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# An Evaluation of Adult Chinook Salmon and Steelhead Behavior at Counting Windows and through Vertical-slot Weirs of Bonneville Dam Using Radiotelemetry: 2001-2002

A Report for Study Code ADS-00-2

by

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Copies of this and related reports from this project can be obtained from at http://www.cnr.uidaho.edu/uiferl/.

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## Abstract

We used radio telemetry to evaluate the behavior of spring–summer Chinook salmon, fall Chinook salmon, and steelhead swimming past counting windows and through vertical-slot weirs of the Bradford Island and Washington shore fishways at Bonneville Dam during 2001 and 2002.

Median times to pass a counting window ranged from 2.0 to14.7 min among all run/year/fishway groups (*n*=12) and were consistently highest for run/year groups initially recorded at the Bradford Island counting window. Ratios of counting window passage times to total dam passage times (first record in tailrace to last record at ladder exit) for individual fish were ≤ 1.0% based on median values, and ≤6.7% based on mean values, of all year/run/fishway groups. The maximum proportion of fish swimming downstream to a transition pool after being recorded at a counting window was for spring–summer Chinook salmon at the Bradford Island counting window in 2001 (2.4%, *n*=340). The median counting window passage times for all fish that swam to a transition pool after being detected at a counting window was approximately 30 h (*n*=24).

Proportions of fish recorded upstream of a counting window and then downstream of a counting window ('up-and-back' behavior) were consistently highest for steelhead among all run/year groups with a maximum of 11.5% (*n*=295) at the Bradford Island counting window during 2001. Of the 4,277 unique fish recorded downstream from a counting window during the two study years, 272 (6.4%) exhibited up-and-back behavior and their median counting window passage time was 43 min.

Among all run/year groups, median times to pass through the vertical-slot weirs of the Bradford Island fishway ranged from 26.5 to 33.5 min and 39.7 to 51.8 min for the Washington-shore fishway. Direct comparisons of passage times between vertical-slot weir sections of the Bradford Island and Washington shore fishways were precluded because of differences in antenna configurations and varying distances between the first vertical-slot weir of each fishway and its corresponding ladder exit.

Based on median values among all run/year groups, ratios of vertical-slot weir passage times to total dam passage times for individual fish were ≤3.8% (*mean* ≤ 7.3%) for groups initially recorded in the Bradford Island vertical-slot weirs and ≤4.8% (*mean* ≤ 9.0%) for the Washington shore vertical-slot weirs. The maximum proportion of fish recorded swimming to a transition pool after being recorded at a vertical-slot weir was for fall Chinook salmon at the Bradford Island fishway in 2001 (1.5%, *n*=204). Overall, 0.6% of fish (*n*=4,277) swam to a transition pool after being detected in a set of vertical-slot weirs and their median passage time was 95.3 h. Six fish (0.1%) were recorded in a set of vertical-slot weirs, swam to a transition pool, and did not pass the dam.

On average, the combined passage of count windows and vertical-slot weirs at termini of the Bonneville fishways accounted for 6.9 to11.8% of total dam passage times among all run/year/fishway groups and 2.8 to 5.6% based on median values.

Analyses assessing the degree of association between counting window or vertical-slot weir passage times and total dam passage times suggested the correlations were positive, but weak. Linear regression models using median weekly passage times as dependent variables and mean daily fish counts (during corresponding weeks) as predictors suggested that steelhead were slightly more likely than Chinook salmon to have increased passage times during periods of high fish counts. On balance, however, any effects of high fish abundance on counting window or vertical-slot weir passage times were believed to be small.

## Introduction

Radio telemetry techniques can be used to identify potential impediments to adult salmonids as they migrate upstream past Columbia River dams, including the counting windows and vertical-slot weirs in dam fishways. Counting windows are covered, lit, and narrow passage points that may create a discontinuity in fishway conditions such that timely upstream movements of fish are inhibited. Fish have been observed by counters to occasionally move upstream and then downstream from counting windows ('up-and-back' behavior) and to hold for extended periods at counting windows. Moreover, the crowding of fish near counting windows, particularly during periods of high fish abundance, may elicit an avoidance response in some fish. As stated in the Federal Columbia River Power System Biological Opinion Action 117 (NMFS 2000), "The Corps shall evaluate adult count station facilities…to either minimize delay of adults or minimize counting difficulties that reduce count accuracy."

