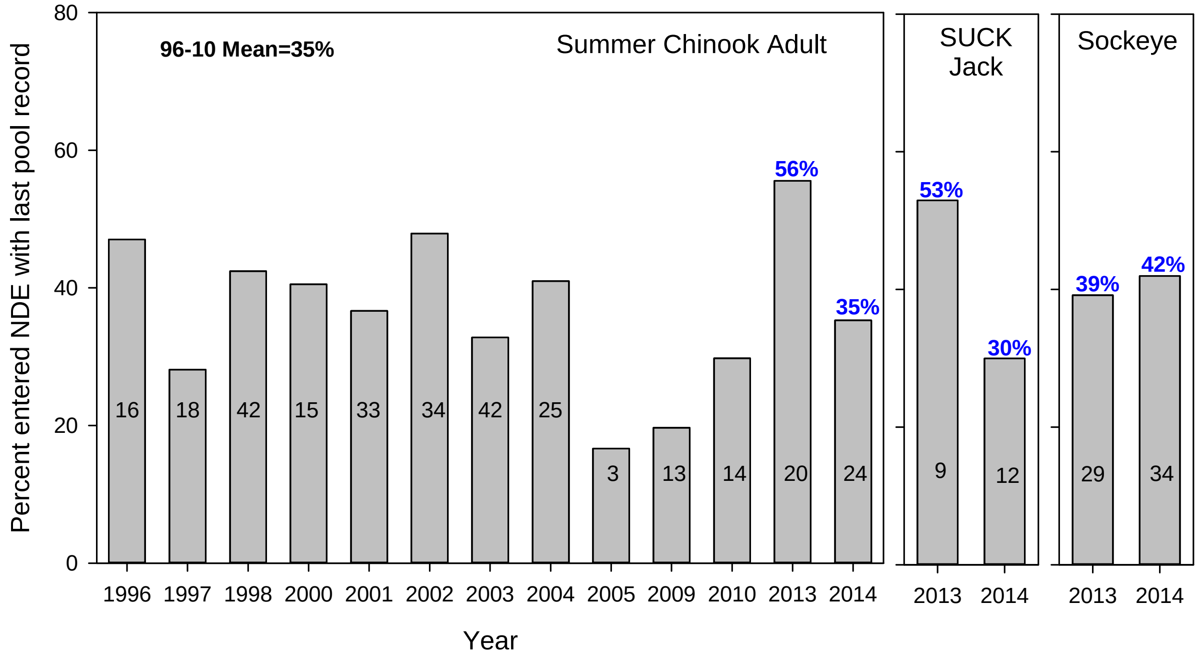

Figure 25. Percent of radio-tagged summer Chinook and sockeye salmon that reached the upstream portion of the transition pool area (LP = last pool) and then passed Bonneville Dam after entering NDE. Sample sizes (number of NDE entries) are inside each bar.

Metric 7: Proportion of PH2 NDE and PH2 SDE approaches and entries. The proportion of spring Chinook salmon that entered and approached NDE relative to SDE ([NDE/(NDE+SDE]) varied among pre-modification years. In most years, approach proportions ranged from 0.34-0.53 and entry proportions ranged from 0.30-0.59; exceptions were in 1996, 2006, and 2010 where the relative number of fish approaching and entering NDE were much higher than SDE (Figure 26). Post-modification proportions fell within the range of pre-modification years.

The mean proportion of adult summer Chinook salmon approaching (0.74) and entering (0.77) NDE compared to SDE was higher during the post-modifications years than the pre-modification years (*mean* approach proportion = 0.52; *mean* entry proportion = 0.57) (Figure 26). Summer jack Chinook and sockeye salmon mean proportions of approaches (0.61) and entries (0.72) were similar between post-modification years.

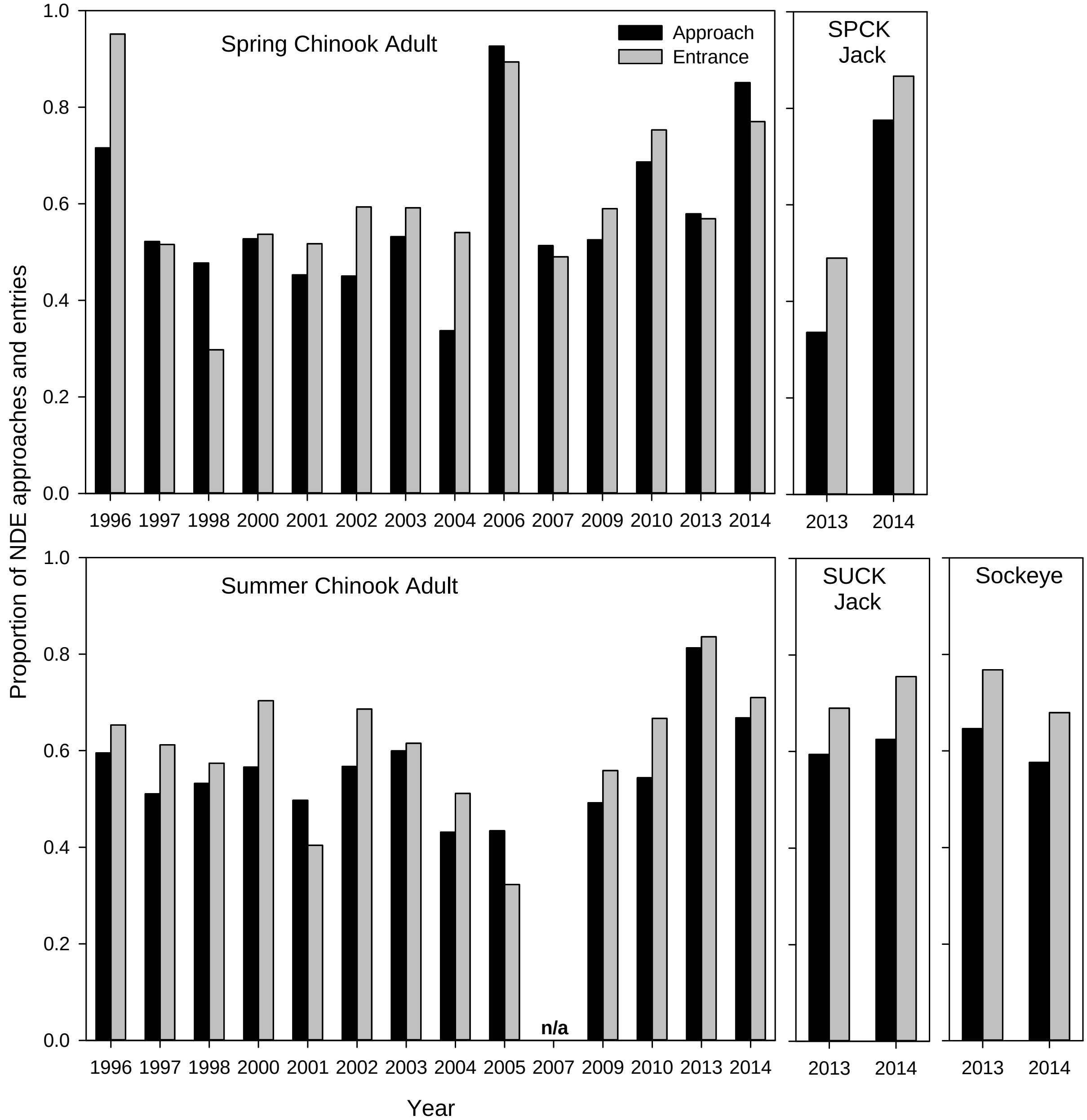

Figure 26. Proportion of NDE approaches and entries of radio-tagged spring (top panel) and summer Chinook and sockeye salmon (bottom panel). Proportion = NDE/(NDE+SDE). Years on x-axes are different.

Cascades Island Results

Of the 384 adult spring Chinook salmon tagged through 31 May 2014, 77 (20%) were recorded approaching and 52 (14%) were recorded entering the CI fishway opening (Figure 27). The post-modification percentages were within the range of values from pre-modification years, when 8–37% (*mean* = 23%) were detected approaching the CI fishway one or more times and 5–32% (*mean* = 19%) were recorded entering the CI fishway. Spring jack Chinook salmon approach (6%) and entrance (9%) means were lower than adult spring Chinook salmon but may be due to small sample sizes (*n* = 8-23 fish approached). The annual percentage of fish detected at the CI fishway increased slightly with increasing river discharge (Figure 28), though the relationship was driven by two extreme years. The 2009-2014 rates were largely within the range of pre-modification CI approach rates, given river conditions.

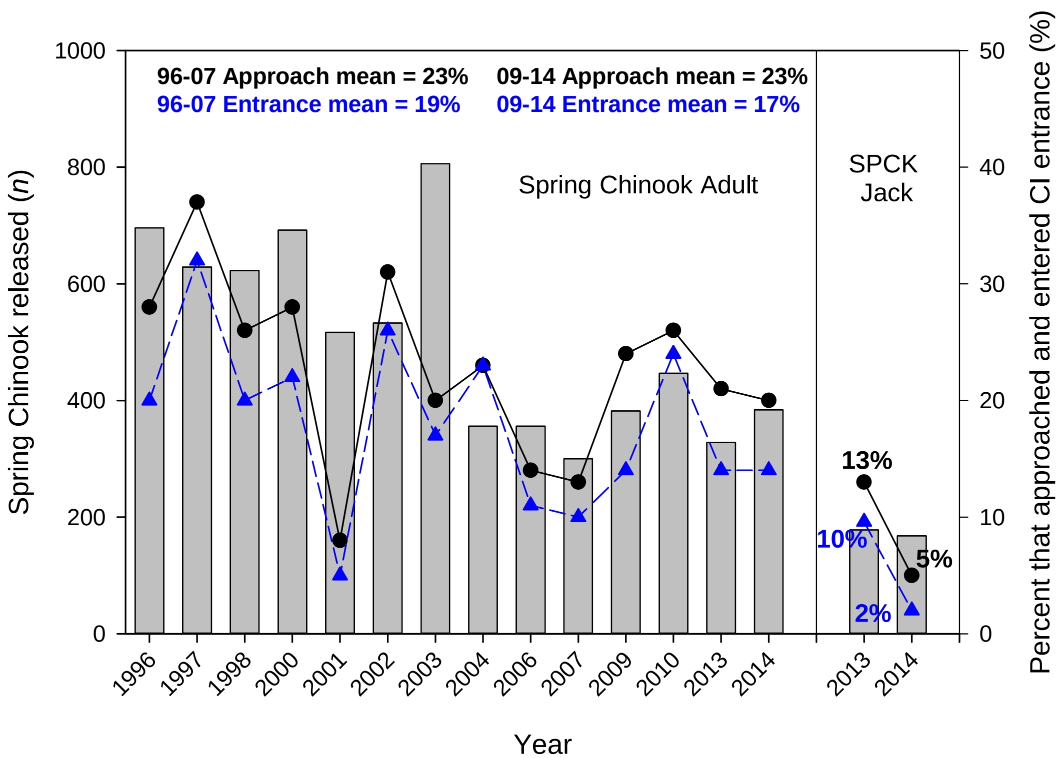

Figure 27. Number of spring Chinook salmon that were radio-tagged (bars) and the percentages that were recorded approaching (circles and solid line) and entering (triangles and dashed line) the Cascades Island fishway. Modifications occurred prior to the 2009 migration.

Of the 216 summer Chinook salmon tagged in 2014, 73 (23%) were recorded approaching and 42 (19%) were recorded entering the CI fishway opening (Figure 29). Adult summer Chinook mean approach percentage (23%) in post-modification years was the same as in pre-modification years (23%). Mean entries were also similar between pre-modification (19%) and post-modification (17%) years. While approach and entrance percetanges decreased from 2013 to 2014 for jack summer Chinook salmon they increased for adult sockeye salmon (Figure 29).

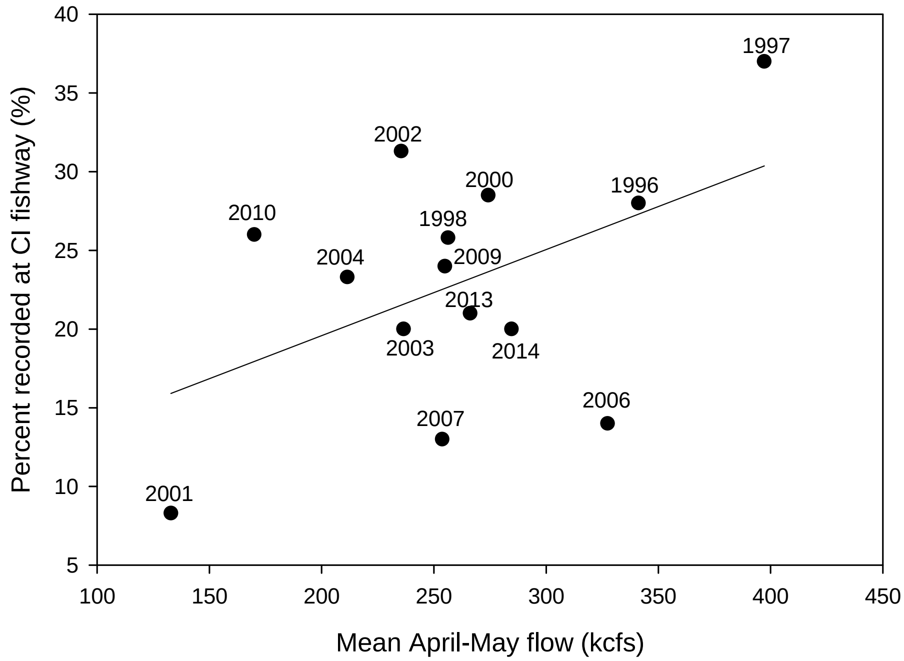

Figure 28. Linear relationship between mean April-May discharge at Bonneville Dam and the percentage of spring Chinook salmon recorded at the Cascades Island fishway ($r^2 = 0.15$, $P = 0.177$).

