Effect of spill on adult salmon passage delay at Columbia River and Snake River dams

W. Nicholas Beer

James J. Anderson*

School of Aquatic and Fishery Sciences

University of Washington

Box 358218

Seattle, WA 98195

nickbeer@uw.edu

jjand@uw.edu

* Corresponding author

Abstract

Spill, used to assist the downstream passage of juvenile Chinook salmon (*Oncorhynchus tshawytscha*), and steelhead (*O. mykiss*) at eight dams in the Columbia/Snake River hydrosystem may delay the upstream passage of the adults. To evaluate the potential effects of spill on adult passage we evaluated the historical relationship between the day-to-day variations of spill and upstream fish passage at the eight dams of the Columbia/Snake river hydrosystem between 1960 and 2010. Seven of the dams had negative relationships in which an increase in spill was statistically correlated with a decrease in passage. The Dalles Dam, which has a unique configuration of spill bays, powerhouses and adult passage facilities, had a significant positive relationship. Steelhead salmon were most sensitive to changes in spill throughout the system, and jack Chinook, the least sensitive. These patterns suggest that the spill-passage relationship is weak but depends on both migration behavior and dam configuration. In general, the analysis indicates that spilling 30% of the river flows to assist juvenile fish downstream passage delays the adult upstream passage by about one day on a total hydrosystem passage of between two and four weeks depending on species.

Introduction

The adult migration of salmon upstream to their spawning grounds is the penultimate stage in their life history and is important because these fish are the survivors that contribute to the next generation. The success of fish passage depends on the fish's ability to move efficiently through the river system and conserve energy for spawning. Delays during upstream passage therefore can affect their fitness by depleting energy reserves which would otherwise be used in spawning. In rivers with dams, upstream passage can be delayed by hydraulic conditions that affect the ability of fish to find and ascend the fishways (Anderson et al. 2009; Beer 2007; Hinch et al. 2000; Keefer et al. 2008b; Salinger et al. 2006).

Research has shown that the configurations of dam structures, flow and spill alter fish passage behavior at dams (Caudill et al. 2006; FERL 2010; Jepson et al. 2009; Keefer et al. 2008a; Leman et al. 1966; Lundqvist et al. 2008). Generally as spill increases proportional to total flow, fish are attracted to the spillway (Lundqvist et al. 2008), but at very high spill volumes, passage times increase (Caudill et al. 2006; FERL 2010) and the fallback of fish over the spillway and through turbines increases (Boggs et al. 2004). A controlled study revealed that low-level spills could attract both Chinook salmon and steelhead at Lower Monumental and Ice Harbor ladders near spill ways (Bjornn et al. 1999). However, passage of Chinook salmon through the Snake River dams was reduced at the highest flow and spill levels (Bjornn et al. 1998). At Little Goose Dam on the Snake River, spill operations generally delayed fish passage (Jepson et al. 2009), and Keefer et al. (2008b) noted that frequent switching of spill conditions provided confusing cues to adult fish and increased their delay in passing. Moderate spill was best for attracting fish to spillway entrances.

The accumulated evidence that spill may increase the delay of adult upstream passage is of concern in the Columbia/Snake river hydrosystem because spill levels have been increased in the past several years to assist the downstream passage of juvenile salmon and steelhead (NMFS 2008) during the time that the adults are moving upstream. To evaluate the potential effects of spill we examine four decades of spill and adult upstream passage for the eight dams of the Columbia/Snake River hydrosystem (Figure 1).

Methods

The method compares changes in adult passage counts and spill levels for each dam and species over four decades of observations. The spill levels and passage numbers at dams vary considerably from day-to-day and to evaluate the effect of the day-to-day variation in spill on fish passage at dams independent of other factors that affect passage, a regression technique was developed that compares daily observed spill and fish passage measures to running means of the measures (Figure 2). Differences between short-term conditions and observed conditions reflect the effect of the daily variations in spill whether or not the general trend in passage numbers is increasing or decreasing.