In addition to counting windows, variations in hydrological conditions associated with different fishway designs may obstruct the passage of some adult fish. Bonneville Dam, for example, has overflow weirs downstream from the counting windows and vertical-slot weirs upstream from the windows. In 2001-2002, we installed receivers and deployed underwater antennas upstream and downstream from count windows and in the vertical-slot weir sections of both the Bradford Island and Washington shore fishways of Bonneville Dam. We collected radio telemetry data to evaluate the behavior of spring–summer Chinook salmon, fall Chinook salmon, and steelhead near the counting windows and through the vertical-slot weir sections of fishways at Bonneville Dam and to assess any evidence that adult salmon passage is hindered in these sections of the ladders.

## Methods

Adult spring–summer Chinook salmon, fall Chinook salmon and steelhead were released with transmitters downstream from Bonneville Dam throughout the migration of each species both years. Fish were collected in the Adult Fish Facility (AFF) adjacent to the Washington shore ladder at Bonneville Dam. During the day, a picketed lead weir was dropped into the ladder and adult migrants were unselectively diverted into the trap. Fish swam from the trap into exit chutes and were diverted into an anesthetic tank [22 mg/l clove oil] (Peake 1998) via electronically controlled guide gates. Anesthetized fish were moved to a smaller tank where lengths, marks and injuries were recorded, and where fish were tagged.

We used passive integrated transponder (PIT) tags as secondary tags during both years. If a fish to be radio tagged did not have a PIT tag before coming into the trap, we inserted one into the fish during tagging. A radio transmitter dipped in glycerin was inserted into the stomach through the mouth. We used 3- and 7-volt transmitters (Lotek Wireless, Newmarket, Ont.), that emitted a digitally coded signal (containing the frequency and code of the transmitter) every 5 s. We also used some combination radio/data storage transmitters (RDST tags) in 2002 that recorded and stored temperature and pressure data, and some combination acoustic/radio transmitters (CART tags) in 2001. All transmitters were cylindrical with 43-47 cm antennas. Seven volt tags weighed 29 g in air (8.3 by 1.6 cm), RDST tags were 34 g (9.0 by 2.0 cm) and CART tags were 28 g (6.0 by 1.6 cm). Code sets allowed us to monitor up to 212 fish on each frequency. Lithium batteries powered the transmitters and all but the RDST tags had a rated operating life of more than nine months. After tagging, fish were placed in an aerated transport tank where they were held until released.

Fish were released about 9.5 km downstream from Bonneville Dam at sites on both sides of the river. We excluded counting window and vertical-slot weir passage times associated with fish re-ascending the dam after they had fallen back. We used dates accepted by USACE to separate between spring, summer, and fall-run fish at Bonneville Dam and combined spring and summer Chinook salmon for these analyses. We calculated counting window and vertical-slot weir passage times as proportions of total dam passage times (defined as the interval between the first detection in the tailrace to last detection at the ladder exit) by dividing passage times of individual fish by the total dam passage times for those same individuals.

We deployed underwater antennas immediately downstream and upstream of the counting windows, in the vertical-slot weirs, and at the ladder exits of the Bradford Island and Washington shore fishways (Figure 1). We defined the window passage time for an individual fish as the difference in time between the first detection at an antenna immediately downstream from a counting window and the first detection at an antenna upstream from a counting window, provided the fish eventually passed the dam after passing a counting window. This calculation was designed to account for the time spent by some fish swimming upstream and then downstream from a counting window. We similarly determined the time fish required to pass from the antenna immediately upstream from the counting windows, through the vertical-slot weirs, to the final record on the antenna at the ladder exit. Groupings were based on the antenna immediately downstream from a counting window or vertical-slot weir where salmon and steelhead were initially detected.

Passage times for some fish did not accurately represent the amount of time used strictly to pass either the windows or weirs. Because of the way we defined passage times, the ‘clock’ started when a fish was first detected on the antenna downstream from either a window or weir. Until a fish passed a window or weir (in either fishway) and stayed ‘passed’, the clock ran. This meant the time fish used swimming downstream to transition pools and (and anywhere else) after swimming to the counting window was included in the counting window or vertical-slot weir passage time.

