TECHNICAL REPORT 2009-6

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Summary

Spill patterns at Little Goose Dam in 2007 were modified in anticipation of a spillway weir installation and the change in spill pattern was associated with reduced daily counts of adult salmon passing the dam. Consequently, the behaviors and upstream passage times of radio-tagged adult spring–summer Chinook salmon were evaluated in response to three spillway discharge patterns at Little Goose Dam during 2008. Simultaneously, tailrace conditions were characterized by monitoring the downstream paths of GPS-equipped drogues. Two of the spill treatments (i.e., Bulk and Alternate) were variations of patterns thought to mimic those produced if a spillway weir was installed. The third treatment (Uniform) was characterized by spilling similar volumes of water through most spillbays.

A total of 360 spring–summer Chinook salmon were radio-tagged and released at Ice Harbor Dam from 15 April through 11 August 2008 and of those, 290 (81%) were recorded at Little Goose Dam. Of the 290 tagged salmon recorded at the dam, 282 (97%) were recorded passing it. Tagged salmon were most active during daylight and least active at night.

Mean daily river discharge at Little Goose Dam ranged from 28.4 to 188.5 kcfs (*mean* = 79.6 kcfs) from 15 April through 31 August 2008. Tailrace eddies near the powerhouse and the north-shore were always present but their size varied with spill treatment and river discharge. Powerhouse eddy size was largest during the Bulk treatment, followed by the Alternate and Uniform treatments, respectively. The size of the north-shore eddy was inversely related to powerhouse eddy size. Differences in eddy sizes between spill patterns diminished with increasing river discharge and patterns converged to a single pattern at ~ 115 kcfs.

During the Alternate and Uniform spill treatments, tagged adults most frequently approached a fishway for the first time at the north-shore fishway opening. In contrast, tagged salmon tended to use the south powerhouse fishway opening as a first approach site during the Bulk spill treatment, particularly at mean daily flows <115 kcfs. At mean daily flows >115 kcfs, distributions of first approach sites among spill treatments were similar. Tagged salmon that entered the tailrace during the Bulk treatment had the highest median time from first tailrace record to first fishway approach (1.6 h, n = 99). They also had the lowest percentage of first fishway approaches resulting in a fishway entry (22%, n = 106). Those that entered the tailrace during the Uniform treatment had the highest percentage of first fishway approaches resulting in a fishway entry (36%, n = 93). During all spill treatments at mean daily flows <115 kcfs, tagged salmon typically used the south powerhouse opening to first enter a fishway. Distributions of first entrance sites among spill treatments were similar at mean daily flows >115 kcfs, with the north-shore fishway opening being used most as a first entry site.

Tagged salmon that entered the tailrace during the Bulk treatment had the highest median time from first tailrace record to first fishway entry (11.9 h, n = 98), followed by those that entered the tailrace during the Alternate treatment (7.3 h, n = 81), and Uniform treatment (5.5 h, n = 83). Of the tagged salmon that entered a fishway, 29% made a fishway exit to the tailrace. The highest median time from first tailrace record to last record at the ladder top was for tagged salmon assigned to the Bulk treatment (22.2 h, n = 96), followed by those assigned to the

Alternate treatment (15.2 h, n = 79), and the Uniform treatment (11.5 h, n = 83). Median times from first fishway entry to last record at the ladder top were similar among treatments (*range* = 2.9 - 3.4 h). Point estimates of treatment differences were confounded by the potential for adults to experience more than one treatment during tailrace passage and dam entry (treatment switching).

We statistically evaluated the differences in tailrace passage times among spill patterns using Cox proportional hazards regression models that statistically controlled for treatment switching and combinations other factors: time-of-day, river temperature, spill volume, flow volume, and spill treatment. Two models were well-supported by the data and these models both revealed significant time-of-day, temperature, spill treatment, and spill treatment x flow volume effects. Point estimates of the instantaneous probability of fishway entry (passage rate) were 51.1-59.5% greater under Uniform and Alternate treatments than Bulk treatments. However, the effect was not statistically significant at lower (<85 kcfs) river discharge in the Alternate vs. Bulk treatment comparison, resulting in a statistically significant spill treatment x flow volume interaction. Overall, the Cox proportional hazards regression analyses were broadly consistent with the hypothesis that the Bulk spill pattern slowed tailrace passage rates switching. Based on these analyses, the Bulk treatment appeared to provide the poorest tailrace conditions for adult spring–summer Chinook salmon passage among spill patterns applied at Little Goose Dam over the range of river conditions encountered during 2008.

Acknowledgements

Many people assisted with the field work and data compilation for this report and its successful completion was made possible through their efforts. They include: M. Donahue, S. Lee, and D. Joosten for overseeing the tagging of adult salmon, K. Johnson for downloading receivers, C. Boggs, J. Evavold, G. Naughton, W. Seybold, M. Suega, and S. Struhs for mobile tracking, and J. Brady, S. Brown, D. Caldwell, C. Frost, G. George, G. Gudgell, J. McComas, T. Mitchell, and M. Walker, for drogue deployments. W. Daigle assisted with the time-event analysis and H. Hansel performed the multiple regression analyses. We thank M. Keefer for his technical review of this report. This study was funded by the U.S. Army, Corps of Engineers, Walla Walla District, with assistance provided by F. Higginbotham, E. Volkman, and S. Milligan.

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Introduction

The patterns and volumes of water directed through spillbays at dams on the Columbia and Snake rivers have been developed to enhance the downstream migration of juvenile salmonids to the ocean. Spill increases the proportion of juvenile fish emigrating through non-turbine routes and reduces migration times through forebays and tailraces (Ferguson et al. 2005). Because of the design of most spillbays, juvenile fish must dive to depths of 15 to 18 m to find downstream passage routes, which typically involves them passing under high pressure and velocity. In recent years, regional fish managers have been evaluating the merits of spillway weirs, which provide more surface-oriented passage routes for juvenile fish. Specifically, managers are considering installing a spillway weir at Little Goose Dam and in 2006 and 2007, they undertook studies of juvenile salmonid passage in response to spill patterns designed to mimic those produced after a spillway weir is installed.

During evaluations of a “modified bulk” spill pattern at Little Goose Dam in May 2007, counts of adult salmon passing Little Goose lagged behind that of the two nearest downstream dams until the spill pattern was changed from a ‘modified bulk’ to a ‘uniform’ pattern. Adult passage at Little Goose Dam was between 32 and 145 fish per day during the five days preceding the spill pattern change on 31 May 2007 and was >2,100 fish each of the two days afterward. The hindered passage of adult salmon at Little Goose Dam in 2007 was believed to have been caused by the recirculation of water in the tailrace of the earthen dam and powerhouse, which reduced the ability of many adults to find and enter fishway openings. Eddy recirculation patterns along both shorelines are characteristic of the bulk spill pattern at Little Goose Dam and become more pronounced as total discharge is reduced. Consequently, the problem is most apparent during the summer, but can also be evident during the spring in low-flow years.

The purpose of this study was to evaluate upstream passage times and behaviors of adult, radio-tagged spring–summer Chinook salmon (*Oncorhynchus tshawytschai)* in response to three different spill patterns (i.e., Alternate, Bulk, and Uniform) at Little Goose Dam in 2008 and to characterize the predominant hydraulic conditions in the tailrace during each of the three spill patterns. At high discharges (>115 kcfs), the spill patterns converge because discharge through each spillbay becomes similar (see Results).

To account for this convergence, we stratified analyses by total river discharge where appropriate.

Methods

Tagging at Ice Harbor Dam

Each day adult spring–summer Chinook salmon were collected for radio-tagging, a crane was used to lower the trap and picket screens into the fishway near the top of the south-shore ladder. Picket screens were used to guide salmon to the main trap. Pneumatically-controlled gates, operated by an individual in a floating booth adjacent to the trap, were used to capture fish. Trapped fish were diverted to a separate holding cage and the cage was lifted over an aerated holding tank on the forebay deck, which received trapped fish via a canvas sleeve in the bottom of the holding pen. The holding pen contained a solid bottom that retained water, ensuring that trapped fish were submerged at all times during the transfer.

At the tagging site, fish were individually transferred to an anesthetic tank (20 ppm eugenol) using rubber nets. Once sedated, fish were moved to a smaller tagging tank. The weight and fork length of each fish was recorded and all fish were inspected for clips, marks, injuries and the overall condition of the fish. Fish were scanned for passive integrated transponder (PIT) tags and if one was not present, one was injected into the pelvic girdle of the fish using a sterile, hypodermic syringe. Fish were outfitted with a 7-volt radio transmitter (Lotek Wireless, Inc[1]. Model MCFT-7A; 83mm x 16mm diameter, 29g in air) inserted to the stomach through the mouth. All transmitters were cylindrical with 47 cm antennas. Code sets allowed us to monitor up to 212 fish on each frequency. Lithium batteries powered the transmitters which had a rated operating life of more than nine months. Tagging generally required about 6 min per fish and fish were anesthetized and submerged at all times except when moved between tanks and when measured for weight and length. Once tagged, fish were placed in a 2,220 L transport tank containing aerated river water. Tagged fish were allowed to fully recover from the anesthesia before being transported to the release site. Tagged fish were released at the boat ramp located

[1] The use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government.

approximately one kilometer upriver from Ice Harbor Dam on the north shore. There were no mortalities associated with handling and tagging and all tagged salmon appeared to be in good condition at the time of release. Fish usually swam away from the release area and out of view shortly after being released. No "jack" salmon were tagged.

We radio-tagged and released a total of 360 spring-summer Chinook salmon at Ice Harbor Dam from 15 April through 11 August 2008 (Figure 1). Radio-tagged salmon represented ~0.5% of the 76,764 Chinook salmon counted passing Ice Harbor Dam during this interval. The mean fork length of tagged salmon was 76.6 cm (*s.d.* = 6.8 cm) and the mean weight 5.87 kg (*s.d.* = 1.79 kg). When mean daily river discharge exceeded 115 kcfs at Little Goose Dam, we decreased the number of salmon tagged at Ice Harbor Dam each day because there was little difference in the Little Goose Dam spill patterns when flows exceeded this threshold.

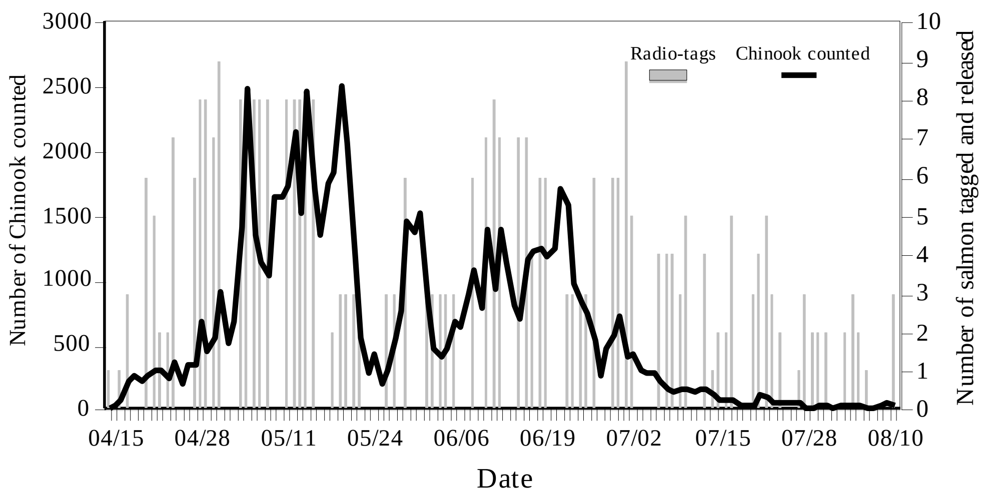


Figure 1. Numbers of adult Chinook salmon counted passing the dam and of salmon trapped, radio-tagged, and released at Ice Harbor Dam from 15 April through 11 August 2008.

Spill Treatments

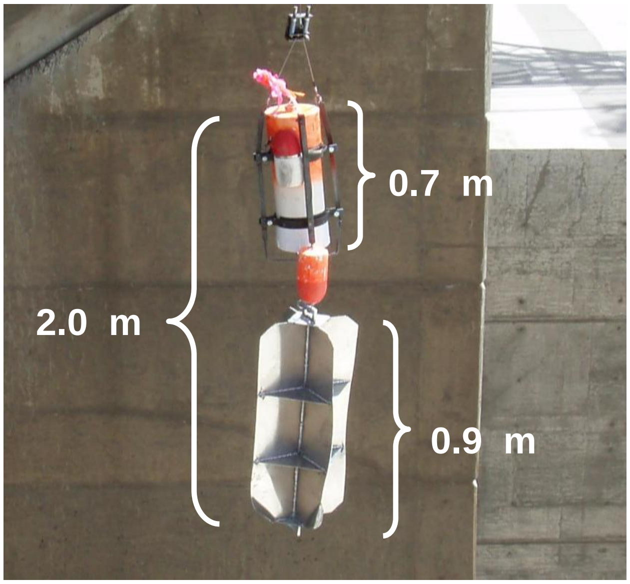
We evaluated the behaviors and passage times of tagged salmon in response to three spill patterns in 2008. The patterns evaluated included the Bulk, Alternate, and Uniform treatments. The Bulk pattern was characterized by routing most of the spilled water through the southern spillbays near the powerhouse. The Alternate pattern was similar to the Bulk pattern but allowed greater proportions of spilled water to be routed through northern spillbays. When river discharge approached or exceeded 115 kcfs, there was no difference in the spill configuration between the bulk and alternate treatments (see Results). The Uniform spill pattern was characterized by spilling similar volumes of water through most spillbays. The target spill volume during the entire study was 30% of total river discharge.

Each of the treatments was applied for two days within each six day interval or block. The sequence of treatments applied within blocks was random with one constraint. The Bulk pattern was not allowed to be applied for four consecutive days (i.e., two days each across two consecutive blocks) because managers believed this might unduly impede adult passage.

Drogue Deployments

The drogues used were similar to those used to describe gross tailrace hydraulic patterns at dams on the Columbia River (Liedtke et al. 1999). Drogues consisted of a float housing a global-positioning system (GPS) receiver attached to a drag element (Figure 2). The float was made of 20 cm diameter polyvinyl chloride (PVC) pipe and was filled with styrofoam and a waterproof box to house the GPS receiver. We used drag elements made of aluminum (50.8 cm width) for drogues released into spillbays and those made from PVC (31 cm diameter) pipe for releases near the adult fishway entrances (Figure 3). The aluminum drag element was much more resilient to damage incurred during passage through the stilling basin, but was heavier and more dangerous to handle than the PVC type. Periodic testing indicated that tracks of drogues with each type of drag element were similar.