The anomaly of spill on day *i* relative to the average of spill over the previous two days is defined:

$$x_i = s_i - (s_{i-1} + s_{i-2})/2 \tag{1}$$

where s_i is the spill on day *i*. Because the day-to-day counts of fish passage at a dam tend to be correlated and may vary by orders of magnitude, fish passage is defined as the ratio of the passage count on day *i*, designated m_i, to the average passage count over a 5 day interval centered on day *i*:

$$y_i = \frac{m_i}{mean(m_{i-2} \ldots m_{i+2})}. \tag{2}$$

In principle, if spill has a negative impact on fish passage, then when the spill on day *i* is above the short term mean the fish passage count on day *i* should fall below the running mean value. Thus, a relationship between the spill anomaly and the passage ratio anomaly should be reflected in the regression:

$$y_i = \alpha + \beta x_i \tag{3}$$

where β is a measure of the effect of spill on passage and α is an intercept that, in principle, tends to 1. The error in the passage anomaly was found to be normally distributed and the coefficients were estimated by minimizing the sum-of-squares where days with less than 10 fish were excluded from the regression.

A first order estimate of the delay due to spill is developed as follows. Assuming that fish pass a dam according to a binomial process, then the mean number that pass in day *i* is $m_i = p_i N_i$ where N_i is the number of fish in the tailrace in day *i* and p_i is the probability of passing in the day. Furthermore, the running average of fish passing over the five day interval is similarly $\bar{m}_i = \overline{p_i N_i}$ where the bar specifies an average over 5 days centered on day *i*. Now the passage ratio on day is defined $y_i = p_i N_i / \overline{p_i N_i}$. Assuming that the number of fish that arrive at a dam is independent of the spill operations then *p* and *N* are independent random variables. Next, the average passage numbers are approximated as $\overline{pN} \sim \bar{p}\bar{N}$. To evaluate this approximation assume *p* is uniformly distributed over an interval (e.g. 0.4 to 0.6) and *N* has a gamma distribution with a mean daily fish passage of 600 and a standard deviation of 300. For these conditions, $\overline{pN}/\bar{p}\bar{N}$ is normally distributed with expected value $E\left[\overline{pN}/\bar{p}\bar{N}\right] = 1.00 \pm 0.02$. With the number of fish arriving at the dam independent of spill, the ratio of the forebay numbers on day *i* to the mean across five days converges to 1. For the numerical example this gives $E\left[N/\bar{N}\right] = 1.00 \pm 0.3$. It follows then that

$$y = \frac{pN}{\overline{pN}} \sim \frac{pN}{\bar{p}\bar{N}} = \frac{p}{\bar{p}} \tag{4}$$

and the approximate relationship between a change in spill, *x*, and the probability of passage of a fish in a day is

$$p = \bar{p}\left(\alpha + \beta x\right). \tag{5}$$

Note that eq.(5) only gives the passage probability for an incremental change in spill from some base passage probability $\bar{p}$ at some level of spill x immediately prior to the incremental change. However, with information or assumptions on the passage probabilities and average delay under base conditions we can estimate the relative effect of spill on passage.

To express the effect of a spill change on the time it takes on the average for a fish to pass a dam assume that fish pass continuously and independently. Then, the cumulative probability distribution of fish passage as a function of time in the tailrace t and spill conditions x is expressed

$$p(x,t) = 1 - \exp\left(-\lambda(x)t\right) \tag{6}$$

where the rate of passage is $\lambda(x)$. Equation (6) is the cumulative probability of passage as a function of time t while eq. (5) is the cumulative probability of passing in one day and so equating the two equations at t = 1 day gives the passage rate as a function of spill as

$$\lambda(x) = -\ln\left(1 - \bar{p}\left(\alpha + \beta x\right)\right) \tag{7}$$

where $\bar{p}$ expresses the average probability of a fish passing in one day given no change in spill. The time required for 50% of the fish to pass can be defined as a function of the change in spill by setting $p(x,t) = 0.5$ in eq. (6) and defining $\lambda(x)$ by eq. (7) to give

$$t_{0.5} = \frac{\ln(0.5)}{\ln\left(1 - \bar{p}\left(\alpha + \beta x\right)\right)}\,. \tag{8}$$

The time is expressed in days.

