Technical Report 2006-5

IDAHO COOPERATIVE FISH AND WILDLIFE RESEARCH UNIT

ADULT CHINOOK SALMON AND STEELHEAD DAM PASSAGE BEHAVIOR IN RESPONSE TO MANIPULATED DISCHARGE THROUGH SPILLWAYS AT BONNEVILLE DAM

Report for study ADS-00-1

By
Christopher C. Caudill, Christopher A. Peery, William R. Daigle, Michael A. Jepson, Charles T. Boggs, Theodore C. Bjornn, and Daniel Joosten
Idaho Cooperative Fish and Wildlife Research Unit
Department of Fish and Wildlife Resources
University of Idaho, Moscow, Idaho 83844-1141

and

Brian J. Burke and Mary L. Moser
Northwest Fisheries Science Center,
National Marine Fisheries Service (NOAA Fisheries),
2725 Montlake Blvd. East, Seattle, Washington 98112

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Study Codes ADS-001 and ADS-002

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Christopher C. Caudill, Christopher A. Peery, William R. Daigle, Michael A. Jepson,
Charles T. Boggs, Theodore C. Bjornn, and Daniel Joosten
Department of Fish and Wildlife Resources
U.S. Geological Survey, Idaho Cooperative Fish and Wildlife Research Unit
University of Idaho, Moscow, Idaho 83844-1141

And

Brian J. Burke and Mary L. Moser
Fish Ecology Division,
Northwest Fisheries Science Center,
National Marine Fisheries Service
2725 Montlake Blvd. East, Seattle, Washington 98112

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Table of Contents

Abstract

The river conditions encountered at dams in the Columbia-Snake River Basin by returning adult salmonids are strongly affected by discharge over dam spillways (spill) during spring run-off. In recent years, dam operators have altered hydrosystem operations to continue spilling through the summer in an effort to improve survival of downstream migrating smolts. However, this action may slow the migration of adults through a number of mechanisms. During 2000, 2002, and 2003, spill levels at Bonneville Dam were alternated between low (~75 kcfs) and high (85-160 kcfs) spill volume conditions to determine the effects of spill on adult upstream migration behavior. We monitored daily dam counts and the migration of radio-tagged adult spring, summer, and fall Chinook salmon and steelhead as they passed the dam during these two treatments.

Daily dam counts of adults were 16.5-32.0% lower during high spill conditions than during low spill conditions. Individual radio-tagged fish could not be assigned or restricted to single treatments, and many of those requiring more than one day to pass the dam experienced both treatment conditions while in the dam tailrace. Among fish experiencing no change in treatments, a greater proportion of spring Chinook salmon and steelhead passed through the tailrace under low spill treatments. Among fish experiencing a switch in treatment during dam passage, a greater proportion of spring Chinook salmon entered the tailrace under the high spill treatment and entered fishways after a switch to low spill treatment than vice versa, suggesting an increase in fishway entrance rates as spill decreased. Cox proportional hazards regression models accounted for the changing treatment and environmental conditions and revealed that individuals in all stocks were 14 - 16% less likely to enter fishways under high than low spill treatments, though the effect was not significant for fall Chinook salmon. Minimum estimates of the difference in median passage time between high and low treatments were 8.64-8.68 hours in spring Chinook salmon in 2002-3, 3.33 hours for fall Chinook salmon in 2002, and 3.85 hours in steelhead in 2002. However, these estimates almost certainly underestimate the effects of constant high spill because of treatment switching. There was no evidence that the differences in median passage time between treatments increased at relatively high spill levels within the high spill treatment. Comparisons of behaviors in the spillway and tailrace between the two treatments supported the hypothesis that migration routes though the tailrace were less direct during high spill. Fallback by spring Chinook salmon was also related to spill and to inter-annual differences in powerhouse priority. The observed relationships between spill and passage behavior were probably related to flow conditions and increased turbulence in the tailrace rather than the result of exposure to high dissolved gas conditions.

The recent observation of a relationship between slow dam passage and delayed mortality upstream in adult salmonids suggests that slow migration may have negative effects on adults. Overall, the results highlight the need for

mechanistic understanding of how behavior at individual dams and the cumulative experience of adults in the hydrosystem affects survival and reproductive success.

Introduction

Salmonids in the Columbia and Snake Rivers encounter as many as nine dams during upstream migration. Environmental conditions encountered by fish at dams are strongly affected by river discharge and the amount of water passed over the dam through the spillbays. Control of spill levels represents perhaps the strongest control on river environment available for dam operators and fisheries managers. Consequently, understanding the relationship between spill level and fish passage is critical. Previous studies (Keefer et al. 2004, Boggs et al. 2004) suggested that the migration rate of adult salmonids slows under high spill and river discharge. However, since high discharge conditions are also associated with periods of high uncontrolled spill—periods when river discharge exceeds turbine capacity, previous investigations were unable to determine the relative roles of discharge versus spill in slowing migration using observational data.

Dam operators and fisheries managers at Columbia Basin dams have voluntarily spilled water during the period of juvenile out-migration (including low discharge periods) as part of salmon recovery efforts since 1994. Dam passage via spillways appears to have higher survival than other passage routes for juveniles (Muir et al. 2001a, 2001b, Berggren et al. 2005). In potential conflict with this management action, spill may negatively affect adult salmonids migrating upstream by altering hydraulic conditions and water quality. Consequently, the U.S. Army Corps of Engineers, University of Idaho, and NOAA-Fisheries conducted an experiment to directly test the effect of spill on adult salmonid migration behavior and rate at Bonneville Dam in 2000, 2002, and 2003 (2001 was a year of low discharge and no-spill conditions during much of the salmon migration season). The results of the spill experiment are the subject of this report.

Spill affects the river environment in several ways. Water from spillways enters the tailrace at high velocity compared to turbine-released water, markedly increasing turbulence and dissolved gas concentrations. High flow velocities may attract adult migrants to tailrace areas but turbulence may slow passage as adults search for relatively low-volume attraction flows at fishway entrances. Slowed migration resulting from spill is a concern because of the potential for reduction in survival and reproductive success caused by the depletion of fixed energetic reserves during migration (Williams 1998). Slowed migration has been associated with unsuccessful migration to spawning tributaries in Columbia and Snake River sockeye salmon (Naughton et al. 2005), as well as Chinook salmon and steelhead (Caudill et al. in review). Spill increases dissolved gas concentrations as atmospheric gases are forced into solution when water spilled at dams is plunged into stilling basins, frequently increasing total dissolved gas (TDG) concentrations to 110-130 % above saturation. Exposure to supersaturated river conditions can cause development of gas bubble disease (GBD) in juvenile and adult salmonids (Backman et al. 2002, Backman and Evans 2002) and in resident fishes (Weitkamp et al. 2003). Late run spring-, summer- and early fall-run salmonids may encounter high spill, high TDG, and high temperatures during spill periods, suggesting the potential for interactive or cumulative effects.

Spill also affects flow patterns in dam forebays and may contribute to fallback—the downstream movement of adults over dams (Boggs et al. 2004)—because greater surface flows through forebays may entrain and/or guide fish into spillbays after exiting fishways (Reischel and Bjornn 2003). The factors controlling fallback are complex and appear to be related to juvenile experience, large-scale homing behaviors, and dam configuration and operations (Reischel and Bjornn 2003; Boggs et al. 2004). Regardless of mechanism, fallback is generally associated with a survival cost (Keefer et al. 2005, but see Naughton et al. 2006).

We performed an experiment during 2000-2003 in collaboration with the U.S. Army Corps of Engineers (USACE) and other regional fisheries agencies to test the effects of spill on adult salmonid passage at Bonneville Dam on the Columbia River. During the spill season, dam operators manipulated the spill at Bonneville Dam while we monitored dam counts and radio-tagged, released, and monitored the passage of adult salmonids using an extensive array of receivers at the dam. We focused our analyses on two behaviors: the time required to pass through the tailrace and enter the fish passage facilities at the dam and the relationship between spill level and fallback. In addition, we used information from a radiotelemetry antenna array deployed in the spillbay during 2003 to examine the relationships between spill treatment, salmon behavior in the tailrace, and dam passage.

Methods

Study system and spill manipulation

The spill manipulation was conducted at Bonneville Dam on the Columbia River. The Columbia River is the third largest river system in North America, draining an area of 671,000 km^2 including nearly all of Idaho and large areas of Oregon, Washington, and British Columbia. Mean annual discharge at the river's mouth is approximately 6,600 m^3 sec^{-1}. Bonneville Dam (river km 235) is the first of a series of mainstem dams that interior Columbia and Snake River basin adult salmonids must pass before reaching natal tributaries (NRC 1996).

During the experiment, daily spill levels were alternated in a randomized block design (Figure 1, Appendix 1) as we radio-tagged fish, released them downstream of the dam, and observed their passage behavior. Many fish experienced more than one treatment because they took more than a single day to pass Bonneville Dam after release. Below, we outline the details of the manipulation, identify the challenges and limitations imposed by the nature of the study system, and describe the analytic approaches used.

Each block included two spill treatments (low, high) which were in effect from approximately 600-1900 hrs for three (2000) or two consecutive days (2002, 2003). The order of treatment within block was randomly assigned. Consequently, treatment levels remained constant for a maximum of six days (2000) or four days (2002, 2003)

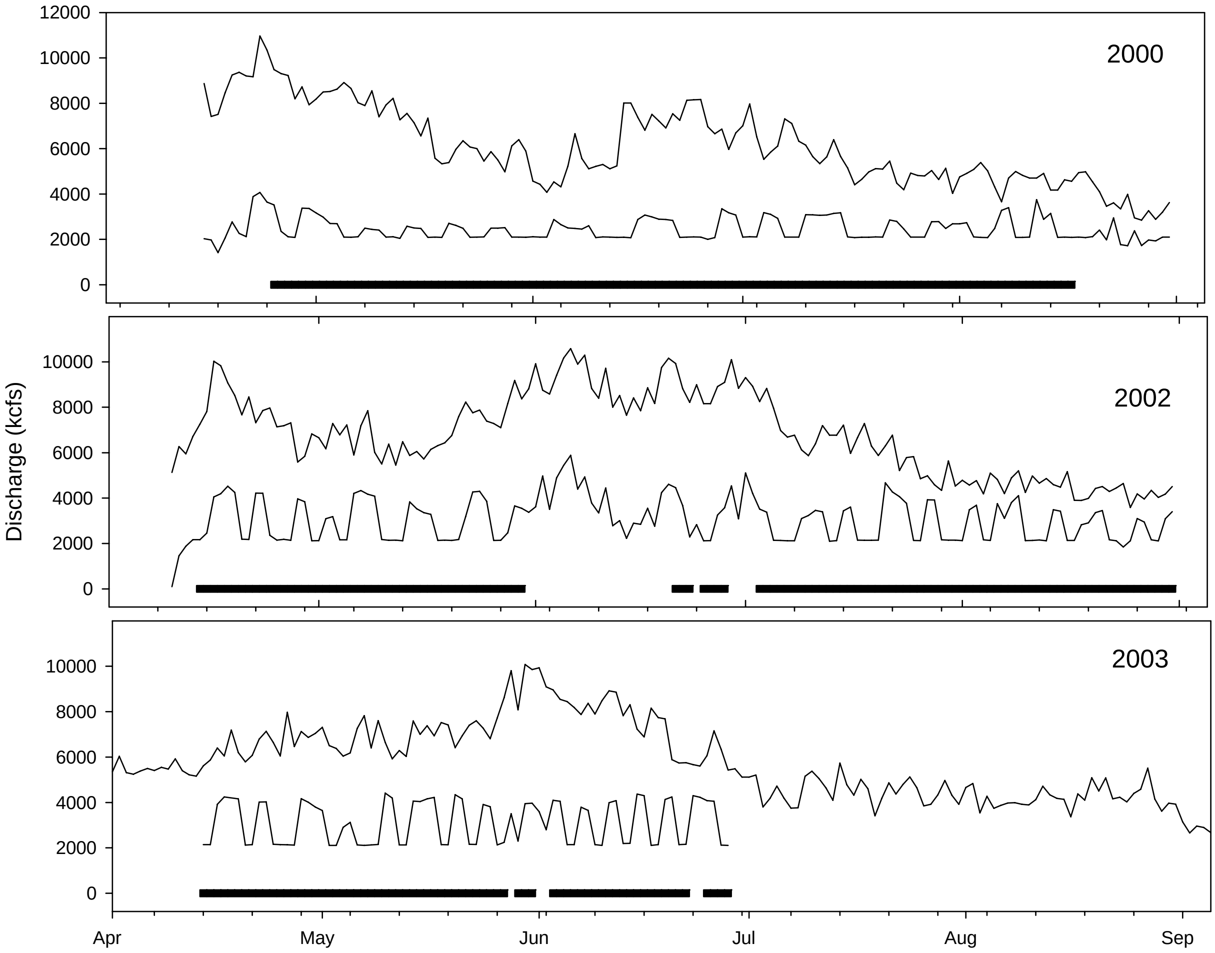

Figure 1: Mean daily Columbia River discharge (upper line) and spill (lower line) at Bonneville Dam during the three year study. Black bars denote the period of spill manipulation; periods of high discharge during 2002 and 2003 resulted in periods of uncontrolled high spill and breaks in the experiment.

across adjacent blocks (e.g. Figure 2). The target uncorrected spill level for the low treatment was 75 kcfs in all years. Spill in the high spill treatment was constrained by a gas cap, the spill level resulting in ≤ 110% TDG in the dam tailrace. The difference in spill level between treatments increased among years of the study and was more variable within the high spill treatment than within the low spill treatment within year (see Results). Within year, the criteria in Table 1 were used to operationally classify days as having high versus low spill for the purposes of analysis.