Drogues were released from spillbays at the edges of the spill pattern and near each fishway entrance. Drogues released from the spillway were lowered into the tailrace side of the spillway near the tainter gate cable winches using a manually operated davit and cable and were released with a cable messenger when they were about a meter above the ogee crest. Drogues released near the north-shore and north powerhouse fishway openings were lowered to the interface of the entrance and the tailrace with a rope and dropped when within about a meter above the water surface. Releases near the south powerhouse opening were made slightly downstream from the auxiliary water supply intake 29.6 m from the downstream edge of the fishway, because releases made near the fishway resulted in entrainment along the powerhouse and did not depict the flow patterns in the rest of the tailrace. The order of the releases among the locations each day was randomly assigned. Drogues that did not exit the boat restricted zone (BRZ) within 30 minutes were retrieved by boat when safe to do so. The tailrace conditions were generally unsafe for small boats when river discharge was over approximately 85 kcfs, so some drogues were within the BRZ for long periods. These were retrieved with grapple hooks from the shore or by boat when they left the BRZ. Drogues were released nearly



daily when river discharge was less than approximately 125 kcfs.

Figure 2. Drogue with aluminum drag element prior to release at the spillway.

Figure 3. Drogues with aluminum and PVC drag elements. Vertical dimensions of both types were identical.

Daily Dam Counts

We tested whether daily dam counts varied significantly among the three spill treatments. We used the general linear model: $\log_e$(mean daily dam count) = spill treatment + block + spill treatment × block + error. The observational unit was the mean daily dam count averaged across two day treatment applications within each block. Mean dam counts were $\log_e$ transformed to meet the model assumption of normality of the error term. The treatment×block interaction tested for consistency in any treatment effect among blocks. We conducted this test on data sets that both included and excluded count data from blocks that contained a date when mean daily flow exceeded 115 kcfs. We used Kolmogorov-Smirnov (K-S) tests (Kiefer 1959) to compare the distributions of daily dam counts of Chinook salmon passing Lower Monumental and Little Goose dams from 2001-2008.

We also used multiple linear regression to examine the associations between dam operations and adult spring–summer Chinook salmon ladder counts at Little Goose Dam. For the years 2005 through 2008, we obtained daily adult Chinook salmon passage counts at Lower Monumental and Little Goose dams from the DART web site (http://www.cbr.washington.edu/dart/) and daily dam operations from the U.S. Army Corps of Engineers in Walla Walla, Washington. Explanatory variables used in the analysis are defined in Table 1. Only dam operations during the daylight photoperiod were included in the analysis since adult salmon passage was enumerated only during the day. Potential explanatory parameters used in models for each year and for all years combined were chosen based on the *r*-square value of the model. Generally, explanatory variables having a *P*-value > 0.5 were excluded from the model, but in 2007 the addition of the turbine unit 1 variable (*P* = 0.1313) reduced the mean square error and produced a better fit. In addition, analyses of data from 2005 were limited to dates prior to July 1, because the spill pattern after that date was unique to that year.

Table 1. Independent variables considered in multiple regression models of adult Chinook salmon passage and dam operations at Little Goose Dam, 2005-2008. LMO = Lower Monumental Dam, PHS = powerhouse.

Parameter	Definition
LMO count	Daily number of adult spring Chinook salmon passing Lower Monumental Dam lagged one day.
Total discharge	Daily mean hourly amount of water discharged from Little Goose Dam (kcfs).
PHS discharge	Daily mean hourly amount of water discharged through the Little Goose Dam powerhouse (kcfs).
Turbine 1 online	Dummy variable = 1 when Unit 1 is on, 0 when it is off.
Spill discharge	Daily mean hourly amount of water discharged through the Little Goose Dam spillway (kcfs).
Percent spill	Daily mean hourly percent of total discharge spilled.
Controlled spill	Daily mean hourly amount of water discharged as spill when the maximum hydraulic capacity of the powerhouse was not exceeded.
Uncontrolled spill	Daily mean hourly amount spill minus controlled spill.
Bulk spill pattern	Dummy variable representing bulk spill pattern. This variable was assigned a value of 1 when the spill pattern was in effect and a value of 0 during other spill patterns.
Non-bulk pattern	Dummy variable = 1 when spill pattern is Uniform, Alternate, or Modified Bulk, 0 otherwise.

Monitoring Movements of Radio-tagged Salmon

All main fishway openings, the transition pool, and the ladder top were monitored with underwater radio antennas connected to radio receivers (Figure 4). The tailrace area was monitored with a total of six radio receivers, each with a single, six-element yagi antenna connected to it. The two most downstream receivers were located approximately 0.5 km from the dam, one on each side of the river. One tailrace receiver was deployed upstream from the juvenile facility on the south-shore and a second was deployed near the north-shore fishway opening. There were two receivers deployed approximately 0.2 km downstream from these receivers, one on the south-shore downstream from the juvenile facility, and the other on the north-shore near the downstream edge of the BRZ. Data from fixed site receivers were augmented with data collected by U. Idaho personnel tracking the movements of tagged salmon from a boat within the dam tailrace (Figure 5).

Radiotelemetry data from fixed receivers were reviewed to remove obvious errors and noise records. Processed data were then coded using automated software to identify behaviors of interest such as first and last records at each antenna site and approaches, entries, and exits at fishway openings. The coded records from the automated processing were reviewed for appropriateness by a trained technician. Coded records were used to calculate passage times and subsequently used for statistical analyses.

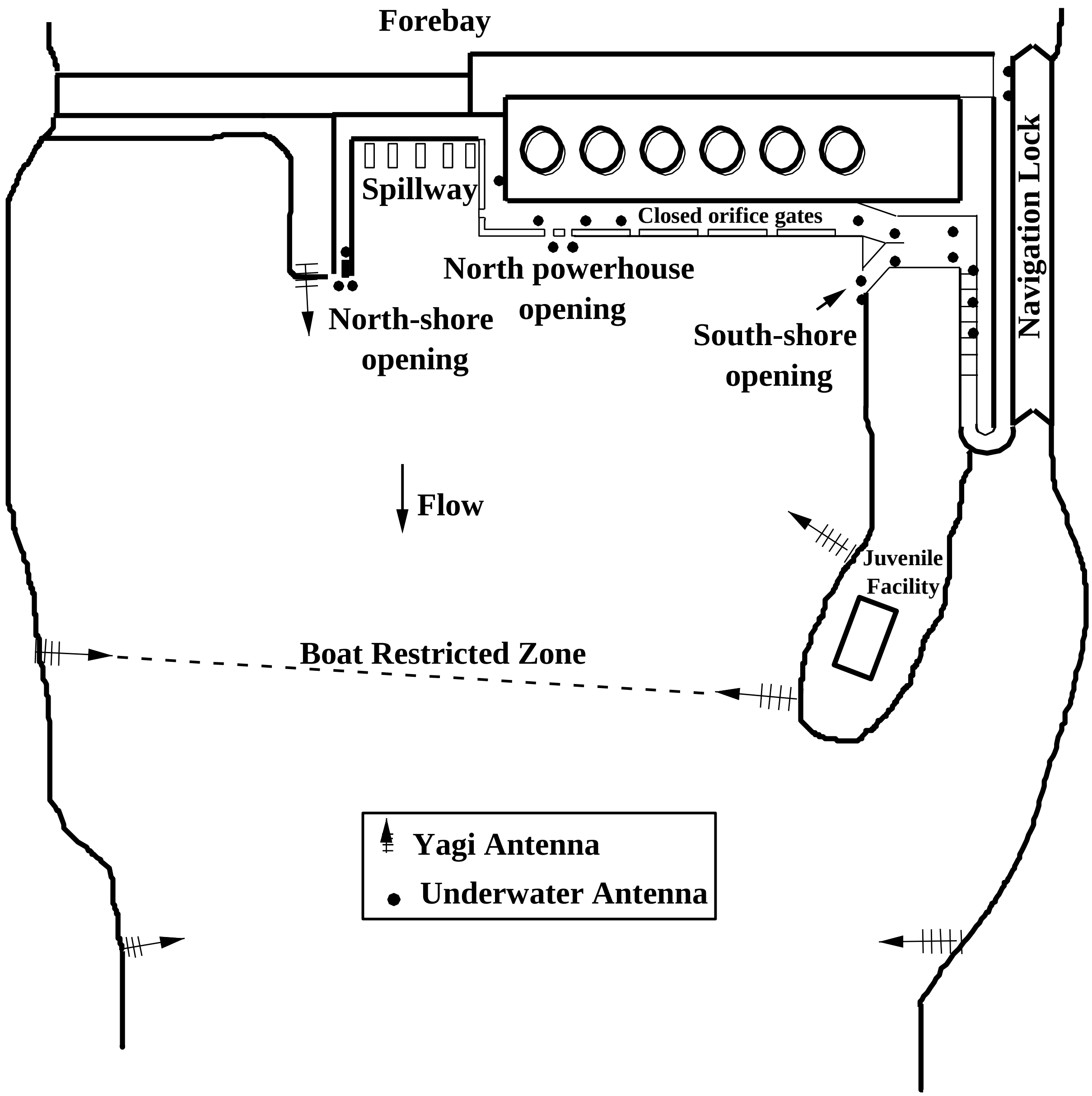


Figure 4. Aerial view of radio antennas deployed at Little Goose Dam during 2008 (not to scale).

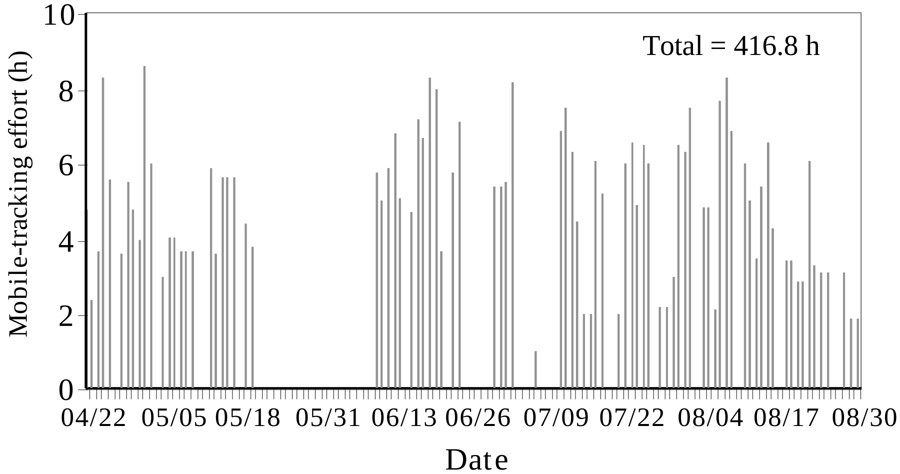


Figure 5. Distribution of mobile tracking effort by U. Idaho personnel in the tailrace of Little Goose Dam during 2008.

Passage Times

We evaluated passage times based on the spill pattern applied and the mean daily flow at the time tagged salmon were first recorded in the tailrace of Little Goose Dam. We compared passage times of tagged salmon between spill patterns for four discharge strata: <50 kcfs, 50-85 kcfs, 85-115 kcfs, and > 115 kcfs. The strata were selected based on operational considerations outlined by the Corps of Engineers (Fred Higginbotham, personal communication) and the convergence of spill patterns at high discharges.

Time-event analysis

Passage times for some fish exceeded the duration of a spill treatment (typically two days; maximum = 4 days) and many fish that were detected in the tailrace did not enter the fishway until the treatment had been switched (“switching”; see Caudill et al. 2006). Additionally, passage times for some fish were long enough that entire treatment blocks passed between first tailrace and first fishway entries (block “skipping”). Consequently, individual fish could 1) pass under the same treatment and block (no switch or skip), 2) pass after a single change in treatment (switch, no skip), 3) skip an entire block and enter the dam under the same treatment as when the fish first entered the tailrace (skip, no switch), or 4) skip a block and pass under a different treatment as the tailrace detection (skip and switch).

Treatment switching and skipping rendered traditional ANOVA approaches inappropriate for estimating the effects of spill pattern on passage. Consequently, we used proportional hazards regression (PHReg), a form of time-event analysis (Fox 1993; Allison 1995; Hosmer and Lemeshow 1999; Castro-Santos and Haro 2003; Naughton et al. 2005) to explicitly incorporate the temporal changes in spill treatment. PHReg is semi-parametric, and differs considerably from typical linear models where the mean response of the population is of interest. PHReg estimates the probability or "hazard" of an event, such as the passage of a dam segment by an individual salmon, occurring within a small time interval, given 1) the event had not occurred prior to the beginning of the time interval, and 2) a set of predictor variables (covariates) such as spill level and temperature at the beginning of the time interval. The probabilities of passage are expressed as a hazard ratio (e.g., the ratio of passage rate among treatments). The PHReg model does not expressly estimate the time to passage, but rather the effect of the predictors on the risk of the event occurring (e.g., first entrance to a fishway).

The PHReg method has two primary advantages in this context. First, predictor variables, including spill treatment are allowed to change throughout the passage event as 'time-varying covariates', explicitly accounting for treatment switching and changes in the river environment. Second, individuals that enter the study, but for which the event is not observed, can be explicitly included in the model 'risk-set' and 'censored' rather than being excluded prior to analysis as in ANOVA (Allison 1995). We censored fish that were detected in the tailrace but that did not enter a fishway. Hazard rates were assumed to be constant through time. We modeled passage hazard in relation to spill pattern while statistically accounting for variation in other environmental factors using information theoretic techniques (Burnham and Anderson 2002) to find the model of four candidates models with the best fit to the data.