Data

The eight dams (Figure 1) used in the analyses are referenced: BON, Bonneville; TDA, The Dalles; JDA, John Day; MCN, McNary; IHR, Ice Harbor; LMN, Lower Monumental; LGS, Little Goose;

and LWG, Lower Granite. Time series of spill volume, spill percentage, and adult passage counts (Chinook , jack Chinook and steelhead salmon) were compiled from DART (www.cbr.washington.edu/dart/) for BON (1960-2010), TDA (1960-2010), JDA (1969-2010), MCN (1970-2010), IHR (1961-2010), LMN (1969-2010), LGS (1975-2010), and LWG (1975-2010) dams.

Results

Although many spill and passage correlations are significant, they are weak relationships because passage variation is mostly due to other processes. The most general statement about spill affects on passage (TABLE 1 and TABLE 2) is that at the Columbia River dams (BON, TDA, JDA, and MCN), there is a slight negative impact caused by increases in spill except for TDA where spill has the opposite effect; increased spill decreases passage time. At the Snake River dams (IHR, LMN, LGS, and LWG), the steelhead were negatively impacted, and the Chinook and jack Chinook had mixed but mostly negative results. The relationship between spill and fish passage is weakest at MCN, i.e. changes in spill do not impact Chinook or jack Chinook passage significantly. The spill anomaly vs. passage anomaly for Chinook salmon at BON (Figure 3) illustrates the typical negative pattern observed.

Equation (8) provides an estimate of the effect of spill in terms of the amount of delay or advance in the passage time in units of one day. Assuming an average passage probability ($\bar{p}$) of 0.5 in one day (Bjornn et al. 1992; Zabel et al. 2008) and from the regressions noting $\alpha = 1$ then the delay at a dam depends on the spill change x and the coefficient β. Using β parameters from Table 3, a 20 kcfs increase in spill delays passage between -0.8 and 4.2 hours. For an increase in spill percentage of 30%, delay varies between -0.5 and 13.8 hours. A worst-case scenario is estimated for each species passing all 8 dams. Assuming that the average passage is at spill level = 0% and using a jump to 30%, then Chinook, steelhead and jacks are delayed 34, 43 and 30 hours respectively from BON to LWG. In comparison, the median travel times between BON and LWG dams from 1998-2002 were 17 and 36 days for spring Chinook and steelhead respectively (Salinger and Anderson 2006).

Discussion

A number of factors limit the ability to detect significant effects of spill on fish passage. First, extreme spill levels which have largest potential delays on passage were rare in the data and therefore did not influence the results as strongly as the common small changes in spill. Second, the effect of spill and flow on fish passage is incompletely understood, and since each dam's configuration is unique, local hydraulic conditions affected fish approach and passage in different ways. Third, daily and seasonal variations in fish passage were large resulting in the runs being exposed to different environmental conditions (DeHart 2010).

Variation in hydraulic conditions likely contributed to the unique relationship of spill and passage at TDA and BON. At most Columbia/Snake river dams, the spillway and powerhouse are on opposite sides of the project, with entrances to the fish ladders on either bank and between the two structures. However, at TDA, the powerhouse is perpendicular to the spillway and separate about 1 km, while at BON the spillway is separated from the two powerhouses by small islands. Bonneville Dam exhibited a consistent negative relationship between spill levels and passage. In contrast, at TDA, the significant relationships between spill and passage were all positive. Other studies have also noted the impacts of spill on passage at BON: Chinook passage was reduced at high levels of spill (Caudill et al. 2006; FERL 2010); fallback of fish after passing a dam, increases with spill (Boggs et al. 2004); and flow and spill dependent hydraulic conditions may delay fish entrance to fishways by increasing the energetic costs of swimming or disrupting their ability to locate the fishway (Caudill et al. 2006; FERL 2010; Jepson et al. 2009).