In early spring, spill levels were high at night to facilitate juvenile passage and because few adult salmonids pass dams at night (Burke et al. 2005; Caudill et al. in review). As the season progressed into summer and discharge declined, spill tapered off to no spill at night. Bonneville Dam is a run-of-the-river dam with little storage

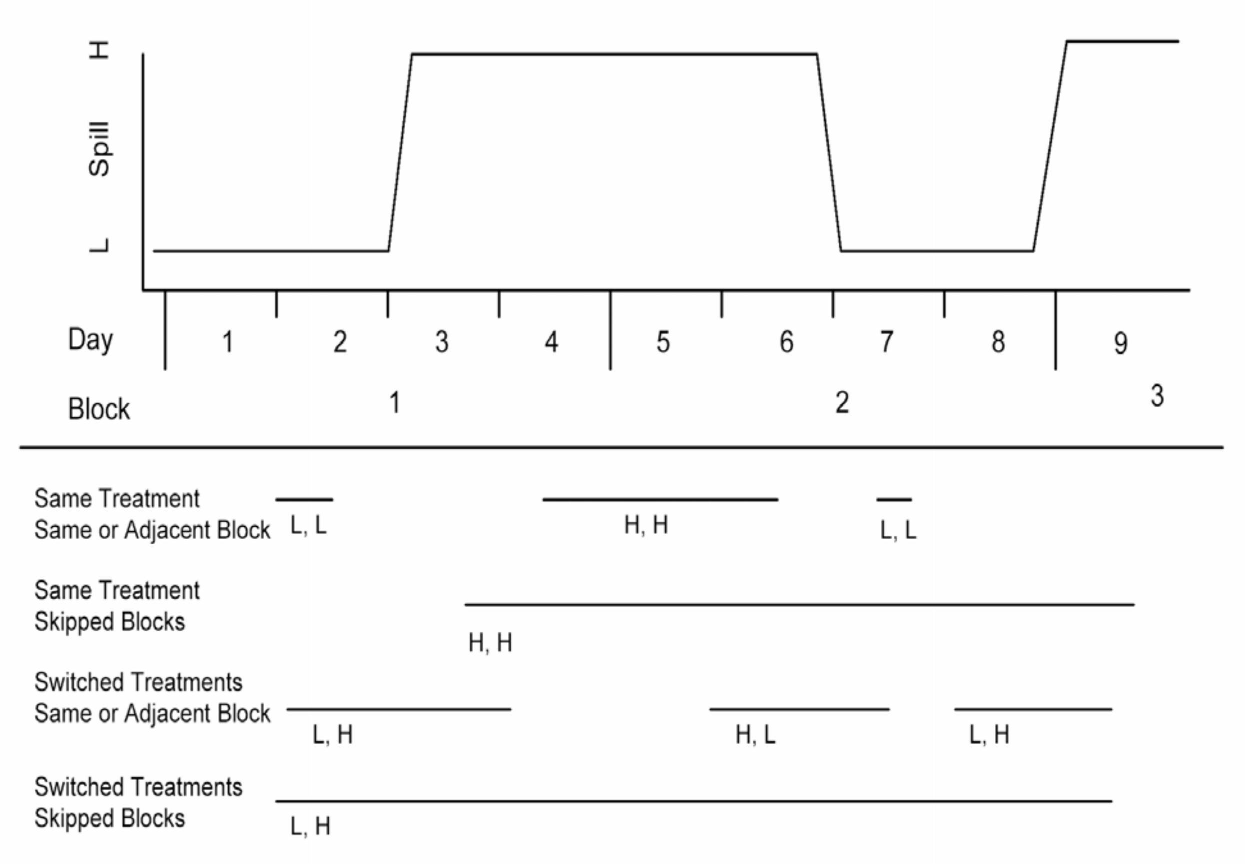

Figure 2: Idealized depiction of treatment switching and skipping. Spill treatments were alternated between high and low within each block in a random order, potentially leading to four-day (2002, 2003) or six-day (2000) periods of constant treatment. Fish were released downstream through this period, and their passage over Bonneville Dam was monitored. Passage time was defined as the first detection in the tailrace 1.8 km downstream of Bonneville Dam until the first detection at a fishway entrance. Some fish passed within individual treatment periods. Others took more than one day to pass and experienced more than one treatment, block or both, resulting in four potential switch-skip combinations. Horizontal lines represent passage events for individual fish and letters below denote treatment combinations as given in Table 1. Nighttime spill levels not shown for clarity.

capacity, and there were several periods of uncontrolled, high spill during periods of high discharge (Figure 1), resulting in a reduction in the number of test blocks.

Hourly spill, discharge, and temperature data were downloaded from the Columbia River Data Access in Real Time archive (DART 2005). Mean daily spill conditions were calculated using data from 600-1900 hrs, inclusive. All spill rates for 2002 and 2003 were corrected for errors using the correction factor (corrected spill = $0.001 \bullet \text{spill}^2 + 0.8788 \bullet \text{spill} - 23.45$; USACE [2005]). This monotonic correction factor did not affect the outcome of any treatment assignments nor results of analyses testing categorical treatment effects.

Table 1: Criteria used to define spill treatment categories based on daily mean spill volumes. Uncorrected volumes for 2002-3 given parenthetically.

	Spill volume (kcfs)			
Treatment	Target	2000	2002	2003
Low	48.1 (75)	< 83.1	< 60.9 (87.3)	< 54.3 (81.0)
High	Varied by Year	> 85.9	> 73.4 (99.0)	> 77.1 (102.5)

Daily dam counts

In addition to monitoring telemetered fish, we tested whether daily dam counts of the run-at-large (provided by the USACE, Terry Hurd, personal comm.) increased during low spill treatment periods compared to high spill treatment periods. We used the paired-observation general linear model

$$\log_e(\text{mean daily dam count}) = \text{treatment} + \text{year} + \text{block(year)} + \text{treatment*year} + \text{error}$$

to test for spill treatment effects for each run. The observational unit was the mean daily dam count averaged across three (2000) or two (2002 & 2003) day treatment application. Average dam counts were $\log_e$ transformed to meet the model assumption of normality of error terms. Observations were paired by block to control statistically for seasonal effects on run size and other river conditions, and blocks were nested within years because blocks were restricted to single year (i.e., block 1 in one year did not correspond to block 1 in other years). The treatment*year interaction tested for consistency in the treatment effect among years.

Tagging and telemetry

Migrating adults were diverted from the Washington-shore fish ladder of Bonneville Dam into the Adult Fish Facility (AFF). Fish passed through passive integrated transponder (PIT) detectors and then passed into a chute where an operator had approximately one second to select fish for tagging based on species and PIT detections. Selected fish were diverted to an anesthetic tank, anesthetized, and tagged with 3 or 7 volt transmitters (Lotek Wireless, Inc., Newmarket, Ont.). Three volt tags were 11 g in air (4.3 x 1.4 cm) and 7 volt tags were 29 g (8.3 x 1.6 cm). In 2002, some fish were tagged with Data Storage Tags (3-volt, 9 × 2 cm, 34 g in air). A PIT tag was inserted into fish not previously PIT-tagged. We tagged fish in approximate proportion to their long term average abundance during the run. Tagging was not truly random because fish were sampled only from the Washington-shore ladder, the proportion sampled each day varied, no fish were sampled at night, and “jack” (precocious adults, by size) Chinook salmon and steelhead with fork lengths < 50 cm were rejected. Fish were placed in a 2275 L tank for recovery and transported and released within three hours. Fish were released from both shores of the Columbia River ~9.5 km downstream of Bonneville Dam in approximately equal proportions. Fish entrance to the tailrace, approach of the dam face, entry into fish ways and progress through the fish passage facility was monitored by an extensive array of aerial and underwater antennas at Bonneville Dam. During 2003, additional underwater antennas were added to the tailrace channel of the spillway approximately 400 m downstream of the dam face in order to better determine behavior of fish relative to spill treatments. More detailed accounts of the tagging procedure and antenna array are available in Keefer et al. (2004) and Boggs et al. (2004).

In this study, we defined passage time as the time from first tailrace detection to the first detection on an internal fishway entrance antenna (time to first entrance). Hydraulic conditions were relatively constant inside fishways compared to the tailrace during the manipulation of spill levels. In broader analyses of passage time, we have observed that alternative definitions of passage time (e.g. tailrace detection to first fishway approach or fishway exit) have similar relationships with environmental conditions as the tailrace-to-first entrance definition (Caudill et al. in review). Only first ascents were included in the analysis (i.e. passage attempts after falling back were excluded) because of the potential for past experience, including potential injuries incurred during fallback, to influence subsequent passage times. The 2003 steelhead sample was not included in some analyses because of inadequate sample size (N = 17 fish).

Treatment "switching" and "skipping"

In this experimental study, spill levels were manipulated. However, it was not a classical experiment because the units of observation (fish) could not be randomly assigned and *restricted* to a single treatment. Specifically, passage times for some fish exceeded one day, and many fish were detected in the tailrace but not at dam entrance antennas until the treatment had changed ("switching"). Additionally, passage times for some fish were long enough that entire treatment blocks passed between first tailrace and first fishway entrance detections ("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 reach 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; Figure 2). For some analyses, we combined fish that switched treatment within block with those switching treatments between adjacent blocks to maximize statistical power.

Statistical analyses of passage time data

We used two statistical approaches to test for treatment effects on passage time of tagged fish. First, we tested for differences in the frequencies of fish passing under high versus low spill conditions within each of the four switch-skip categories using chi-square tests. Second, because fish frequently encountered more than one treatment condition, traditional ANOVA approaches were not appropriate for estimating effects on passage time. Rather, we used proportional hazards regression (PHReg), a form of time-event analysis (Fox 1993, Allison 1995, Hosmer and Lemeshow 1998, Castro-Santos and Haro 2003, Naughton et al. 2005), as an analytical approach which explicitly incorporated 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 hazard or odds ratios, and are familiar from the outcomes of medical trials. For example, a drug trial may find that treatment with a cancer drug reduces the probability of remission by 5 times compared to a placebo. Similarly, we may find high spill decreases the probability of fishway entrance during a time interval by one half. In these examples, the PHReg model does not expressly estimate the time to remission or passage, but rather the effect of the treatment (drug or high spill) on the *risk* of the event occurring (recurrence of cancer or entrance to the fishway). The risk or hazard, expressed as an odds ratio, and is assumed to be constant through time.

The primary advantages of the PHReg method are twofold. First, predictor variables, such as spill level, are allowed to change through time ('time-varying covariates') which explicitly accounts for treatment switching as well as a dynamic river environment. Second, individuals that enter the study, but for which the event is not observed (a common occurrence in radio-telemetry studies), can be explicitly included in the model rather than being excluded prior to analysis. As an example, a salmon that is detected in the tailrace of a dam enters the 'risk set' of individuals that might be observed to pass the dam. However, if the individual does not pass, perhaps because it was caught in a fishery downstream, it is said to have been 'lost to followup', and can be 'censored' from the study. We censored fish for two reasons. First, some fish were detected in the tailrace, but were not detected at an entrance antenna, either for operational reasons (e.g., an antenna outage) or because the fish did not pass the dam. Second, we censored a small number of fish that passed at night when spill was not being manipulated and few fish pass (Burke et al. 2005; Naughton et al. 2005, Caudill et al. in review). The inability to estimate mean differences in passage time represents the primary disadvantage of the PHReg approach. Other parametric approaches to the analysis of time-event data are available, but do not allow time-varying covariates (Allison 1995, Castro-Santos and Haro 2003).

We modeled passage hazard in relation to spill while statistically accounting for variation in other environmental factors and fish traits. We tested for spill effects on passage hazard using a model that included the time-varying covariates of spill treatment, river temperature, and river discharge. We tested for spill effects using a categorical variable coding the treatment as either high or low treatment as outlined above. Temperature was included as a covariate because of its known effects on fish energetics and behavior (e.g. 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. We also included two fish traits, fish length and presence of a fin clip. Fish length was consistently and negatively associated with passage times in a larger analysis (Caudill et al. in review). We included a variable coding for the presence or absence of a fin clip to test for differences between fish of known hatchery origin and those presumed to be of wild origin. The unclipped group may have included hatchery fish, but the proportion was unknown.

Interannual differences in river condition have a strong effect on migration behavior (Boggs et al. 2004, Keefer et al 2004a, 2004b), and we consequently stratified by year for overall tests of spill effects for each run. Unfortunately, the quantitative differences among years can not be directly estimated in a single model (Allison 1995 pg. 160), and this analytical limitation also prevented tests of year*spill interactions. To examine interannual effects, we also ran models for single years, recognizing the potential loss of statistical power. We used 95% CI of model odds ratios—defined as the passage hazard at high spill compared to hazard at low spill—to test for differences among years in spill effects and qualitatively assess the potential for year*treatment interactions. See Caudill et al. (in review) for further details on PHReg and its application to the analysis of adult salmonid passage time at lower Columbia and lower Snake River dams.

While odds ratios from PHReg provide the most accurate test of treatment effects, we were also interested in estimating the treatment effect on median passage time. We used paired t-tests to test for differences in median passage time for each species and year using treatment conditions at the time of tailrace entry. The replicate for each test was the $\log_e$(median passage time), paired by block, and we graphically expressed the magnitude of the treatment effect as the mean difference between back-transformed means for each block. Note that back transformation of means calculated from $\log_e$ transformed data and associated CIs represent estimates of the true population medians with CIs for the median, and are not equivalent to the mean and CI calculated from the original, untransformed data (McArdle and Anderson 2004). These estimates represent the *minimum* estimates of the magnitude of treatment effects because of treatment switching. Additionally, these tests were conservative in the sense that they had much lower statistical power than the PHReg tests because of lower replication and because the effects of other environmental variables were not controlled statistically.

Finally, we tested whether passage times increased with increasing spill levels within the high spill treatment over the broad range of high spill levels applied (see Results). In particular, we were interested in whether there was evidence of a threshold effect of spill on passage time whereby passage dropped markedly at some spill level within the high spill treatment. To examine this possibility, we regressed the difference in median passage time for each block, as calculated above, against the mean daytime spill during the high spill treatments using a quadratic function: mean difference = intercept + a*(mean high spill) + b*(mean high spill)^2. A positive slope or step-function would indicate that passage times increased at higher levels of spill within the high spill treatment. All statistical analyses were performed in SAS v. 9.1 using PROC GLM, PHREG, CATMOD, or LOGISTIC (SAS Institute, Cary NC).