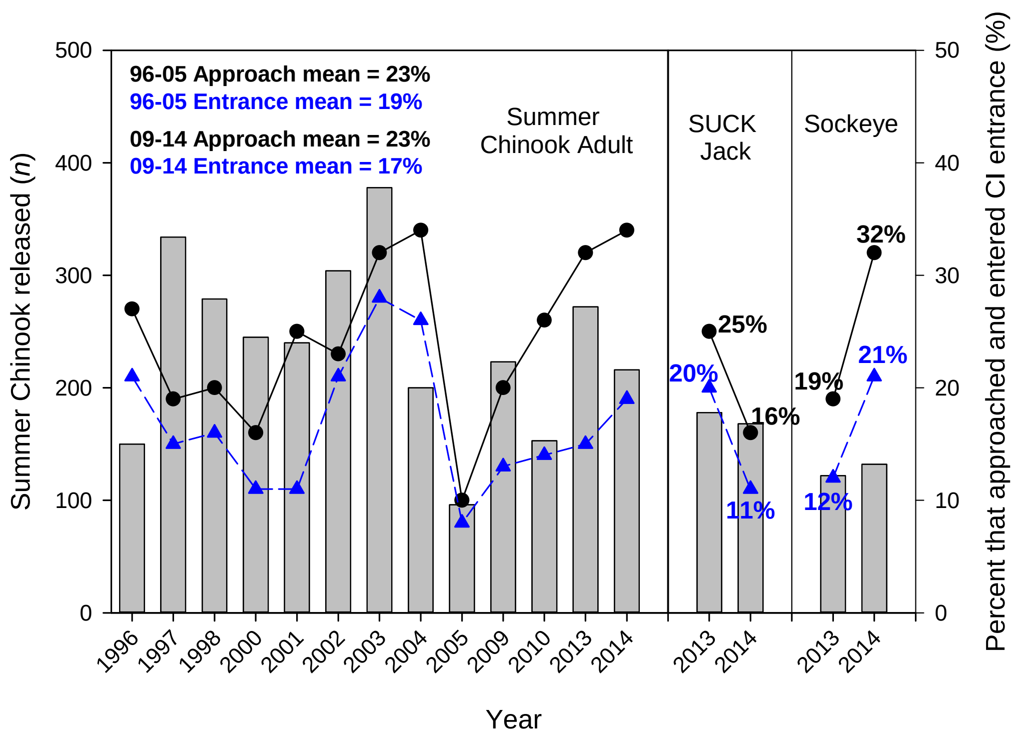

Figure 29. Number of summer Chinook and sockeye salmon that were radio-tagged (bars) and the percentages that were recorded approaching (circles and solid line) and entering (triangles and dashed line) the Cascades Island fishway.

Metric 1: Entrance efficiency. The CI entrance efficiency estimates in pre-modification years ranged from 0.48–0.98 for radio-tagged adult spring Chinook salmon (*mean* = 0.73, Figure 30), with the lowest estimate in 2001 when river flow and spill were low and few fish used the CI fishway. The mean entrance efficiency post-modification was 0.66. The entrance efficiency estimate in 2010 was 0.73, at the higher end of the range from previous years. In contrast, the entrance efficiency in 2009 was at the low end of the range (0.58) while the entrance efficiencies in 2013 (0.67) and 2014 (0.68) were closer to the pre-modification mean (0.73). In a χ^2test comparison, post-modification entrance efficiency was significantly lower than in pre-modification years ($\chi^2 = 9.80$, $P = 0.002$). In pairwise χ^2tests among years, results were mixed with some higher and some lower between pre- and post-modification years (Appendix Table 4). Entrance efficiency for jack spring Chinook salmon was 0.74 in 2013 and 0.50 in 2014 (note small sample size in 2014).

For radio-tagged adult summer Chinook salmon, the CI entrance efficiency estimates prior to entrance modifications ranged from 0.45–0.90 (*mean* = 0.76; Figure 31). The entrance efficiency in post-modification years ranged from 0.47-0.67 (*mean* = 0.56). In a χ^2test comparison, post-modification entrance efficiency was significantly lower than in pre-modification years ($\chi^2 = 41.29$, $P < 0.001$). In pairwise χ^2 tests among years, results were mixed with some higher and some lower between pre- and post-modification years (Appendix Table 5). Summer jack Chinook salmon and sockeye salmon mean entrance efficiencies were 0.72 and 0.63, respectively.

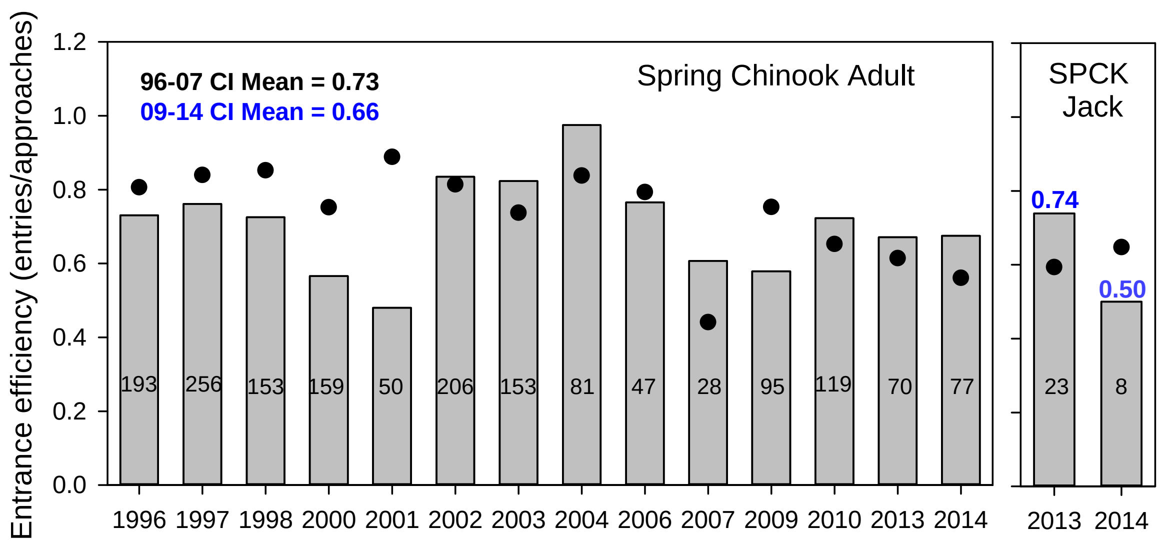

Figure 30. Cascades Island (gray bars) and Bradford Island (solid circles) entrance efficiency (unique entrances/unique approaches) for radio-tagged spring Chinook salmon. Sample sizes (number of approaches to CI) are inside each bar. Modifications occurred prior to the 2009 migration.

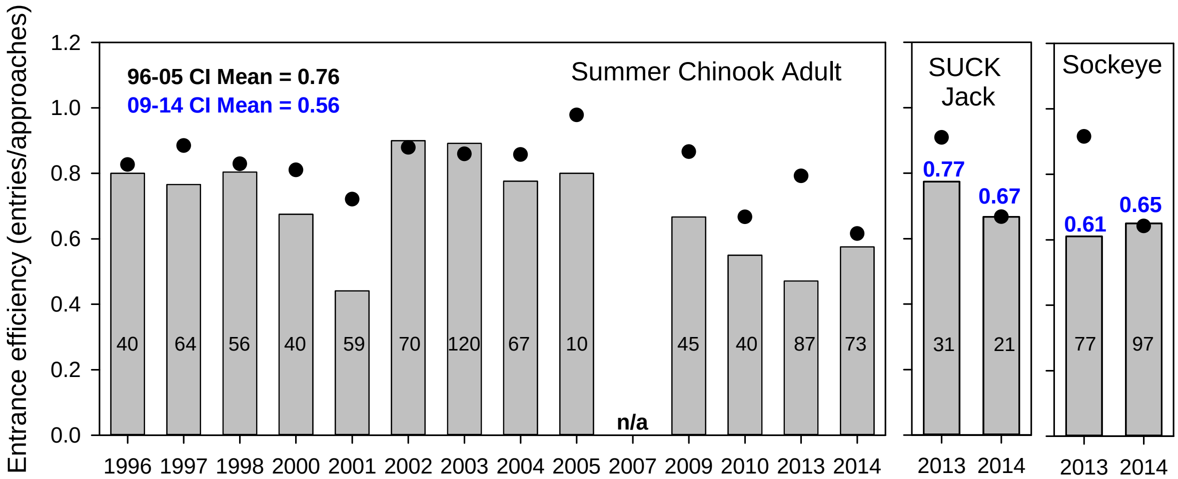

Figure 31. Cascades Island (gray bars) and Bradford Island (solid circles) entrance efficiency (unique entrances/unique approaches) for radio-tagged summer Chinook and sockeye salmon. Sample sizes (number of approaches to CI) are inside each bar. Modifications occurred prior to the 2009 migration.

Metric 2: Exit Ratio. Exit ratios for radio-tagged adult spring Chinook salmon prior to modifications at the CI entrance were variable, ranging from 0.05–0.50 (*mean* = 0.29; Figure 32). Post-modification exit ratios were lower and less variable, ranging from 0.00-0.13 (*mean* = 0.06). Exit ratio estimates in 2013 (0.13) were slightly higher than all other post-modification estimates but were still at the low end of the range across all study years. In a χ^2 test comparison, the post-modification exit ratios were significantly lower than in pre-modification years (χ^2 = 85.62, $P < 0.001$). In pairwise χ^2 tests among years, post-modification years were significantly lower than pre-modification years in nine pre-modification year comparisions to 2010, eight of the pre-modification comparisons to 2009 and 2014, and in six of the pre-modification year comparisons to 2013 (Appendix Table 6). Exit ratios for jack spring Chinook salmon in 2013 (0.06) and 2014 (0.13) were similar to the post-modification mean for adult spring Chinook salmon.

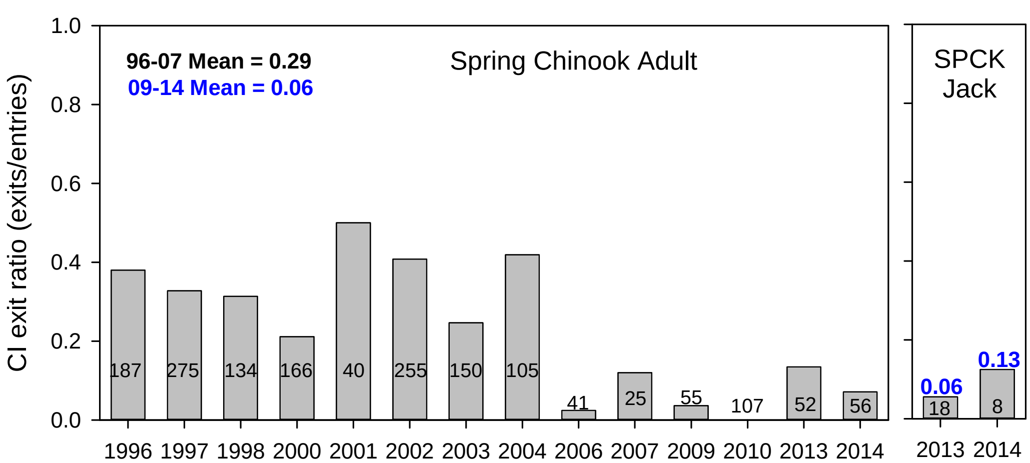

Figure 32. Cascades Island fishway exit ratios (exits/entries) for radio-tagged spring Chinook salmon. Sample sizes (number of entries) are inside each bar. Modifications occurred prior to the 2009 migration.

For adult summer Chinook salmon, exit ratios were more variable and generally higher than those for adult spring Chinook salmon but followed the same general trend of fewer exits in post-modification years (Figure 33). Exit ratios prior to entrance modifications at CI ranged from 0.22–0.80 (*mean* = 0.51). Post-modification exit ratios ranged from 0.17-0.51 (*mean* = 0.32). Exit ratios in 2010 (0.26) were the lowest among all study years. In a χ^2 test comparison, post-modification exit ratiod were significantly lower than in pre-modification years ($\chi^2 = 40.34$, $P < 0.001$). In pairwise χ^2 tests among years, post-modification ratios were significantly lower than in pre-modification years in eight of the pre-modification year comparisons to 2013, five of the pre-modification year comparisons to 2010, four of the pre-modification year comparisons to 2014, and in two of pre-modification year comparisons in 2009 (Appendix Table 7). Jack summer Chinook salmon (0.12) and sockeye salmon (0.23-0.24) exit ratios were lower than both pre- and post-modification means for adult summer Chinook salmon.