Several studies show steelhead were most impacted and jack Chinook least impacted by spill. Factors could include differences in fish size, run timing, behavioral preferences, and other conditions (e.g. temperature). Steelhead are known to be sensitive to velocities, flows, temperature gradients and other conditions at the fishway entrances and ladders (NMFS 2000). Additionally a study of individually tracked radio-tagged Chinook, concluded that smaller fish pass dams more quickly than larger ones (Zabel et al. 2008). Plausibly, jack Chinook, which are smaller than the main Chinook run, may avoid high flows by seeking near-shore fish ladders and therefore are less susceptible to changes in the hydraulic effects of spill.

On the Columbia and Snake Rivers, spill is stipulated at target levels (NMFS 2008) to aid juvenile passage but delay of adults could affect survival and spawning success (Dauble et al. 2000). The target levels are either volumes or percentages ranging from 20 to 100 KCFS or 30% to 40%, depending on the dam which results in an upstream passage delay of about one day or about 5% to 8% of the total passage time through the hydrosystem.

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Figures

FIGURE 1. Map showing the Columbia and Snake rivers and the locations of dams on the migration route from Bonneville Dam to Lower Granite Dam.

FIGURE 2. Example of passage (#/d) and spill (kcfs) vs. day of year and passage ratio anomaly and spill ratio anomaly vs. day of year.

FIGURE 3 Relationship between spill anomaly (kcfs) and passage ratio anomaly for Chinook salmon at BON. The negative correlation is significant ($p < 0.00001$). Values outside of 4 standard deviations are cropped.