The models we evaluated included combinations of spill treatment, time-of-day (TOD), river temperature, spill volume, flow volume and a spill treatment * flow volume category interaction. Preliminary analyses revealed a strong positive correlation between hourly total dissolved gas and spill volume (R^2 = 0.803, N = 1,999 hourly observations), preventing simultaneous evaluation of both predictors. We evaluated spill volume as a predictor because slowed adult salmon passage has been observed at high spill volumes at Bonneville Dam (Caudill et al. 2006) and we have observed no evidence for strong dissolved gas effects on adult migration behavior (Johnson et al. 2005, 2007). We caution that interpretation of causal effects related to spill volume is complicated by the intercorrelation. We treated spill treatment and flow volume as categorical variables. Preliminary analyses indicated no significant difference between < 50 kcfs and 50-85 kcfs flow categories or between 85-110 kcfs and > 110 kcfs flow categories. Consequently, we combined the subcategories into two flow volume categories (low flow, ≤85 kcfs and high flow, >85 kcfs) to increase statistical power. We also included a spill treatment × flow volume category interaction term to test whether spill treatment effects were consistent at high vs. low flow categories and to account for the convergence of spill pattern at high river discharge. We compared differences in Akaike's Information Criterion (AIC) values among models and selected the model with the most explanatory power (lowest AIC value and highest weights) among those evaluated (Burnham and Anderson 2002).

Results

River Conditions

Mean daily river discharge at Little Goose Dam ranged from 49.6 to 100.7 kcfs (*mean* = 70.5 kcfs) from 15 April through 16 May 2008. On 17 May 2008, mean daily flow exceeded 115 kcfs and remained above this level until 26 June 2008 (Figure 6). Mean daily flows decreased steadily in late June through early July and ranged between 30-50 kcfs from mid-July through August. Mean daily spill volumes ranged from 26 to 52% of mean daily river discharge values from April through August. Mean daily river temperatures ranged between 8.0 and 20.9 ºC and were characterized by a general warming trend for the duration of the study (Figure 7).

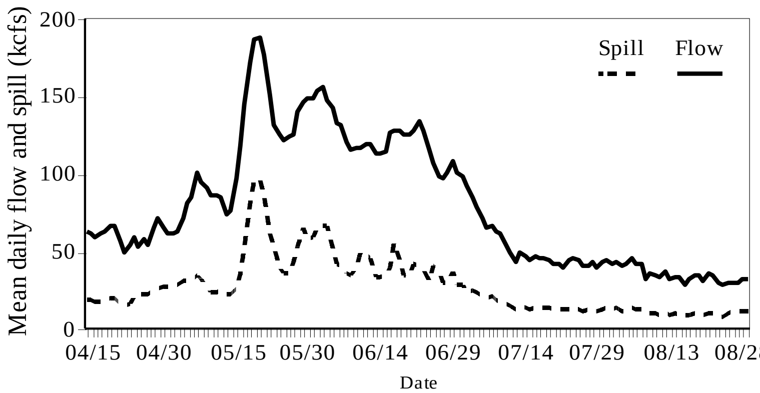


Figure 6. Mean daily river discharge and spill volume at Little Goose Dam from 15 April through 30 August 2008.

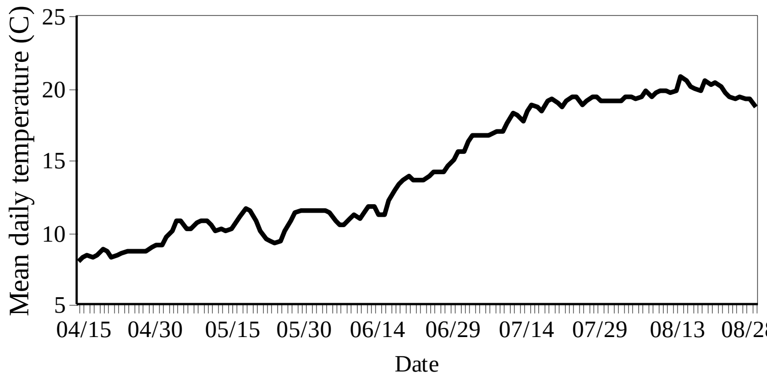


Figure 7. Mean daily river temperature at Little Goose Dam from 15 April through 30 August 2008.

Drogue Deployments

We released 847 drogues into the Little Goose Dam tailrace from 10 April through 29 August 2008 (Table 2). Of the 847 drogues released, 804 (95%) collected useable GPS data. No drogues were released from 17 May to 26 May and from 27 May to 8 June due to high river discharge. Drogues were released during river discharges ranging from 20 to 151 kcfs. Despite releases made almost daily, the seasonal pattern of river discharge resulted in most of the data being collected when discharge was less than 50 kcfs (Table 2). We released 455 drogues at less than 50 kcfs, 188 between 50 and 85 kcfs, 93 between 85 and 115 kcfs, and 68 above 115 kcfs.

Table 2. Number of drogues released during different discharge ranges at all release locations and treatments at Little Goose Dam during 2008.

		Treatment		
Discharge Range	Release Location	Alternative Bulk	Bulk	Uniform

< 50 kcfs	South Powerhouse Opening	68	57	59
	North Powerhouse Opening	47	41	31
	Spillway	19	22	13
	North Shore Opening	31	38	29
	Subtotal	165	158	132
50 – 85 kcfs	South Powerhouse Opening	14	21	25
	North Powerhouse Opening	12	12	19
	Spillway	15	16	12
	North Shore Opening	8	17	17
	Subtotal	49	66	73
85 – 115 kcfs	South Powerhouse Opening	15	6	9
	North Powerhouse Opening	9	6	9
	Spillway	6	3	4
	North Shore Opening	8	6	12
	Subtotal	38	21	34
> 115 kcfs	South Powerhouse Opening	6	6	9
	North Powerhouse Opening	5	6	4
	Spillway	5	6	6
	North Shore Opening	5	5	5
	Subtotal	21	23	24
	Total	273	268	263

The percentage of drogues that reached the end of the BRZ varied by release location. Most of the drogues from the north powerhouse opening (74.6%; 135 of 181) reached the BRZ line, but less than half of those released at the other sites did. Those that did not reach the BRZ line in a short period were caught in the tailrace eddies and often remained there for up to four hours before being retrieved, though some were retrieved the following day. Approximately 26% of the drogues released at the north powerhouse opening (26.4%; 53 of 201), 33.9% (100 of 295) of those released at the south powerhouse opening, and 42.5% (54 of 127) of those released from the spillway traveled to the BRZ line within 30 minutes.

Qualitative examinations of drogue paths indicate several trends. Re-circulations, or eddies, downstream from the earthen dam and powerhouse were always present. The re-circulations were affected by the shape and bathymetry of the tailrace. For example, the powerhouse eddy is located over a large shallow area in the powerhouse tailrace (Figure

8) and the north-shore eddy is affected by a large shallow area located mid-river near the smolt bypass outfall (not shown). The depths in the powerhouse tailrace are over 35 m near the powerhouse, but much of the area downstream is less than 5 m. The size and cohesiveness of the eddies varied with total discharge and spill treatment (representative examples in Figure 9). The size and cohesiveness of the powerhouse eddy increased with river discharge and was smallest during the Uniform treatment, intermediate during the Alternate treatment, and greatest during the Bulk treatment. The trends in size and cohesiveness of the north-shore eddy were generally the opposite from the powerhouse eddy: eddy diameter decreased with river discharge and was greatest during the Uniform treatment, intermediate during the Alternate treatment, and smallest during the Bulk treatment. The differences in drogue paths among the treatments diminished with increasing river discharge until approximately120 kcfs, when they were nearly identical. This is consistent with the design of the spill patterns, which became increasingly similar as discharge increased until merging into a single uniform pattern at approximately 115 kcfs (see insets on Figure 9).

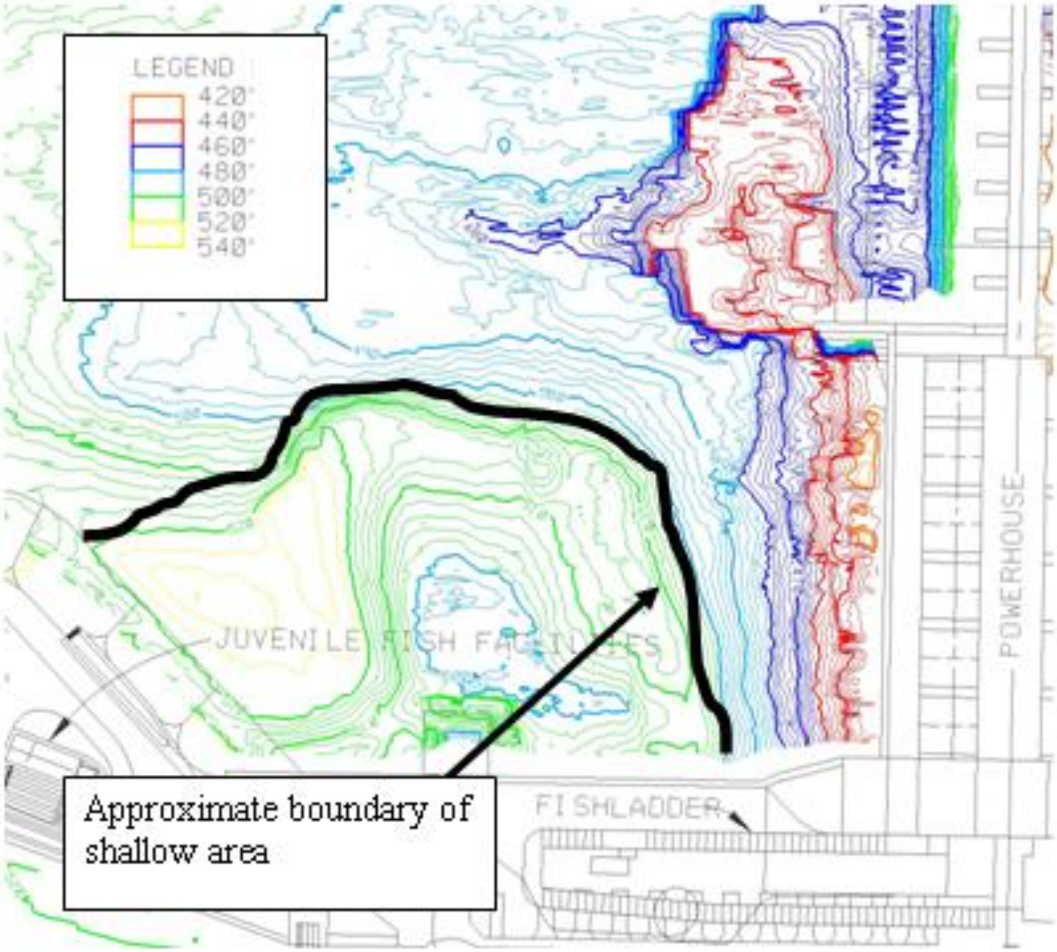


Figure 8. Map of Little Goose Dam tailrace showing river bed elevations. Water depth during the 2008 studies was roughly tailwater elevation of 537.5 ft minus the bed elevation. The dark line indicates the approximate boundary of the shallow area drogues were often entrained within. Schematic from Sean Milligan, USACE, Walla Walla, Washington.

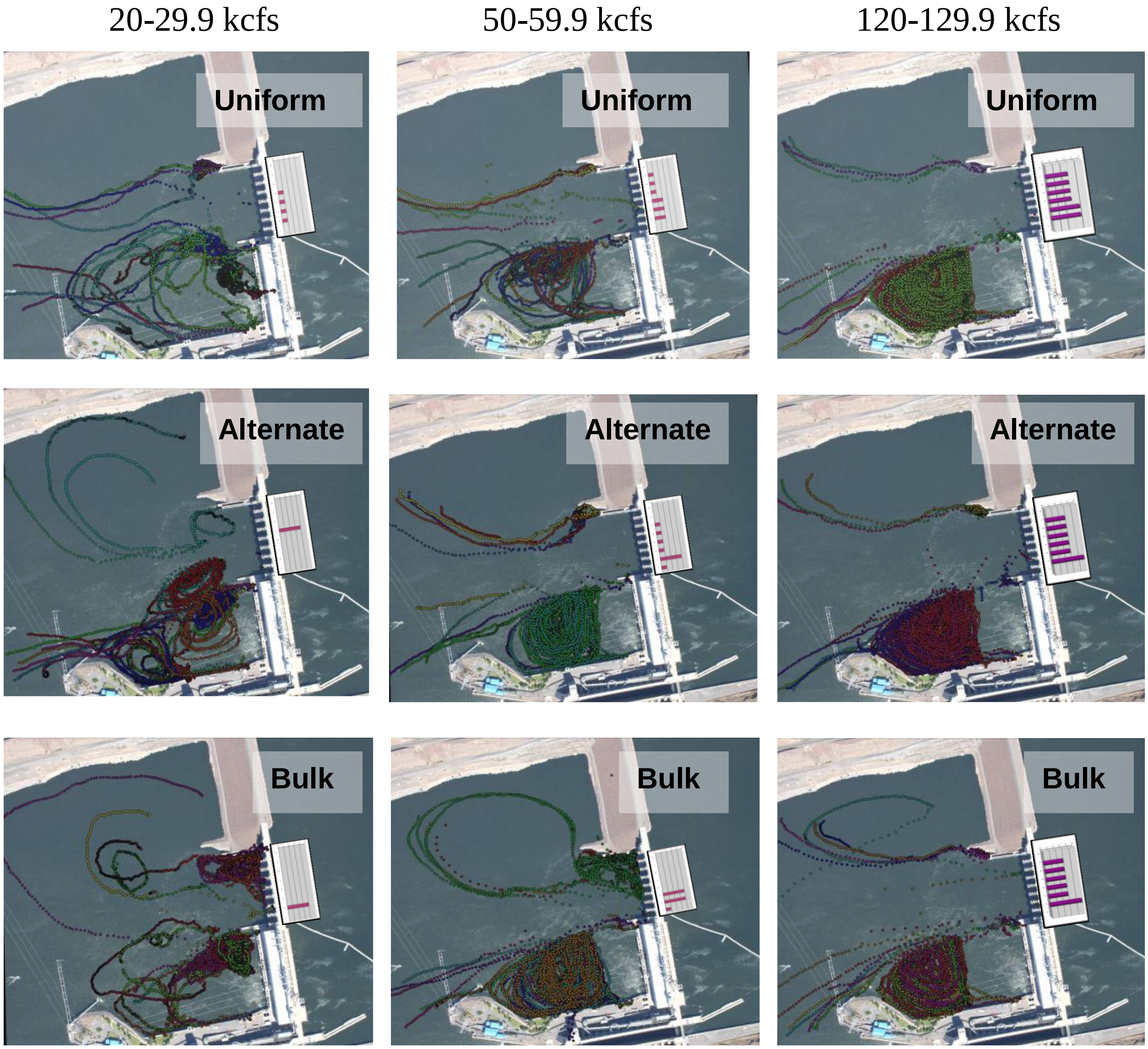


Figure 9. Paths of drogues released during Uniform, Alternate, and Bulk spill treatments at three representative river discharge ranges. Plots of spill gate openings are shown near the spillway of each plot with a y-axis range from 0 to 5 stops. A background image during a period of no spill was used for clarity and does not represent the conditions during drogue releases.