Fallback:

We also examined the relationship between spill and fallback because fallback was observed to increase significantly, though weakly, with increasing spill at Bonneville Dam (Reischel and Bjornn 2003). Fallback events in the Columbia-Snake system appear to be related to two different phenomena. Some fallback events occur shortly (< 24 hours) after adults exit fishways and appear to be related to disorientation in forebays and entrainment in water masses flowing through spillbays. At Bonneville

Dam, such fallback is often associated with the Bradford Island fishway exit, perhaps because shoreline orientation and hydrodynamic cues attract some fish into the vicinity of the spillbays (Reischel and Bjornn 2003). A second class of fallback events appears related to large scale orientation and homing because fish fallback one or more days after fishway exit, often after exiting the dam forebay, and in some cases after ascending and falling back over one or more upstream dams (Boggs et al. 2004). This class of fallback has been termed 'overshoot fallback' because these events presumably occur as adults return downstream in search of natal tributaries. We first performed statistical analysis for adults falling back on the same day as their fishway exit. Same-day fallback approximates the 24 hour criterion used by Boggs et al. (2004) and limited the analysis to individuals exposed to constant spill conditions between fishway exit and the fallback event. Powerhouse priority (PHP) appears to be strongly associated with inter-annual variation in fallback at Bonneville Dam, where larger proportions of adults fall back in years with Powerhouse 1 priority (e.g. 2000) than in years with priority to Powerhouse 2 (2002, 2003). Because of low frequencies of fallback in 2002 and 2003, we lumped these years, and tested for associations between powerhouse priority, treatment and the probability of falling back using the logistic regression model Fallback (yes, no) = treatment (low, high) + PHP (1, 2). We tested for a treatment*PHP interaction in spring Chinook salmon, the only species with adequate sample size to test the interaction. This interaction was not significant ($\chi^2 = 0.28$, $P = 0.5964$), and was dropped from the model to maximize statistical power. We also compared the frequencies of overshoot fallback events, defined here as events among individuals that fell back one or more days after fishway exit. We matched treatments based on the spill conditions at the time of the fall back event and directly compared frequencies of fallback events between treatments using χ^2 tests where sample size allowed.

Behavior in the spillway, 2003:

Prior to the spill season in 2003, we deployed two antenna arrays across the spillway. The north array consisted of 7 individual antennas and was anchored near mid-channel 370 m downstream of the dam (Appendix 2). The anchor of this array shifted downstream to a point approximately 450 m downstream of the dam on the first day of spill. The south array consisted of eight antennas and remained stationary at 370 m throughout the 2003 spill season. In all cases, we analyzed spring and summer Chinook salmon separately, and no transformations were necessary to meet the assumptions of the statistical tests. Fall Chinook salmon and steelhead were excluded from all analyses due to inadequate sample size. We used the spillway antennas in addition to other antennas at the dam to evaluate the following three aspects of fish behavior:

<u>Entrance used by radio-tagged fish:</u> We calculated the average daily proportion of fish entering different fishway entrances using the first entrance event for each fish for each treatment and block combination. We tested whether the proportion of fish entering at the north and south shore spillway entrances (combined) differed by treatment using a paired t-test, pairing by block.

Use of the spillway entrance by fish detected on the spillway antenna: We also tested whether, among fish detected on the spillway antenna, the proportion of fish using the spillway entrances differed by spill treatment. This analysis tests whether individuals detected on the spillway antenna under high spill were as likely to continue on to spillway entrances as those entering under low spill. Individuals that switched treatments or blocks were excluded from these analyses. We tested whether the proportion of fish entering at the north and south shore spillway entrances (combined) differed by treatment using a paired t-test, pairing by block.

Mean number of spillway detections per fish each day: We calculated the number of detection events per day per unique fish on each spillway antenna under the assumption that fish with indirect passage routes through the tailrace and spillway would have a greater number of detections per day, i.e., we used the number of daily detections as an index of spillway "milling". During coding of telemetry data, only detections separated by 30 minutes or more on each array were considered separate events. We tested whether the mean number of detections per day, averaged by block, differed by treatment using a paired t-test, again pairing by block.

Results

Spill treatments:

Spill manipulation resulted in 19 6-day blocks in 2000, 29 4-day blocks in 2002, and 18 4-day blocks in 2003 (Appendix 1). Experimental periods included the first month of the fall Chinook salmon run in 2000 and 2002 (study duration: 14 April-31 August in both years), but not in 2003 (study duration: 14 April-28 June). High river discharge in 2002 and 2003 led to periods of uncontrolled high spill and breaks in the application of spill treatments (Figure 1). Spill level varied within treatments, primarily for high spill levels, and by year (Table 1, Figure 3). Spill levels were relatively constant in the low-spill treatment within and among years. In the high-spill treatment, mean spill increased each year as flows allowed and as operators strove to create biologically meaningful separation between treatments (Figure 3).

Daily dam counts

The daily mean number of adults passing count windows differed between treatments in most runs, though this effect was not consistent among years (Table 2, Figure 4). The effect of spill on daily dam counts was only marginally significant in fall Chinook salmon, though sample size for this run was the smallest (Table 2c). Except for summer Chinook salmon, the difference in daily dam count was largest in 2002.

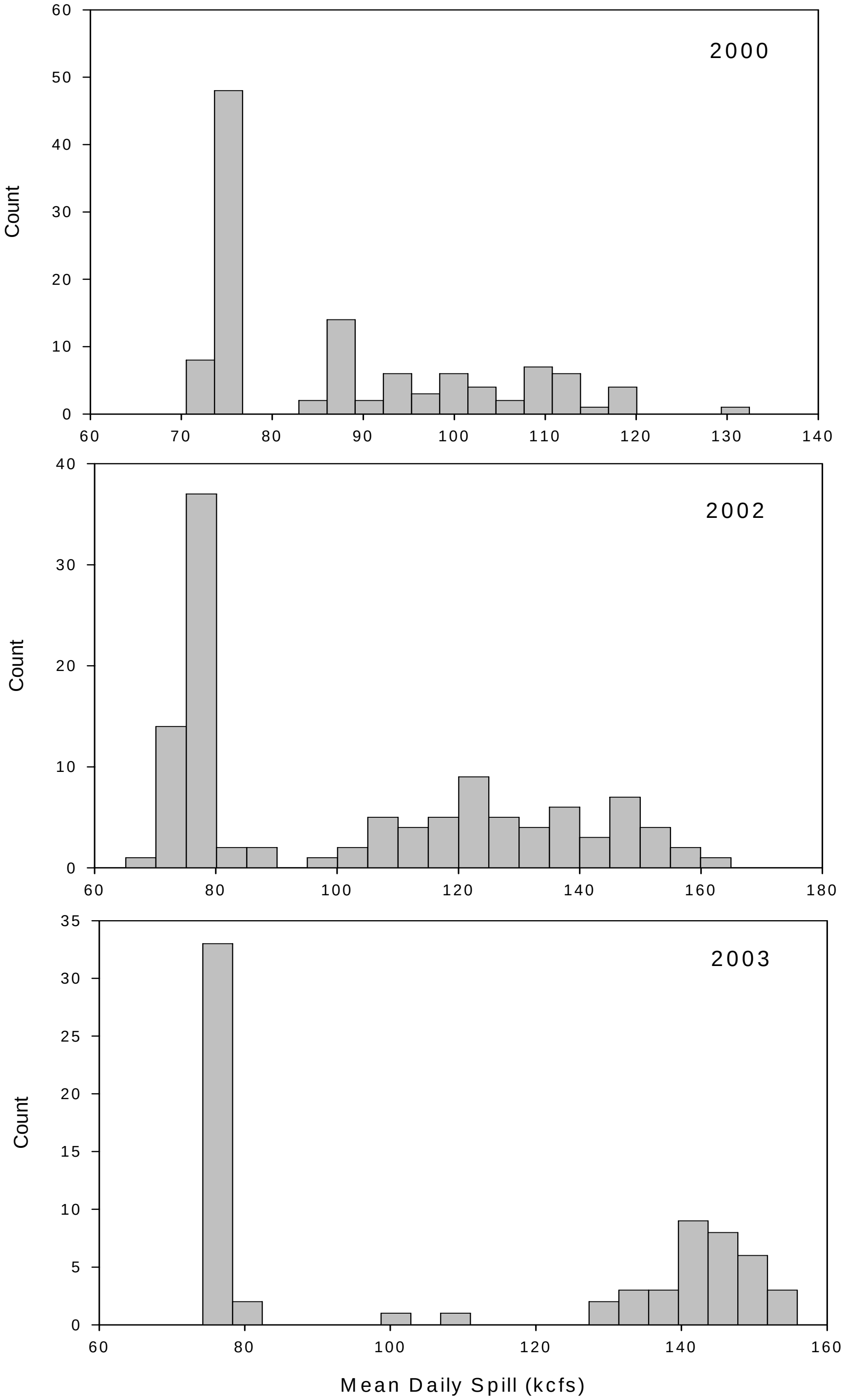

Figure 3: Frequency of mean daily spill during the experiment by year. Mean daily spill calculated from hourly estimates for the period 600-1900 hrs. Spill levels within the high spill treatment and the mean difference in spill between treatments increased during the experiment. Note differences in magnitude of x-axis among panels. Spill values shown are uncorrected.

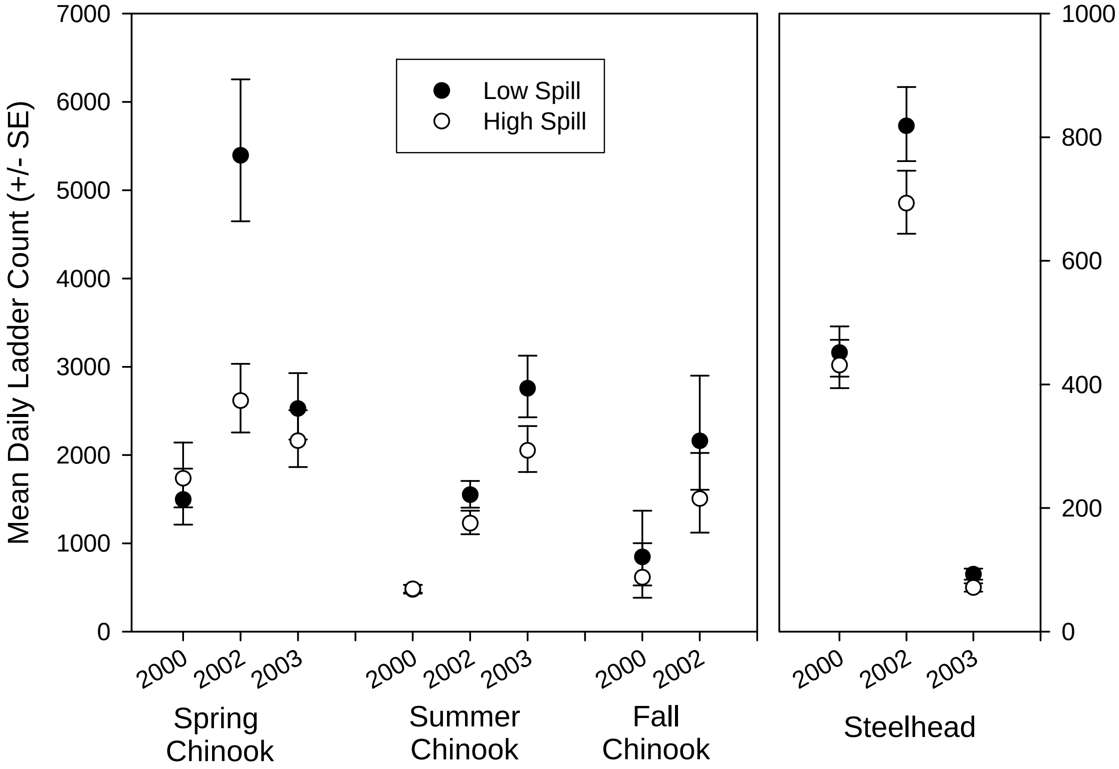

Figure 4: Mean daily ladder count by spill treatment, year, and run during the spill experiment. Note difference in scale for steelhead.

Table 2: Results of ANOVA tests of the effect of spill treatment on $\log_e$(mean daily dam counts) at Bonneville Dam during the 2000, 2002 and 2003 spill test. Treatment effects were tested by pairing by block, within year.

a) Spring Chinook Salmon

Source	DF	Sum of Squares	Mean Square	F Value	*P*
Model	32	32.62931112	1.01966597	16.28	<.0001
Error	27	1.69139972	0.06264443		
Corrected Total	59	34.32071084			

Source	DF	Type III SS	Mean Square	F Value	*P*
Spill Treatment	1	0.79787441	0.79787441	12.74	0.0014
Year	2	6.26167613	3.13083807	49.98	<.0001
Block(Year)	27	23.01648810	0.85246252	13.61	<.0001
Spill Treatment*Year	2	1.80005367	0.90002683	14.37	<.0001

b) Summer Chinook Salmon

Source	DF	Sum of Squares	Mean Square	F Value	*P*
Model	29	30.57511996	1.05431448	47.25	<.0001
Error	22	0.49087064	0.02231230		
Corrected Total	51	31.06599060			

Source	DF	Type III SS	Mean Square	F Value	*P*
Spill Treatment	1	0.35319452	0.35319452	15.83	0.0006
Year	2	21.54180164	10.77090082	482.73	<.0001
Block(Year)	24	7.69238096	0.32051587	14.36	<.0001
Spill Treatment*Year	2	0.22205257	0.11102629	4.98	0.0165

c) Fall Chinook Salmon

Source	DF	Sum of Squares	Mean Square	F Value	*P*
Model	12	31.21910345	2.60159195	19.12	<.0001
Error	9	1.22450143	0.13605571		
Corrected Total	21	32.44360488			

```
Source                   DF    Type III SS    Mean Square   F Value       P

    Spill Treatment       1     0.49386659     0.49386659      3.63   0.0891
    Year                  1     3.63761113     3.63761113     26.74   0.0006
    Block(Year)           9    26.91623087     2.99069232     21.98   <.0001
    Spill Treatment*Year  1     0.00243282     0.00243282      0.02   0.8966
```

d) Steelhead

```
                                  Sum of
    Source                DF     Squares    Mean Square   F Value        P

    Model                 68   497.6400259      7.3182357    187.79   <.0001

    Error                 63     2.4551671      0.0389709

    Corrected Total      131   500.0951930


    Source                DF   Type III SS    Mean Square   F Value        P

    Spill Treatment       1      0.7991725      0.7991725     20.51   <.0001
    Year                  2    112.8593382     56.4296691   1447.99   <.0001
    Block(Year)          63    383.7259893      6.0908887    156.29   <.0001
    Spill Treatment*Year  2      0.2233649      0.1116825      2.87   0.0644
```

Passage frequencies and treatment switching and skipping:

If high spill increases passage times, we would expect 1) the proportion of fish passing during a single treatment to be greater under low than high spill and 2) that a greater proportion of fish would experience a switch of treatments from high to low than vice versa, assuming “delayed” fish rapidly pass with the switch to lower spill conditions. Among fish that passed with no switching of treatments, a greater proportion of spring Chinook salmon and steelhead passed under low spill conditions (Table 3a), though the difference in proportions for steelhead was marginally significant (P = 0.0555). No difference in proportion was observed for summer or fall Chinook salmon. Among fish that switched treatments but that did not skip blocks, significantly more spring Chinook salmon entered the tailrace under high spill conditions and subsequently entered fishways under low spill than the converse (*P* = 0.0002) (Table 3c). This suggests that these fish passed once conditions improved with the switch to low spill and/or that lower average passage time under low spill simply resulted in less treatment switching. The other runs exhibited similar patterns, but differences were not significant (Table 3c). Among fish that skipped blocks but did not switch treatments, only steelhead exhibited significant treatment effects (*P* = 0.0431), where a greater proportion passed under low spill conditions. Spring Chinook salmon that switched treatments and skipped blocks also completed passage under low spill more frequently than high, though this difference was marginally significant (*P* = 0.0614; Table 3d). Other runs had low sample sizes for this switch-skip category.