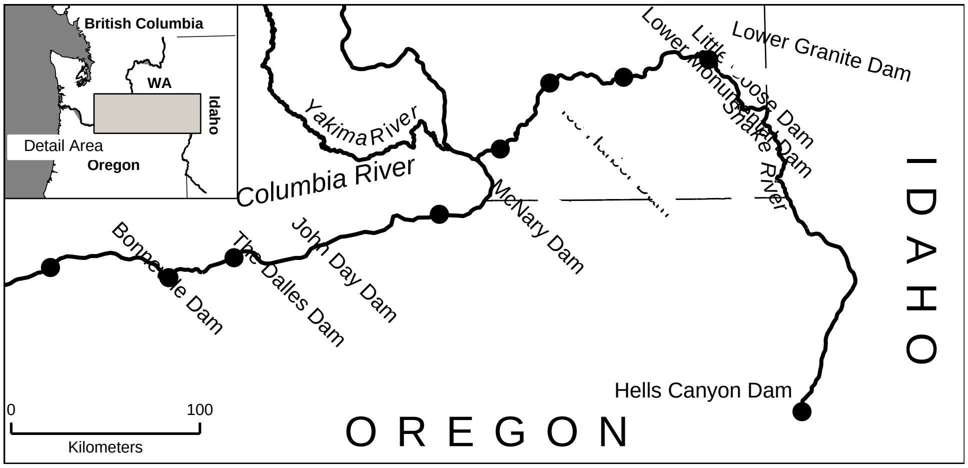
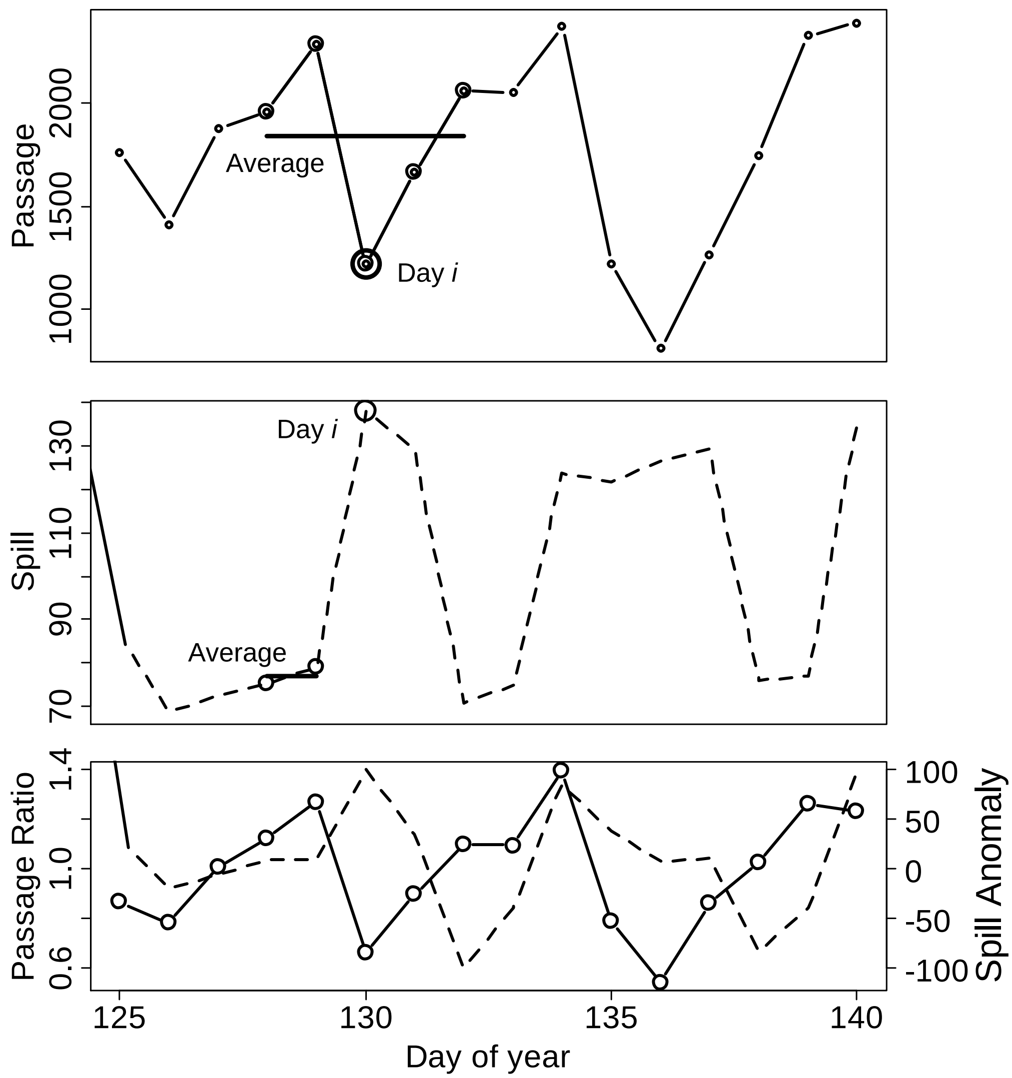

British Columbia
WA
Idaho
Detail Area
Oregon
Yakima River
Columbia River
Lower Granite Dam
Lower Monumental Dam
Little Goose Dam
Snake River
McNary Dam
John Day Dam
The Dalles Dam
Bonneville Dam
Hells Canyon Dam
I D A H O
O R E G O N
0
100
Kilometers

Figure 1



Passage
1000
1500
2000
Average
Day *i*
Spill
70
90
110
130
Day *i*
Average
Passage Ratio
0.6
1.0
1.4
Spill Anomaly
100
50
0
-50
-100
125
130
135
140
Day of year