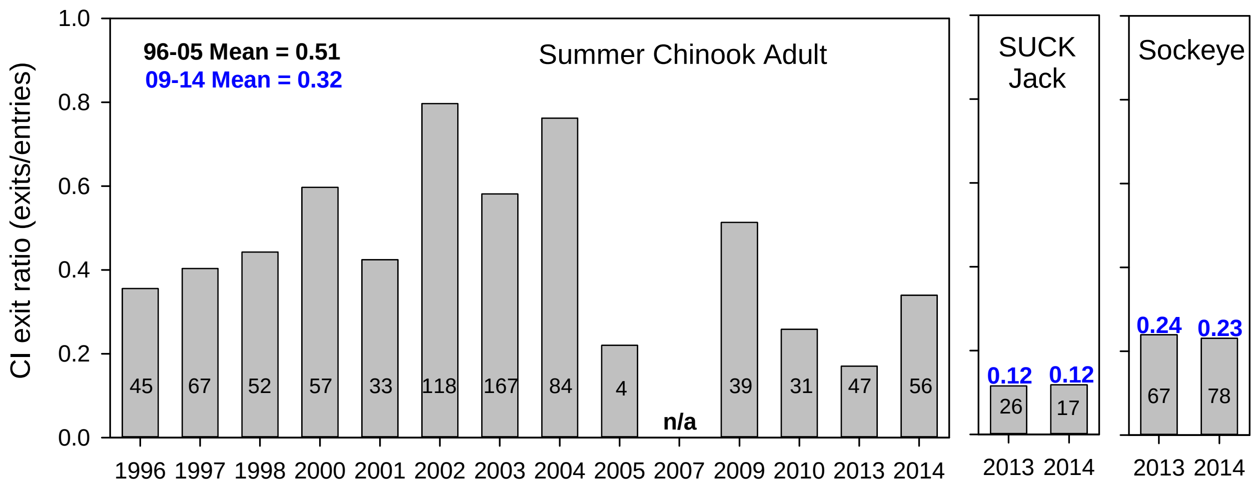

Figure 33. Cascades Island exit ratios (exits/entries) for radio-tagged summer Chinook and sockeye salmon. Sample sizes (number of entries) are inside each bar. Modifications occurred prior to the 2009 migration.

Metric 3: Entrance time. Passage times for spring and summer Chinook salmon from first CI approach to first CI entry were strongly right-skewed in all study years (Figure 34-35). Generally, the majority of fish moved rapidly into the fishway, but a few had long passage times when they repeatedly approached the fishway without entering or moved to the tailrace or to other fishways and then returned to enter. For adult spring Chinook salmon, annual median approach-entrance times ranged from a couple minutes to 46 min in years prior to fishway entrance modifications, with tagged salmon in the small 2007 sample (n = 20) having the longest median passage time (46 min). Post-modification, the medians ranged from 21 min in 2014 to 59 min in 2009. The median passage time for jack spring Chinook salmon was 12 min in 2013 and 81 min for the small sample in 2014. General linear model results for log-transformed passage times indicated significantly longer entrance times for adult spring Chinook salmon post-fishway modification ($df = 1$, $F = 18.3$, $P < 0.001$). In pairwise comparisons, the 2009 mean was significantly longer than means in 6 of the 10 pre-modification years (1996, 1997, 1998, 2000, 2004, and 2006). The 2010 and 2014 mean entrance time was significantly longer than 5 of 10 pre-modification years (same as previous list, but excluding 2004). The 2013 mean was significantly longer than only the 1996 and 1997 means.

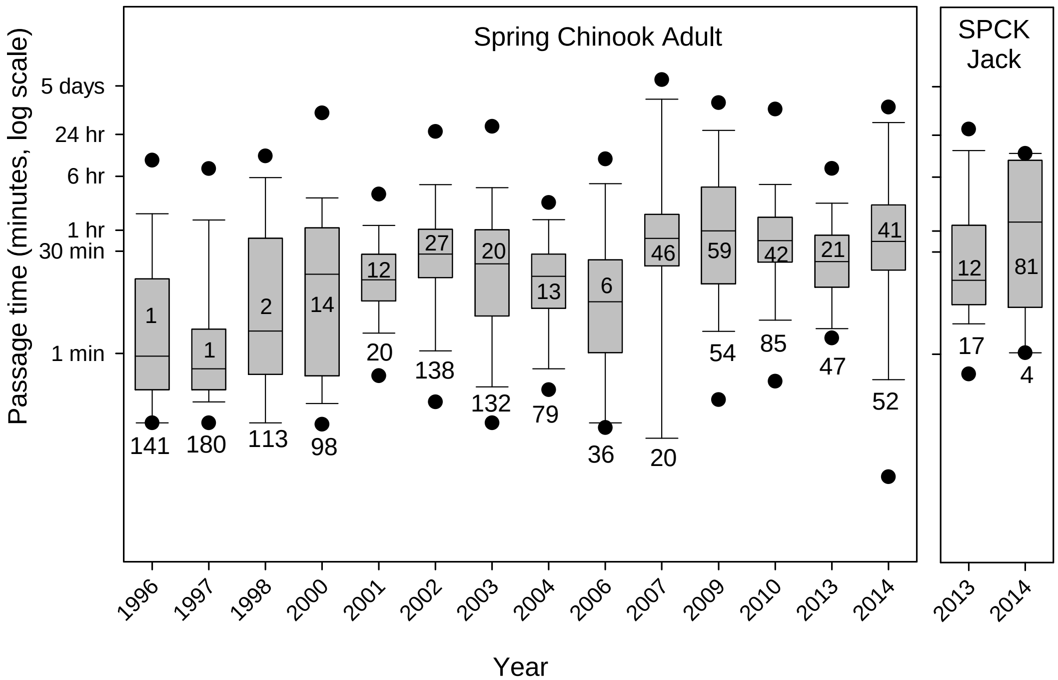

Figure 34. Spring Chinook salmon passage time distributions (plotted on log scale) from approach to entry at Cascades Island fishway. Values inside boxes are median times. Distributions show 5^{th}, 10^{th}, 25^{th}, 50^{th}, 75^{th}, 90^{th} and 95^{th} percentiles; sample sizes are shown at bottom.

Median CI approach-entrance times for adult summer Chinook salmon in pre-modification years were <1–55 min (*mean* = 14 min; Figure 35). The median in post-modification years ranged from < 1 min in 2010 to 27 min in 2013 (*mean* = 15 min). General linear model results for log-transformed passage times indicated significantly longer entrance times for adult summer Chinook salmon post-fishway modification ($df = 1$, $F = 15.6$, $P < 0.001$). However pairwise comparisons between pre- and post-modification years were mixed. Mean 2010 passage times were significantly faster than 2000 and 2001 mean passage times. The 2013 mean was significantly slower than the 2010 mean (post-modification) and the 1996,1997, 1998, and 2002 means. The 2009 and 2014 means were significantly longer than the 1996, 1997, and 1998 means (pre-modification) and the 2010 mean (post-modification). The median approach-to-entry time for jack summer Chinook salmon in 2013 (22 min) was similar to those of adult Chinook salmon in 2013 but higher than adults in 2014 (56 min). Adult sockeye salmon median passage times (12-13 min) in both years were similar to those observed for adult summer Chinook salmon in 2014.

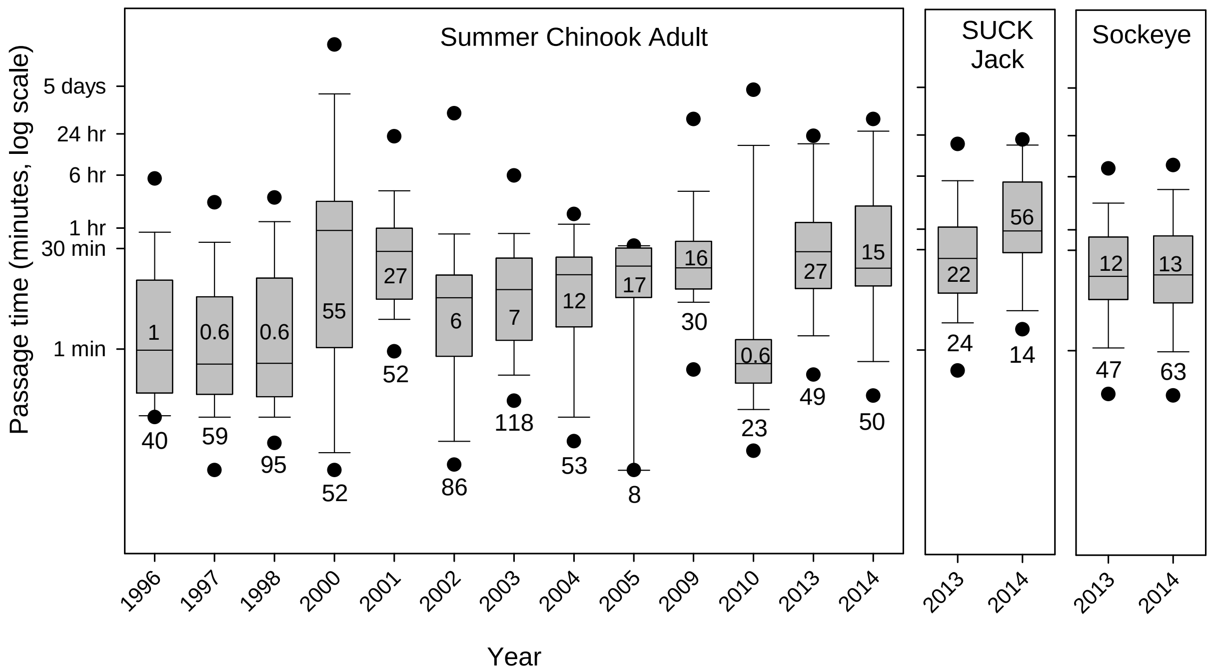

Figure 35. Summer Chinook and sockeye salmon passage time distributions (plotted on log scale) from approach to entry at Cascades Island fishway. Values inside boxes are median times. Distributions show 5th, 10th, 25th, 50th, 75th, 90th and 95th percentiles; sample sizes are shown at bottom.

Similar to the comparisions of salmon behavior at NDE and SDE, we compared fish passage times at CI and the Bradford Island Fishway entrance (BI) on the opposite side of the spillway channel. Prior to 2009, spring Chinook salmon had median approach-to-entry times at the BI fishway opening that were higher than or equal to those at the CI fishway opening in all years except 2001 and 2003 (Figures 34 and 36). In contrast, the 2009 CI median approach-to-entry time (59 min) for adult spring Chinook salmon was more than two times higher than the 2009 BI median time (26 min). The 2010 (42 min) and 2014 (41 min) median CI approach-to-entry times were also higher than their respecitive BI values 25 min and 35 min, respectivly. However, in 2013 the median approach-to-entry passage time at CI was lower than at BI, a trend more in line with pre-modification years. Jack spring Chinook salmon passage time medians were also lower (2013) and higher (2014) than at BI. For adult summer Chinook salmon, median CI approach-to-entry times were similar to those at BI except in most pre-modification years, except in 2000 and 2001 when CI values were relatively higher (Figures 35 and 37). In 2009, the median approach-to-entry time at the CI fishway opening was eight times higher than at the BI fishway opening, whereas the 2010 CI and BI approach-to-entry times were each 1 min or less. Approach-to-entry times in 2013 for summer Chinook salmon were similar to 2009 in that CI entry times were seven times higher at CI than at BI fishway openings (Figure 35). In 2014, CI passage times were two times higher than BI. Summer jack Chinook and sockeye salmon passage times in 2013-2014 were also much lower at BI than at CI.

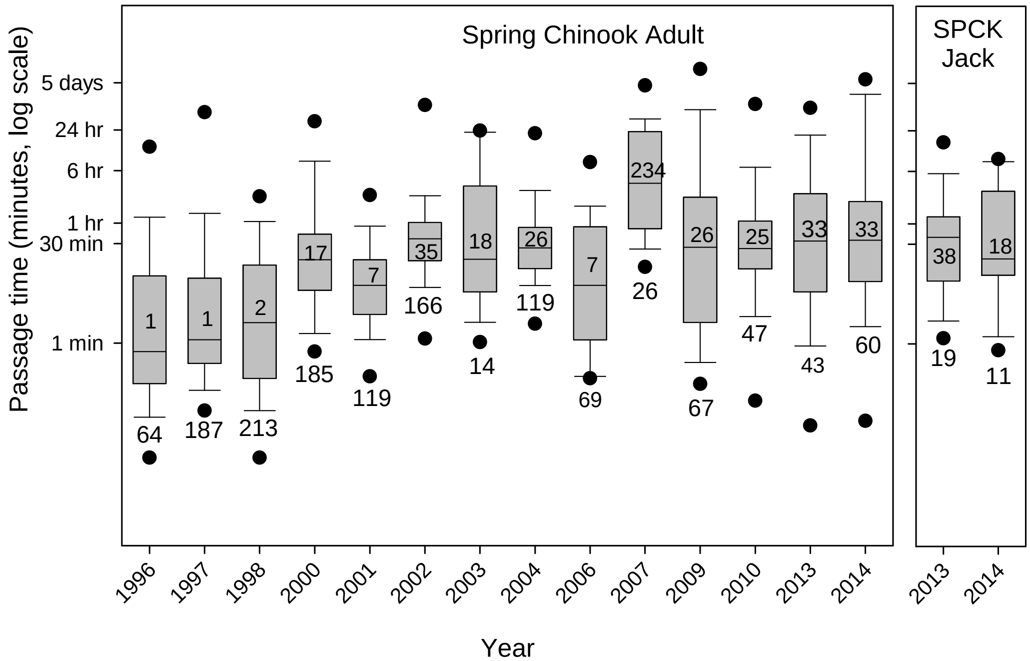

Figure 36. Spring Chinook salmon passage time distributions (plotted on log scale) from approach to entry at the Bradford Island fishway. Values inside boxes are median times. Distributions show 5th, 10th, 25th, 50th, 75th, 90th, and 95th percentiles; sample sizes are listed at bottom.