Daily Dam Counts

With all count data included during the study year, we found no significant differences in $\log_e$-transformed mean daily dam counts among spill treatments (P = 0.82, df = 2), blocks (P = 0.08, df = 21) or the spill treatment × block interaction term (P = 0.99, df = 42). We found similar results when we excluded blocks that contained a date when mean daily flow exceeded 115 kcfs. Specifically, we found no significant differences in $\log_e$-transformed mean daily dam counts among spill treatments ($P = 0.71$, $df = 2$), blocks ($P = 0.10$, $df = 14$), or the spill treatment × block interaction term ($P = 0.99$, $df = 28$). Based on K-S tests, there were no significant differences in the distributions of daily counts of adult Chinook salmon passing Lower Monumental and Little Goose dams during 2001-2006 versus 2008 (Figure 10). Distributions during 2007 were significantly different ($P < 0.033$, $df = 1$), a likely result of the modified spill patterns during that year.

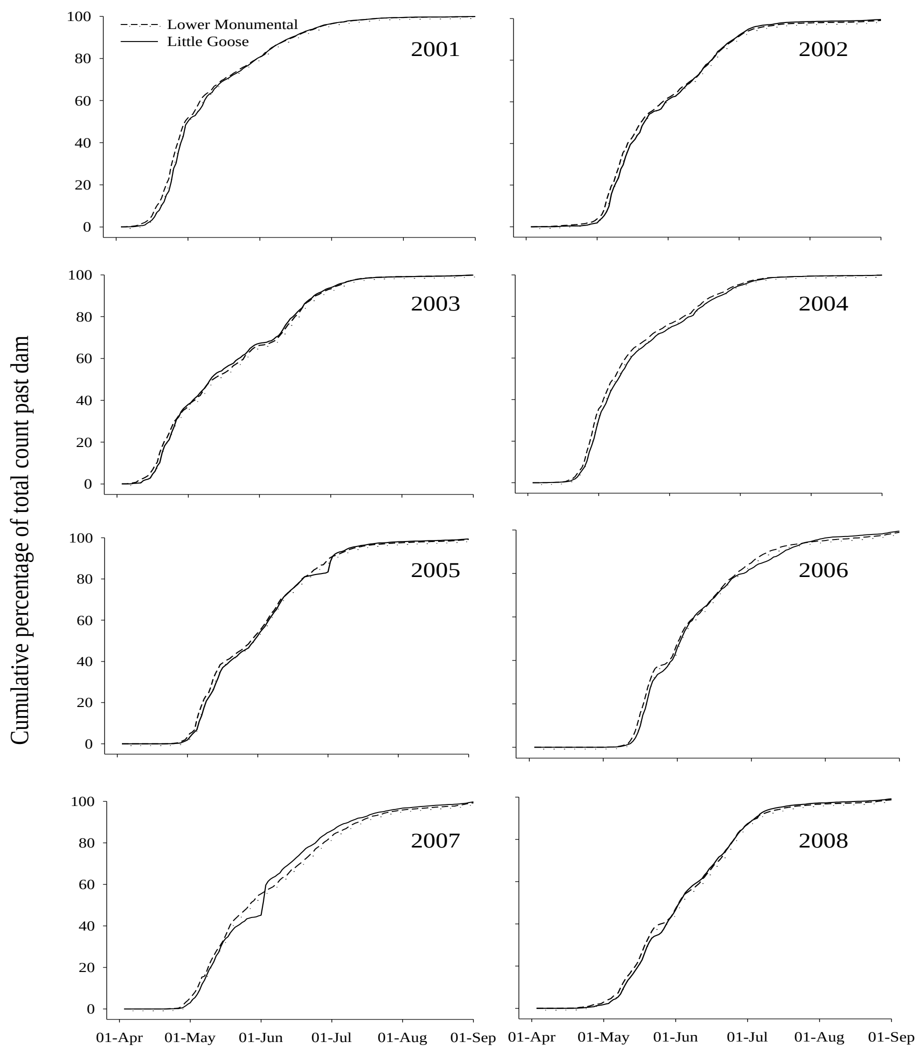


Figure 10. Distributions of cumulative percentage of adult Chinook salmon counted passing Lower Monumental and Little Goose dams from 1 April through 31 August, 2001-2008.

Multiple regression analyses indicated several variables with significant effects on daily counts of salmon at Little Goose Dam. Ladder counts of adult spring Chinook salmon generally varied as a function of the counts at Lower Monumental Dam on the previous day. However, varying dam operations at Little Goose Dam modified this basic relation and, under some conditions, fewer salmon were counted at Little Goose Dam than expected based on counts at Lower Monumental Dam on the previous day. In each year from 2005 through 2008, combinations of factors such as uncontrolled spill at high discharges, and particular spill patterns or high percent spill at low discharges resulted in reduced counts compared to those expected. The dam operations and therefore the variables that were useful predictors of ladder counts varied among years.

The 2005 migration season included periods with little spring spill and court-ordered summer spill. The no-spill period occurred from mid-April to 20 June except for a brief time of uncontrolled spill from 17 to 24 May (Figure 11). Uniform spill occurred from 19 June to 01 July at an average of 45% of the river discharge. The only variables included in the final model were the counts at Lower Monumental Dam the previous day (positive effect) and the percent spill at Little Goose Dam (negative effect; Table 3). The 20% uncontrolled spill in May had little association with adult passage, whereas greater than 60% percent spill at total discharges ranging from about 40 to 60 kcfs between 21 and 29 June was associated with a reduced rate of passage. This resulted in a large pulse (>1500 fish) of fish passing on 30 June after percent spill was reduced to about 40%.

In 2006, bulk and uniform spill treatments were implemented with 30% spill at Little Goose Dam to evaluate their effects on juvenile passage and survival. High runoff often resulted in exceeding the powerhouse hydraulic capacity and the use of uncontrolled spill. Changes in adult spring Chinook salmon counts in 2006 were explained principally by changes in counts at Lower Monumental Dam, turbine and controlled spill discharge, and the amount of uncontrolled spill discharge (Table 3). There was a positive effect of powerhouse discharge mediated by a negative effect of uncontrolled spill. Daily adult counts rose sharply in mid-May with concurrent increases in turbine and controlled spill discharges (Figure 11).

Table 3. Results of multiple regressions of the effects of dam operations on daily ladder counts of adult spring Chinook salmon at Little Goose Dam during 2005 through 2008, and for all years combined. Parameters are defined in Table 1.

Year	Parameter	Estimate	Std Error	*P*	*r*-square
2005	Intercept	89.7781	25.4210	0.0008	0.8487
	LMO Adult Count	0.7288	0.0429	<0.0001	
	Percent spill	-3.2062	0.5839	<0.0001	
2006	Intercept	-59.06514	38.5271	0.1298	0.8486
	LMO Adult Count	0.75369	0.4682	<0.0001	
	Uncontrolled spill	-7.78912	2.5456	0.0031	
	PHS discharge	1.74711	0.6210	0.0064	
2007	Intercept	-2409.2112	739.2667	0.0016	0.7091
	LMO Adult Count	0.3602	0.0707	<0.0001	
	Spill discharge	-72.3857	24.5188	0.0041	
	Percent spill	73.5647	24.6381	0.0038	
	Bulk spill pattern	-174.6767	38.2239	<0.0001	
	PHS discharge	38.0214	24.6381	0.0005	
	Turbine 1 Online	103.5204	67.6901	0.1313	
2008	Intercept	-146.9169	129.5864	0.2602	0.7342
	LMO Adult Count	0.6872	0.6900	<0.0001	
	Uncontrolled spill	-15.0620	3.3416	0.0051	
	Bulk spill pattern	-228.4486	84.4927	0.0083	
	Total discharge	4.3295	1.5028	0.0051	
2005-2008	Intercept	77.1182	26.8050	0.0043	0.7944
	LMO Adult Count	0.7263	0.0289	<0.0001	
	Spill discharge	7.4186	1.2971	<0.0001	
	Uncontrolled spill	-11.6985	1.9492	<0.0001	
	Percent spill	-9.3233	1.2078	<0.0001	
	Non-bulk pattern	146.3502	26.5567	<0.0001	

Total discharges exceeded powerhouse capacity from 17 to 24 May 2006 and resulted in uncontrolled spill. This resulted in tailrace conditions that were negatively associated with adult passage and lower counts relative to the Lower Monumental Dam counts (Figure 11). A surge in passage followed the end of uncontrolled spill and daily counts at Little Goose Dam surpassed those at Lower Monumental Dam until 27 May. Spill pattern was not a significant predictor of adult ladder counts in 2006.

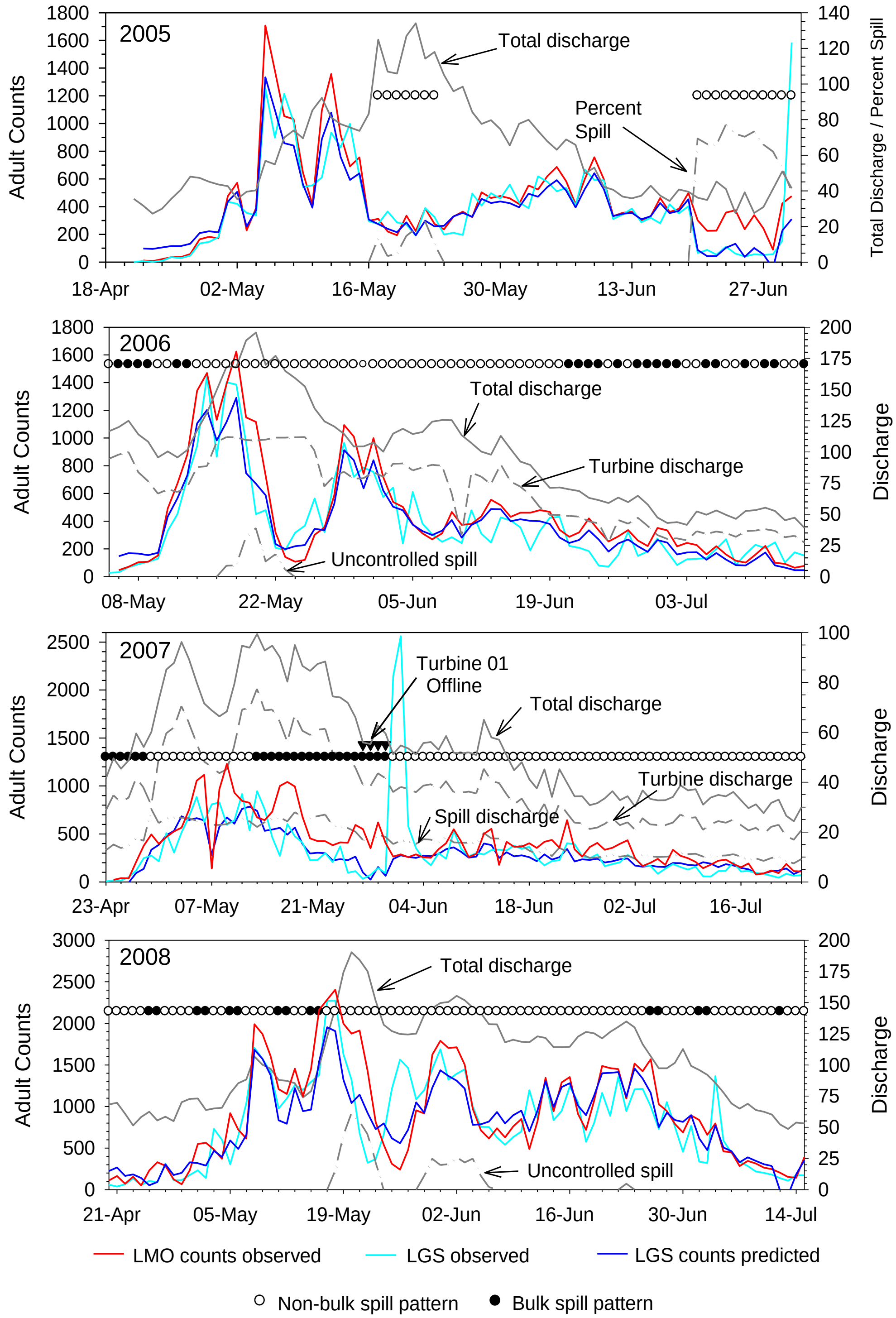


Figure 11. Observed and predicted counts of adult spring Chinook salmon at Little Goose Dam (LGS) in relation to those at Lower Monumental dam (LMO) and other variables. See Table 1 for variable definitions and Table 3 for predictive regression equations. Discharge is in kcfs.

Planned dam operations in 2007 included 30% spill using a bulk spill pattern and a period of spill to the gas cap in mid-May. Total discharge in 2007 did not exceed the capacity of the powerhouse and generally did not exceed the planned operations. However, a period of reduced turbine discharges and relatively high spill discharge near May 7 created periods of high percent spill and tailrace conditions that were associated with lower rates of adult passage (Figure 11). The bulk spill pattern and a 4-day period when turbine unit 1 was offline appeared to contribute to the low counts at the end of May. Counts at Little Goose Dam were as low as 32 fish per day while those at Lower Monumental Dam remained > 400 fish per day. In response to the low counts at Little Goose Dam, the bulk spill pattern was changed to a uniform-like pattern and turbine unit 1 was brought back on line. The result was a pulse of over 5,880 fish passing between 31 May and 04 June. The final model for 2007 suggested a negative association of spill discharge (volume) and a positive effect of percent spill to adult counts, however, percent spill varied little during the season (Table 3). There was also a negative effect of presence of the bulk spill pattern, which resulted in an average 175 fewer fish per day than the Uniform pattern. The effect of Unit 1 being on was the addition of 103 fish per day and a decrease of this number when it was off.