FIGURE 2

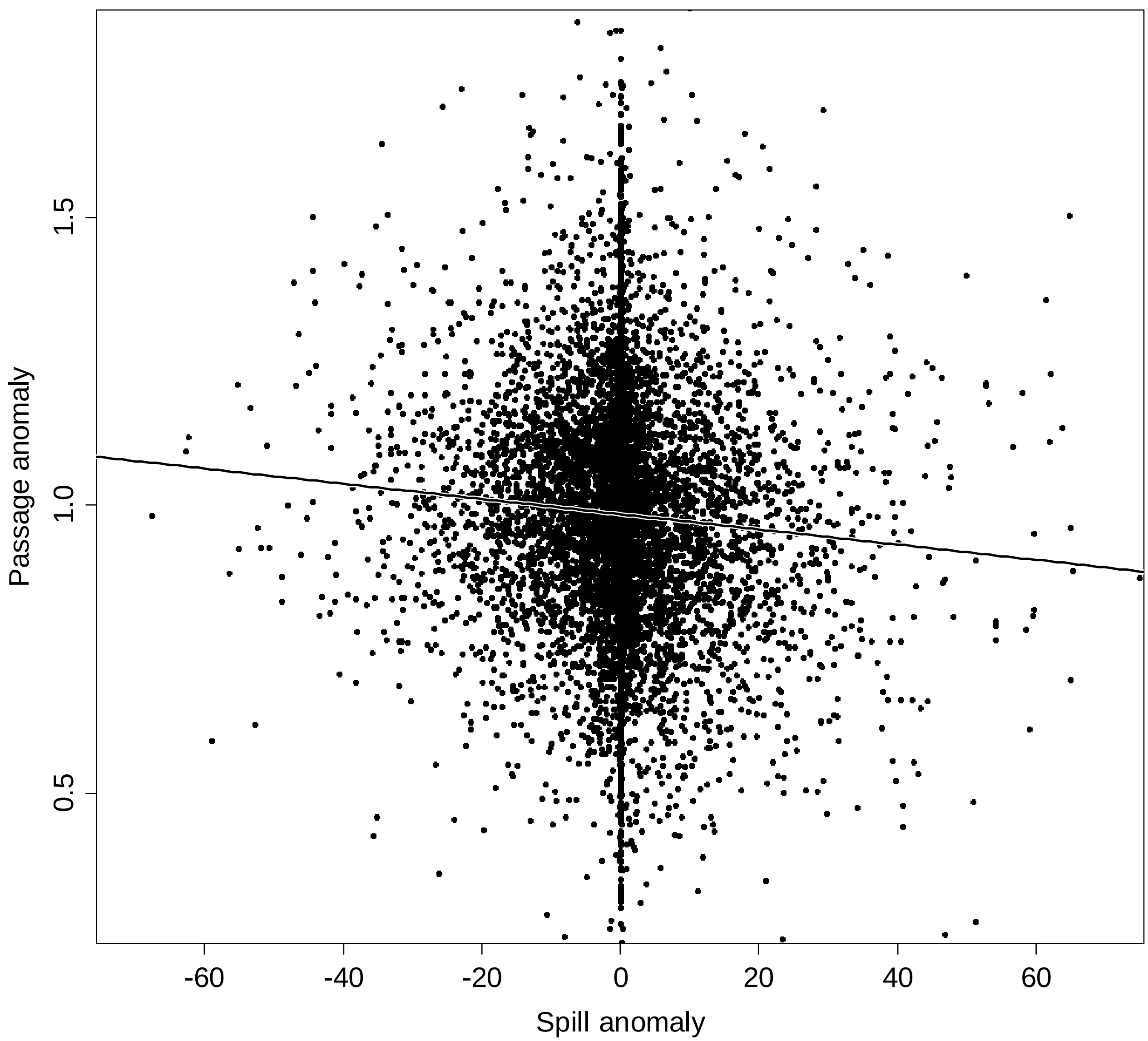


FIGURE 3

TABLE 1. Correlations and p-value of regressions, in parentheses, between spill volume anomalies and passage ratio anomalies.