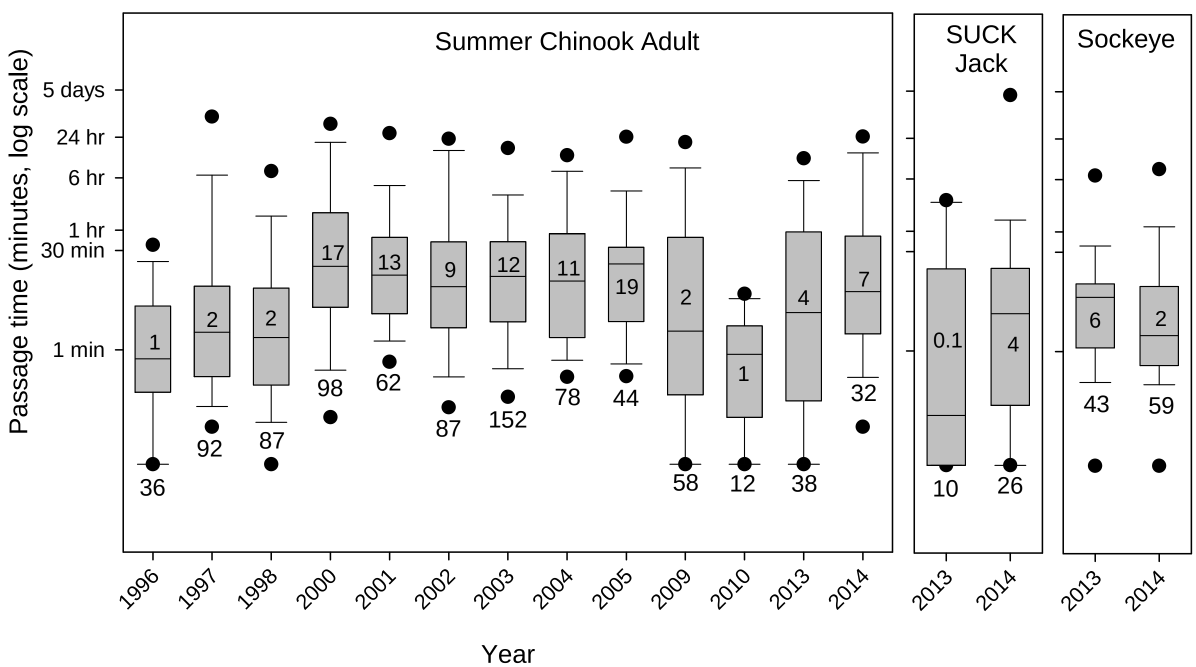

Figure 37. Summer Chinook and sockeye salmon passage time distributions (plotted on log scale) from approach to entry at the Bradford Island fishway. Values inside boxes are median times. Distributions show 5th, 10th, 25th, 50th, 75th, 90th, and 95th percentiles; sample sizes are at bottom.

For tagged adult spring Chinook salmon, the median CI approach-to-entry times in 2009 and 2010 was unexpectedly long compared to past approach-to-entry times at CI and at the BI fishway opening (Figure 38). In contrast, the relationship between CI and BI entry times for spring Chinook salmon was relatively close to 1:1 in 2013-2014 and in 1997-2006. Both 2007 and 2009 were outliers, with the small 2007 sample (*n* = 28) having relatively long BI approach-to-entry times and the 2009 sample having long CI approach-to-entry times.

For tagged adult summer Chinook salmon, the median CI approach-to-entry time in 2013 was high compared to past approach-to-entry times at CI and the BI fishway opening whereas in 2010, both times were equally low (Figure 38). Summer Chinook salmon in 2009 and 2014 had median CI approach-to-entry times similar to those in previous years.

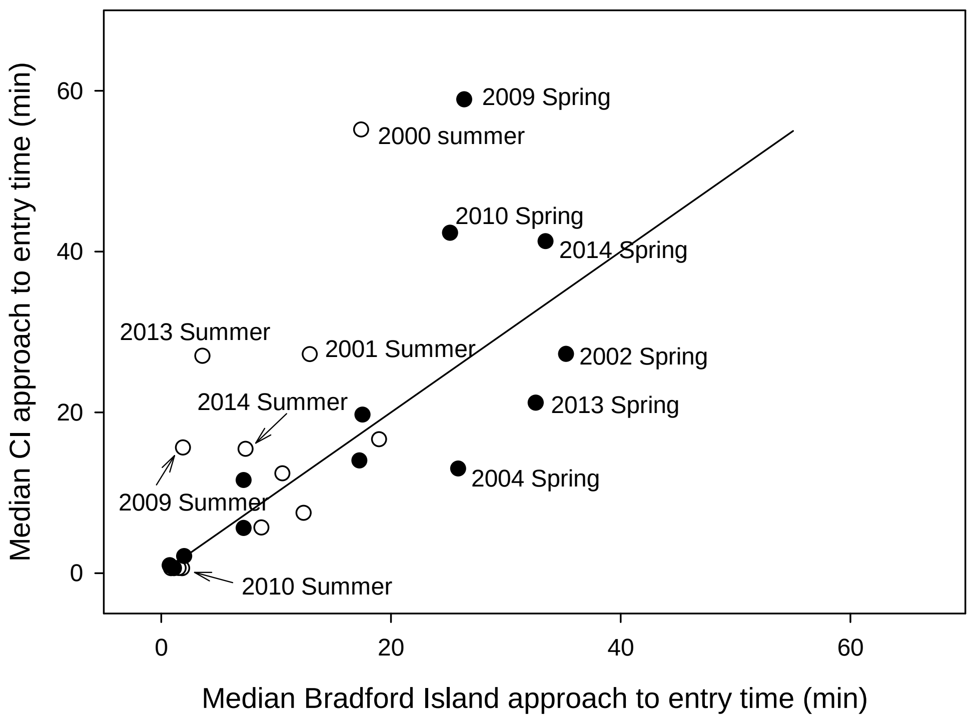

Figure 38. Scatterplot of annual median first approach to first entry times (min) at the Bradford Island and Cascades Island fishway entrances for radio-tagged spring (solid circles) and summer (open circles) Chinook salmon. Note outlier not shown includes 2007 spring Chinook (CI=46.0; BI=234.3).

There tended to be stronger correlations between spring Chinook CI approach-to-entry times and environmental conditions in 2009 than in 2010, 2013, and 2014 (Table 3). Negative correlation coefficients indicated faster approach-to-entry times when tailwater elevation and flow were relatively high in 2013. Positive correlation coefficients indicated faster approach-to-entry times when spill levels tapered off in 2014. Flow and tailwater elevations were lower when tagged salmon first approached the CI opening in 2010 compared to 2009, 2013, and 2014 (Figure 39). Tailwater elevation, flow, and water temperatures were slightly higher in 2013 and 2014 compared to in 2009 and 2010. Overall, river environmental conditions in post-modification year (2009-2013) included the range of conditions fish have encountered in the pre-modification years excluding 1997, a year of near-record spring runoff. River environment parameters that were consistently correlated with passage times were tailwater elevation, flow, and water temperature. General linear model results indicated a significant flow association for adult spring Chinook salmon passage times collectively for all study years ($df = 1$, $F = 11.0$, $P < 0.001$).

Table 3. Correlation coefficients (r) between environmental conditions spring Chinook salmon encountered when they first approached the Cascades Island opening and log-transformed approach-to-entry times, by year. Bold indicates P <0.05.

Year	Flow	Spill	Temp	Tailwater elev.	Date
1996	**-0.22**	**-0.20**	0.13	**-0.23**	0.07
1997	0.07	0.07	0.02	0.08	0.01
1998	**-0.23**	-0.08	-0.17	**-0.23**	-0.18
2000	-0.17	**-0.22**	**-0.23**	-0.16	-0.18
2001	-0.17	0.31	0.36	-0.04	0.37
2002	**-0.15**	**-0.18**	**-0.15**	**-0.17**	-0.13
2003	-0.11	**0.18**	-0.08	-0.14	-0.10
2004	-0.08	-0.12	-0.13	-0.07	-0.13
2006	-0.25	-0.26	-0.23	-0.27	-0.20
2007	-0.20	0.08	0.02	-0.23	0.04
2009	**-0.52**	**-0.40**	**-0.41**	**-0.52**	**-0.45**
2010	-0.14	-0.12	-0.21	-0.14	-0.19
2013	**-0.34**	-0.08	-0.11	**-0.35**	-0.16
2014	0.24	**0.28**	0.19	0.22	0.14

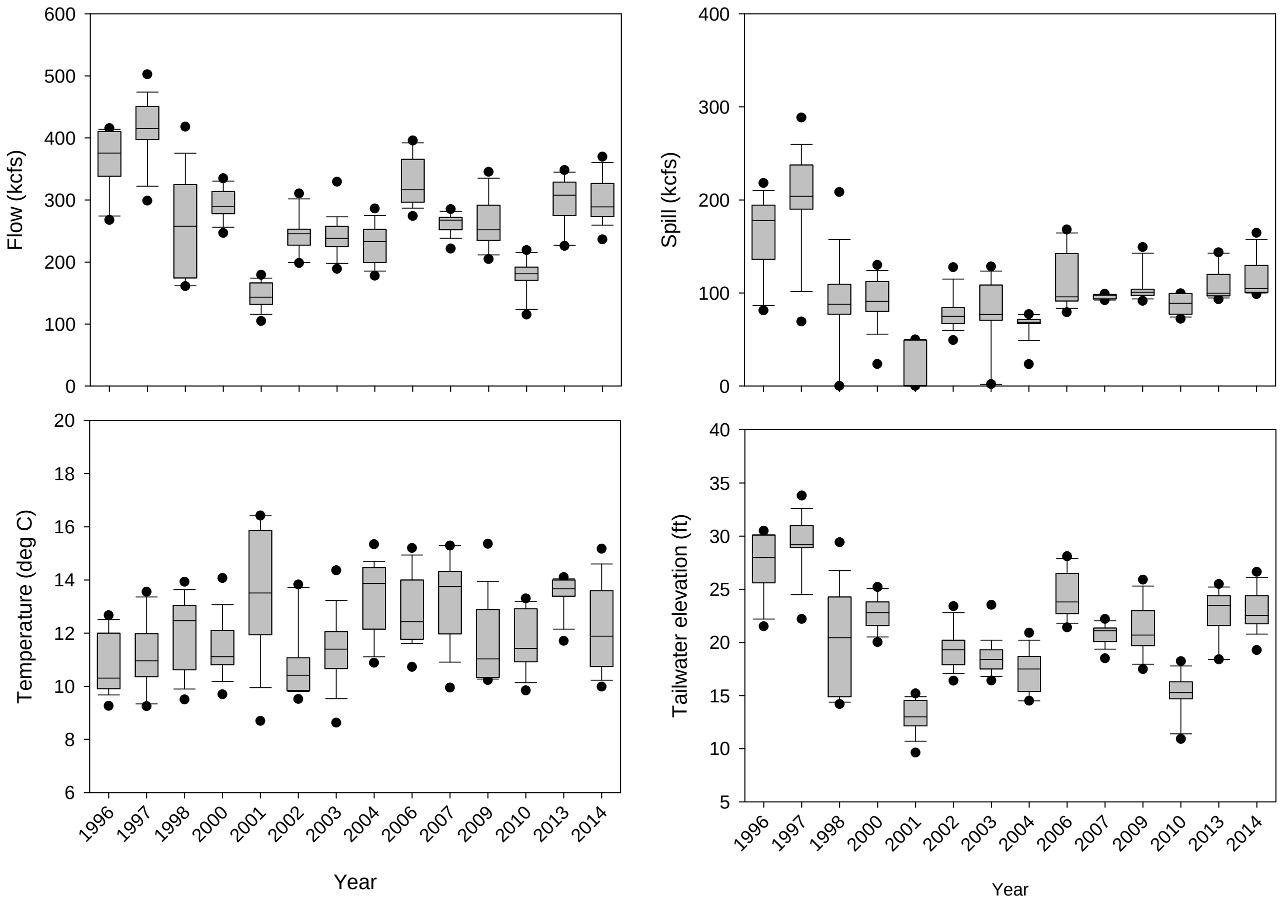

Figure 39. Box plots of the total discharge ('flow'), spill, tailwater elevation, and temperature on the days that radio-tagged adult spring Chinook salmon first approached the Cascades Island fishway opening. Distributions show 5th, 10th, 25th, 50th, 75th, 90th, and 95th percentiles.