Planned dam operations in 2008 consisted of three spill pattern treatments and 30% spill, however the runoff volume was high and uncontrolled spill was common. The most significant predictive factors in 2008 were similar to those in 2006: uncontrolled spill and high percentages of (unplanned) spill beginning on 17 May (Figure 11). When uncontrolled spill was reduced on 23 May, the frequency of fish passing increased and counts at Little Goose Dam were higher than those at Lower Monumental Dam. Bulk spill during 2008 also had a significant negative association with adult passage relative to the Alternate and Uniform patterns. The model included significant positive effects of count at Lower Monumental Dam, spill discharge, and total discharge and negative effects of the amount of uncontrolled spill and the spill percent (Table 3).

The model based on data from all years was composed of a subset of variables used in the year-specific models and had a similar fit of about R^2 = 0.8 (Table 3). The independent variables in this model included operation-based factors such as spill discharge, presence of uncontrolled spill, the spill percent, and the spill pattern. There was a positive effect of increases in overall discharge, as indicated by the estimate for the spill discharge variable. Negative effects of the percent spill and amount of uncontrolled spill mediated this effect.

Detections of Radio-tagged Spring–Summer Chinook Salmon at Little Goose Dam

Among the 360 spring–summer Chinook salmon outfitted with transmitters at Ice Harbor Dam through 11 August 2008, 290 (81%) were recorded on or upstream from the tailrace receiver sites at Little Goose Dam (Table 4). Of the 290 tagged salmon recorded at the dam, 91% or more were recorded during their first passage of the tailrace area, their first fishway approach, their first fishway entrance, or their passing the ladder top. A total of 65,597 adult Chinook salmon were counted at Little Goose during the same period (Figure 12). Fifteen fallback events were recorded by eleven unique radio-tagged salmon and ten re-ascension events were recorded by eight unique radio-tagged salmon. No post-fallback passage events were evaluated as part of this report and all passage times presented here are for initial passage events only.

Table 4. Number and percent of adult radio-tagged Chinook salmon recorded at Little Goose Dam from 15 April through 30 August 2008, that were recorded on their first passage of the tailrace, first approach at a fishway opening, first fishway entry, and exit from the top of the ladder.

2008	Freq.	Percent
Recorded at dam	290	100
Known to pass dam	283	98
Recorded first tailrace passage	265	91
Recorded first (known) fishway approach	289	100
Recorded first (known) fishway entrance	286	99
Recorded ladder exit	282	97

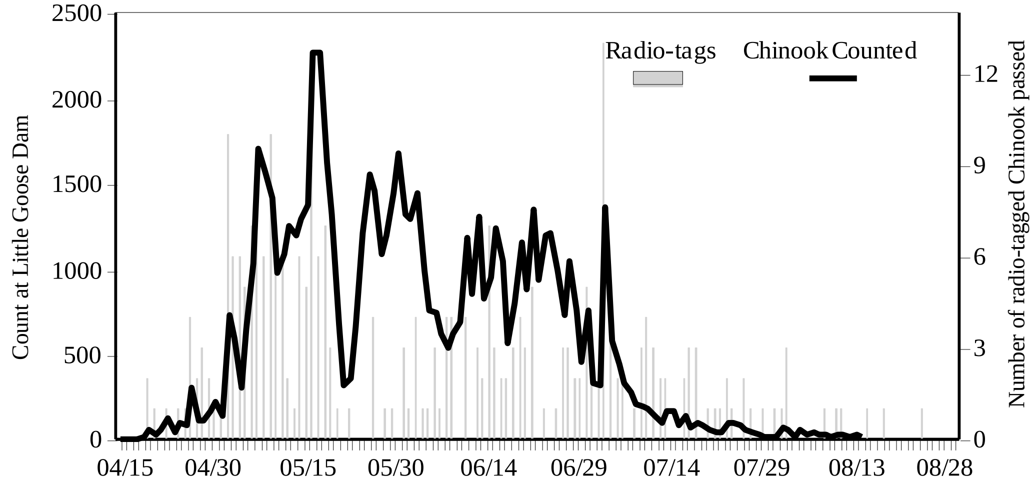


Figure 12. Number of adult spring-summer Chinook salmon counted passing Little Goose Dam (line) and the daily number of radio-tagged salmon passing the dam (bars) from 15 April through 30 August 2008.

Diel Passage Behaviors

Tagged salmon at Little Goose Dam were most active during daylight hours and least active at night (Figure 13). Tailrace entries by tagged salmon generally increased during early morning and maximum percentages occurred between 0800 and 1000 hrs. The peak in tailrace entry was followed by a general diminution of tailrace arrival through the rest of the day. The distribution of first fishway approaches was generally similar to that of tailrace entries although there was a modest secondary peak in first approaches in the early afternoon. First fishway entries tended to be more evenly distributed through the daylight hours and were highest between 1600 and 1700 hrs. The distribution of ladder exits was later overall, a likely reflection of the time fish used to swim through fishways and ascend ladders.

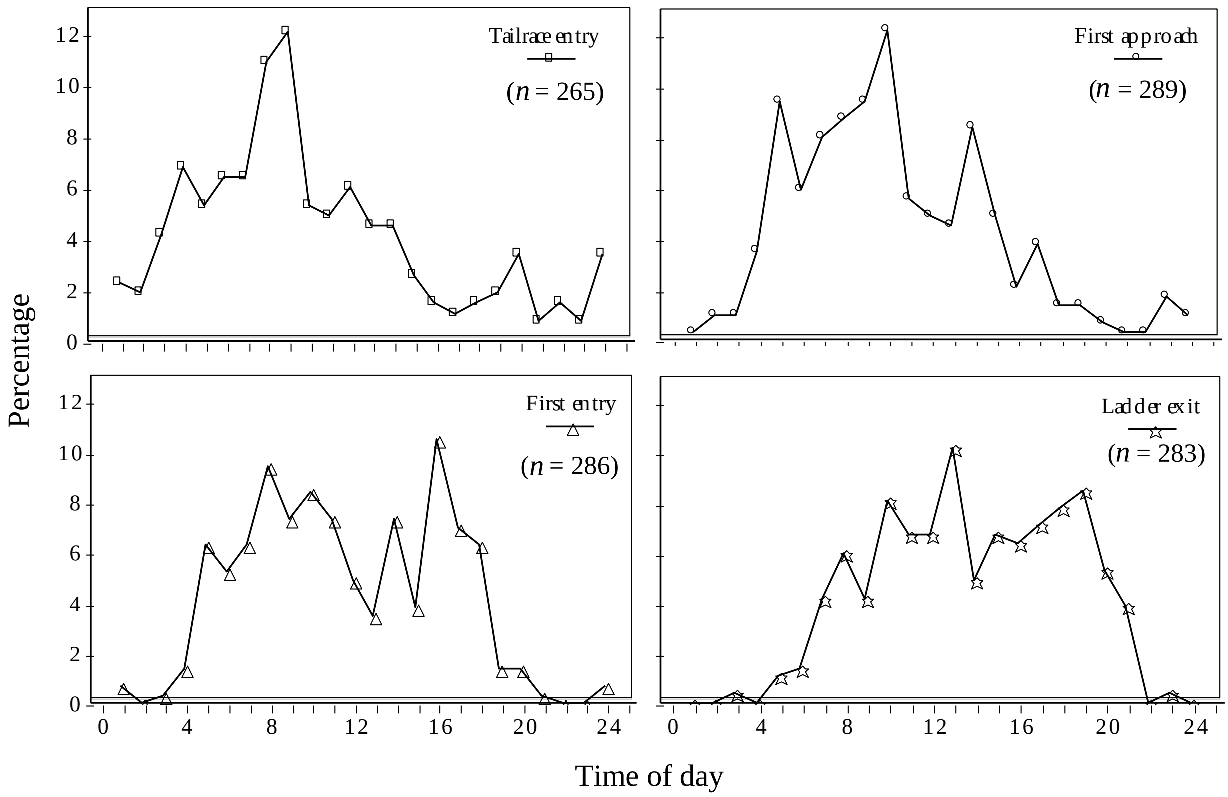


Figure 13. Time-of-day detection distributions for adult spring-summer Chinook salmon at Little Goose Dam during 2008.

Sites of Tailrace and BRZ Entry

Qualitative comparison of available mobile track data and fixed site data for tailrace and BRZ sites indicated that most adults could be accurately assigned to having passed along the north-shore, mid-channel or south-shore using fixed site signal strength and sequence of detections. We estimated that approximately 45% of the tagged salmon entered the Little Goose tailrace via the north-shore of the river, 35% entered via the south-shore, and the remaining 20% entered in mid-river. Initial detections of tagged salmon on BRZ receivers were generally consistent with those of tailrace receivers. Of the tagged salmon estimated to have entered the tailrace via the north-shore, initial BRZ detections on north-shore receivers ranged between 73-85% among spill treatments. Among tagged salmon estimated to have entered the tailrace via the south-shore, initial BRZ detections on south-shore receivers ranged between 46-83% among spill treatments. Mobile tracking detections were consistent with those at the two tailrace receivers and were useful for determining that tagged salmon were not reacting to spill patterns downstream from the BRZ. Example mobile tracks are presented in Figure 14. Mobile tracking efforts within the BRZ were hampered by hazardous boating conditions resulting from high river discharges (> 100 kcfs) from mid-May through June.

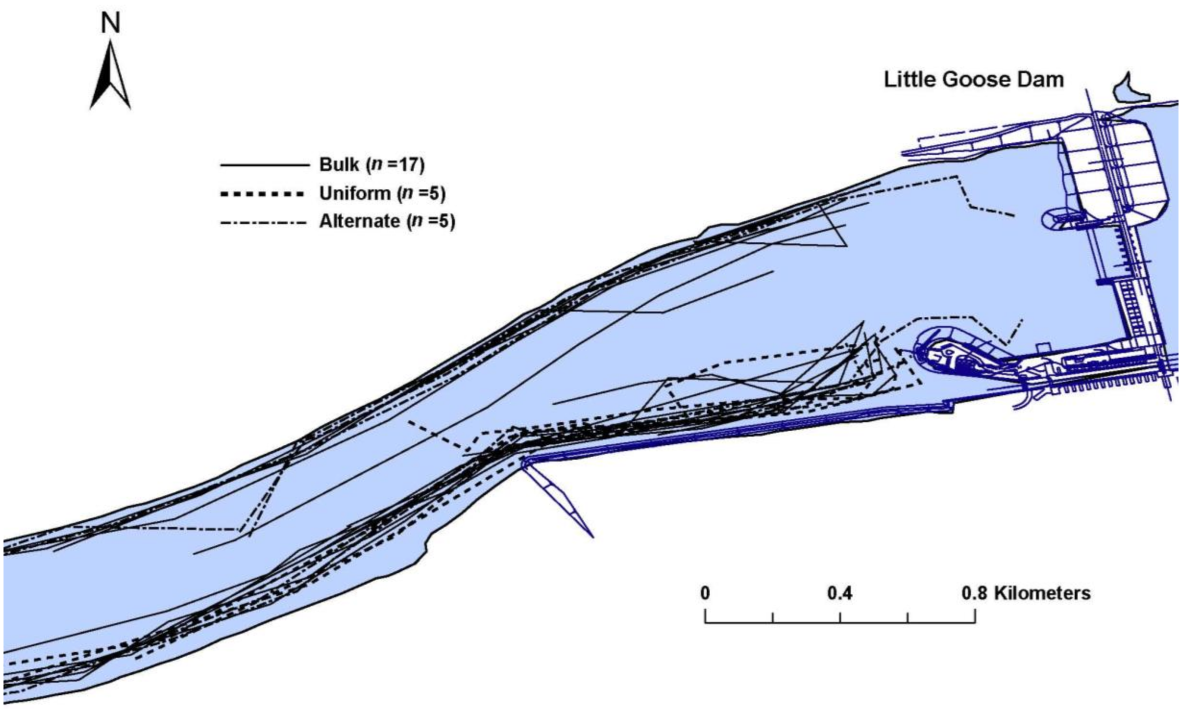


Figure 14. Mobile tracks of adult radio-tagged Chinook salmon made within one hour of their detections on fixed-site tailrace receivers at Little Goose Dam in 2008.

Distributions of First Fishway Approaches

During the Alternate and Uniform spill treatments, the north-shore fishway opening was the site most used by tagged salmon to first approach a fishway (Table 5). It was the site most used across all mean daily flow categories, except at flows less than 50 kcfs during the Uniform treatment. In contrast, tagged salmon tended to use the south powerhouse fishway opening as a first approach site during the Bulk spill treatment, particularly at mean daily flows less than 115 kcfs. At mean daily flows higher than 115 kcfs, distributions of first approach sites across spill treatments were similar. Among all spill treatment and mean daily flow categories, ≤10% of tagged salmon used the north powerhouse fishway opening as a first approach site.

Table 5. Treatment-, flow-, and site-specific frequencies and percentages of first fishway approaches made by radio-tagged spring–summer Chinook salmon at Little Goose Dam in 2008. PH = powerhouse.

		Frequency				Percent		
Mean Daily Flow (kcfs)	Spill Trt.	South PH	North PH	North-shore	Total	South PH	North PH	North-shore
≤50	Alternate	6	2	11	19	32%	10%	58%
>50 & ≤85		5	3	12	20	25%	15%	60%
>85 & ≤115		5	3	17	25	20%	12%	68%
>115		9	1	16	26	35%	4%	61%
All		25	9	56	90	**28%**	**10%**	**62%**
≤50	Bulk	4	2	2	8	50%	25%	25%
>50 & ≤85		19	3	17	39	49%	8%	43%
>85 & ≤115		21	4	13	38	55%	11%	34%
>115		6	1	14	21	28%	5%	67%
All		50	10	46	106	**47%**	**9%**	**44%**
≤50	Uniform	4	0	3	7	57%	0%	43%
>50 & ≤85		4	4	17	25	16%	16%	68%
>85 & ≤115		10	2	16	28	36%	7%	57%
>115		8	1	24	33	24%	3%	73%
All		26	7	60	93	**28%**	**8%**	**64%**
All	All	101	26	162	289	**35%**	**9%**	**56%**

Fishway Approach Efficiencies

Of the 289 first fishway approaches made by tagged salmon, 27% resulted in fishway entries (Table 6). Among spill treatments, 36% of first fishway approaches resulted in fishway entries during the Uniform treatment, 24% during the Alternate treatment, and 22% during the Bulk treatment. During all spill treatments and flows, no first approach at the north powerhouse opening resulted in an entry. At low flows, first approach efficiencies were similar among the Alternate and Bulk treatments (*range* = 25-26%) whereas no first approach made during the Uniform treatment resulted in a fishway entry, though sample size was limited ($n_{uniform}$ = 7). At mean daily flows >50 and ≤85 kcfs, first approach efficiencies were similar among spill treatments (*range* = 10-16%), although the openings with highest efficiencies differed between the Alternate and Bulk treatments. The highest first approach efficiencies occurred during the Uniform treatment when mean daily flows exceeded 115 kcfs (64%). The highest first approach efficiencies generally occurred during high flows, when the north-shore opening tended to have higher first approach efficiencies than the south powerhouse opening.