Table 3: Frequency of entrances by spill treatment at the time of first tailrace entrance (F1) and first fishway entrance (E1) for fish that: a) did not switch treatment or skip blocks, b) did not switch treatment and skipped one or more blocks between F1 and E1, c) switched treatments and did not skip blocks, or d) switched treatments and skipped blocks. See Figure 1 for category definitions.

a) Same treatment, same block

F1, E1 Treatments	Fall CK	%	Steelhead	%	Spring CK	%	Summer CK	%
High, High	64	49.64	316	46.33	334	45.63	202	52.88
Low, Low	70	50.36	366	53.67	398	54.37	180	47.12
P	0.9324		0.0555		0.0180		0.2603	
N	134		682		732		382	

b) Same treatment with skipped blocks

F1, E1 Treatments	Fall CK	%	Steelhead	%	Spring CK	%	Summer CK	%
High, High	3	33.33	20	36.36	142	51.08	19	55.88
Low, Low	6	66.67	35	63.64	136	48.92	15	44.12
P	0.3173		0.0431		0.719		0.4927	
N	9		55		278		34	

c) Switch of treatment, no skip of blocks

F1, E1 Treatments	Fall CK	%	Steelhead	%	Spring CK	%	Summer CK	%
High, Low	19	51.35	90	55.56	249	59.14	46	54.76
Low, High	18	48.65	72	44.44	172	40.86	38	45.24
P	0.8694		0.1573		0.0002		0.3827	
N	37		162		421		84	

d) Switch of treatments and skipped blocks

F1, E1 Treatments	Fall CK	%	Steelhead	%	Spring CK	%	Summer CK	%
High, Low	1	100	5	55.56	35	62.5	-	
Low, High	-		4	44.44	21	37.5	1	100
P	-		0.7389		0.0614		-	
N	1		9		56		1	

Passage time:

The experimental design precluded meaningful comparisons of treatment effects on average passage time. Nonetheless, comparison of cumulative passage curves (Figure 5a, b) classified by treatment condition at the time of tailrace entry reveal that individuals entering the tailrace under high spill conditions consistently had longer passage times through the tailrace. Note that the times depicted in Figure 5 do not accurately represent the treatment effects because of the potential for treatment switching.

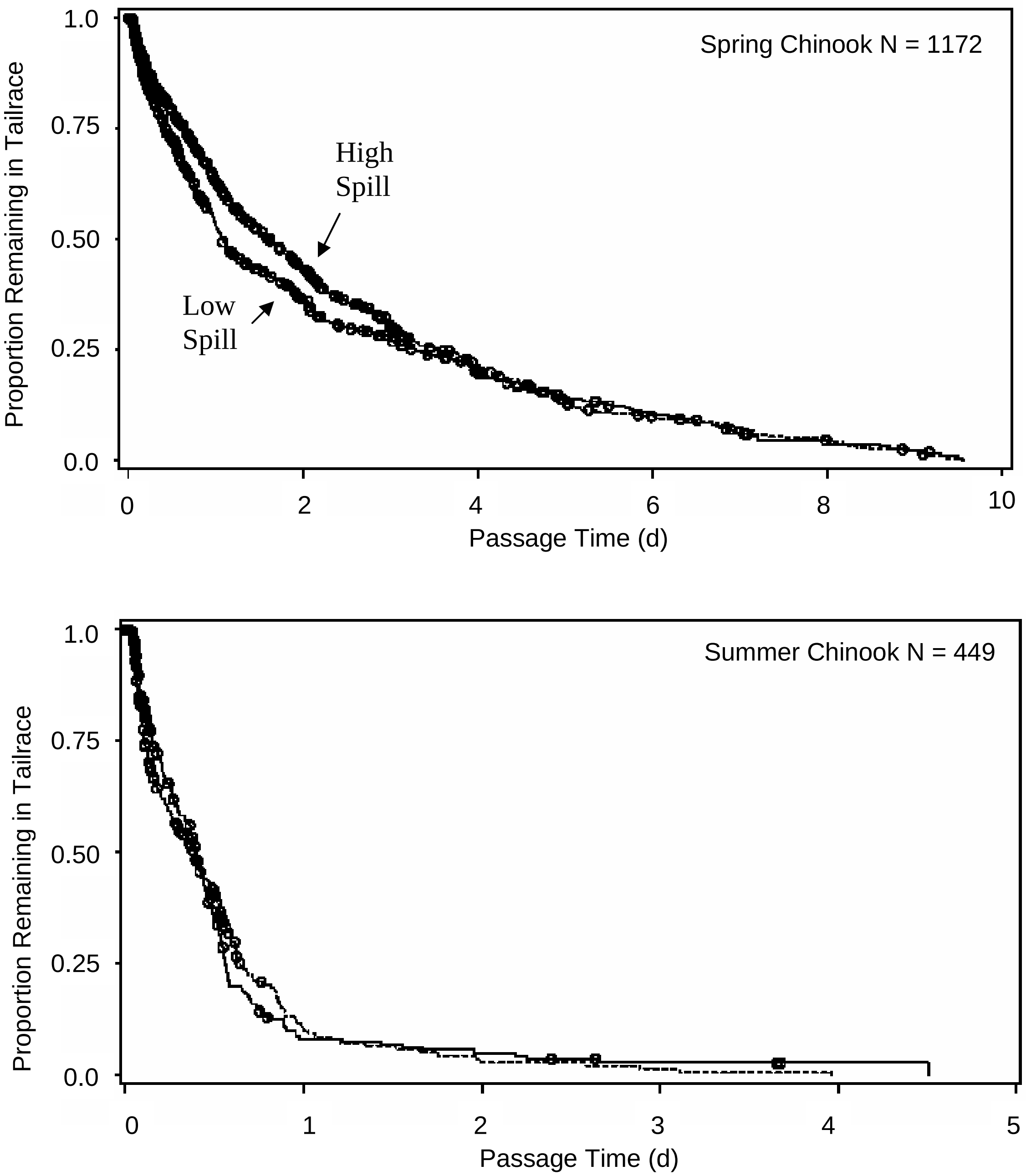

Figure 5a) Cumulative passage time curves for spring Chinook salmon (top panel) and summer Chinook salmon (bottom panel) at Bonneville Dam during the three year study. Solid line denotes fish entering tailrace under low spill conditions, high spill is indicated by dashed line, and circles indicate the times of censoring.

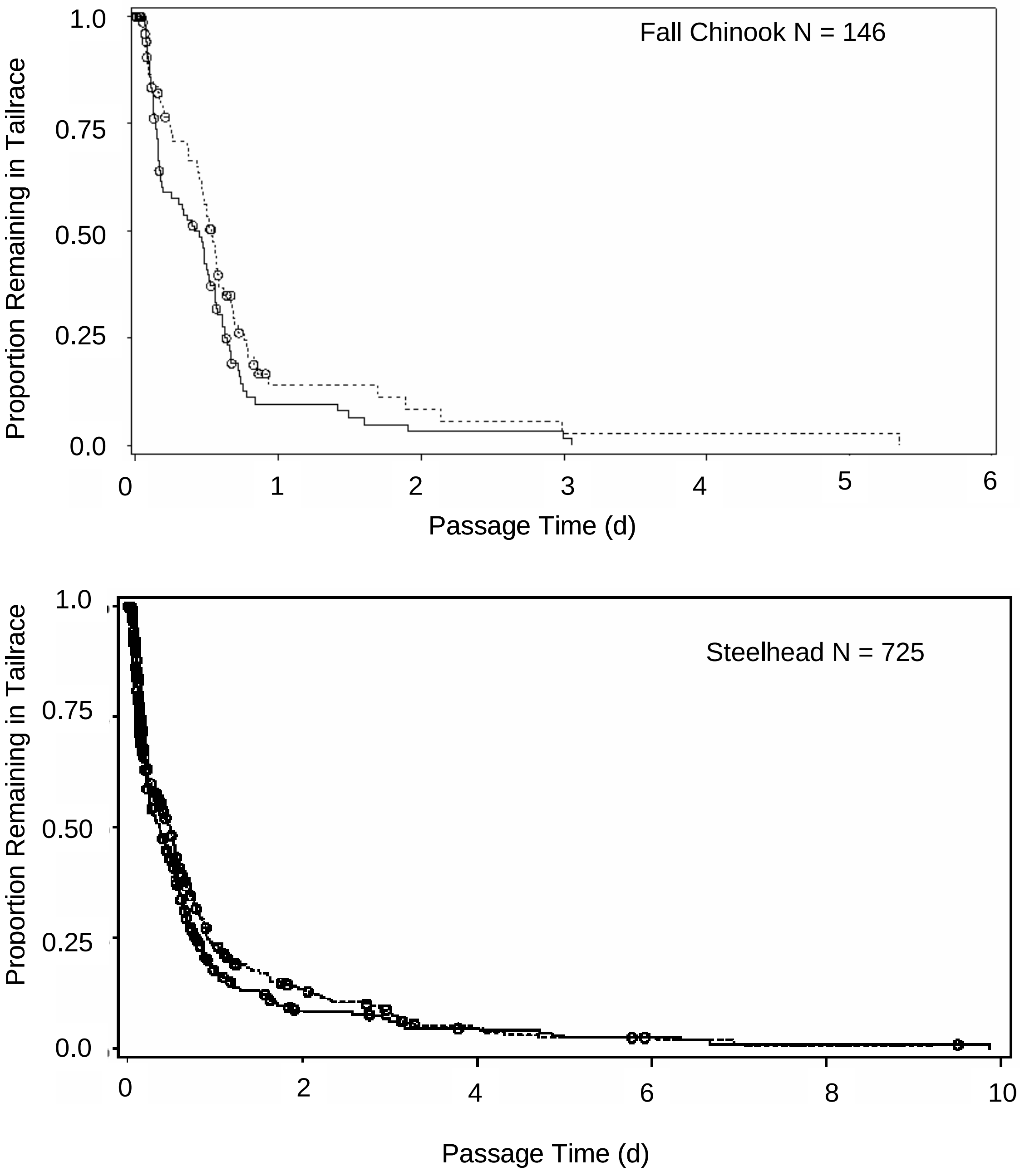

Figure 5b) Cumulative passage time curves for fall Chinook salmon (top panel) and steelhead (bottom panel) at Bonneville Dam during the three year study. Solid line denotes fish entering tailrace under low spill conditions (lower curve in both plots), high spill is indicated by dashed line (upper curve in both plots), and circles indicate the times of censoring.

The PHReg approach accounted for treatment switching by evaluating the risk of passage through time as spill conditions changed. The results of these analyses found consistent support for slowed migration during high spill treatments (Table 4, Figure 6). The analyses produced odds ratios of 0.842-0.862, though the spill effect was not significant for fall Chinook salmon (P = 0.1353), perhaps due to the smaller sample size. These ratios indicate that individuals were 14 - 16% less likely to enter fishways under high spill than low spill conditions during any given time interval, given they had entered the tailrace. Total river discharge had weak (spring Chinook salmon) or undetectable effects (other runs) on passage hazard within years, after accounting for the effects of spill level. Temperature was positively associated with passage hazard in spring Chinook salmon, an association presumably resulting from increased metabolic activity and swimming speed as spring temperatures warmed. In contrast, passage hazard was negatively associated with temperature in steelhead, possibly because steelhead generally experienced warmer temperatures and passage slowed at the highest temperatures. Fish length was negatively associated with passage hazard in summer Chinook salmon, indicating larger fish had slower passage times. Origin (hatchery vs. wild) was not significantly associated with passage hazard of any run except summer Chinook salmon (*P* = 0.0601) in all models but one (summer Chinook salmon, categorical model), consistent with the results of a larger PHReg analysis of passage time at Columbia and Snake river dams (Caudill et al. in review).

The differences among years in the magnitude of the spill treatment (Figure 3) suggested interannual differences in the effect of spill on passage behavior. The overall PHReg models statistically controlled for any such differences by stratifying the analyses by year before testing for effects. However, these models do not produce estimates by year (Allison 1995). Consequently, we re-ran each model for each year to examine interannual patterns in passage hazard in relation to spill (Figure 6; see Appendix 3 for the full results of these models). The odds ratio was not significant for any run in 2000, the year with the smallest difference between high and low flow treatments. The odds ratios were significantly below 1.0 in most other run-year combinations, consistent with the differences among years in the magnitude of the spill manipulation (Figure 6).

The minimum estimates of treatment effect on median passage time were generally consistent with patterns revealed in the PHReg analyses (Figure 7). The mean difference in median passage time between high and low treatments within block was significantly greater than zero in several cases, and these paralleled the results of the PHReg tests closely. Point estimates for spring Chinook salmon in 2002 and 2003 were very similar, with a mean difference of 8.64 and 8.68 h longer passage time per block for salmon entering the tailrace under high spill conditions compared to low spill conditions. Fall Chinook salmon and steelhead exhibited significant differences of 3.33 and 3.85 h, respectively. In contrast to the PHReg results, differences for summer Chinook salmon were not significant in any year, probably because of the low replication for the paired t-tests (N = 6-11 per year). We note again that the estimates of mean difference in passage time probably underestimated the mean difference for

Table 4: Results of Cox proportional hazards regression (PHReg) tests of spill treatment effects by run. Odds are expressed as the decrease in the probability of passage for high spill compared to low spill. Odds ratios for other variables scaled as the change in hazard per 1˚C increase in temperature, 1 cm increase in fork length, an increase in discharge of 10,000 kcfs, and as the increase in passage hazard for wild compared to hatchery individuals.