Correlations between CI approach-to-entry times for adult summer Chinook salmon and environmental conditions in 2009 and 2010 were generally not statistically significant ($P > 0.05$; Table 4). Negative correlation coefficients indicated faster approach-to-entry times when temperatures were relatively high in 2013. Significant, positive correlations in 2009 and 2013 indicated slower entry times with increased spill. Water temperature, and the date that fish approached the CI fishway were weakly associated with passage time in 2013 and lower flow and tailwater elevation were associated with longer passage times in 2014. Adult summer Chinook salmon experienced lower temperatures, higher spill volumes, and higher tailwater elevations in 2010 compared to in 2009, 2013, and 2014 (Figure 40). General linear model results indicated no associaton between passage time and date or flow for summer Chinook salmon across all study years.

Table 4. Correlation coefficients (r) between environmental conditions tagged summer Chinook salmon encountered when they first approached the Cascades Island opening and log-transformed approach-to-entry times, by year. Bold indicates $P < 0.05$.

Year	Flow	Spill	Temp	Tailwater elev.	Date
1996	-0.28	-0.20	**0.48**	-0.27	**0.40**
1997	0.16	0.16	-0.25	0.15	**-0.29**
1998	-0.19	-0.08	0.20	-0.19	0.18
2000	0.12	-0.09	0.04	0.03	0.05
2001	0.21	0.20	-0.19	0.22	-0.24
2002	-0.23	-0.12	**0.25**	-0.05	**0.26**
2003	**-0.20**	-0.13	0.15	**-0.20**	0.18
2004	-0.09	0.08	0.11	-0.09	0.10
2005	-0.43	-0.22	0.58	**0.95**	0.55
2009	-0.32	**-0.37**	0.33	-0.33	0.30
2010	-0.17	-0.19	-0.33	-0.14	-0.14
2013	-0.09	0.04	**-0.34**	-0.10	**-0.37**
2014	**-0.59**	-0.21	0.27	**-0.59**	**0.34**

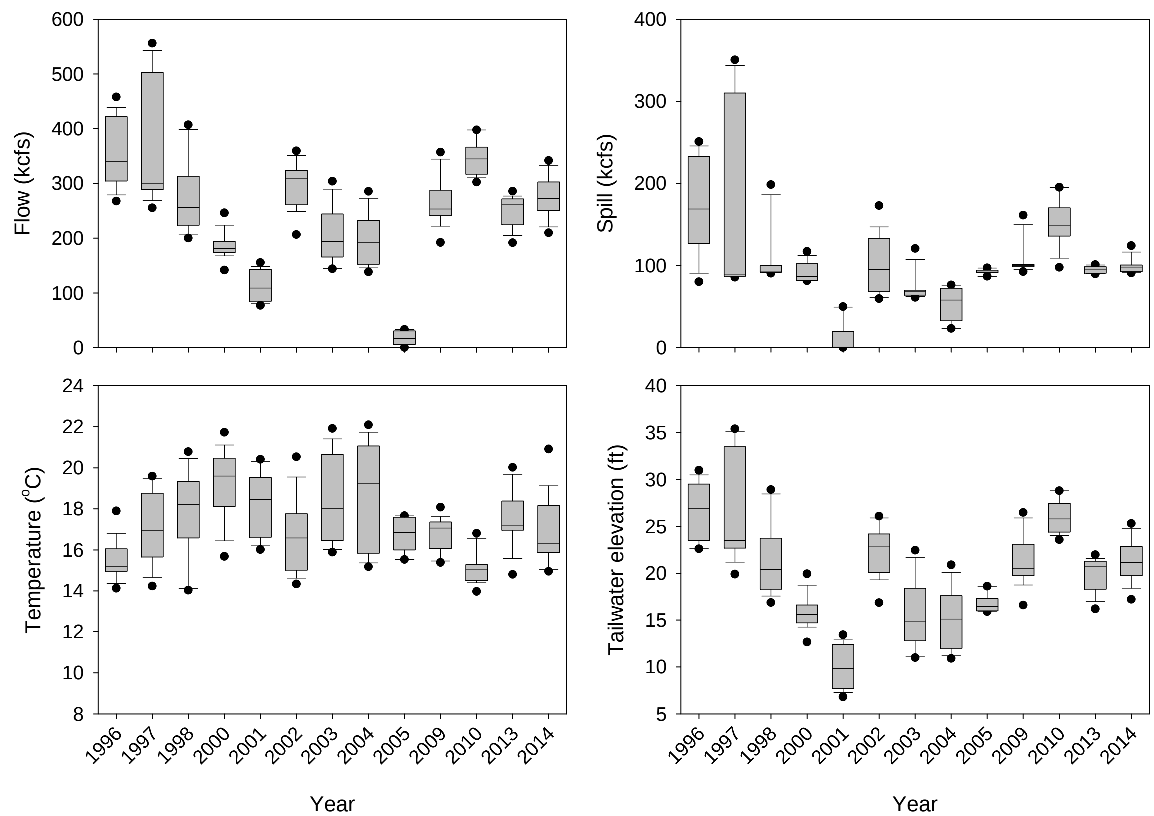

Figure 40. Box plots of the total discharge ('flow'), spill, water temperature, and tailwater elevation on the days that radio-tagged adult summer Chinook salmon first approached the Cascades Island fishway opening. Distributions show 5th, 10th, 25th, 50th, 75th, 90th, and 95th percentiles.

Metric 4: Entrance to base of ladder time. After tagged adult spring Chinook salmon entered the CI fishway, the median time to reach the ladder base ranged from 7–16 min in pre-modification years (Figure 41). Post-modification year medians were similar and ranged from 8 min (2014) to 14 min (2010). General linear models did not indicate a significant difference between pre- and post-modification groups ($df = 1$, $F = 1.14$, $P = 0.29$). Median base-of-ladder passage times for jack spring Chinook salmon were 17-31 min. In some years, sample sizes for the passage time metrics were slightly smaller than the fishway approach and entry sample sizes because some fish did not enter the CI fishway and some did not reach the ladder antenna. In addition, there was no base-of-ladder antenna in 1996 or 2006.

For adult summer Chinook salmon, the median time to reach the ladder base ranged from 7–22 min prior to fishway modificatons. The medians after modification ranged from 9 min in 2014 to 20 min in 2010 (Figure 42). Base of ladder passage times were signifiantly faster after the fishway modifications ($df = 1$, $F = 10.1$, $P = 0.002$). Pairwise comparisons indicated significantly faster times in 2014 than in 1998, 2000, 2003, and 2004 and significantly faster passage times in 2013 compared to 2003 and 2004. No differences were observed between 2009 and 2010 and any pre-modification years. Median base-of-ladder times for jack summer Chinook salmon were 11 min in 2013 and 2014 while adult sockeye salmon times were slightly faster at 6 and 4 min, respectively (Figure 42).

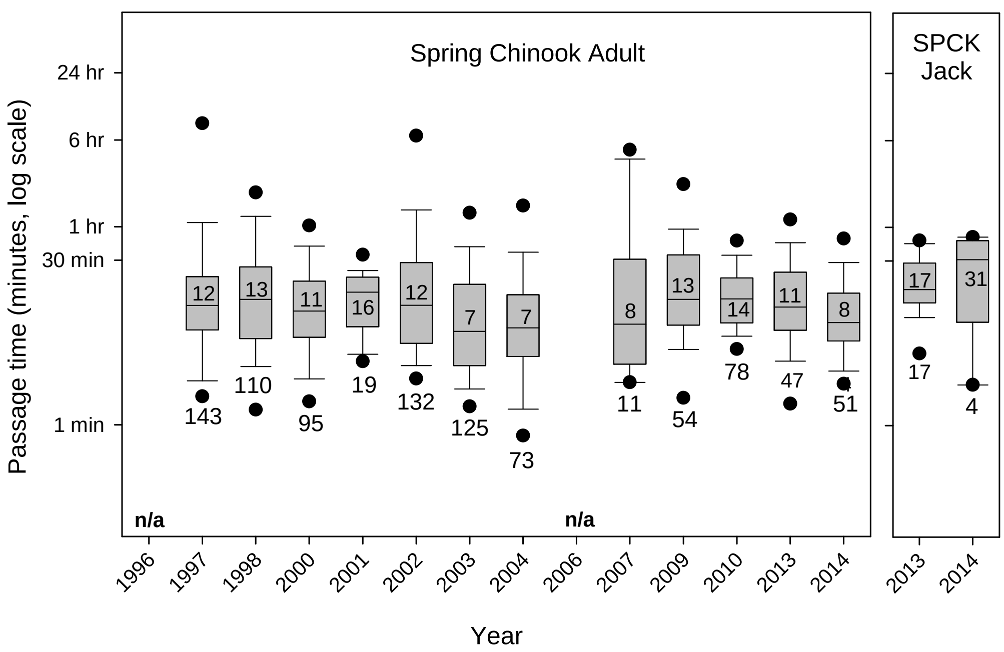

Figure 41. Spring Chinook salmon passage time distributions (plotted on log-scale) from Cascades Island fishway entry to the antenna at the base of the ladder (not monitored in 1996 and 2006). Numbers inside boxes are median times. Distributions show 5th, 10th, 25th, 50th, 75th, 90th, and 95th percentiles; sample sizes are below boxes.

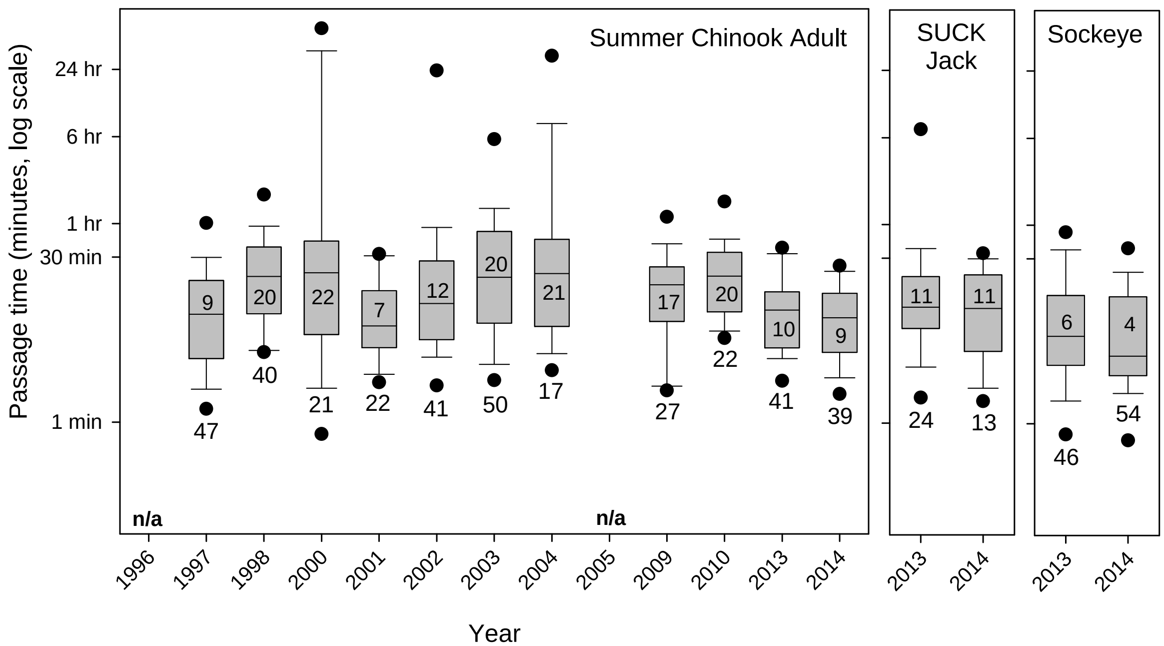

Figure 42. Summer Chinook and sockeye salmon passage time distributions (plotted on log-scale) from Cascades Island fishway entry to the antenna at the base of the ladder (not monitored in 1996 and 2005). Numbers inside boxes are median times. Distributions show 5^{th}, 10^{th}, 25^{th}, 50^{th}, 75^{th}, 90^{th}, and 95^{th} percentiles; sample sizes are below boxes.

***Metric 5:* Extended passage times.** During pre-modification years, the percentage of adult spring Chinook salmon with long passage times (> 1 h) through the two passage segments ranged from 12–45% (*mean* = 21%) for CI approach to CI entrance and from 0–14% (*mean* = 7%) from CI entrance to the first ladder antenna (Figure 43). The mean approach-to-entry percent in post-modification years was 37% and ranged from 19% in 2013 to 48% in 2009. Significanly more adult spring Chinook salmon had longer (> 1 h) entrance times after the fishway modification ($df = 1$, $\chi^2 = 47.0$, $P < 0.001$). In contrast, the percentage of spring Chinook with >1 h entry-base of ladder times was lower after the fishway was modified and (ranged from 1% in 2010 to 7% in 2009) compared to the pre-modification years (*mean* = 7%). Jack spring Chinook salmon with longer passage times through both passage segments were similar to or less than the post-modification percentages for adults (approach-to-entry >1 h = 24-50%) and (entry-ladder > 1 h = 0%).