Table 6. Treatment-, flow-, and site-specific percentages of first approaches resulting in fishway entries by radio-tagged spring–summer Chinook salmon at Little Goose Dam in 2008. PH = powerhouse.

		Percentage of 1st approaches resulting in entries			
Mean Daily Flow (kcfs)	Spill Trt.	South PH	North PH	North-shore	Total
≤50	Alternate	33	0	27	26
>50 & ≤85		0	0	17	10
>85 & ≤115		20	0	24	20
>115		33	0	44	38
All		24	0	29	24
≤50	Bulk	25	0	50	25
>50 & ≤85		26	0	0	13
>85 & ≤115		14	0	8	10
>115		50	0	64	57
All		24	0	24	22
≤50	Uniform	0	0	0	0
>50 & ≤85		25	0	18	16
>85 & ≤115		20	0	38	29
>115		12	0	83	64
All		15	0	48	36
All	All	22	0	35	27

Overall, 20% of the approaches made by tagged salmon at the south powerhouse and north-shore fishway openings resulted in fishway entries (Table 7) whereas only 12% of the approaches at the north powerhouse fishway opening did so. Total approach efficiencies were similar among spill treatments when all mean daily flows were combined (*range* = 16-20%). When mean daily flows exceeded 115 kcfs, the relative frequency of approaches at the north-shore opening was highest during all spill treatments. Approach efficiencies were also highest at high flows, ranging from 34-53% among treatments. Few (1-8%) approaches resulted in fishway entries at the north powerhouse and north-shore openings during the Bulk treatment when mean daily flows were >50 and ≤115 kcfs. During the Bulk and Uniform treatments, approaches at the north powerhouse fishway opening were most likely to result in fishway entries during low flows.

Table 7. Treatment-, flow-, and site-specific approach frequencies and the percentage of those approaches resulting in fishway entries by radio-tagged spring–summer Chinook salmon at Little Goose Dam in 2008. PH = powerhouse.

		Approach frequency				Entries/Approaches (%)			
Mean Daily Flow (kcfs)	Spill Trt.	South PH	North PH	North-shore	Total	South PH	North PH	North-shore	Total
≤50	Alternate	75	52	48	175	28	19	29	26
>50 & ≤85		122	77	115	314	22	21	15	19
>85 & ≤115		94	59	74	227	16	5	27	17
>115		47	33	65	145	17	3	34	21
All		338	221	302	861	21	14	24	20
≤50	Bulk	66	49	34	149	20	31	26	25
>50 & ≤85		127	72	93	292	21	1	1	10
>85 & ≤115		142	97	80	319	20	8	5	13
>115		42	28	51	121	19	4	45	26
All		377	246	258	881	20	10	14	16
≤50	Uniform	59	40	34	133	20	40	15	25
>50 & ≤85		185	122	165	472	17	5	5	10
>85 & ≤115		105	71	98	274	28	10	26	22
>115		48	32	74	154	8	3	53	29
All		397	265	371	1033	19	11	21	18
All	All	1112	732	931	2775	20	12	20	18

Distribution of First Fishway Entries

During all spill treatments at mean daily flows <115 kcfs, tagged salmon typically used the south powerhouse opening to first enter a fishway (Table 5). Its use as a first entry site appeared to be most pronounced during the Bulk spill treatment when mean daily flows were >50 kcfs and <115 kcfs and to a lesser extent, during the Uniform spill treatment when mean daily flows were <85 kcfs. During the Alternate spill treatment at mean daily flows <115 kcfs, the south powerhouse opening was only slightly more frequently used than the north-shore opening as a first entry site. As with first approaches, the north powerhouse opening was used infrequently as a first entrance site during all spill treatments and mean daily flow categories. Its use moderately increased when mean daily flows were <50 kcfs, however. At mean daily flows >115 kcfs, distributions of first entrance sites among all spill treatments were similar, with the north-shore opening being used most to first enter a fishway.

Table 8. Treatment-, flow-, and site-specific frequencies and percentages of first fishway entries made by radio-tagged spring–summer Chinook salmon at Little Goose Dam during 2008.

		Frequency				Percent		
Mean Daily Flow (kcfs)	Spill Trt.	South PH	North PH	North-shore	Total	South PH	North PH	North-shore
≤50	Alternate	7	4	6	17	41%	24%	35%
>50 & ≤85		13	2	8	23	56%	9%	35%
>85 & ≤115		14	3	11	28	50%	11%	39%
>115		6	1	21	28	21%	4%	75%
All		40	10	46	96	**42%**	**10%**	**48%**
≤50	Bulk	5	2	4	11	46%	18%	36%
>50 & ≤85		23	1	1	25	92%	4%	4%
>85 & ≤115		24	6	3	33	73%	18%	9%
>115		5	0	18	23	22%	0%	78%
All		57	9	26	92	**62%**	**10%**	**28%**
≤50	Uniform	4	2	1	7	57%	29%	14%
>50 & ≤85		22	1	4	27	81%	4%	15%
>85 & ≤115		13	3	15	31	42%	10%	48%
>115		2	0	31	33	6%	0%	94%
All		41	6	51	98	**42%**	**6%**	**52%**
All	All	138	25	123	286	**48%**	**9%**	**43%**

Passage Times

For all mean daily flow categories exceeding 50 kcfs, radio-tagged Chinook salmon exposed to the Bulk treatment consistently had the highest median times to first approach a fishway opening after entering the tailrace. For all tagged salmon, the median time to first approach a fishway opening during the Bulk treatment was approximately 36-45% higher than the median times during the other two spill treatments. Median times to first approach a fishway varied little among spill treatments (*range* = 0.8–1.0 h) when mean daily flows were <50 kcfs, although sample sizes were small for two treatments (Table 9 and Figure 15). Independent of spill treatment, median times for tagged salmon to first approach a fishway opening generally increased with increasing river discharge.

Table 9. Median times (h) for adult radio-tagged spring–summer Chinook salmon to pass from first tailrace record to first fishway approach, first tailrace record to first fishway entrance, first fishway entrance to the ladder top, and first tailrace record to the ladder top at Little Goose Dam in 2008. Values do not account for spill treatment switching or skipping but are based on the spill treatment at the time of first tailrace entry. Sample sizes are provided in Figures 15-18.

	Spill Treatment	<50 kcfs	50-≤85 kcfs	85-≤115 kcfs	> 115 kcfs	All
First tailrace to first fishway approach	Alternate	1.0	1.0	0.9	2.0	1.2
	Bulk	0.8	1.5	1.6	2.5	1.6
	Uniform	0.9	1.1	1.1	1.6	1.1
First tailrace to first fishway entry	Alternate	2.9	5.0	8.4	6.9	7.3
	Bulk	2.6	16.3	13.4	11.8	11.8
	Uniform	2.3	19.9	5.0	3.7	5.5
First fishway entry to ladder top	Alternate	14.2	7.3	2.6	2.7	3.5
	Bulk	7.3	2.9	3.1	3.0	2.9
	Uniform	4.9	3.4	2.9	3.4	3.1
First tailrace to ladder top	Alternate	26.0	21.7	13.4	10.2	14.5
	Bulk	14.6	21.6	24.4	14.8	21.6
	Uniform	10.6	26.4	9.4	12.9	11.5

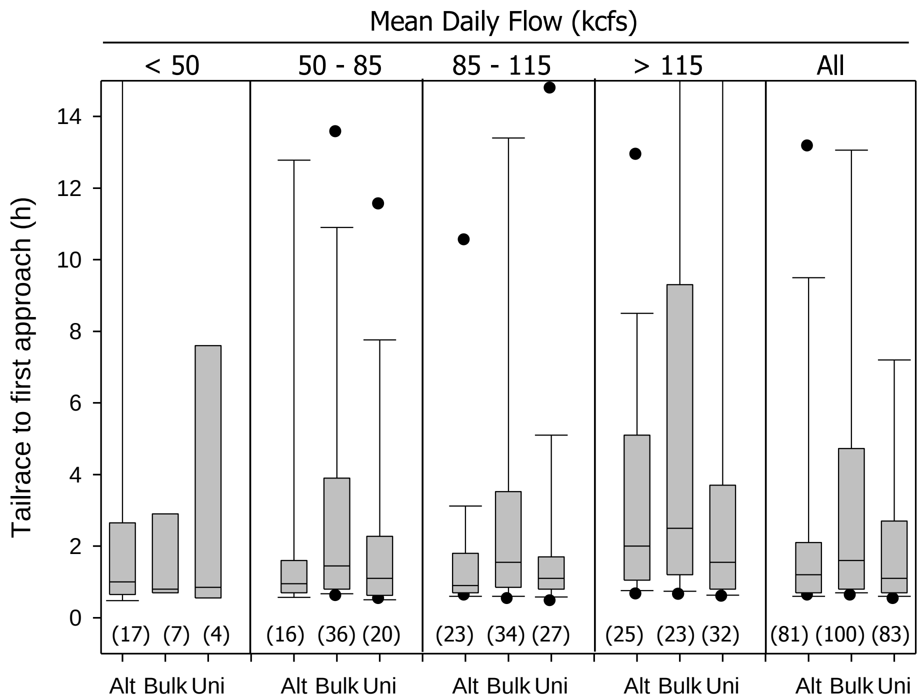


Figure 15. Median (line), quartile (box), 5th and 95th (points), and 10th and 90th (whiskers) percentile of times (h) for radio-tagged spring–summer Chinook salmon to pass from the tailrace to their first fishway approach at Little Goose Dam in 2008. Panels depict passage times for tagged salmon that entered the tailrace during different spill treatments and ranges of mean daily river discharge. Sample sizes are in parentheses at bottom of each box plot.

Passage times from first tailrace record to first fishway entrance generally followed similar patterns. When mean daily flows were <50 kcfs, median times to first enter a fishway were less than 3 h and were similar among all spill treatments (Table 9 and Figure 16). Tagged salmon that entered the tailrace when mean daily flows were 50–85 kcfs during the Bulk and Uniform treatment had similar passage time distributions and the Uniform treatment had the highest median time to first enter a fishway opening. When mean daily flows exceeded 85 kcfs, tagged salmon assigned to the Bulk treatment had the highest median time to first enter a fishway (13.4 h). Differences in median times to first enter a fishway were generally more pronounced among treatments than median times to first approach a fishway, particularly at the higher flows. Overall, the median time to first entry among tagged salmon entering the tailrace during the Bulk spill was 62% higher than salmon assigned the Alternate treatment. The median time to first entry for the Bulk treatment was more than two times higher than the Uniform treatment median.

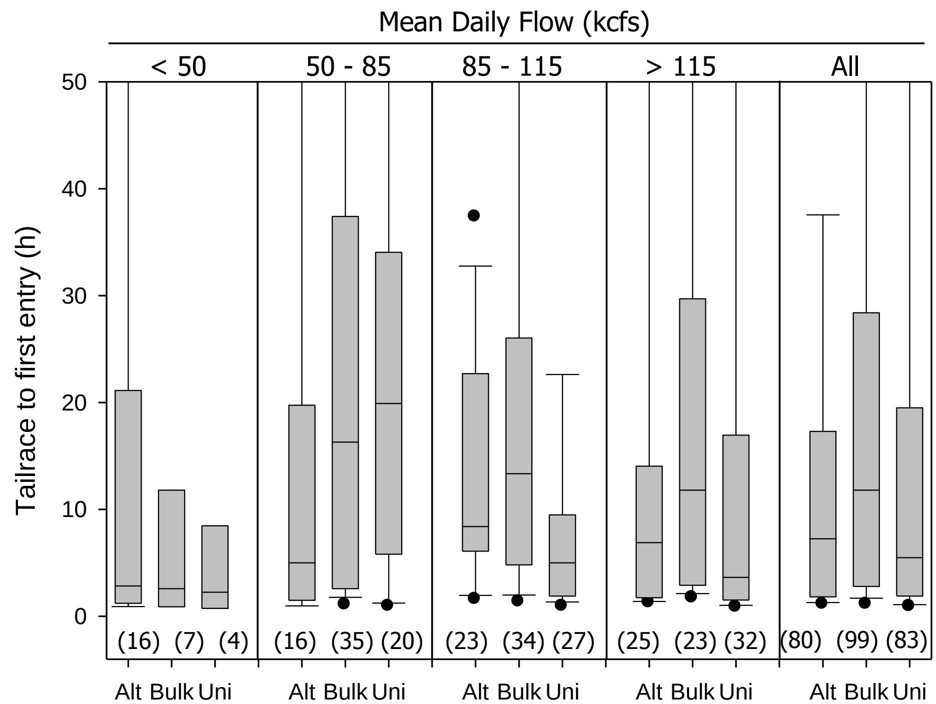


Figure 16. Median (line), quartile (box), 5th and 95th (points), and10th and 90th (whiskers) percentile of times (h) for radio-tagged spring–summer Chinook salmon to pass from the tailrace to their first fishway entry at Little Goose Dam in 2008. Panels depict passage times for tagged salmon entering the tailrace during different spill treatments and ranges of mean daily river discharge. Sample sizes are in parentheses at bottom of each box plot.

Passage times from first entry to ladder exit were not consistently related to spill treatment (Figure 17). The highest variation in median times to pass the dam after first entering a fishway was for tagged salmon that entered the tailrace when mean daily flows were <50 kcfs and for tagged salmon that entered the tailrace during the Alternate treatment when flows were <85 kcfs (*range* = 2.9-14.2 h) (Figure 11). The high passage times for these fish was likely a reflection of the disproportionately high percentage of them that exited the dam to the tailrace. Specifically, 25 of the 41 tagged salmon in this group (61%) exited the dam to the tailrace whereas only 20% (49/242) of all other tagged salmon exited the dam to the tailrace. Apart from tagged salmon that entered the tailrace when mean daily flows were <50 kcfs or encountered the Alternate spill treatment at the

50-85 kcfs stratum, median times to pass the dam after first entry varied little among mean daily flow categories (*range* = 2.6-3.5 h).