Run	Factor	d.f.	Estimate	Std Err	χ^2	*P*	Odds
Spring Chinook	Treatment	1	-0.16705	0.03462	23.2837	<.0001	0.846
	Discharge	1	0.00464	0.00099	22.1115	<.0001	1.005
N=1172	Temperature	1	0.38009	0.02947	166.3537	<.0001	1.462
Censored=219	Length	1	-0.00317	0.00353	0.8096	0.3682	0.997
	Clips	1	-0.10637	0.07061	2.2696	0.1319	0.899
Summer Chinook	Treatment	1	-0.1514	0.0636	5.6659	0.0173	0.860
	Discharge	1	-0.00019	0.00144	0.0172	0.8957	1.000
N=449	Temperature	1	-0.01031	0.04234	0.0592	0.8077	0.990
Censored = 69	Length	1	-0.02367	0.00652	13.1743	0.0003	0.977
	Clips	1	-0.24535	0.13049	3.5353	0.0601	0.782
Fall Chinook	Treatment	1	-0.14806	0.09913	2.2308	0.1353	0.862
	Discharge	1	0.00354	0.00569	0.3872	0.5338	1.004
N = 146	Temperature	1	-0.07191	0.08482	0.7186	0.3966	0.931
Censored = 17	Length	1	-0.01549	0.01224	1.6003	0.2059	0.985
	Clips	1	0.05187	0.24066	0.0465	0.8293	1.053
Steelhead	Treatment	1	-0.17212	0.04494	14.6708	0.0001	0.842
	Discharge	1	0.000207	0.00139	0.022	0.8821	1.000
N = 725	Temperature	1	-0.07199	0.03034	5.6294	0.0177	0.931
Censored = 124	Length	1	0.00669	0.00597	1.2543	0.2627	1.007
	Clips	1	0.04691	0.08988	0.2724	0.6017	1.048

constant high versus low spill conditions because many fish appeared to pass once spill volume decreased with a switch to low spill treatments (e.g., Table 3).

The comparison of mean difference in passage times as a function of spill level during the high spill treatment provided no evidence that median passage time increased with increasing spill in a linear, quadratic or step fashion (Figure 8). Similar patterns were obtained when analyzing single species or years. This result implies that, within the high spill treatment, similar treatment effects were induced at relatively low (e.g., ~100 kcfs) and relatively high (e.g., 140+ kcfs) high spill levels.

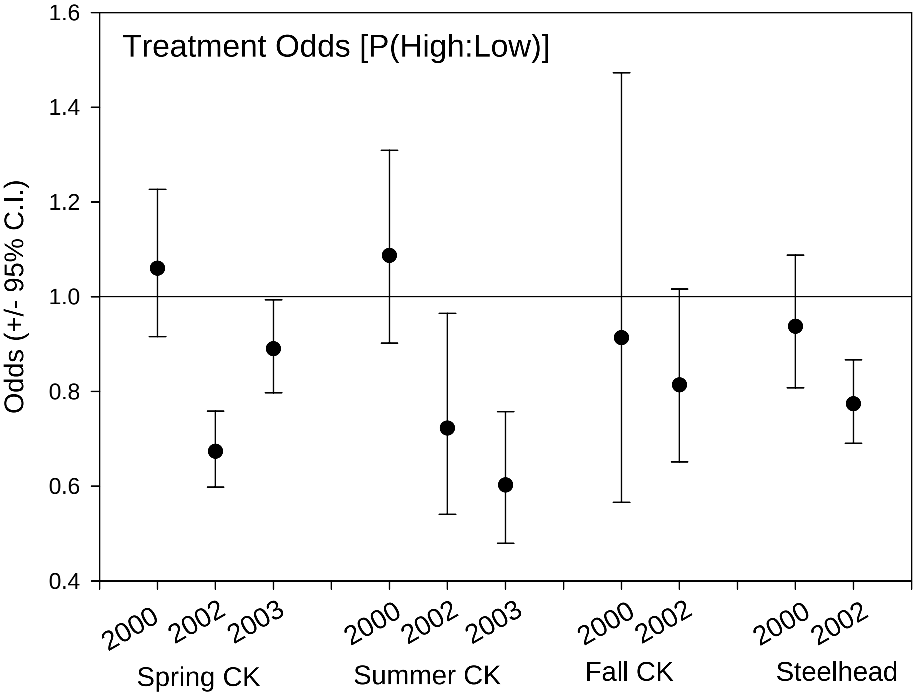

Figure 6: Odds ratios from proportional hazards regression analyses for each year by species. Odds ratios were considered significant where the 95% CI does not overlap 1.0. Points falling below the line at 1.0 indicate lower passage rate, and longer passage times at high spill.

Fallback:

Few fall Chinook salmon fell back and were not considered in statistical analyses. Patterns of fallback among fish that fell back the same day they exited a fishway (i.e., “near-time” or “operational” fallback) in the other three runs were related both to interannual differences in powerhouse priority and/or to spill treatment (Tables 5 & 6). Fallback rates in spring Chinook salmon and steelhead were five to more than an order of magnitude lower in years with higher discharge through Powerhouse 2 (2002 and 2003; Table 5). The smaller sample of summer Chinook salmon exhibited a qualitatively similar, but not statistically significant association with power house priority (Tables 5b). Spill treatment was significantly associated with the probability of fallback by summer Chinook salmon and steelhead ($P < 0.05$), and marginally so for spring Chinook salmon (Table 5b, $P = 0.0870$).

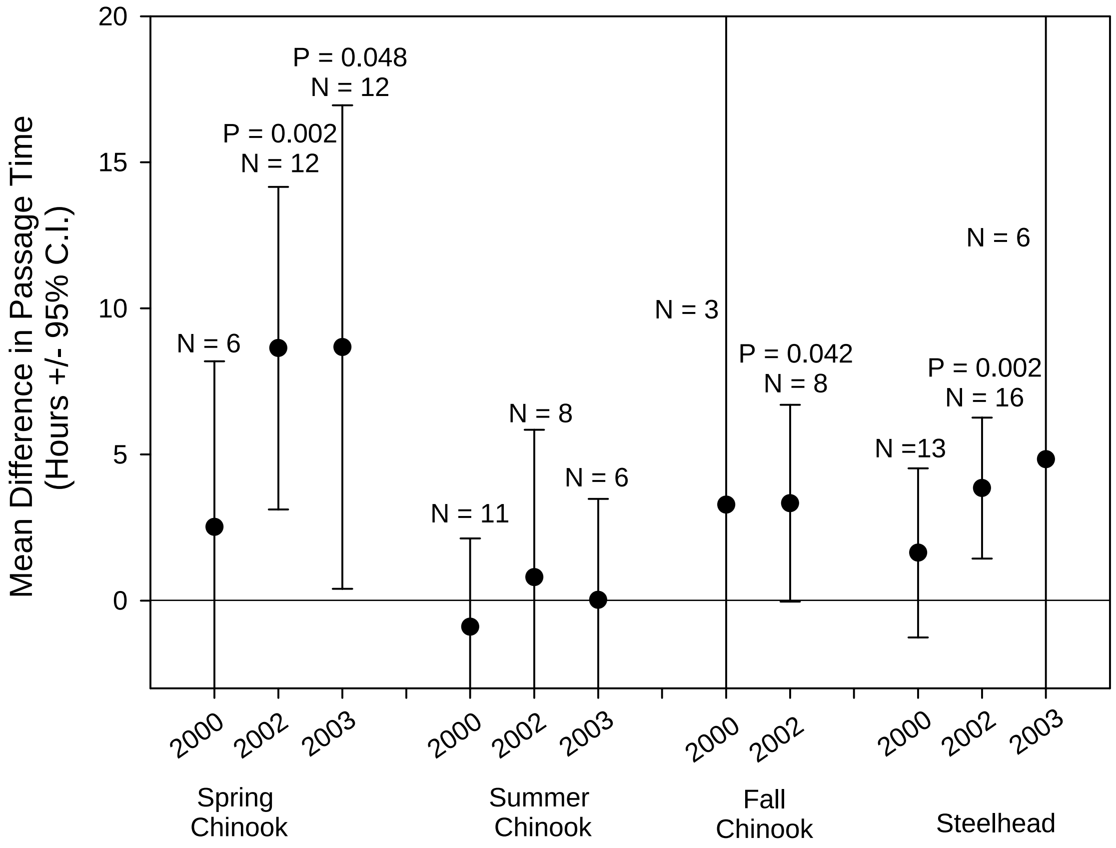

Figure 7: Minimum estimate of the spill treatment effect on median passage time. Differences in passage time were estimated as (passage time, high spill)$_i$ – (passage time, low spill)$_i$ for each block, 1-i. Treatments were assigned based on tailrace entrance times, and consequently differences underestimate mean treatment effects because of treatment switching. *P* values from paired t-tests using log$_e$-transformed data; *P* values ≥ 0.169 not shown (see text for further details).

Overshoot fallback by spring Chinook salmon (the only run with adequate sample size for analysis) exhibited a much weaker association with powerhouse priority than did those falling back and exiting on the same day (compare Tables 5 and 6), consistent with the putative mechanisms of same-day vs. overshoot fallback (Boggs et al. 2004). Combining all years to maximize statistical power, there was a marginally significant association between spill treatment and overshoot fallback in spring Chinook salmon (Table 6; $\chi^2 = 3.400$, *P* = 0.0652, n = 85).

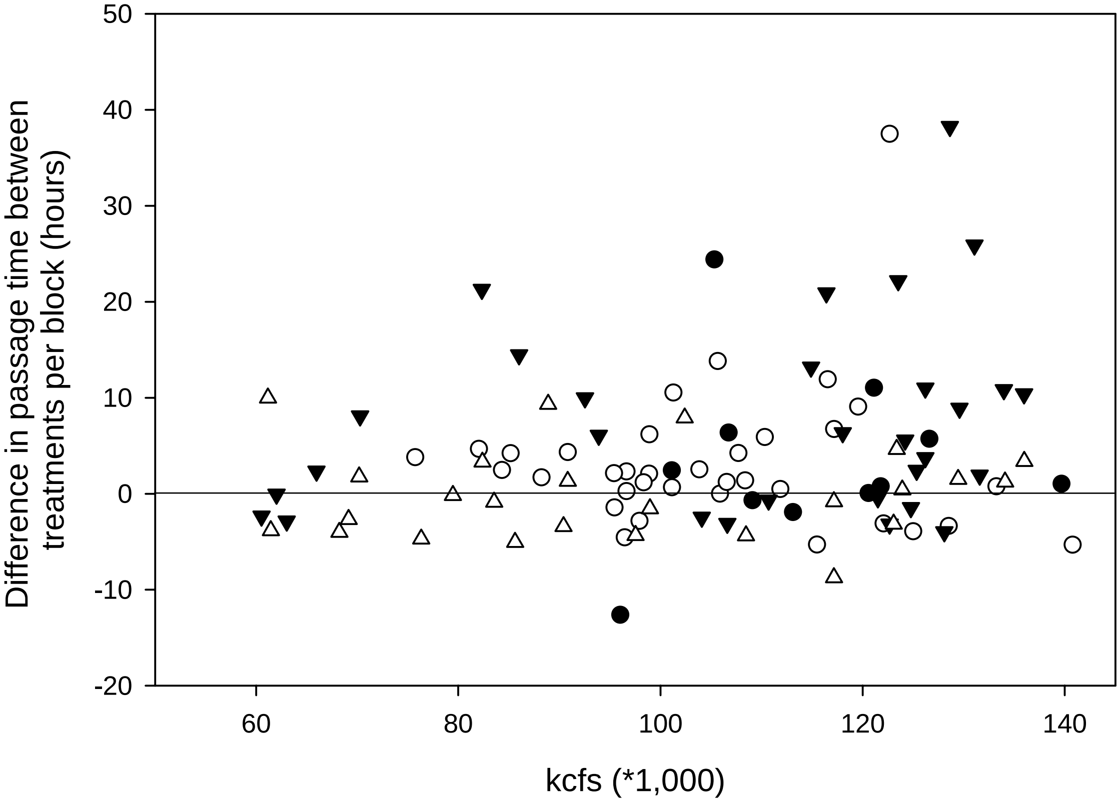

Figure 8: Comparison of the difference in passage time between treatments for each block versus spill volume during the high spill treatment, 2000, 2002, 2003. There was no evidence that the difference in passage time between treatments increased at relatively high spill levels within the high spill treatment (quadratic regression, P = 0.6940, N = 101). Black triangles = spring Chinook salmon, open triangles = summer Chinook salmon, black circles = fall Chinook salmon, open circles = steelhead.

Behavior in the tailrace, 2003:

We tested whether the proportion of fish using spillway entrances differed by spill treatment for all radio-tagged fish (Figure 9). Use of the spillway entrances decreased during the high spill treatments for both spring Chinook ($\text{Mean}_{\text{high}}$ = 23.3%, Mean_{low} = 39.7%; t = - 2.416, N = 12, *P* = 0.034), and summer Chinook salmon ($\text{Mean}_{\text{high}}$ = 13.9%, Mean_{low} = 31.3%; t = - 6.917, N = 6, *P* = 0.001). The decrease in spillway entrance use during high spill corresponded to an increase in the use of Power House (PH) 2 entrances in spring Chinook salmon and an increase in PH1 entrances by summer Chinook salmon (Figure 9).

Table 5: a) Frequency of fallback events occurring on the same day as the fishway exit by treatment, run, and year. Power house priority changed after 2000. b) Results of logistic regression tests. Fall Chinook salmon not tested because of inadequate sample size.

	Year	2000		2002		2003		Total	
Run:	Fallback	Low	High	Low	High	Low	High	Low	High
Spring Chinook	No	158	169	380	179	303	288	841	636
	Yes	13	25	8	3	4	8	25	36
	% FB	7.60%	12.89%	2.06%	1.65%	1.30%	2.70%	2.89%	5.36%
Summer Chinook	No	110	126	56	52	79	58	245	236
	Yes	2	9	0	0	0	4	2	13
	% FB	1.79%	6.67%	0.00%	0.00%	0.00%	6.45%	0.81%	5.22%
Fall Chinook	No	18	15	72	62	-	-	90	77
	Yes	0	1	0	0	-	-	0	1
	% FB	0.00%	6.25%	0.00%	0.00%			0.00%	1.28%
Steelhead	No	174	149	266	242	6	10	446	401
	Yes	9	22	1	3	0	0	10	25
	% FB	4.92%	12.87%	0.37%	1.22%	0.00%	0.00%	2.19%	5.87%

b)

Spring Chinook:	d.f.	χ^2	*P*
Intercept	1	491.1	<0.0001
Spill Treatment	1	2.93	0.0870
Power House Priority	1	38.98	<0.0001

Summer Chinook:	d.f.	χ^2	*P*
Intercept	1	96.63	<0.0001
Spill Treatment	1	5.75	0.0164
Power House Priority	1	2.45	0.1175

Steelhead:	d.f.	χ^2	*P*
Intercept	1	1271.04	<0.0001
Spill Treatment	1	9.13	0.0025
Power House Priority	1	46.72	<0.0001

Table 6: Frequency of fallback among individuals falling back one or more calendar days after exiting a Bonneville Dam fishway by treatment at the time of the fallback event.