Because passage times were based on first detections at antennas downstream from either the counting window or vertical-slot weirs, fish exhibiting up-and-back behavior could have passage time ‘clocks’ running for both segments (count window and vertical-slots) simultaneously. We adopted this approach because we believe it allowed for maximal estimates of both counting window and vertical-slot weir passage

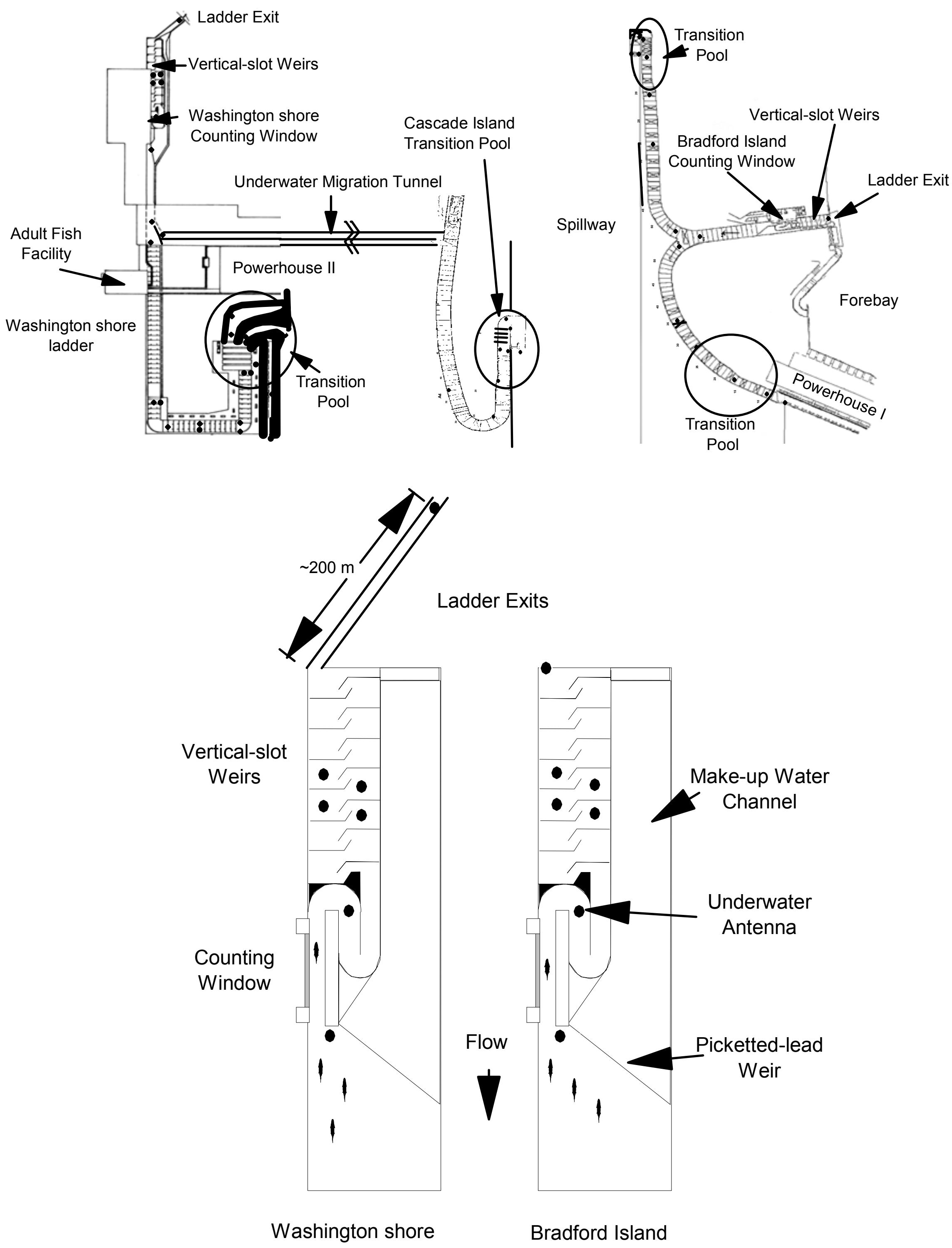


Figure 1. Aerial view of counting windows and vertical-slot weirs in relation to transition pools (upper panel) and position of radio antennas (indicated by closed dots) deployed near counting windows and in vertical-slot weirs of Bradford Island and Washington Shore fishways at Bonneville Dam in 2001 and 2002 (lower panel).

times. To this extent, we believe it was the most conservative approach for assessing any negative effects associated with either the windows or weirs.