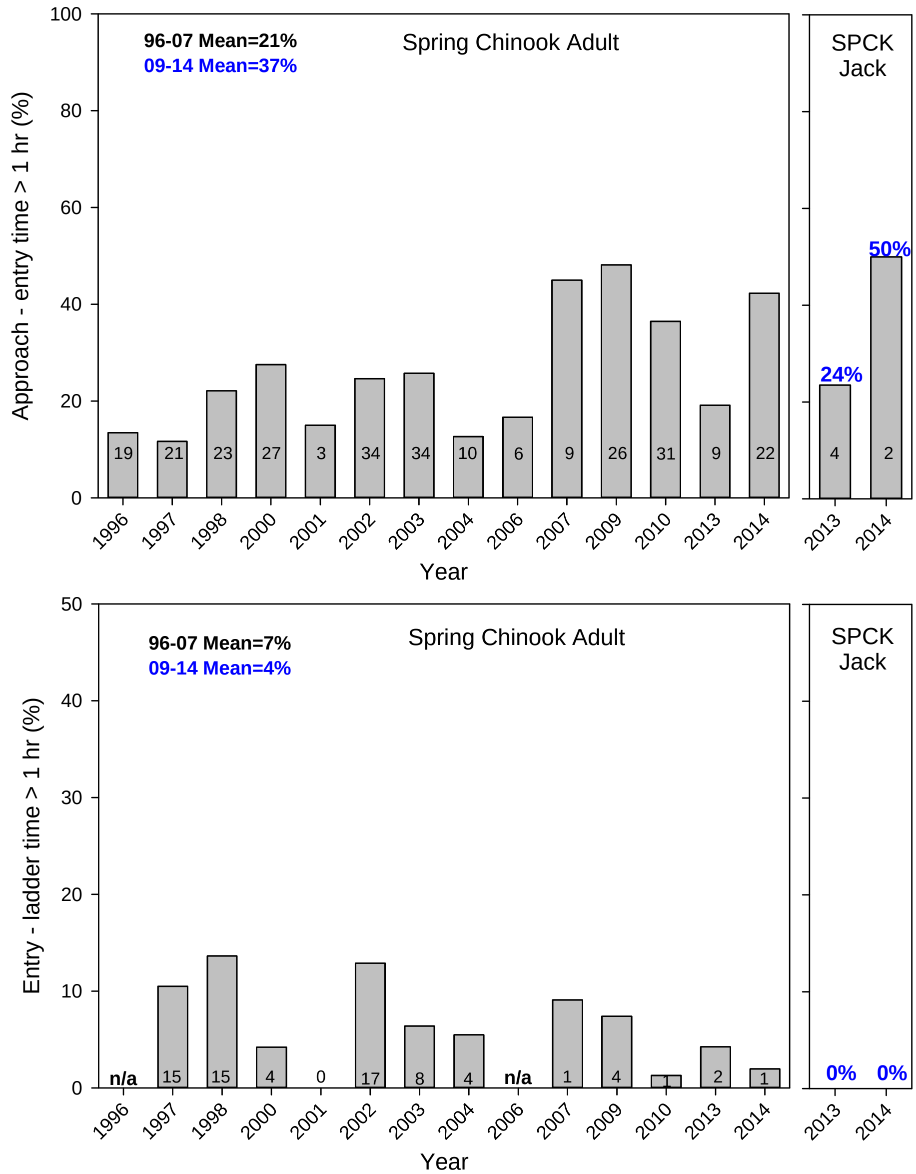

Figure 43. Percentages of radio-tagged spring and summer Chinook salmon that took > 1 h to enter the Cascades Island fishway (top panel) and to pass from the fishway opening to the base of the ladder (bottom panel). Sample sizes are inside each bar.

In 1996–2004, the percentage of adult summer Chinook salmon with long passage times (> 1 h) through the two passage segments ranged from 4–48% (*mean* = 15%) from CI approach to CI entrance and from 0–20% (*mean* = 8%) from CI entrance to the first ladder antenna (Figure 44). Percentages of adult summer Chinook salmon with approach-to-entry times (> 1 h) in posts-modification years ranged from 9% (2010) to 33% (2014). Logistic regression results indicated no statistical difference between pre- and post-modification groups ($df = 1$, $\chi^2 = 3.2$, $P = 0.08$) at $\alpha = 0.05$. The percentage of jack summer Chinook taking > 1 h from approach to entry (25-50%) was similar to adult summer Chinook salmon; the percent of sockeye salmon was lower (17-22%). Entry to base of ladder (>1) percentages for jack summer Chinook (0-4%) and sockeye (2-4%) salmon were low compared to previous adult summer Chinook salmon values.

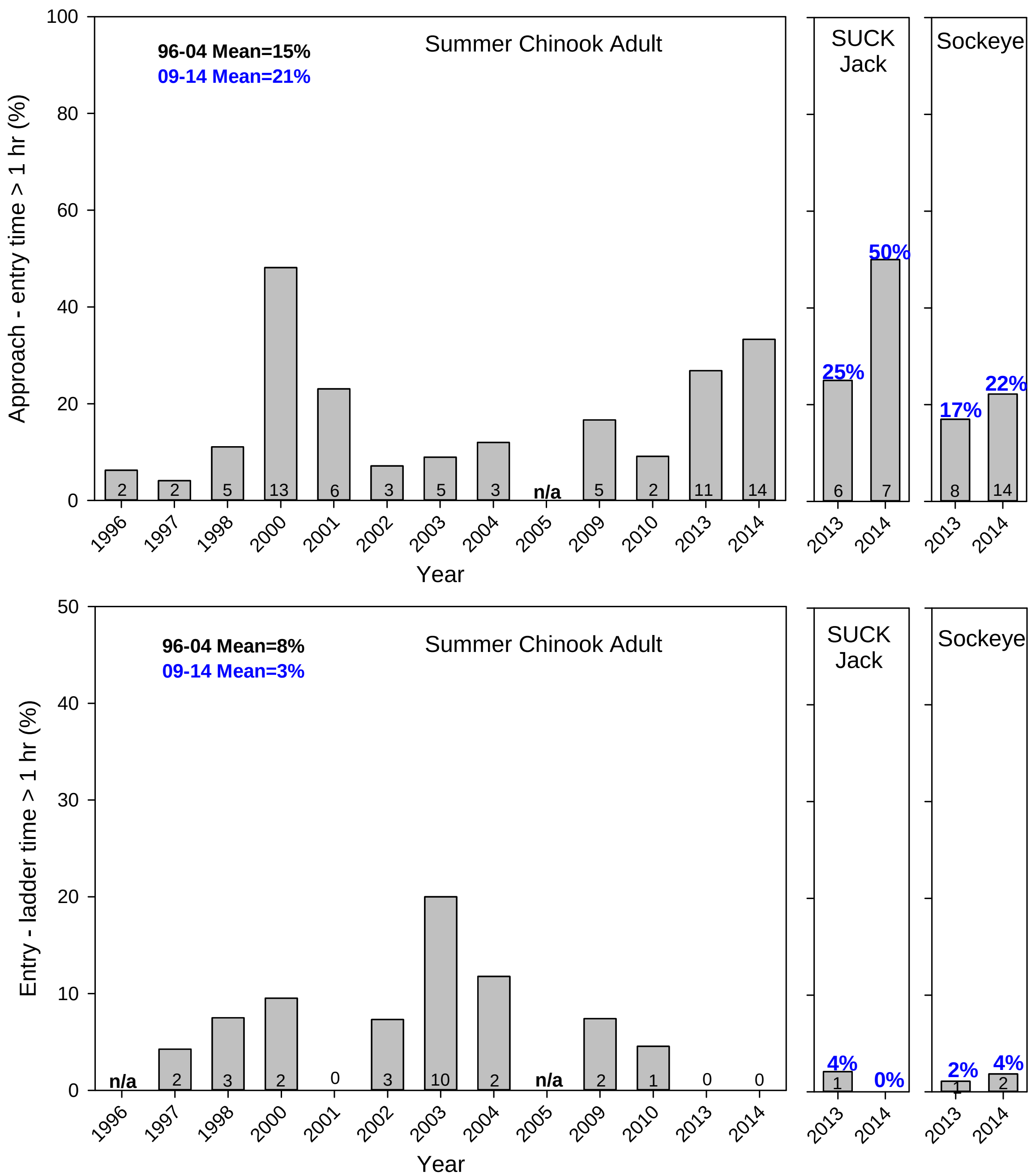

Figure 44. Percentages of radio-tagged summer Chinook and sockeye salmon that took > 1 h to enter the Cascades Island fishway (top panel) and to pass from the fishway opening to the base of the ladder (bottom panel).

Discussion

General summary

Developing an optimal fish passage structure is challenging, particularly in altered river corridors that support fish communities with diverse behaviors and swimming capabilities (Haro et al. 2004; Thiem et al. 2012; Keefer et al. 2013). Efforts have recently been made to facilitate adult Pacific lamprey passage at lower Columbia and Snake River dams by modifying fishway structures (e.g., Moser et al. 2011) and adjusting fishway operations (e.g., Johnson et al. 2012). The primary objective of this study was to evaluate whether the structural modifications made to the PH2 NDE in 2013 and the CI fishway in 2009 were associated with increased passage times or the avoidance or decreased use of the modified fishways by adult salmon. Adult spring Chinook salmon were of primary concern because delayed passage could result in increased predation by sea lions in the Bonneville tailrace (Stansell et al. 2009, 2014; Keefer et al. 2012) or harvest by anglers.

Our multi-metric approach attempted to evaluate important elements of salmon passage behavior at the modified fishways, including entrance attraction and selection, success and duration of entrance attempts, and behavior in the lower fishway and fishway exits to the tailrace. Results for individual metrics indicated that the modifications had a mix of negative, neutral or positive effects on passage behavior and success (Tables 5 and 6).

Table 5. Qualitative classification of each post-modification passage metric compared to values from pre-modification years at the north downstream entrance (NDE) at Powerhouse 2. Green indicates better post-modification performance, white indicates no change, yellow indicates somewhat reduced performance, and red indicates substantially lower post-modification performance.

	Spring Chinook		Summer Chinook	
Metric	Adult	Jack	Adult	Jack
1) Entrance efficiency	Slightly low	High	High	High
2) Exit ratio	Low	Low	Near average	Near average
3) Approach-Entry time[1]	Near average	Fast	Fast	Fast
4) Entry-Ladder base time	Fast	Near average	Fast	Near average
5a) Approach-Entry > 1 h[1]	Near average	Low	Near average	Slightly high
5b) Entry-Ladder base > 1 h	Low	Near average	Low	Low
6) Entry-Transition area	Low	Near average	Slightly high	Slightly high
7) NDE:SDE use	Near average	Near average	High	Near average

[1] Some estimates in 2013 and 2014 were potentially longer due to use of aerial Yagi antennas

Averaging across all metrics, the weight of evidence in the 2013 and 2014 results suggests the following:

● there was no evidence for dramatic passage delays or sharply reduced passage efficiency metrics at NDE for adult Chinook salmon in 2013 or 2014 relative to previous years, though entrance efficiencies indicated passage conditions may have been slightly less favorable for adult spring Chinook salmon. A similar pattern of lower entrance efficiencies was observed at SDE suggesting that the river environment was associated with reduced entrance efficiency estimates.

● there appeared be no net change in passage for adult spring Chinook salmon at NDE compared to prior years, with some metrics improving, some remaining neutral, and some declining slightly compared to results in the past.

● data from jack Chinook salmon at NDE suggest better performance by jacks compared to adults, either because the overall passage performance of jacks is higher than adults (and was higher in past years) or because conditions at NDE were more favorable for jacks than adults post-modification.

Table 6. Qualitative classification of each post-modification passage metric compared to values from pre-modification years at the Cascade Island (CI) entrance. Green indicates better post-modification performance, white indicates no change, yellow indicates somewhat reduced performance, and red indicates substantially lower post-modification performance.

	Spring Chinook		Summer Chinook	
Metric	Adult	Jack	Adult	Jack
1) Entrance efficiency	Slightly low	Near average	Low	Near average
2) Exit ratio	Low	Low	Low	Low
3) Approach-Entry time	Slightly high	Near average	High	High
4) Entry-Ladder base time	Near average	Slightly high	Low	Low
5a) Approach-Entry > 1 h	Slightly high	Near average	Near average	High
5b) Entry-Ladder base > 1 h	Near average	Low	Low	Low

● the overall results for summer Chinook salmon at CI indicated neutral or positive changes in passage for adults and possibly for jacks, though again, there were no previous jack studies for direct comparison.

● results at CI were mixed for both runs, though two key metrics (entrance efficiency and passage time metrics) indicated passage conditions may have been less favorable in post-modification years.

Below we discuss the magnitude of the differences among years for key metrics, identify potential mechanisms, implications, and areas of concern for each run and location.