		Year		
	Treatment	2000	2002	2003
Spring Chinook	Low	14	10	10
	High	20	20	11
Summer Chinook	Low	0	0	0
	High	1	1	1
Fall Chinook	Low	0	0	0
	High	0	1	0
Steelhead	Low	3	1	0
	High	0	2	0

We also tested whether individuals detected on the spillway antennas were less likely to subsequently use a spillway fishway entrance under high spill by comparing the mean daily proportion of spillway-detected fish that used spillway entrances for each treatment. In both cases, the proportion of spillway-detected fish using spillway entrances was significantly lower under high spill (Figure 10; spring Chinook: $\text{Mean}_{\text{high}}$ = 53.0%, Mean_{low} = 81.2%; t = - 2.733, N = 12, *P* = 0.019; summer Chinook: $\text{Mean}_{\text{high}}$ = 23.9%, Mean_{low} = 53.9%; t = - 4.049, N = 6, *P* = 0.010).

Finally, we estimated the mean number of coded detections per fish per day for each block as an estimate of ‘milling’ in the tailrace. The detection events per fish was lower in both spring and summer Chinook salmon, though not significantly so in the former case (Figure 11; spring Chinook: $\text{Mean}_{\text{high}}$ = 4.25 detections / fish, Mean_{low} = 3.837 detections; t = 0.901, N = 12, *P* = 0.387; summer Chinook: $\text{Mean}_{\text{high}}$ = 5.25 detections / fish, Mean_{low} = 3.046; t = 4.416, N = 6, *P* = 0.007).

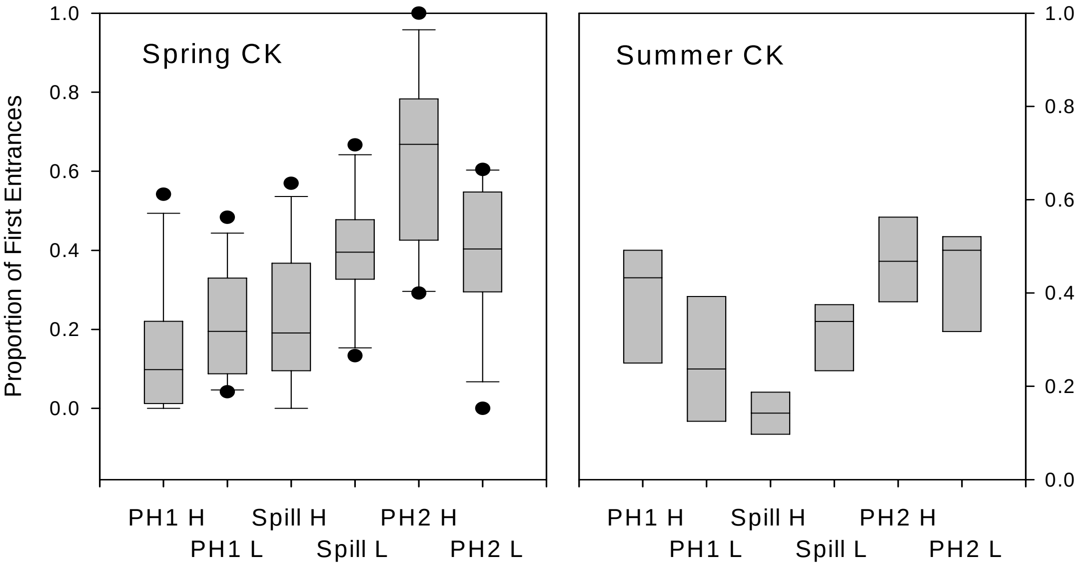

Figure 9: Mean daily proportion of individuals using PH 1, PH 2, or spillway fishway entrances under high (H) or low (L) spill conditions. Analyses excluded fish which switched treatments or blocks and included only first entrance events. N = 12 blocks for spring Chinook salmon and N = 6 blocks for summer Chinook salmon.

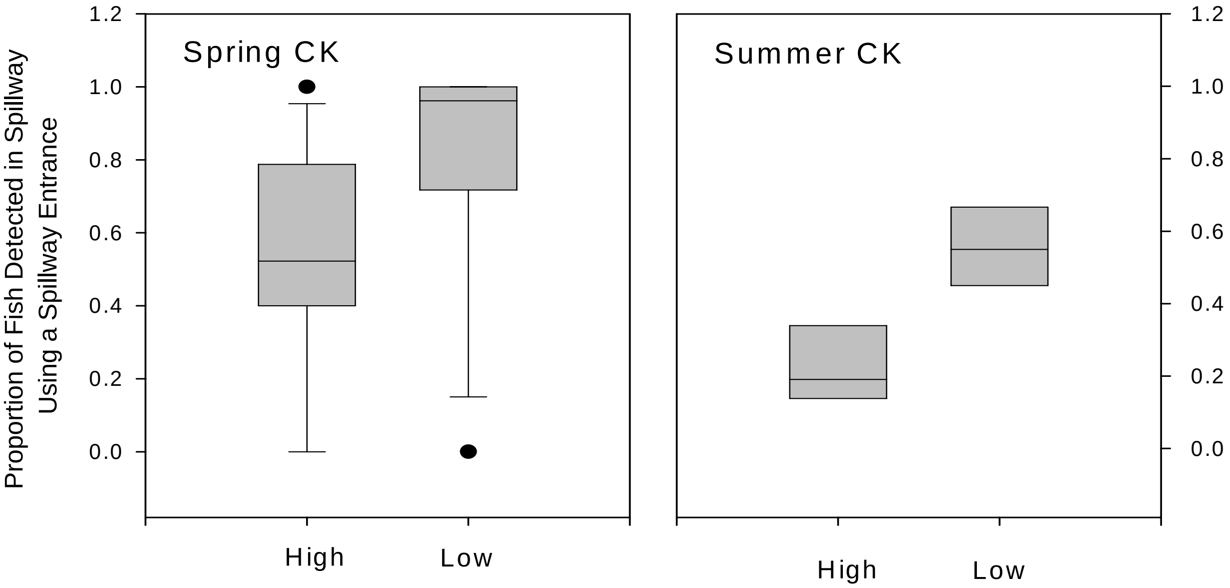

Figure 10: Mean daily proportion of fish detected on the spillway antenna that subsequently used a spillway entrance in 2003 for each block during high and low spill treatment periods. Analyses excluded fish that switched treatments or blocks and included only first entrance events. N = 12 blocks for spring Chinook salmon and N = 6 blocks for summer Chinook salmon.

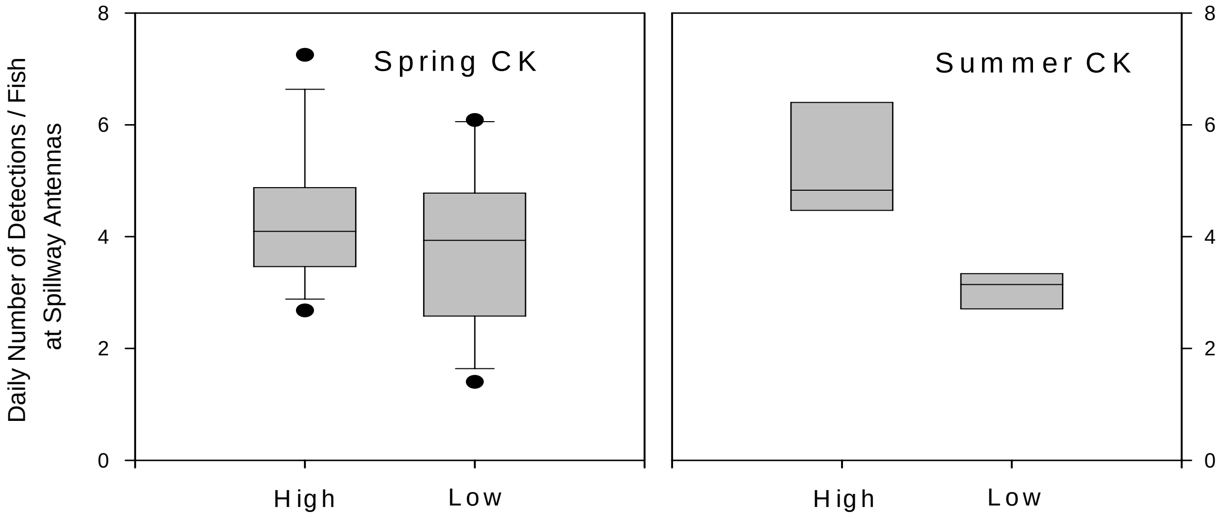

Figure 11: The daily mean number of coded detections on the spillway antenna by spill treatment in 2003. Analyses only includes those fish detected at least one time on the antennas and detection events were separated by at least 30 minutes. N = 12 blocks for spring Chinook salmon and N = 6 blocks for summer Chinook salmon.

Discussion

Overall, the results of this experiment were consistent with the hypothesis that high spill levels (85-160 kcfs) slowed the migration of adult salmonids at Bonneville Dam compared to passage rates at lower spill conditions. Importantly, the constraints imposed by the study system resulted in many fish experiencing more than one spill treatment and prevented accurate estimation of the effect of constant high spill levels on average passage times. Despite this apparent limitation, the comparison of the number of fish passing during high versus low treatments using dam counts and the comparison of the number of radio-tagged fish in different switch-skip categories provided indirect evidence of slowed migration at high spill in spring Chinook salmon and steelhead. The use of PHReg incorporated the alternation of spill treatment during passage by individual fish. These analyses explicitly asked whether passage rate increased as spill conditions changed, while statistically controlling for variation in other predictor variables. PHReg revealed consistent evidence that high spill conditions slowed passage—individual fish that had entered the tailrace were 14-16% less likely to enter a fishway during any given interval under high spill conditions compared to low spill conditions. Comparison of median passage time between treatments by block suggested the median passage time was slowed by at least 3.3 – 8.7 hours under high spill conditions. Patterns of behavior in the tailrace suggested that individual fish were less likely to use spillway entrances and appeared to take less direct routes through the tailrace during high spill treatments. Fallback also increased during high spill in some cases. Fallback events occurring on the same day as fishway exit increased at high spill, though interannual differences in powerhouse priority at Bonneville Dam appeared to have had the greatest effect on same-day fallback overall. The relationship between spill and overshoot fallback was weaker and only marginally significant for spring Chinook salmon and may have been related in part to interannual differences in flow; other runs had too few overshoot fallback events to evaluate the relationship.

Comparison of the number of passage events among different switch-skip categories provides qualitative information on the effects of spill on passage rate. In the absence of a spill treatment effect, we would expect fish that did not switch treatments to pass at equal rates between treatments. If high spill slowed passage, then a greater proportion of individuals entering the tailrace would remain in the tailrace until the switch of a treatment one or more days later, resulting in a lower number observed passing under the High, High combination (Table 3a). Indeed, 7.3 % fewer steelhead and 8.7 % fewer spring Chinook salmon passed under the High, High combination compared to Low, Low. Similarly, among fish that experienced two treatments in the same or adjacent blocks (Table 3c), we would predict a smaller proportion to pass after a switch to high spill (Low, High) than a switch to low spill (High, Low) if high spill conditions slowed passage. Consistent with this prediction, 18.3 % fewer spring Chinook salmon passed under high spill after entering the tailrace under low spill than the converse, suggesting these fish moved relatively rapidly to fishway entrances as spill level was lowered. These conclusions were supported by the dam counts and PHReg analyses. Overall, the results suggest that passage conditions in the tailrace improved with the switch to lower spill conditions.

Spill has strong effects on the flow environment and dissolved gas concentrations in the tailrace. Overall, the results of this and other studies suggest the slowed migration and increased fallback were related to hydraulic factors rather than physiological stress caused by exposure to supersaturated gas conditions. Overall migration rate, as measured by ground speed, is reduced in adult salmonids at higher river discharges (e.g., Keefer et al. 2004) and in areas of high hydraulic complexity and turbulence (Hinch and Rand 1998). As spill levels increase, turbulence in the tailrace increases in general, and especially in the Bonneville Dam spillway channel, suggesting decreased ground speeds (for a given swim speed) and decreases in route-finding efficiency increase the energetic cost of passage. The lower proportion of fish using spillway entrances during high spill (Figure 9, 10) and the increase in the number of detections on spillway antennas in summer Chinook salmon (Figure 11) were consistent with the hypothesis that individuals entering the spillway during high spill conditions did not reach or orient to spillway entrances as rapidly as fish entering during low spill conditions. High water velocities in the spillway may have also contributed to the increased passage times during high spill periods by decreasing ground speed. However, the patterns of fishway use and detections per fish (Figure 11) suggest that the increases in passage time may have been primarily caused by a decrease in the ability of individuals to orient to fishway entrances. Both increased search time and slower ground speeds at a given swim speed may have increased the costs of transiting the tailrace and spillway channel during high spill periods. For example, the energetic costs in sockeye salmon of passing turbulent reaches were related to both the time spent passing as well as swim speed *per se* (Hinch and Rand 1998). Similarly, Brown et al. (2000) found most of the energetic cost of passing Bonneville Dam occurred in the tailrace compare to the fishways or forebays during 2000 and 2001.

In contrast to the clear effects of flow and turbulence on migration rates, there was little evidence that high spill levels had negative indirect effects on adults by increasing total dissolved gas concentrations. In a related study at Bonneville Dam, Johnson (2003) and Johnson et al. (2005) estimated the potential for high TDG concentrations to negatively affect upstream migrating adults. While individual fish frequently were exposed to supersaturated dissolved gas conditions, most fish remained at depths that provided adequate hydrostatic compensation and little potential for gas bubble formation, suggesting gas concentrations were not responsible for the reduced migration rate at high spill. Despite this general pattern, individual fish frequently made short ascents to depths that did not provide hydrostatic compensation, suggesting the potential for frequent short-term exposure to high internal dissolved gas concentration that was uncompensated by hydrostatic pressure.

What may have been the significance of the observed treatment effects on adult fitness? The results suggest that the spill treatment increased tailrace passage times by approximately 25-33% in some cases (e.g., spring Chinook salmon in 2002). However, estimating the total effect on passage time was problematic, and there was consistent evidence of slowed passage, including increases in the number of fish remaining at the dam overnight. Moreover, recent studies with Columbia Basin adult salmonids have revealed that relatively slow passage of single dams or the lower Columbia Hydrosystem was associated with a lower probability of reaching spawning habitat (sockeye salmon, Naughton et al. 2005; spring, summer, fall Chinook salmon, Caudill et al. in review). These patterns suggest the potential for slowed migration at single projects and/or the cumulative effects at one or more projects to decrease adult survival to spawning grounds. We note that alternative mechanisms such as poor initial condition could have created the observed correlation between passage time and fate (Caudill et al. in review), and studies of underlying mechanisms are on-going. Regardless, there is the potential for cumulative or interactive factors to negatively affect returning adults. For instance, during summer, warm water temperatures increase the energetic costs of swimming, high spill may have sub-lethal effects on physiological state due to short-term high TDG exposure, and high spill may increase the impacts of both by increasing passage time. The cumulative effect at several projects may further interact with poor initial condition to further reduce the probability of successful migration. The potential for such effects may increase if river temperatures continue to warm and / or if the condition of returning adults declines as ocean conditions change.