We also deployed underwater antennas in the transition pools of the Bradford Island fishway and determined the time used by fish to swim through the overflow weirs of the Bradford Island fishway. Specifically, we calculated the interval between the last record in the transition pool and the first record immediately downstream from a counting window for a given fish and then divided this value by the number of weirs the fish passed (min/weir). We used correlation techniques (Sokal and Rohlf, 1969) to evaluate the degree of association between counting window or vertical-slot weir passage times and total dam passage times. Finally, we used linear regression techniques (Sokal and Rohlf, 1969) to evaluate any affects of ladder-specific fish counts on counting window or vertical-slot weir passage times. Specifically, we grouped radio-tagged fish with similar passage dates for each fishway (using weekly blocks), weighed each block by the number of observations within that block, and used weekly median passage times as the dependent variable. The independent variable was the daily mean fish count (all species counted) for each fishway and corresponding week. Ladder-specific fish count data for this analysis were provided by Larry Beck, USACE.

## Results

### *Passage Times*

Counting Windows

Among the three fish runs, spring−summer Chinook salmon had the highest median counting window passage times for three of the four fishway/year combinations, with values ranging from 6.7 to 14.7 min. (Figure 2). Fall Chinook salmon consistently had the lowest median passage times. With the exception of the Washington shore during 2002, steelhead median values were between the spring−summer Chinook and fall Chinook salmon median values. For all years and runs, median counting window passage times at the Bradford Island fishway were higher than those at the Washington shore counting window (Table 1). Median counting window passage times in the Bradford Island fishway were higher in 2002 than in 2001 but this pattern was not evident for the Washington shore fishway. The median time to pass a counting window for all radio-tagged fish during both years was 8.5 min (*n*=4,271).

Vertical-slot Weirs

As when passing count windows, spring−summer Chinook salmon generally had the highest median passage times through the vertical-slot weirs (Figure 3). For fall Chinook salmon and steelhead, median passage times through vertical-slot weirs were slightly higher in 2001 than in 2002. The converse was true for spring−summer Chinook salmon.