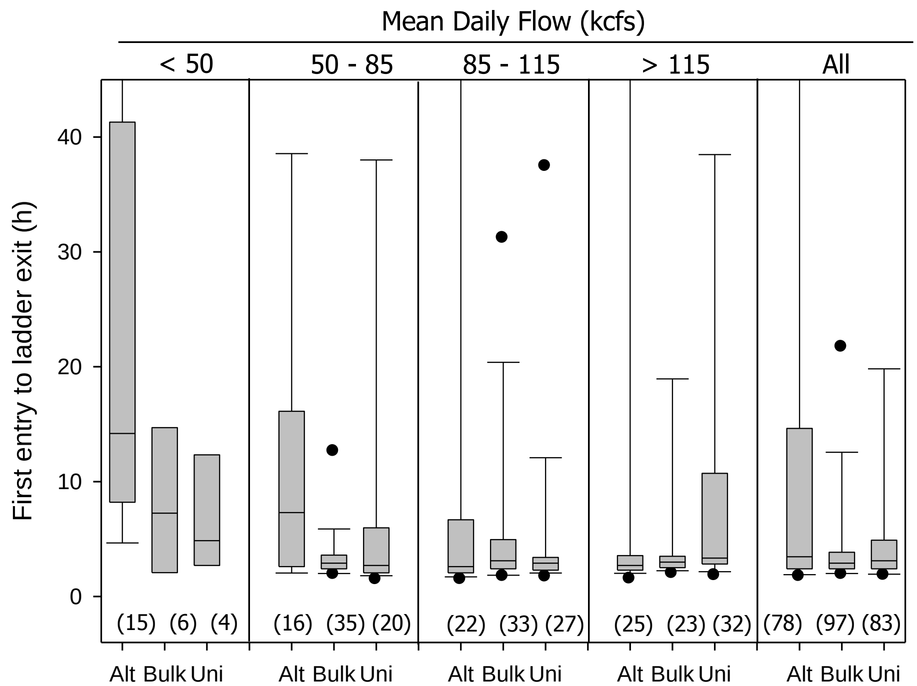


Figure 17. Median (line), quartile (box), 5th and 95th (points), and10th and 90th (whiskers) percentile of times (h) for radio-tagged spring–summer Chinook salmon to pass from first fishway entry to the ladder top at Little Goose Dam in 2008. Panels depict passage times for tagged salmon entering the tailrace during different spill treatments and ranges of mean daily river discharge. Sample sizes are in parentheses at bottom of each box plot.

Overall, the patterns in total dam passage times (tailrace to ladder exit; Figure 12) were similar to tailrace passage times (tailrace to first entry; Figure 10), with the exception that the long fishway passage times in the Alternate treatment were apparent in total passage time during the low flow period. When mean daily flows were 85-115 kcfs, the highest median dam passage time was during the Bulk treatment. Similarly, the median dam passage time was highest for tagged salmon entering the tailrace during the Bulk treatment when mean daily flows exceeded 115 kcfs. As in other passage segments, differences in median dam passage times among spill treatments decreased when mean daily flows exceeded 115 kcfs.

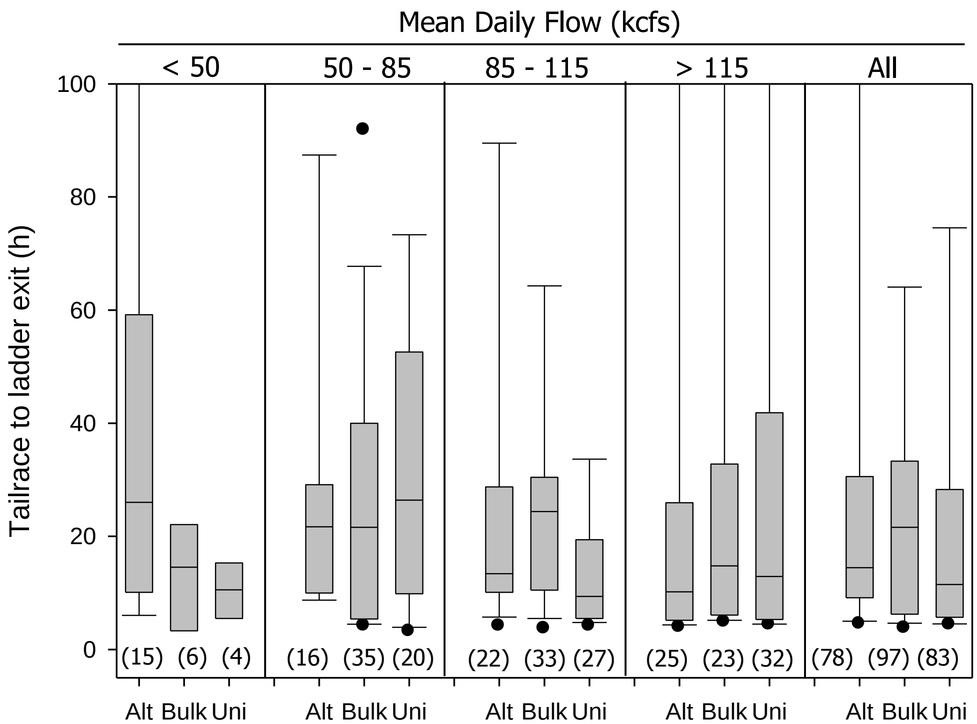


Figure 18. Median (line), quartile (box), 5th and 95th (points), and10th and 90th (whiskers) percentile of times (h) for radio-tagged spring–summer Chinook salmon to pass from the tailrace to the ladder top at Little Goose Dam in 2008. Panels depict passage times for tagged salmon entering the tailrace during different spill treatments and ranges of mean daily river discharge. Sample sizes are in parentheses at bottom of each box plot.

Time of Tailrace Arrival versus Passage Times

Passage times from tailrace to first fishway entry and to the ladder top were associated with the time of tailrace entry (Figures 13-14). With all spill treatments combined, tagged salmon first detected in the tailrace before 1600 hrs had a median time from tailrace to first entry of 6.0 h (n = 229). In contrast, tagged salmon detected in the tailrace after 1600 hrs each day had a median time from tailrace to first entry of 16.6 h (n = 33). Dam passage times exhibited similar patterns. Specifically, tagged salmon first detected in the tailrace before 1600 hrs had a median time from tailrace to ladder top of 13.1 h (n = 226) whereas those detected in the tailrace after 1600 hrs each day had a median dam passage time of 22.6 h (n = 32).

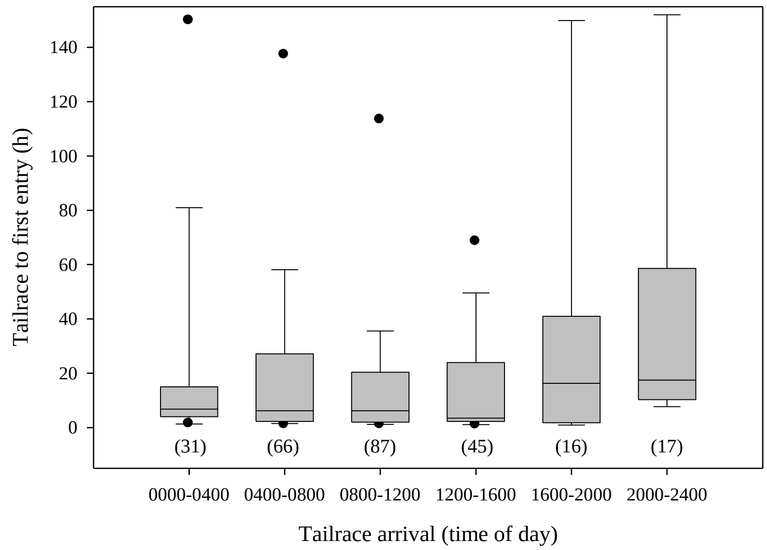


Figure19. Median (line), quartile (box), 5th and 95th (points), and10th and 90th (whiskers) percentile of times (h) for radio-tagged spring–summer Chinook salmon to pass from the tailrace to first fishway entry at Little Goose Dam in 2008. Panels depict passage times for tagged salmon entering the tailrace during different times of day. Sample sizes are in parentheses at bottom of each box plot.

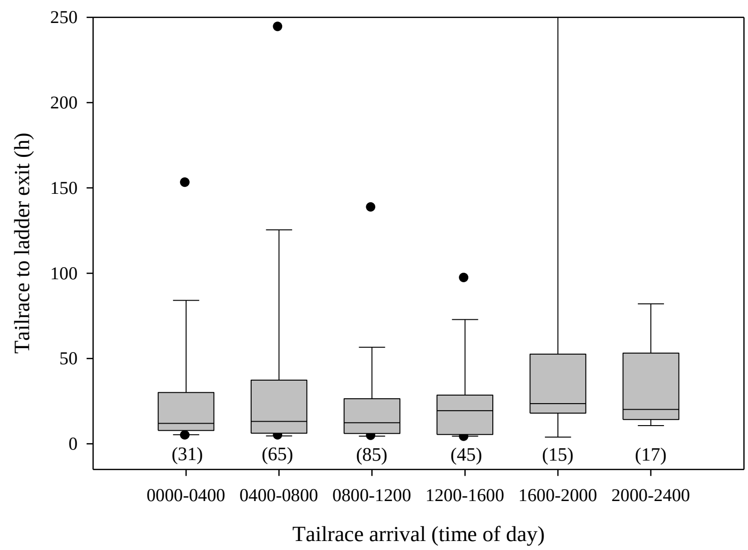


Figure 20. Median (line), quartile (box), 5th and 95th (points), and10th and 90th (whiskers) percentile of times (h) for radio-tagged spring–summer Chinook salmon to pass from the tailrace to ladder top at Little Goose Dam in 2008. Panels depict passage times for tagged salmon entering the tailrace during different times of day. Sample sizes are in parentheses at bottom of each box plot.

Time-Event Analysis

Among the four PHReg models evaluated for tailrace passage time (tailrace entry to first fishway entry), the model that included spill treatment, time-of-day (TOD), temperature, spill volume, flow volume category, and the flow volume category × spill treatment interaction term was best supported by the data (Model D, Table 10). An identical model excluding spill volume was statistically indistinguishable (Model B, ΔAIC < 2). Similar models excluding the interaction term were not well supported by the data (ΔAIC > 4, W_i < 0.057), consistent with qualitative patterns observed in median passage times among treatments and flow categories (Figure 16). Specifically, the interaction term indicated that the differences in passage time between treatments were greater during high river discharge conditions. Results for models D and B are outlined below.

Several environmental predictors were significantly associated with passage rate. Significant differences in instantaneous passage rates were found in time of day (day versus night; P <0.0001) and temperature (P < 0.0001). The hazard ratio estimates for time of day (6.041-6.133) suggested that tagged salmon were six times more likely to enter a fishway opening during daytime hours compared to nighttime hours, consistent with past studies of salmonid passage (e.g., Naughton et al. 2005, Caudill et al. 2007). The hazard ratio estimates for temperature (1.140-1.150) suggested that individuals were 14-15% more likely to be initially detected inside a fishway opening for each 1 ºC increase in water temperature over the range of temperatures observed. We found no significant linear relationships between instantaneous passage rates and spill volume (P = 0.1306, Model D only) when simultaneously accounting for flow volume category. Similarly, there was no overall flow volume (P = 0.3906-0.7327) effect, though this variable was important in describing the interaction between spill treatment and flow on passage rate (Flow Vol. Cat. X Spill Treatment P = 0.0142-0.0202).

Table 10. Akaike information criterion (AIC) estimates for PHReg models (Model letter refers to Table 11) including spill treatment as a categorical variable. ΔAIC values are differences between the model AIC value and the model with the lowest AIC value. W*i* values are AIC weights, which reflect the weight of evidence in favor of model *i* being the most explanatory model among those evaluated. TOD = time of day (day vs. night).

Model	Parameters	AIC	ΔAIC	W*i*
D	Spill Trt. + TOD + Spill Vol. + Temp. + Flow Vol.	2306.929	0.000	0.496

	Category + Flow Vol. Category × Spill Trt. (interaction)			
B	Spill Trt. + TOD + Temp + Flow Vol. Category + Flow Vol. Category × Spill Trt. (interaction)	2307.375	0.446	0.397
A	Spill Trt. + TOD + Temp. + Flow Vol. Category	2311.241	4.312	0.057
C	Spill Trt. + TOD + Spill Vol. + Temp. + Flow Vol. Category	2311.506	4.577	0.050

Passage rate differed among spill treatments (Spill Treatment effect), though the treatment effect differed between high and low river discharge categories (Flow Vol. Cat. X Spill Treatment effect). Specifically, we observed a significant overall spill treatment effect (i.e., there was evidence that passage rate differed in consistent ways between the high and low river discharge categories; *P* = 0.022-0.034) because passage rates during Uniform and Alternate treatments were 51.1-59.9% faster than during Bulk treatment periods when estimated across all river discharges (hazard ratios = 1.511-1.599; Table 11). However, there was evidence that passage rates were significantly different between treatments for the Alternate vs. Bulk at high, but not low river discharges (hazard ratio_{low} ~1.0; hazard ratio_{high} = 1.434; analyses not shown) using models restricted to low or high discharges, respectively. In contrast, the estimated differences in passage rate were comparatively similar at low and high river discharges for the Uniform vs. Bulk comparisons (hazard ratio_{low} = 1.838; hazard ratio_{high} = 1.648), consistent with the overall treatment effect. The observed statistical interaction may have resulted from an undetected difference at low river discharges for the Alternate vs. Bulk treatment or a true interactive effect. Regardless, the results were generally consistently with qualitative patterns in the data (e.g., Figure 16) and revealed passage rates were slower during Bulk treatments during most treatment and flow combinations.

Table 11. Results of Cox Proportional Hazard regression tests of spill treatment effects and selected covariates on instantaneous rates of first fishway entry by radio-tagged spring–summer Chinook salmon at Little Goose Dam during 2008. Hazard ratios are expressed as the change in the probability of first fishway entry for one spill treatment compared to another, the change associated with an increase in spill volume of 10 kcfs, the change associated with changing from daytime to nighttime, or the change in flow volume category (≤ 85 kcfs or > 85 kcfs). The hazard ratio for temperature is scaled as the change in hazard per 1˚C increase. Sample size is 265 fish for all analyses. Three fish were censored during each analysis.