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Appendix 1: Mean daily daytime spill, flow, and treatment assignments during the spill experiment, 2000-3.

	2000				2002					2003				
Date	**Flow**	**Uncorrected Spill**	**Treatment**	**Block**	**Flow**	**Uncorrected Spill**	**Corrected Spill**	**Treatment**	**Block**	**Flow**	**Uncorrected Spill**	**Corrected Spill**	**Treatment**	**Block**
14-Apr					256.3	76.5	49.6	Low	1	198.2	75.5	48.6	Low	1
15-Apr	313.2	71.6			275.9	86.6	60.2	Low	1	207.4	75.4	48.5	Low	1
16-Apr	262.0	69.8			354.2	143.0	122.6	High	1	226.0	138.5	117.4	High	1
17-Apr	265.0	50.1			347.2	148.1	128.6	High	1	213.5	149.7	130.6	High	1
18-Apr	298.5	72.7			320.6	159.7	142.4	High	2	253.9	148.3	128.9	High	2
19-Apr	326.5	97.7			300.7	150.0	130.8	High	2	218.7	147.0	127.3	High	2
20-Apr	330.5	79.9			270.9	77.3	50.5	Low	2	204.4	74.8	47.9	Low	2
21-Apr	324.9	74.9			298.6	76.7	49.9	Low	2	214.5	75.6	48.7	Low	2
22-Apr	323.7	137.0			258.5	149.1	129.8	High	3	239.7	141.7	121.2	High	3
23-Apr	387.1	143.6			277.3	148.7	129.4	High	3	251.9	142.2	121.8	High	3
24-Apr	365.1	128.8			281.3	83.3	56.6	Low	3	234.7	76.0	49.1	Low	3
25-Apr	334.8	124.3			252.0	75.9	49.0	Low	3	213.5	75.6	48.7	Low	3
26-Apr	328.7	83.1	Low	1	253.9	77.1	50.3	Low	4	281.6	75.2	48.3	Low	4
27-Apr	325.7	74.8	Low	1	258.3	75.6	48.7	Low	4	228.4	75.0	48.0	Low	4
28-Apr	289.3	73.7	Low	1	197.3	140.0	119.1	High	4	251.7	147.2	127.5	High	4
29-Apr	308.0	119.2	High	1	206.2	135.5	114.0	High	4	242.5	141.6	121.1	High	4
30-Apr	280.0	118.7	High	1	241.0	74.7	47.8	Low	5	248.8	134.1	112.4	High	5
1-May	289.1	111.6	High	1	235.1	75.0	48.1	Low	5	258.2	128.6	106.1	High	5
2-May	300.0	105.3	High	2	218.0	109.2	84.4	High	5	229.8	74.6	47.6	Low	5
3-May	300.9	95.3	High	2	257.1	112.4	87.9	High	5	225.1	74.2	47.3	Low	5
4-May	304.4	95.0	High	2	239.6	76.3	49.5	Low	6	213.3	102.6	77.2	High	6
5-May	314.7	74.4	Low	2	255.2	76.2	49.4	Low	6	218.1	110.2	85.6	High	6

	2000				2002					2003				
Date	Flow	Uncorrected Spill	Treatment	Block	Flow	Uncorrected Spill	Corrected Spill	Treatment	Block	Flow	Uncorrected Spill	Corrected Spill	Treatment	Block
6-May	305.5	73.9	Low	2	208.2	148.5	129.2	High	6	256.4	75.0	48.1	Low	6
7-May	283.4	74.6	Low	2	253.9	152.9	134.2	High	6	276.2	74.3	47.4	Low	6
8-May	278.8	88.2	High	3	277.2	147.2	127.6	High	7	226.0	75.1	48.2	Low	7
9-May	301.9	86.1	High	3	212.4	144.2	124.0	High	7	268.4	75.9	49.0	Low	7
10-May	261.4	85.0	High	3	194.2	76.8	49.9	Low	7	234.6	155.9	137.9	High	7
11-May	279.7	74.3	Low	3	225.1	75.4	48.5	Low	7	209.0	148.0	128.5	High	7
12-May	290.0	74.6	Low	3	192.6	75.8	48.9	Low	8	221.9	75.0	48.1	Low	8
13-May	256.6	72.2	Low	3	228.9	74.7	47.8	Low	8	212.8	75.1	48.2	Low	8
14-May	266.7	91.0	High	4	207.5	135.3	113.8	High	8	268.1	143.1	122.8	High	8
15-May	252.3	88.3	High	4	213.9	124.7	101.7	High	8	247.2	142.6	122.2	High	8
16-May	231.7	87.4	High	4	202.0	118.7	94.9	High	9	260.4	146.7	127.0	High	9
17-May	259.4	73.7	Low	4	216.9	115.9	91.8	High	9	245.0	148.9	129.6	High	9
18-May	197.0	74.0	Low	4	222.9	75.4	48.5	Low	9	265.7	75.5	48.6	Low	9
19-May	188.2	73.6	Low	4	227.3	75.7	48.8	Low	9	261.8	75.3	48.4	Low	9
20-May	190.1	95.5	High	5	238.7	75.3	48.3	Low	10	226.5	153.3	134.7	High	10
21-May	210.9	92.5	High	5	268.2	76.8	50.0	Low	10	245.0	146.9	127.2	High	10
22-May	223.9	87.9	High	5	290.5	112.7	88.3	High	10	261.4	76.2	49.3	Low	10
23-May	214.5	73.9	Low	5	273.9	150.6	131.6	High	10	268.3	76.0	49.1	Low	10
24-May	211.8	74.3	Low	5	278.2	151.7	132.9	High	11	256.8	138.1	117.0	High	11
25-May	192.4	74.4	Low	5	261.1	136.3	114.9	High	11	240.4	134.5	112.8	High	11
26-May	207.1	88.2	High	6	257.4	75.3	48.4	Low	11	272.7	75.2	48.3	Low	11
27-May	194.2	88.1	High	6	250.8	75.5	48.6	Low	11	304.3	78.9	52.1	Low	11
28-May	175.9	89.0	High	6	288.4	87.3	60.9	Low	12	346.2	123.6	100.5		
29-May	216.1	74.0	Low	6	324.4	129.0	106.6	High	12	285.3	81.0	54.3	Low	12
30-May	225.9	74.3	Low	6	295.5	125.3	102.4	High	12	356.1	139.2	118.3	High	12
31-May	207.9	73.9	Low	6	311.3	119.1	95.4			348.0	140.1	119.3	High	12
1-Jun	161.4	74.6	Low	7	350.2	127.5	104.9			350.8	127.0	104.2		
2-Jun	156.1	74.2	Low	7	309.1	175.7	161.8			320.9	98.9	73.3		

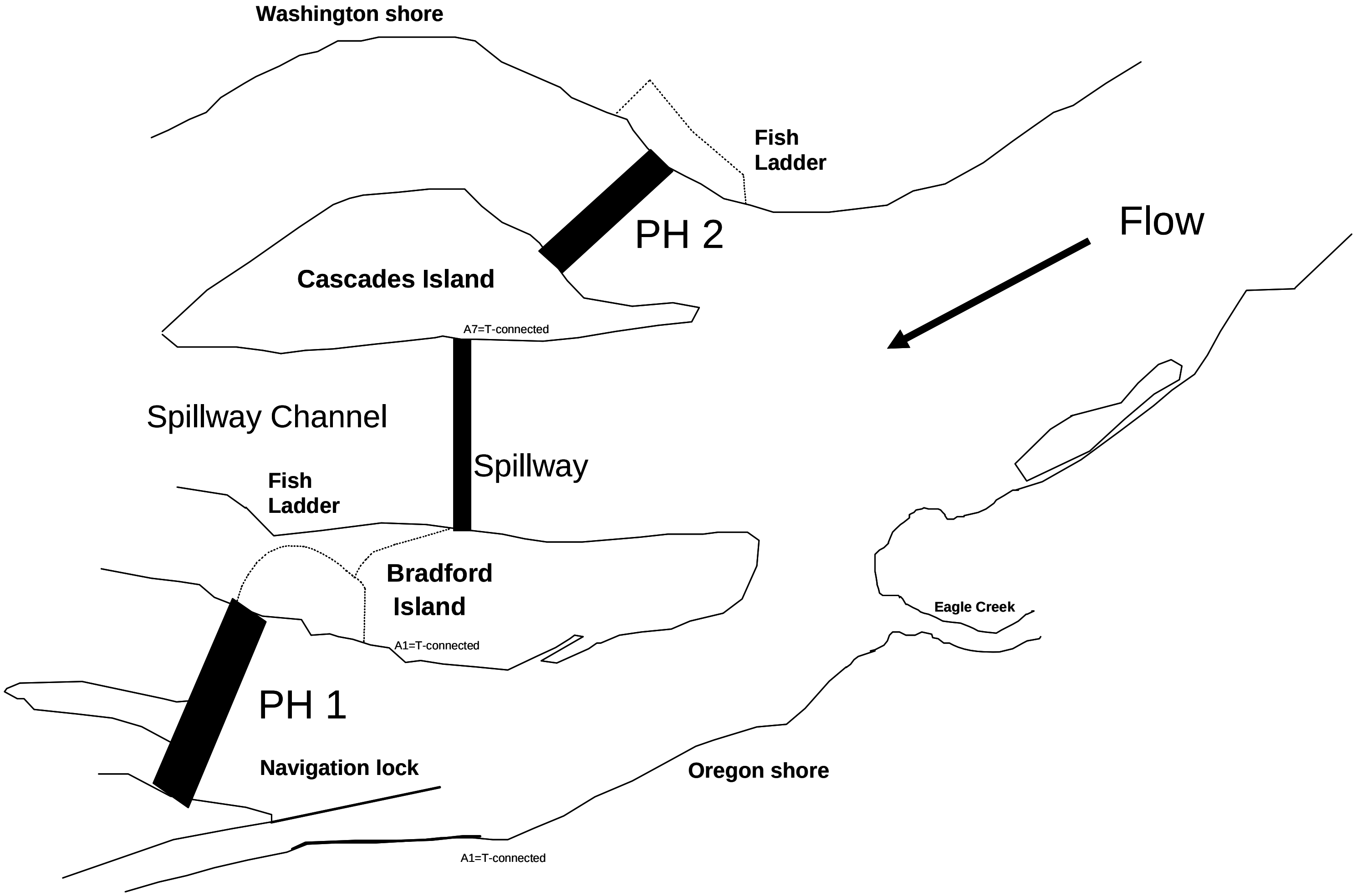
	2000				2002					2003				
Date	**Flow**	**Uncorrected Spill**	**Treatment**	**Block**	**Flow**	**Uncorrected Spill**	**Corrected Spill**	**Treatment**	**Block**	**Flow**	**Uncorrected Spill**	**Corrected Spill**	**Treatment**	**Block**
3-Jun	143.9	74.0	Low	7	303.2	123.8	100.6			316.4	144.8	124.7	High	13
4-Jun	160.1	101.5	High	7	332.1	172.8	158.3			301.5	143.1	122.7	High	13
5-Jun	152.3	93.5	High	7	359.1	192.0	182.1			298.2	75.8	48.9	Low	13
6-Jun	184.7	88.3	High	7	373.8	207.8	202.3			289.1	75.7	48.8	Low	13
7-Jun	235.2	87.6	High	8	349.6	155.2	137.0			278.1	133.9	112.1	High	14
8-Jun	196.2	86.7	High	8	363.5	174.2	160.0			295.3	129.0	106.6	High	14
9-Jun	180.5	91.7	High	8	311.9	133.4	111.6			278.9	75.4	48.5	Low	14
10-Jun	184.1	73.5	Low	8	296.6	118.2	94.4			299.7	74.2	47.3	Low	14
11-Jun	187.2	74.5	Low	8	343.0	156.8	138.9			314.9	140.8	120.1	High	15
12-Jun	180.5	74.2	Low	8	282.6	98.1	72.4			312.9	144.1	124.0	High	15
13-Jun	185.0	73.7	Low	9	301.0	106.1	81.0			276.1	77.4	50.6	Low	15
14-Jun		73.8	Low	9	270.1	78.6	51.8			293.3	77.6	50.8	Low	15
15-Jun	282.8	73.2	Low	9	297.0	102.0	76.6			255.4	154.1	135.8	High	16
16-Jun	260.4	101.6	High	9	277.2	100.5	74.9			243.1	151.7	132.9	High	16
17-Jun	240.4	108.5	High	9	312.7	125.4	102.5			287.9	74.5	47.6	Low	16
18-Jun	265.4	105.6	High	9	288.4	97.5	71.7			273.4	75.5	48.6	Low	16
19-Jun	254.9	102.2	High	10	344.5	149.7	130.5			271.2	146.0	126.1	High	17
20-Jun	244.1	101.5	High	10	358.8	162.7	146.0			207.8	149.8	130.6	High	17
21-Jun	266.0	100.1	High	10	350.7	157.6	139.8	High	13	202.6	75.5	48.6	Low	17
22-Jun	256.0	73.7	Low	10	311.7	129.6	107.2	High	13	203.0	76.2	49.3	Low	17
23-Jun	287.0	74.3	Low	10	290.3	80.6	53.9	Low	13	200.1	152.0	133.2		
24-Jun	287.7	74.5	Low	10	317.5	99.8	74.3			197.9	149.4	130.1		
25-Jun	288.4	74.3	Low	11	288.2	75.0	48.1	Low	14	214.1	144.0	123.8	High	18
26-Jun	246.0	70.5	Low	11	288.2	75.2	48.3	Low	14	252.6	143.1	122.8	High	18
27-Jun	235.0	73.4	Low	11	314.7	115.0	90.8	High	14	224.5	74.8	47.9	Low	18
28-Jun	242.1	118.2	High	11	321.4	126.1	103.3	High	14	191.5	74.4	47.4	Low	18
29-Jun	210.6	112.0	High	11	356.6	160.2	143.0							
30-Jun	236.3	108.6	High	11	312.1	109.0	84.2							