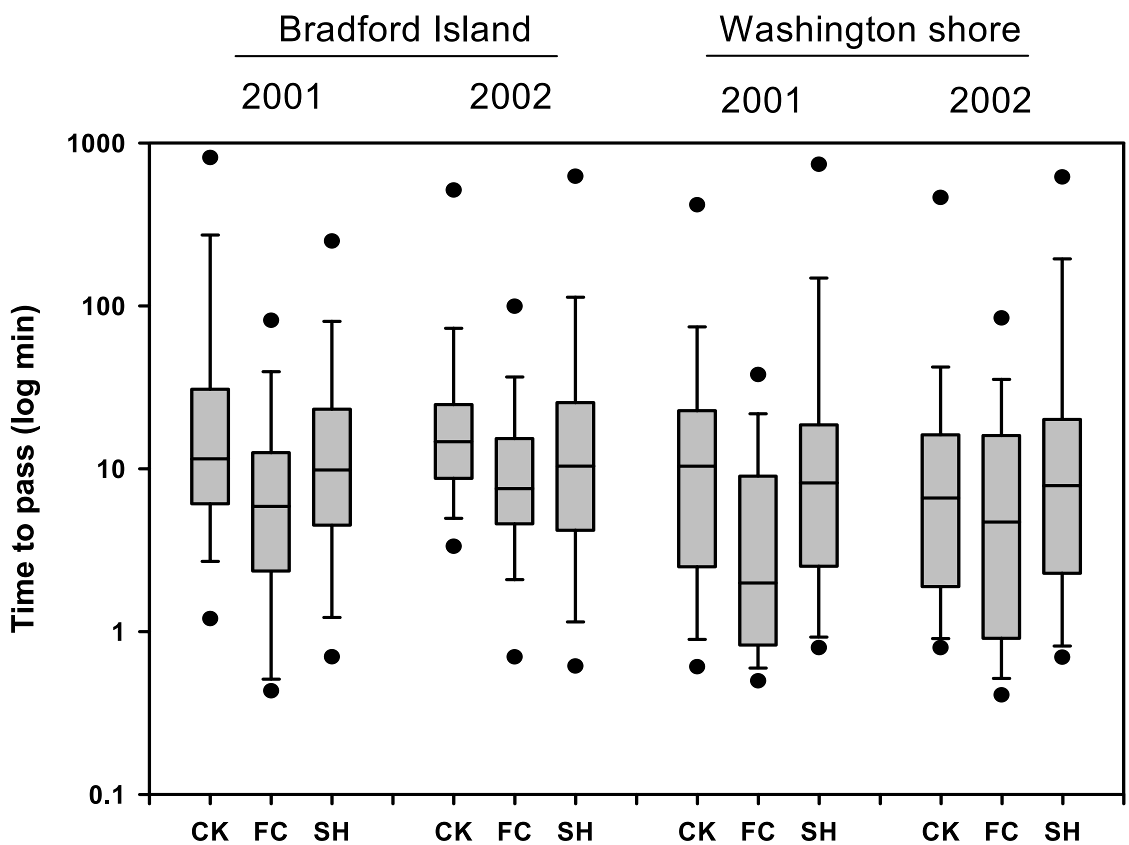


Figure 2. Median, quartile, 5th, 10th, 90th and 95th percentile counting window passage times (min) for Bradford Island and Washington shore fishways at Bonneville Dam, 2001-2002. (CK = spring−summer Chinook salmon, FC = fall Chinook salmon, and SH = steelhead). Sample sizes are given in Table 1.

Table 1. Median, mean, standard deviation of the mean, range, and sample sizes for counting window passage times for radio-tagged spring−summer Chinook salmon (CK), fall Chinook salmon (FC), and steelhead (SH) at Bradford Island and Washington shore fishways at Bonneville Dam, 2001-2002.

| | | Bradford Island | | | | |
|---|---|---|---|---|---|---|
| Year | Species (Run) | Median (min) | Mean (min) | S.D. (min) | Range (min) | N |
| 2001 | CK | 11.5 | 119.2 | 425.5 | 0.4-5,781.9 | 340 |
| 2001 | FC | 5.9 | 109.3 | 854.5 | 0.2-9,862.7 | 204 |
| 2001 | SH | 9.8 | 181.1 | 1520.6 | 0.4-24,024.0 | 295 |
| 2002 | CK | 14.7 | 133.7 | 934.3 | 0.5-15,765.2 | 361 |
| 2002 | FC | 7.6 | 57.2 | 424.6 | 0.2-6,876.3 | 277 |
| 2002 | SH | 10.4 | 105.5 | 434.4 | 0.3-4,859.9 | 369 |

Table 1 Cont.

| Year | Species (Run) | Washington Shore Median (min) | Mean (min) | S.D. (min) | Range (min) | N |
|---|---|---|---|---|---|---|
| 2001 | CK | 10.4 | 62.6 | 245.4 | 0.3-3,258.3 | 410 |
| 2001 | FC | 2.0 | 47.6 | 330.1 | 0.3-5,178.8 | 293 |
| 2001 | SH | 8.2 | 121.5 | 542.3 | 0.4-7,772.2 | 438 |
| 2002 | CK | 6.7 | 86.7 | 591.2 | 0.4-8,783.0 | 464 |
| 2002 | FC | 4.7 | 93.5 | 1,011.2 | 0.3-18,316.0 | 360 |
| 2002 | SH | 7.9 | 225.0 | 1766.2 | 0.4-33,427.6 | 460 |