Model	**Model Parameter(s)**	**d.f.**	**Reference**	**Test Trt.**	**Estimate**	**Std Err**	χ^2	***P***	**Hazard**

			Trt.						Ratio
D	Time of Day	1	-	-	1.79852	0.26066	47.6100	<0.0001	6.041
	Temperature	1	-	-	0.13125	0.02443	28.8728	<0.0001	1.140
	Spill Volume	1	-	-	-0.07126	0.04714	2.2856	0.1306	0.931
	Spill Treatment	2	-	-	-	-	0.1166	0.7327	-
			Bulk	Alternate	0.45683	0.20176	5.1267	0.0236	1.579
			Bulk	Uniform	0.46964	0.18599	6.3763	0.0116	1.599
			Uniform	Alternate	-0.01280	0.19084	0.0045	0.9465	0.987
	Flow Vol. Category	1	-	-	-0.09874	0.28915	0.1166	0.7327	0.906
	Flow Vol. Cat. X Spill Treatment Interaction	2	-	-	-	-	8.5107	0.0142	-
B	Time of Day	1	-	-	1.81370	0.26049	48.4794	<0.0001	6.133
	Temperature	1	-	-	0.13984	0.02406	33.7864	<0.0001	1.150
	Spill Treatment	2	-	-	-	-	6.7656	0.0340	-
			Bulk	Alternate	0.41308	0.19982	4.2737	0.0387	1.511
			Bulk	Uniform	0.44894	0.188557	5.8525	0.0156	1.567
			Uniform	Alternate	-0.03585	0.18994	0.0356	0.8503	0.965
	Flow Vol. Category	1	-	-	0.23700	0.27606	0.7370	0.3906	-
	Flow Vol. Cat. X Spill Treatment Interaction	2	-	-	-	-	7.8079	0.0202	-
A	Time of Day	1	-	-	1.80846	0.26056	48.1724	<0.0001	6.101
	Temperature	1	-	-	0.10931	0.02164	25.5252	<0.0001	1.116
	Spill Treatment	2	-	-	-	-	5.4660	0.0650	-
			Bulk	Alternate	0.07471	0.15821	0.2230	0.6368	1.078
			Bulk	Uniform	0.35118	0.15342	5.2396	0.0221	1.421
			Uniform	Alternate	-0.27647	0.17115	2.6095	0.1062	0.758
	Flow Vol. Category	1	-	-	-	-	0.0006	0.9797	-
C	Time of Day	1	-	-	1.79572	0.26073	47.4354	<0.0001	6.024
	Temperature	1	-	-	0.10166	0.02225	20.8740	<0.0001	1.107
	Spill Volume	1	-	-	-0.05843	0.04559	1.6428	0.1999	0.943
	Spill Treatment	2	-	-	-	-	5.5520	0.0623	-
			Bulk	Alternate	0.09312	0.15892	0.3433	0.5579	1.098
			Bulk	Uniform	0.35695	0.15333	5.4197	0.0199	1.429
			Uniform	Alternate	-0.26383	0.17177	2.3590	0.1246	0.768
	Flow Vol. Category	1	-	-	0.9786	0.16068	0.3709	0.5425	1.103

Detections of Radio-tagged Steelhead at Little Goose Dam

Eighty-six adult steelhead were collected and outfitted with radio transmitters at Ice Harbor Dam from 8 July through 29 August 2008. Of these, 27 were recorded on receiver sites at Little Goose Dam before 1 September 2009, the date when spill ceased.

Of these 27 tagged steelhead, six were initially recorded on dates when the Alternate spill pattern was applied, seven during the Bulk spill pattern, and 14 during the Uniform spill pattern. Mean daily flows were less than 50 kcfs on all dates when tagged steelhead were first detected at Little Goose Dam before 1 September 2009. Forty-eight percent of the tagged steelhead were recorded during their first passage of the tailrace area, 81% were recorded during their first fishway approach, 93% were recorded during their first fishway entrance, and 85% were recorded when passing the ladder top (Table 11). Four fallback events were recorded by four unique radio-tagged steelhead and three re-ascension events were recorded by three unique radio-tagged steelhead. No post-fallback passage events were evaluated as part of this report and all passage times presented here are for initial passage events only.

Table 11. Number and percent of adult radio-tagged steelhead recorded at Little Goose Dam through 30 August 2008, that were recorded on their first passage of the tailrace, first approach at a fishway opening, first fishway entry, and exit from the top of the ladder.

2008 - Steelhead	Freq.	Percent
Recorded at dam	27	100
Known to pass dam	23	85
Recorded first tailrace passage	13	48
Recorded first (known) fishway approach	22	81
Recorded first (known) fishway entrance	25	93
Recorded ladder exit	23	85

The median time for adult steelhead to first approach a fishway opening after being detected in the tailrace was 3.2 h (Table 12). The median time to enter a fishway after first approaching one was 0.7 h. The median time from the tailrace to first entry was 11.4 h and the median time to pass from the tailrace to the ladder top was 19.7 h. Sample size limited any quantitative analyses beyond calculation of these descriptive statistics.

Table 12. Sample sizes of adult radio-tagged steelhead recorded at Little Goose Dam through 30 August 2008 and their median times to pass (h) from first tailrace record to first fishway approach, first fishway approach to first fishway entry, first tailrace to first fishway entrance, and from first tailrace to the ladder top at Little Goose Dam, 2008.

Metric	N	Minimum (h)	Median (h)	Maximum (h)

Tailrace to 1st approach	13	0.6	3.2	16.0
1st Approach to 1st entry	25	<0.1	0.7	83.9
Tailrace to 1st entry	13	0.7	11.4	86.4
Tailrace to ladder top	9	3.3	19.7	522.2

Detections of Radio-tagged Fall Chinook Salmon at Little Goose Dam

Fifty-one adult fall Chinook salmon were collected and outfitted with radio transmitters at Ice Harbor Dam from 12-29 August 2008. Of these, 22 were recorded on receiver sites at Little Goose Dam before 1 September 2009, the date when spill ceased. Of these 22 tagged salmon, ten were initially recorded on dates when the Alternate spill pattern was applied, eight during the Bulk spill pattern, and four during the Uniform spill pattern. Mean daily flows were less than 50 kcfs on all dates when tagged fall Chinook were first detected at Little Goose Dam before 1 September 2009. Sixty-eight percent of the tagged fall Chinook salmon were recorded during their first passage of the tailrace area, all were recorded during their first fishway approach, 95% were recorded during their first fishway entrance, and all were recorded when passing the ladder top (Table 13). Five fallback events were recorded by five unique radio-tagged fall Chinook salmon and one re-ascension event was recorded by a radio-tagged fall Chinook salmon. No post-fallback passage events were evaluated as part of this report and all passage times presented here are for initial passage events only.

Table 13. Number and percent of adult radio-tagged fall Chinook salmon recorded at Little Goose Dam through 30 August 2008, that were recorded on their first passage of the tailrace, first approach at a fishway opening, first fishway entry, and exit from the top of the ladder.

2008 – Fall Chinook	Freq.	Percent
Recorded at dam	22	100
Known to pass dam	22	100
Recorded first tailrace passage	15	68
Recorded first (known) fishway approach	22	100
Recorded first (known) fishway entrance	21	95
Recorded ladder exit	22	100

The median time for adult fall Chinook salmon to first approach a fishway opening after being detected in the tailrace was 1.5 h (Table 14). The median time to enter a fishway after first approaching one was 0.2 h. The median time from the tailrace to first entry was 3.1 h and the median time to pass from the tailrace to the ladder top was 23.3 h. Sample size limited any quantitative analyses beyond calculation of these descriptive statistics.

Table 14. Sample sizes of adult radio-tagged fall Chinook salmon recorded at Little Goose Dam through 30 August 2008 and their median times to pass (h) from first tailrace record to first fishway approach, first fishway approach to first fishway entry, first tailrace to first fishway entrance, and from first tailrace to the ladder top at Little Goose Dam, 2008.

Metric	N	Minimum (h)	Median (h)	Maximum (h)
Tailrace to 1st approach	15	0.5	1.5	46.7
1st Approach to 1st entry	22	<0.1	0.2	238.6
Tailrace to 1st entry	15	0.8	3.1	269.7
Tailrace to ladder top	15	3.0	23.3	272.8

Discussion

The results of these evaluations were broadly consistent with the hypothesis that the Bulk spill pattern slowed the migration of adult spring–summer Chinook salmon at Little Goose Dam. Operational constraints resulted in some fish experiencing more than one spill treatment which rendered traditional statistical techniques inappropriate for analysis of passage times. The use of Cox Proportional Hazards Regression (PHReg), however, incorporated the change of spill treatments during the passage of individual fish. Specifically, this analysis evaluated whether passage rates increased as spill conditions changed, while statistically controlling for variation in other predictor variables.

Flow volume categories were evaluated as a covariate because migration rates are reduced in adult salmonids at high river discharges (Keefer et al. 2004; Caudill et al. 2006) and in areas of high hydraulic complexity (Hinch and Rand 1998). Turbulence in the tailrace generally increases with increasing spill volumes, which can result in increased search times and the inability of some individuals to orient to fishway openings. Additionally, spill pattern and gross surface circulation patterns in the tailrace converged among treatments at the highest river discharges. Temperature was included as a covariate because of its known effects on fish energetics and behavior (Brett 1995). Chinook salmon swim faster and have shorter passage times (corresponding to increased passage hazard) as temperatures warm through the spring and early summer (e.g., Keefer et al. 2008).

Results of multiple linear regression analyses indicates several factors related to dam operations could be used as predictors of adult ladder counts, but they did not point to a single condition that should be avoided. There were positive effects of discharge in several of the models, indicating ladder counts generally increased during periods of higher discharge. Spill operations generally had negative effects, except for spill discharge (volume), which was related to overall discharge. Spill percent and the presence of a bulk spill pattern had negative effects in several years. The amount of uncontrolled spill was an important factor in the 2008 model and the overall model and had a negative effect. The number of variables in the models and examination of the data plots suggest adult ladder counts were affected by several factors in concert, such as the presence of low discharge, high spill percent, and turbine 1 being off. The fit of the models may be improved if the passage dates of the fish that build up in the tailrace when conditions are poor could be predicted. We did not include this effect in our models, but the data plots clearly indicated this occurred. For example, in 2007 there was a lag of passage in late May as indicated by the divergence of counts at Lower Monumental and Little Goose dams and this caused thousands of fish to pass within about 2 days after changes in the spill pattern and powerhouse operations.

Why didn’t dam counts decrease significantly during the Bulk treatment? Possible explanations include salmon entering a fishway during one spill treatment and passing the counting window after a treatment change the ensuing day. Alternately, the Bulk treatment was deployed for a maximum of two days at a time, which may not have provided enough time for a large accumulation of adults in the tailrace and consequent dramatic increases in passage rates and daily counts with changes in spill pattern. A similar pattern was observed by Caudill et al. (2006) during a spill manipulation at Bonneville Dam. In that study, daily dam counts were not strongly associated with spill pattern while passage times analyzed using PHReg clearly indicated that slowed passage was associated with high spill rates. Despite not currently having the means for obtaining reliable real-time estimates of Chinook salmon escapement to the Tucannon River, a Snake River tributary entering Lower Monumental reservoir, the continued monitoring and in-season comparisons of counts at Little Goose versus Lower Monumental Dam are recommended, as evidenced by the divergence in passage distributions between Lower Monumental and Little Goose dams in 2007. However, we caution that the use of dam counts may not be sensitive enough to detect biologically significant alterations to adult salmonid passage behavior at dams.

The use of drogues characterized surface hydraulic conditions across a range of spill and flow conditions. Large eddies were always present in the tailrace, though their size and cohesiveness varied with discharge and spill patterns. The size of the eddy downriver from the powerhouse increased with river discharge and was most cohesive during the Bulk spill pattern. This eddy and another downriver from the earthen dam presumably resulted from the interaction of river discharge and the shape and bathymetry of the tailrace. Large shallow areas exist downriver from the powerhouse and mid-river near the bypass outfall. Well under 50% of the drogues released at the spillway and two fishway openings at the powerhouse reached the BRZ line within 30 minutes, which is inconsistent with data from other dams. Nearly all drogues released into the tailraces of John Day and The Dalles dams reached the BRZ (about the same distance as in this study) and their median travel times ranged from about 4 to 20 min, depending on the release location (Beeman et al. 2006; Liedtke et al. 2009).

The mechanism by which fishway openings were made less attractive for entry during the Bulk spill treatment was likely related to tailrace conditions. Specifically, at mean daily flows <115 kcfs, the highest percentage of first approaches during the Bulk treatment occurred at the south powerhouse fishway, which was where and when the powerhouse eddy was largest. However, only 14-26% of the first approaches at the south powerhouse fishway resulted in entries during the Bulk treatment. In contrast, tagged salmon that entered the tailrace during the Uniform treatment had the highest percentage (36%) of first approaches that resulted in fishway entries. The importance of salmon first entering a fishway was underscored by the observation that relatively few (29%) tagged salmon exited back to the tailrace and by the relatively small variation in median times from first fishway entry to the ladder top. These observations may have been reflections of the biological imperative for salmon to reach spawning grounds, generally favorable passage conditions inside the Little Goose Dam fishway, unfavorable hydraulic conditions in the tailrace, or perhaps most likely, a combination of the three.

Increased metabolic cost of dam passage is a mechanism by which the spill treatments may decrease adult salmonid survival and reproductive success. Increased passage times may cause the premature depletion of energetic reserves, which are fixed at the time of freshwater entry (Williams 1998), and slowed migration has been associated with unsuccessful migration to spawning tributaries in the Columbia and Snake River sockeye salmon (Naughton et al. 2005, Caudill et al. 2007).

Based on the combined findings of the qualitative comparisons of median passage times, the percentage of first fishway approaches resulting in fishway entries, the relatively small difference in dam passage times once salmon entered the fishway, and the statistical analyses of passage time, the Bulk treatment appeared to provide the least optimal tailrace conditions for adult Chinook salmon passage among all spill patterns applied at Little Goose Dam over the range of river flows encountered in 2008.

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