	2000					2002						2003				
Date	Flow	Uncorrected Spill	Treatment	Block		Flow	Uncorrected Spill	Corrected Spill	Treatment	Block		Flow	Uncorrected Spill	Corrected Spill	Treatment	Block
1-Jul	247.6	74.2	Low	12		328.7	180.4	167.6								
2-Jul	281.4	74.7	Low	12		315.3	148.8	129.4								
3-Jul	230.4	74.6	Low	12		291.5	124.0	100.9	High	15						
4-Jul	195.0	112.4	High	12		311.9	119.2	95.5	High	15						
5-Jul	206.4	109.7	High	12		281.1	75.6	48.7	Low	15						
6-Jul	216.0	103.3	High	12		246.3	75.3	48.3	Low	15						
7-Jul	258.3	74.2	Low	13		236.2	75.0	48.0	Low	16						
8-Jul	251.0	74.1	Low	13		239.0	74.7	47.8	Low	16						
9-Jul	223.3	74.1	Low	13		216.3	109.4	84.7	High	16						
10-Jul	217.4	108.9	High	13		207.3	114.0	89.7	High	16						
11-Jul	199.4	108.8	High	13		225.5	122.1	98.7	High	17						
12-Jul	188.5	107.9	High	13		254.1	119.9	96.3	High	17						
13-Jul	199.1	108.6	High	14		239.3	74.0	47.0	Low	17						
14-Jul	225.9	111.0	High	14		238.9	75.0	48.1	Low	17						
15-Jul	199.6	112.1	High	14		254.8	121.3	97.9	High	18						
16-Jul	181.6	74.5	Low	14		210.6	127.3	104.7	High	18						
17-Jul	155.6	73.5	Low	14		235.6	75.8	48.9	Low	18						
18-Jul	164.1	73.9	Low	14		257.3	75.4	48.5	Low	18						
19-Jul	175.4	73.9	Low	15		222.1	75.6	48.7	Low	19						
20-Jul	180.9	74.4	Low	15		207.5	75.9	49.0	Low	19						
21-Jul	180.0	74.1	Low	15		222.4	164.9	148.7	High	19						
22-Jul	192.4	100.7	High	15		239.2	150.8	131.8	High	19						
23-Jul	158.1	98.7	High	15		184.1	143.4	123.2	High	20						
24-Jul	148.1	86.8	High	15		204.3	133.1	111.2	High	20						
25-Jul	173.8	74.1	Low	16		205.9	75.3	48.4	Low	20						
26-Jul	170.0	74.2	Low	16		171.3	75.0	48.1	Low	20						
27-Jul	169.3	74.1	Low	16		175.9	138.4	117.3	High	21						
28-Jul	177.8	98.1	High	16		162.0	138.2	117.1	High	21						

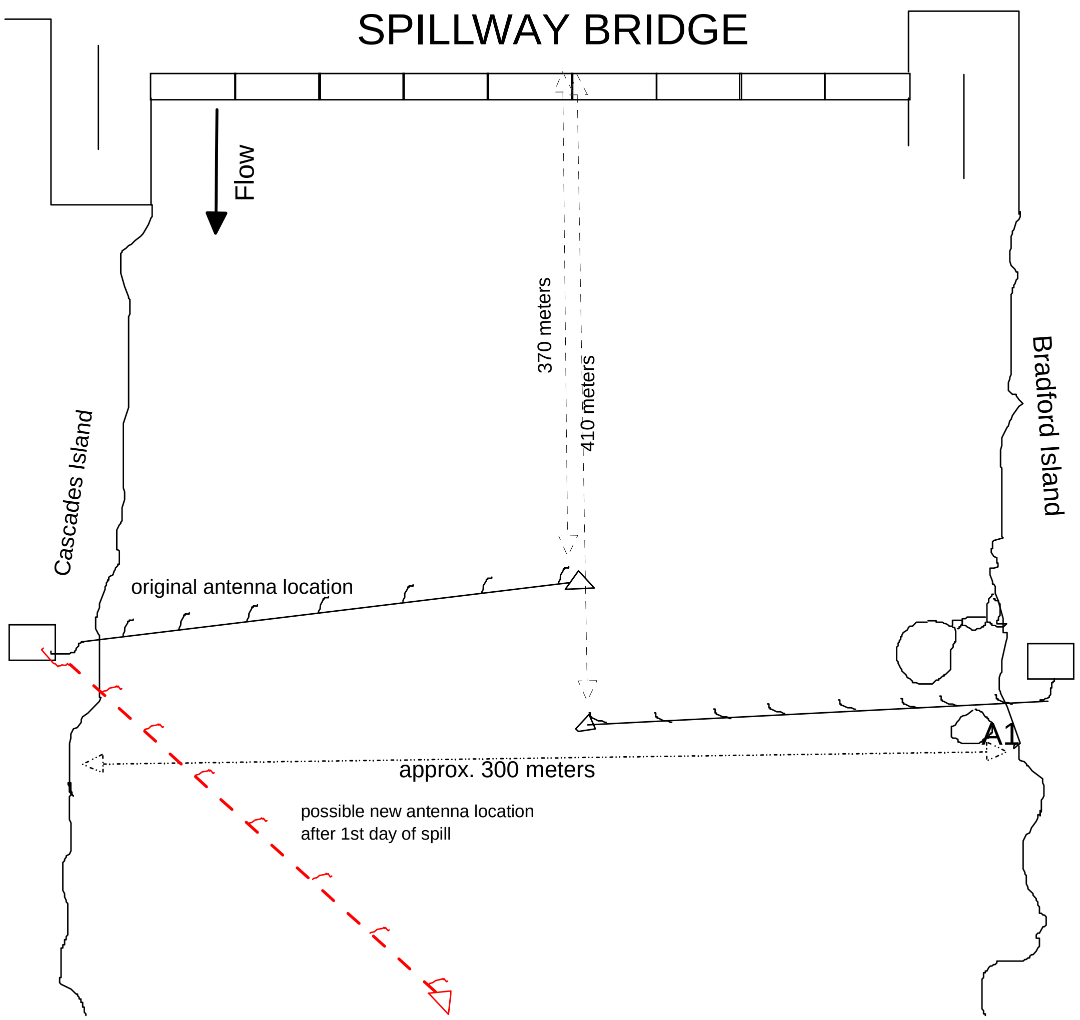
	2000					2002						2003				
Date	Flow	Uncorrected Spill	Treatment	Block		Flow	Uncorrected Spill	Corrected Spill	Treatment	Block		Flow	Uncorrected Spill	Corrected Spill	Treatment	Block
29-Jul	164.0	98.5	High	16		153.4	76.2	49.4	Low	21						
30-Jul	181.3	87.4	High	16		198.9	76.0	49.1	Low	21						
31-Jul	142.3	95.0	High	17		160.0	75.8	48.9	Low	22						
1-Aug	167.7	95.0	High	17		168.8	75.2	48.3	Low	22						
2-Aug	173.4	96.5	High	17		161.4	123.2	100.0	High	22						
3-Aug	179.4	74.5	Low	17		168.4	130.0	107.7	High	22						
4-Aug	190.3	73.8	Low	17		147.7	76.4	49.5	Low	23						
5-Aug	177.3	73.4	Low	17		180.2	75.3	48.4	Low	23						
6-Aug	152.4	87.6	High	18		170.3	132.5	110.5	High	23						
7-Aug	129.2	115.8	High	18		148.2	109.8	85.1	High	23						
8-Aug	166.0	119.9	High	18		172.8	134.3	112.6	High	24						
9-Aug	176.3	73.7	Low	18		183.4	145.1	125.1	High	24						
10-Aug	170.2	73.7	Low	18		150.0	75.1	48.2	Low	24						
11-Aug	166.2	74.3	Low	18		175.5	75.2	48.3	Low	24						
12-Aug	165.9	132.4	High	19		164.5	76.0	49.1	Low	25						
13-Aug	173.4	101.7	High	19		171.7	74.9	48.0	Low	25						
14-Aug		111.1	High	19		162.3	122.9	99.7	High	25						
15-Aug	147.4	73.7	Low	19		158.2	120.9	97.5	High	25						
16-Aug	163.3	74.0	Low	19		182.4	75.3	48.4	Low	26						
17-Aug	161.0	73.7	Low	19		137.9	75.4	48.5	Low	26						
18-Aug	174.5	74.2				137.4	99.6	74.0	High	26						
19-Aug	175.9	73.5				140.8	102.7	77.3	High	26						
20-Aug	160.1	74.9				156.2	118.7	95.0	High	27						
21-Aug	144.8	85.1				159.3	121.7	98.3	High	27						
22-Aug	122.2	70.0				151.5	76.3	49.4	Low	27						
23-Aug	127.5	104.1				157.0	75.0	48.1	Low	27						
24-Aug	118.1	62.5				163.9	65.2	38.1	Low	28						
25-Aug	140.5	60.7				126.7	74.6	47.7	Low	28						

	2000					2002						2003				
Date	**Flow**	**Uncorrected Spill**	**Treatment**	**Block**		**Flow**	**Uncorrected Spill**	**Corrected Spill**	**Treatment**	**Block**		**Flow**	**Uncorrected Spill**	**Corrected Spill**	**Treatment**	**Block**
26-Aug	103.9	84.0				147.8	109.4	84.7	High	28						
27-Aug	100.5	61.1				139.8	104.0	78.8	High	28						
28-Aug	115.4	69.7				153.2	76.4	49.5	Low	29						
29-Aug	101.8	68.4				142.2	74.4	47.5	Low	29						
30-Aug	112.8	74.2				147.5	109.1	84.3	High	29						
31-Aug	128.0	74.0				159.1	120.1	96.6	High	29						

Appendix 2a): Bonneville Dam showing locations of the spillway and two powerhouse channels. Entrance antennas were located inside fishway entrances at PH1, PH2, and the spillway. Tailrace antennas were ~1.8 km downstream of the powerhouses and spillway.



Appendix 2b): Location of spillway channel antennas in 2003.



Appendix 3: PHReg model results by year.

Run	**Year**	**N**	**Censored**	**Factor**	**d.f.**	**Estimate**	**Std Err**	**X2**	**P**	**Odds**
Spring CK	2000	286	73	Clips	1	-0.11145	0.1406	0.6283	0.428	0.895
				Discharge	1	-0.00228	0.00279	0.6673	0.414	0.998
				Length	1	-0.0182	0.01385	1.7259	0.1889	0.982
				Temperature	1	0.36463	0.0696	27.4485	<.0001	1.44
				Treatment	**1**	**0.0582**	**0.07455**	**0.6096**	**0.435**	**1.06**
	2002	407	95	Clips	1	-0.05543	0.11655	0.2262	0.6343	0.946
				Discharge	1	0.00302	0.00167	3.2516	0.0714	1.003
				Length	1	-0.00224	0.00676	0.1098	0.7404	0.998
				Temperature	1	0.34355	0.05103	45.3218	<.0001	1.41
				Treatment	**1**	**-0.39512**	**0.06061**	**42.4916**	**<.0001**	**0.674**
	2003	479	148	Clips	1	-0.10699	0.11613	0.8488	0.3569	0.899
				Discharge	1	0.00339	0.00201	2.8407	0.0919	1.003
				Length	1	0.00786	0.00565	1.9369	0.164	1.008
				Temperature	1	0.50472	0.06776	55.4759	<.0001	1.657
				Treatment	**1**	**-0.11656**	**0.0562**	**4.3011**	**0.0381**	**0.89**
Summer CK	2000	219	97	Clips	1	-0.23075	0.19277	1.4329	0.2313	0.794
				Discharge	1	-0.00125	0.00311	0.1619	0.6875	0.999
				Length	1	-0.02372	0.0101	5.5181	0.0188	0.977
				Temperature	1	-0.0408	0.0566	0.5198	0.4709	0.96
				Treatment	**1**	**0.08326**	**0.09499**	**0.7682**	**0.3808**	**1.087**
	2002	101	39	Clips	1	-0.30754	0.3347	0.8443	0.3582	0.735
				Discharge	1	0.00612	0.00451	1.8368	0.1753	1.006
				Length	1	0.0084	0.01472	0.3257	0.5682	1.008
				Temperature	1	-0.00263	0.15683	0.0003	0.9866	0.997
				Treatment	**1**	**-0.32523**	**0.14766**	**4.8512**	**0.0276**	**0.722**
	2003	129	39	Clips	1	-0.45832	0.24497	3.5004	0.0614	0.632
				Discharge	1	-0.003	0.0031	0.9376	0.3329	0.997
				Length	1	-0.05184	0.01407	13.5824	0.0002	0.949
				Temperature	1	0.01875	0.18592	0.0102	0.9197	1.019
				Treatment	**1**	**-0.50658**	**0.11663**	**18.8675**	**<.0001**	**0.603**
Fall Ck	2000	29	5	Clips	1	-0.98983	0.62454	2.5119	0.113	0.372
				Discharge	1	0.01279	0.01315	0.9469	0.3305	1.013
				Length	1	-0.01901	0.02983	0.4063	0.5239	0.981
				Temperature	1	0.03541	0.13198	0.072	0.7885	1.036
				Treatment	**1**	**-0.09069**	**0.24389**	**0.1383**	**0.71**	**0.913**
	2002	117	33	Clips	1	0.43075	0.29499	2.1322	0.1442	1.538
				Discharge	1	0.01171	0.00806	2.1114	0.1462	1.012
				Length	1	-0.01989	0.01488	1.7869	0.1813	0.98
				Temperature	1	-0.42906	0.39637	1.1718	0.279	0.651
				Treatment	**1**	**-0.20611**	**0.11345**	**3.3008**	**0.0692**	**0.814**

Run	**Year**	**N**	**Censored**	**Factor**	**d.f.**	**Estimate**	**Std Err**	**X2**	**P**	**Odds**
Steelhead	2000	276	92	Clips	1	0.03145	0.15424	0.0416	0.8384	1.032
				Discharge	1	-0.00457	0.00319	2.0481	0.1524	0.995
				Length	1	0.00485	0.01138	0.1814	0.6702	1.005
				Temperature	1	-0.07039	0.0467	2.2716	0.1318	0.932
				Treatment	**1**	**-0.0646**	**0.07596**	**0.7232**	**0.3951**	**0.937**
	2002	432	105	Clips	1	0.02722	0.11454	0.0565	0.8121	1.028
				Discharge	1	0.00106	0.00172	0.3824	0.5363	1.001
				Length	1	0.0104	0.00766	1.8439	0.1745	1.01
				Temperature	1	-0.0693	0.04833	2.056	0.1516	0.933
				Treatment	**1**	**-0.2564**	**0.05796**	**19.5678**	**<.0001**	**0.774**