PH2 NDE efficiencies

The structural modifications made at Bonneville Dam had the potential to affect adult salmonid behavior by changing hydraulic attributes and/or the olfactory environment at the NDE opening and/or in the attraction plume outside of the fishway opening. The LFS flume and water supply adjacent to the PH2 NDE also had the potential to affect hydraulics outside the opening or to change the environment by introducing underwater noise and/or low frequency vibration from water passing over the new structure. The introduction of odors or chemicals (e.g., human scent, unseasoned aluminum, and caulking) near the entrance might also slow or stop migration. Unfortunately from a research perspective, the modifications were installed simultaneously and could not be independently installed and removed in an experimental manner, as was the case for evaluations of structural modifications at Bonneville Dam in 2005 (e.g., sea lion exclusion devices, SLEDs) and at other locations (e.g., Naughton et al. 2007). Consequently, this evaluation relied on before-after inter-annual comparisons and comparison to a reference site (SDE) to assess the combined effects of all the modifications simultaneously.

The proportion of radio-tagged salmon that approached PH2 NDE varied considerably year to year and was expected to vary primarily in association with operational and environmental factors acting at larger scales than the entrance modifications. The proportion of radio-tagged spring Chinook salmon that approached PH2 NDE in 2013 was 12% lower than the historic mean (~ 5% lower than the mean after the shift to PH2 priority in 2001), but only ~3% lower in 2014. In 2013 and 2014, proportionately fewer radio-tagged salmon approached the PH2 NDE entrance and entrance efficiencies were somewhat lower than average.

We expected entrance rates to be more closely linked to conditions at the entrance and potentially affected by the modifications. The number of radio-tagged spring Chinook that entered in 2013 and 2014 was ~ 50% less than the historic mean, but entrance use at NDE has been generally declining since 2006, perhaps due to sea lion activity or other factors. Despite the lower NDE entrance efficiencies in 2013 and 2014, we have little reason to think the differences were related to the newly-constructed lamprey flume system (LFS). Among-year differences in the ratio of fish approaching and entering the PH2 NDE compared to the PH2 SDE did not provide any indication of a shift away from use of NDE by radio-tagged spring Chinook salmon. In fact, we observed relatively high entrance efficiencies for summer Chinook and sockeye salmon at the PH2 NDE and proportionally more radio-tagged summer Chinook salmon, jacks, and sockeye salmon approached and entered the PH2 NDE relative to the SDE compared to past years.

Inter-annual variation in entrance efficiencies are common, fluctuating 2-5 fold between years, and the entrance efficiency in 2013 and 2014 was higher than or similar to four of the 12 years prior to the fishway modification. Moreover, entrance efficiencies were the highest observed for summer Chinook salmon, suggesting conditions at the PH2 NDE during the spring were related to other environmental or structural issues rather than the modifications. Jacks tagged during the same time as the larger adults had relatively high entrance efficiencies in 2013 and similar entrance efficiencies in 2014, which made it less plausible that factors related to the LFS (olfactory signals, noise, vibration, failed attempts to enter the lamprey-specific openings, etc.) contributed to the lower entrance efficiencies for tagged adult spring Chinook salmon.

Other possibilities for the observed differences in NDE entrance use and entrance efficiency in 2013 and 2014 may have been related to changes in the radiotelemetry array. The use of an aerial antenna at the PH2 NDE opening in 2013-2014 may have inflated detection probabilities for fish migrating higher in the water column (i.e., fish may have been detected further from the entrance than historically when underwater antennas were used). In previous studies where we have had both underwater and aerial antennas at a single fishway opening, there have not been large differences in fish detection. Nonetheless, while this methodological change (a result of the Bonneville fishway dewatering schedule) likely affected estimation of these metrics, we think any change had minor effects on the metrics and were unlikely to affect the outcome of pre- vs. post-modification comparisons.

We observed little evidence of altered behavior after salmon entered at the PH2 NDE. Exit ratios indicated that there was no altered behavior related to recent modifications at the PH2 NDE for radio-tagged adult spring or summer Chinook salmon. The percentage of spring Chinook salmon that exited to the tailrace in 2013-2014 was similar to the observed low exit ratio rates since 2006. Chinook salmon entrance-to-ladder times also provided no evidence of negative effects of the modifications on behavior inside the fishway. In contrast, the proportion of radio-tagged fish that reached the ladder (Metric 6) after entering the NDE was at the lower end of the historic range for adult spring Chinook salmon. The opposite was true for adult summer Chinook salmon, which had a similar or slightly higher success reaching the lower ladder at PH2 after the LFS modification.

It is not clear whether SLEDs or the presence of predators in the tailrace may have been responsible for the relatively low percentages of spring Chinook salmon exiting fishways in 2006-2007 and 2009-2013 compared to summer Chinook salmon. It is possible that some spring-run salmon that might otherwise have exited a fishway remained inside as a predator avoidance strategy, whereas the pinnipeds are largely gone when the summer Chinook salmon arrive. Observed inter-annual variability in the exit ratio also presumably reflects differences in conditions inside the fishway entrance and transition pool, which can vary with tailwater elevation and river conditions (e.g., temperature, discharge; Keefer et al. 2003, 2013; Caudill et al. 2013) and sampling error.

PH2 NDE passage times

For tagged spring Chinook salmon, the median NDE approach-to-entry time in 2013 and 2014 suggested minimal pre-post modification differences compared to past approach-to-entry times. Spring Chinook salmon approach-to-entry times in 2013 were in the middle of the range in previous years and were faster than in 2 of the last 3 years and the 2014 passage times were in the lower end of the range. In 2013, over half the fish that eventually entered PH2 NDE took > 1 h to enter, which was not unusual: 69% and 71% of spring Chinook salmon took > 1 h to enter in 2007 and 2009, respectively. In 2014, 40% of spring Chinook took longer > 1 h which was in the middle of the range historically. In contrast, the 2013 and 2014 summer Chinook salmon results suggested conditions near the fishway opening provided some of the best conditions observed across all study years. The median approach-to-entry times were some of the fastest observed and relatively fewer radio-tagged summer Chinook salmon were observed having extended (> 1 h) entry times.

Longer entry times for spring Chinook salmon in 2013 compared to 2010 and 2014 at NDE could have been attributed to annual differences in flow and spill and water temperature (e.g., Keefer et al. 2008). Correlation results suggested that environmental factors encountered in 2013 (May) and 2014 (April and May) were related to the variability in adult salmon entrance times. In 2013, due to tagging constraints associated with late transmitter delivery, all fish were tagged in May whereas historically tagging commenced in early to mid-April before water temperatures reached 10 ºC. Consequently, fish sampled later in the run as water temperatures began to increase took longer to enter the fishway as passage times were found to be positively correlated to increased water temperatures. Flow and spill encountered by tagged salmon were also relatively high in 2013 as a result of only tagging fish in May, and these covariates were negatively correlated with adult passage time. Encountered water temperature, flow, and spill were closer to average in 2014 as tagging commenced in early April. Notably, the median NDE entry time for jack spring Chinook salmon was < 1 min, and entry times for summer Chinook were also relatively fast. The weight of evidence suggests that longer NDE entry times in 2013 by spring adults were not directly related to structural or hydraulic changes associated with the LFS.

Cascades Island

The modified entrance weir at the Cascades Island entrance had the highest potential to affect hydraulics outside of the opening. The bollard field likely affected flow conditions outside the opening to a lesser degree, potentially by decreasing mean velocity and increasing turbulence in the bottom portion of the attraction plume from the opening. Inside the opening, the bollards altered near-bottom flows, and the CI LPS had limited potential to affect hydraulics. Importantly, the annual percentages of radio-tagged Chinook salmon that have approached and entered the CI fishway have changed little since the CI fishway modifications. Collectively, the metrics used to assess adult Chinook salmon behavior at CI suggest the modifications have had neutral, or perhaps slightly negative effects on passage efficiency (see Table 6). Post-modification entrance efficiencies at CI have been quite variable and slightly lower – on average – for radio-tagged adult spring Chinook salmon. The lowest estimates were in 2009, and results from 2010-2014 suggest that unfavorable passage conditions associated with the modifications in 2009 may have been ameliorated by 2010. Conversely, exit ratios at CI were lower post-entrance modification for all groups, suggesting potentially improved retention.

The multi-year results indicated longer entrance times for spring Chinook salmon at the CI fishway opening in post-modification years, however, a similar trend in longer passage times was also observed at the Bradford Island fishway. This may reflect, in part, the change in proportionately increased spill from end spillbays in recent years. Since the fishway entrance modifications at CI, there has also been an increase in the number of fish with extended passage times, though the majority fish passed within an hour of approach. The slower CI approach-to-entry times in 2009 may have been produced by changes in hydraulics (AECOM, 2010 memorandum to Lois Loesch, U.S. Army Corps of Engineers) or olfactory conditions near the CI entrance directly caused by the modifications and/or other conditions outside fishways and in the tailrace. We speculate that the concentration of any disruptive olfactory cues originating from the modifications may have declined over time as the new structures have "seasoned" by leaching and by the accumulation of biofilms (e.g., Moser et al. 2011).

Median entrance times for summer Chinook salmon were similar to or lower than those for spring Chinook salmon. It is unlikely that increases in passage times at the scale we observed represents biologically significant increases nor do they provide conclusive evidence of degraded conditions at the CI fishway entrance given the annual variability in passage times (particularly post-modification). Furthermore, inter-annual variability in entry times (often up to > 10-fold differences in median approach-to-entry times) is common at unaltered, but structurally similar fishways (see Figure 34). We did not directly examine the potential effects of spill patterns on these results. The shift from concentrated spill in the center spillbays in early study years to greater spill from end spillbays adjacent to the CI and Bradford fishway openings in later years was potentially important and may have contributed to the general pattern of longer approach to entry at CI in more recent years, however, it is difficult to match up spill bay data with fish times. Reduction of near-shore spill (i.e., spill in end spillbays) could be considered as a potential method to improve passage times. However, the scope for improvement is relatively modest given median times below one hour and would have to be weighed against other factors such as juvenile downstream passage and operational considerations.

We also note that the PH2 NDE and CI approach-to-entry times encompassed the time and behaviors of tagged salmon that may have made multiple approaches at an opening before entering. As a consequence, the time tagged salmon used before re-approaching and subsequently entering are likely influenced by conditions elsewhere at the dam and not with any attributes of the opening *per se*. To this extent, we believe that entrance efficiency and fishway exit ratios may be a better overall index than passage times of the effects of the modifications made at the PH2 NDE and CI fishway openings.

In conclusion, the four years of data collected post-modification at the CI entrance suggest that there may have been some limited adverse effects near the opening, but that behaviors inside the fishway have not changed or have improved. Four post-modification years of data collected suggested that once salmon entered the CI opening, they did not have difficulty swimming past the modified area (i.e., past bollards and the LPS) to the base of the ladder.

References

AECOM, 2010. Memorandum to Lois Loesch, U.S. Army Corps of Engineers, on Bonneville Cascades Island fish ladder entrance velocity measurements.

Caudill C.C., W.R. Daigle, M.L. Keefer, C.T. Boggs, M.A. Jepson, B.J. Burke, R.W Zabel, T.C. Bjornn, C.A. Peery. 2007. Slow dam passage in adult Columbia River salmonids associated with unsuccessful migration: delayed negative effects of passage obstacles or condition-dependent mortality? Canadian Journal of Fisheries and Aquatic Sciences 64:979-995.

Haro, A., T. Castro-Santos, J. Noreika, and M. Odeh. 2004. Swimming performance of upstream migrant fishes in open-channel flow: a new approach to predicting passage through velocity barriers. Canadian Journal of Fisheries and Aquatic Sciences 61:1590-1601.

Jepson, M.A., M.L. Keefer, C.C. Caudill, and B.J. Burke. 2010. Adult Chinook salmon passage behavior at Bonneville Dam in relation to structural modifications made to the Cascades Island Fishway-2009. Technical Report 2010-1 of University of Idaho to the US Army Corps of Engineers, Portland District.

Jepson, M.A., M.L. Keefer, C.C. Caudill, and B.J. Burke. 2011. Passage behavior of adult spring Chinook salmon at Bonneville Dam including evaluations of passage at the modified Cascades Island fishway, 2010. Technical Report 2011-1 of University of Idaho to the US Army Corps of Engineers, Portland District.

Johnson, E.L., C.C. Caudill, M.L. Keefer, T.S. Clabough, C.A. Peery, M.A. Jepson, M.L. Moser. 2012. Movement of radio-tagged adult Pacific lampreys during a large-scale fishway velocity experiment. Transactions of the American Fisheries Society 00:1-9.

Keefer, M. L., C. A. Peery, R. Stansell, M. Jonas, and B. Burke. 2003. Passage of radio-tagged adult salmon and steelhead at John Day Dam with emphasis on fishway temperatures: 1997-1998. Technical Report 2003-1 of University of Idaho to U.S. Army Corps of Engineers, Portland District.

Keefer, M. L., C. A. Peery, R. R. Ringe, and T. C. Bjornn. 2004. Regurgitation rates of intragastric radio transmitters by adult Chinook salmon and steelhead during upstream migration in the Columbia and Snake rivers. North American Journal of Fisheries Management 24:47-54.