	BON	TDA	JDA	MCN	IHR	LMN	LGS	LWG
Chinook	-0.066	0.054	-0.064	-0.027	-0.035	-0.005	-0.025	0.017
	(<0.001)	(<0.001)	(<0.001)	(0.013)	(0.002)	(0.650)	(0.100)	(0.201)
Steelhead	-0.055	0.036	-0.036	-0.044	-0.067	-0.045	-0.068	-0.036
	(<0.001)	(0.002)	(0.002)	(<0.001)	(<0.001)	(<0.001)	(<0.001)	(0.006)
jack Chinook	-0.062	-0.001	-0.027	-0.010	-0.021	-0.010	-0.050	-0.014
	(<0.001)	(0.947)	(0.043)	(0.378)	(0.118)	(0.504)	(0.008)	(0.419)

TABLE 2. Correlation between spill percentage anomalies and passage ratio anomalies (p-value of regression significance).

	BON	TDA	JDA	MCN	IHR	LMN	LGS	LWG
Chinook	-0.034 (0.001)	0.032 (0.004)	-0.075 (<0.001)	-0.020 (0.071)	-0.036 (0.001)	-0.046 (<0.001)	-0.058 (<0.001)	-0.010 (0.452)
Steelhead	-0.040 (<0.001)	0.012 (0.295)	-0.035 (0.003)	-0.022 (0.052)	-0.055 (<0.001)	-0.082 (<0.001)	-0.089 (<0.001)	-0.088 (<0.001)
jack Chinook	-0.052 (<0.001)	-0.007 (0.583)	-0.019 (0.142)	0.008 (0.477)	-0.033 (0.014)	-0.041 (0.005)	-0.069 (<0.001)	-0.052 (0.002)

TABLE 3. Passage anomaly regression coefficient (*β*) for volume or percentage increases, significance of regressions and hours of delay for a 20 kcfs and 30% spill increase.

Fish run	Dam	β using spill volumes	$p < 0.01$	Hours delay at 20 kcfs	β using spill percentage	$p < 0.01$	Hours delay at 30%
Chinook	BON	-0.000880	Yes	0.6	-0.116300	Yes	2.1
	TDA	0.000689	Yes	-0.5	0.025660	Yes	-0.4
	JDA	-0.001629	Yes	1.2	-0.566800	Yes	13.5
	MCN	-0.000444	No	0.3	-0.069160	No	1.2
	IHR	-0.001238	Yes	0.9	-0.133200	Yes	2.5
	LMN	-0.000241	No	0.1	-0.235600	Yes	4.6
	LGS	-0.001717	No	1.2	-0.436100	Yes	9.5
	LWG	0.001110	No	-0.8	-0.067900	No	1.2
Steelhead	BON	-0.0006419	Yes	0.4	-0.121300	Yes	2.2
	TDA	0.0004762	Yes	-0.3	0.022730	Yes	-0.4
	JDA	-0.0008278	Yes	0.6	-0.232600	Yes	4.5
	MCN	-0.0006695	Yes	0.5	-0.068470	Yes	1.2
	IHR	-0.0028520	Yes	2.0	-0.193400	Yes	3.7
	LMN	-0.0023710	Yes	1.7	-0.369000	Yes	7.8
	LGS	-0.0054840	Yes	4.2	-0.575600	Yes	13.8
	LWG	-0.0024900	Yes	1.8	-0.454500	Yes	10.0
jack Chinook	BON	-0.0009866	Yes	0.7	-0.189900	Yes	3.6
	TDA	-0.0000115	No	0.0	-0.005378	No	0.1
	JDA	-0.0006935	No	0.5	-0.139000	No	2.6
	MCN	-0.0001736	No	0.1	0.029320	No	-0.5
	IHR	-0.0008814	No	0.6	-0.138900	No	2.6
	LMN	-0.0004442	No	0.3	-0.221600	Yes	4.3
	LGS	-0.0032130	Yes	2.4	-0.490200	Yes	11.1
	LWG	-0.0007562	No	0.5	-0.302700	Yes	6.1