Keefer, M.L., C.A. Peery, W.R. Daigle, M.A. Jepson, S.R. Lee, C.T. Boggs, K.R. Tolotti and B.J. Burke. 2005. Escapement, harvest, and unknown loss of radio-tagged adult salmonids in the Columbia River-Snake River hydrosystem. Canadian Journal of Fisheries and Aquatic Sciences 62(4):930-949.

Keefer, M. L., D. C. Joosten, C. L. Williams, C. M. Nauman, M. A. Jepson, C. A. Peery, T. C. Bjornn, R. R. Ringe, K. R. Tolotti, S. R. Lee, L.C. Stuehrenberg, M. M. Moser, and B. J. Burke. 2008. Adult salmon and steelhead passage through fishways and transition pools at Bonneville Dam, 1997-2002. Technical Report 2008-5 of Idaho Cooperative Fish and Wildlife Research Unit report to the U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Keefer, M.L., M.L. Moser, C.T. Boggs, W.R. Daigle, and C.A. Peery. 2010. Effects of body size and river environment on the upstream migration of adult Pacific lampreys (*Lampetra tridentate*). North American Journal of Fisheries Management 30:376-385.

Keefer, M.L., C.A. Peery, S.R. Lee, W.R. Daigle, E.L. Johnson, and M.L. Moser. 2011. Behavior of adult Pacific lampreys in near-field flow and fishway design experiments. Fisheries Management and Ecology 18:177-189.

Keefer, M.L., R.J. Stansell, S.C. Tackley, W.T. Nagy, K.M. Gibbons, C.A. Peery, and C.C. Caudill. 2012. Use of radiotelemetry and direct observation to evaluate sea lion predation on adult Pacific salmonids at Bonneville Dam. Transactions of the American Fisheries Society 141(5):1236-1251.

Keefer, M. L., C. C. Caudill, T. S. Clabough, M. A. Jepson, E. L. Johnson, C. A. Peery, M. D. Higgs, and M. L. Moser. 2013. Fishway passage bottleneck identification and prioritization: a case study of Pacific lamprey at Bonneville Dam. Canadian Journal of Fisheries and Aquatic Sciences 70:1551-1565.

Keefer , M. L, M. A. Jepson, T. S. Clabough, E. L. Johnson, C. C. Caudill, B. J. Burke, and K. E. Frick. 2015. Reach conversion rates for radio-tagged Chinook and sockeye salmon and steelhead in the lower Columbia River, 2013-2014. Technical Report 2015-8 of University of Idaho to the U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Moser, M.L., M.L, Keefer, H.T. Pennington, D.A. Ogden, and J.E. Simonson. 2011. Development of Pacific lamprey fishways at a hydropower dam. Fisheries Management and Ecology 18:190-200.

Naughton, G. P., C. C. Caudill, C. A. Peery, T. S. Clabough, M. A. Jepson, T. C. Bjornn and L. C. Stuehrenberg. 2007. Experimental evaluation of fishway modifications on the passage behaviour of adult Chinook salmon and steelhead at Lower Granite Dam, Snake River, USA. River Research and Applications 23: 99-111.

Stansell, R., S. Tackley, W. Nagy, and K. Gibbons. 2009. Evaluation of Pinniped predation on adult salmonids and other fish in the Bonneville Dam tailrace. U.S. Army Corps of Engineers, Fisheries Field Unit, Cascade Locks, OR.

Stansell, R. J., B. K. van der Leeuw, K. M. Gibbons, and W. T. Nagy. 2014. Evaluation of Pinniped predation on adult salmonids and other fish in the Bonneville Dam tailrace, 2014. U.S. Army Corps of Engineers, Fisheries Field Unit, Cascade Locks, OR.

Thiem, J. D., T. R. Binder, P. Dumont, D. Hatin, C. Hatry, C. Katopodis, K. M. Stamplecoskie, and S. J. Cooke. 2012. Multispecies fish passage behavior in a vertical slot fishway on the Richelieu River, Quebec, Canada. River Research and Applications 29:582-592.

Zar, J. H. 1999. *Biostatistical Analyses – 4th Ed.* Upper Saddle River, New Jersey: Prentice Hall, Inc.

Appendix

Note: pair-wise comparisons are uncorrected for multiple comparisons.

Appendix Table 1. Spring Chinook salmon PH2 NDE entrance efficiency. χ^2 pairwise comparisons. Bold indicates P < 0.05.

Year	Year	*p*-value	Year	Year	*P*-value
1996	2013	**<0.001**	1996	2014	**<0.001**
1997	2013	**<0.001**	1997	2014	**<0.001**
1998	2013	**<0.001**	1998	2014	**<0.001**
2000	2013	0.062	2000	2014	0.148
2001	2013	**0.001**	2001	2014	**<0.001**
2002	2013	0.353	2002	2014	0.097
2003	2013	**<0.001**	2003	2014	**<0.001**
2004	2013	**0.005**	2004	2014	**<0.001**
2006	2013	**0.001**	2006	2014	**<0.001**
2007	2013	0.154	2007	2014	**0.039**
2009	2013	0.648	2009	2014	0.310
2010	2013	0.130	2010	2014	**0.028**
2014	2013	0.625			

Appendix Table 2. Summer Chinook salmon PH2 NDE entrance efficiency. χ^2 pairwise comparisons. Bold indicates P < 0.05.

Year	Year	*p*-value	Year	Year	*P*-value
1996	2013	0.093	1996	2014	0.624
1997	2013	**<0.001**	1997	2014	**0.003**
1998	2013	0.102	1998	2014	0.810
2000	2013	**0.001**	2000	2014	**0.032**
2001	2013	**<0.001**	2001	2014	**<0.001**
2002	2013	0.091	2002	2014	0.752
2003	2013	**0.005**	2003	2014	0.142
2004	2013	**0.003**	2004	2014	0.085
2005	2013	**0.043**	2005	2014	0.219
2009	2013	**<0.001**	2009	2014	**<0.001**
2010	2013	**<0.001**	2010	2014	**<0.001**
2014	2013	0.208			

Appendix Table 3. Spring Chinook salmon PH2 NDE exit ratio. χ^2 pairwise comparisons. Bold indicates $P < 0.05$.

Year	Year	*p*-value	Year	Year	*P*-value
1996	2013	**<0.001**	1996	2014	**<0.001**
1997	2013	**<0.001**	1997	2014	**<0.001**
1998	2013	**0.035**	1998	2014	0.061
2000	2013	**<0.001**	2000	2014	**<0.001**
2001	2013	0.358	2001	2014	0.639
2002	2013	**0.023**	2002	2014	**0.037**
2003	2013	**0.048**	2003	2014	0.081
2004	2013	**0.018**	2004	2014	**0.029**
2006	2013	*0.848	2006	2014	0.461
2007	2013	*0.649	2007	2014	*0.927
2009	2013	*0.660	2009	2014	0.336
2010	2013	*0.238	2010	2014	*0.076
2014	2013	*0.649			

*Note 25% of the cells have expected counts less than 5.

Appendix Table 4. Spring Chinook salmon CI entrance efficiency. χ^2 pairwise comparisons. Bold indicates $P < 0.05$.

Year	Year	*P*-value	Year	Year	*P*-value	Year	Year	*P*-value	Year	Year	*P*-value
1996	2009	**0.010**	1996	2010	0.879	1996	2013	0.348	1996	2014	0.364
1997	2009	**0.001**	1997	2010	0.417	1997	2013	0.126	1997	2014	0.129
1998	2009	**0.017**	1998	2010	0.959	1998	2013	0.410	1998	2014	0.429
2000	2009	0.841	2000	2010	**0.007**	2000	2013	0.134	2000	2014	0.108
2001	2009	0.255	2001	2010	**0.003**	2001	2013	**0.035**	2001	2014	**0.028**
2002	2009	**<0.001**	2002	2010	**0.016**	2002	2013	**0.004**	2002	2014	**0.003**
2003	2009	**<0.001**	2003	2010	**0.047**	2003	2013	**0.012**	2003	2014	**0.011**
2004	2009	**<0.001**	2004	2010	**<0.001**	2004	2013	**<0.001**	2004	2014	**<0.001**
2006	2009	**0.029**	2006	2010	0.569	2006	2013	0.270	2006	2014	0.281
2007	2009	0.790	2007	2010	0.230	2007	2013	0.546	2007	2014	0.515
2010	2009	**0.028**	2013	2010	0.456	2014	2013	0.960			
2013	2009	0.227	2014	2010	0.478						
2014	2009	0.195									

Appendix Table 5. Summer Chinook salmon CI entrance efficiency. χ^2 pairwise comparisons. Bold indicates $P < 0.05$.

Year	Year	*P*-value	Year	Year	*P*-value	Year	Year	*P*-value	Year	Year	*P*-value
1996	2009	0.167	1996	2010	**0.017**	1996	2013	**0.001**	1996	2014	**0.016**
1997	2009	0.255	1997	2010	**0.022**	1997	2013	**<0.001**	1997	2014	**0.019**
1998	2009	0.118	1998	2010	**0.008**	1998	2013	**<0.001**	1998	2014	**0.006**
2000	2009	0.935	2000	2010	0.251	2000	2013	**0.033**	2000	2014	0.299
2001	2009	**0.022**	2001	2010	0.286	2001	2013	0.716	2001	2014	0.124
2002	2009	**0.002**	2002	2010	**<0.001**	2002	2013	**<0.001**	2002	2014	**<0.001**
2003	2009	**0.001**	2003	2010	**<0.001**	2003	2013	**<0.001**	2003	2014	**<0.001**
2004	2009	0.200	2004	2010	**0.014**	2004	2013	**<0.001**	2004	2014	**0.012**
2005	2009	*0.409	2005	2010	0.149	2005	2013	***0.049**	2005	2014	*0.173
2010	2009	*0.271	2013	2010	0.410	2014	2013	0.189			
2013	2009	**0.033**	2014	2010	0.795						
2014	2009	0.323									

*Note 25% of the cells have expected counts less than 5.

Appendix Table 6. Spring Chinook salmon CI exit ratio. χ^2 pairwise comparisons. Bold indicates $P < 0.05$.

Year	Year	*P*-value	Year	Year	*P*-value	Year	Year	*P*-value	Year	Year	*P*-value
1996	2009	**<0.001**	1996	2010	**<0.001**	1996	2013	**<0.001**	1996	2014	**<0.001**
1997	2009	**<0.001**	1997	2010	**<0.001**	1997	2013	**0.005**	1997	2014	**<0.001**
1998	2009	**<0.001**	1998	2010	**<0.001**	1998	2013	**0.013**	1998	2014	**<0.001**
2000	2009	**0.003**	2000	2010	**<0.001**	2000	2013	0.224	2000	2014	**0.018**
2001	2009	**<0.001**	2001	2010	**<0.001**	2001	2013	**<0.001**	2001	2014	**<0.001**
2002	2009	**<0.001**	2002	2010	**<0.001**	2002	2013	**<0.001**	2002	2014	**<0.001**
2003	2009	**<0.001**	2003	2010	**<0.001**	2003	2013	0.092	2003	2014	**0.005**
2004	2009	**<0.001**	2004	2010	**<0.001**	2004	2013	**<0.001**	2004	2014	**<0.001**
2006	2009	0.739	2006	2010	*0.105	2006	2013	*0.060	2006	2014	*0.301
2007	2009	*0.152	2007	2010	***<0.001**	2007	2013	*0.858	2007	2014	*0.472
2010	2009	*0.047	2013	2010	***<0.001**	2014	2013	0.278			
2013	2009	*0.067	2014	2010	***0.005**						
2014	2009	*0.414									

*Note 25% of the cells have expected counts less than 5.

Appendix Table 7. Summer Chinook salmon CI exit ratio. χ^2 pairwise comparisons. Bold indicates P < 0.05.

Year	Year	*P*-value	Year	Year	*P*-value	Year	Year	*P*-value	Year	Year	*P*-value
1996	2009	0.146	1996	2010	0.369	1996	2013	**0.043**	1996	2014	0.864
1997	2009	0.272	1997	2010	0.164	1997	2013	**0.008**	1997	2014	0.467
1998	2009	0.505	1998	2010	0.093	1998	2013	**0.004**	1998	2014	0.273
2000	2009	0.417	2000	2010	**0.002**	2000	2013	**<0.001**	2000	2014	**0.006**
2001	2009	0.453	2001	2010	0.162	2001	2013	**0.012**	2001	2014	0.423
2002	2009	**0.001**	2002	2010	**<0.001**	2002	2013	**<0.001**	2002	2014	**<0.001**
2003	2009	0.440	2003	2010	**0.001**	2003	2013	**<0.001**	2003	2014	**0.002**
2004	2009	**0.006**	2004	2010	**<0.001**	2004	2013	**<0.001**	2004	2014	**<0.001**
2005	2009	*0.317	2005	2010	0.972	2005	2013	0.688	2005	2014	0.714
2010	2009	***0.031**	2013	2010	0.347	2014	2013	0.052			
2013	2009	***0.001**	2014	2010	0.433						
2014	2009	*0.091									

*Note 25% of the cells have expected counts less than 5.