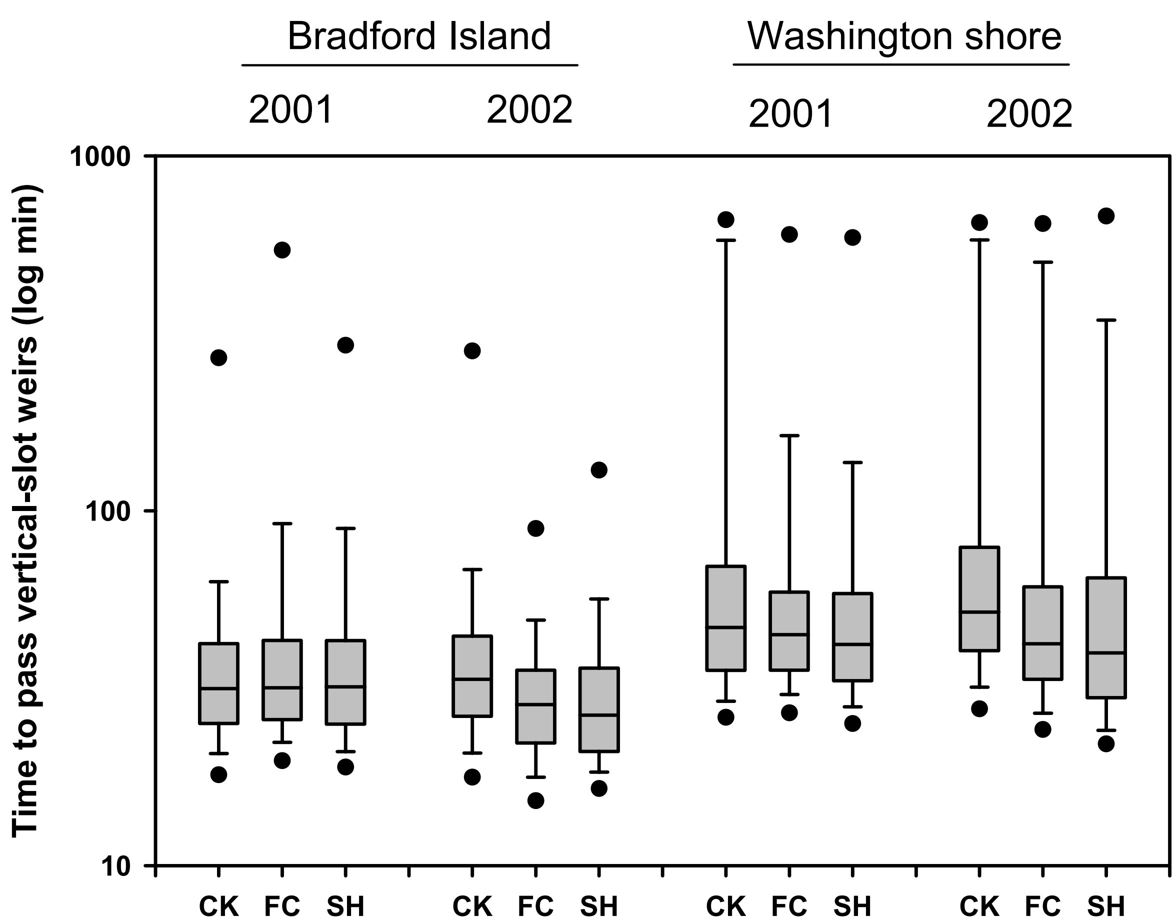


Figure 3. Median, quartile, 5th, 10th, 90th and 95th percentile vertical-slot weir passage times (min) for Bradford Island and Washington shore fishways at Bonneville Dam, 2001-2002. (CK = spring−summer Chinook salmon, FC = fall Chinook salmon, and SH = steelhead). Sample sizes are given in Table 2.

Table 2. Median, mean, standard deviation of the mean, range, and sample sizes for vertical-slot weir passage times for radio-tagged spring−summer Chinook salmon (CK), fall Chinook salmon (FC), and steelhead (SH) at Bradford Island and Washington shore fishways at Bonneville Dam, 2001-2002.

| | | Bradford Island | | | | |
|---|---|---|---|---|---|---|
| Year | Species (Run) | Median (min) | Mean (min) | S.D. (min) | Range (min) | N |
| 2001 | CK | 31.5 | 76.7 | 340.2 | 12.7-5,802.2 | 322 |
| 2001 | FC | 31.7 | 149.6 | 857.8 | 16.9-9,892.4 | 204 |
| 2001 | SH | 32.1 | 201.8 | 1524.8 | 11.8-24,054.9 | 294 |
| 2002 | CK | 33.5 | 103.1 | 839.0 | 11.7-15,786.3 | 357 |
| 2002 | FC | 28.4 | 50.5 | 108.2 | 11.0-777.4 | 275 |
| 2002 | SH | 26.5 | 78.6 | 359.6 | 12.4-4,898.0 | 367 |
| | | Washington Shore | | | | |
| Year | Species (Run) | Median (min) | Mean (min) | S.D. (min) | Range (min) | N |
| 2001 | CK | 46.9 | 145.4 | 325.2 | 18.1-5,099.7 | 415 |
| 2001 | FC | 44.7 | 100.0 | 175.5 | 16.8-1,420.9 | 291 |
| 2001 | SH | 42.0 | 130.3 | 491.4 | 17.1-7,773.5 | 436 |
| 2002 | CK | 51.8 | 179.5 | 610.5 | 18.3-8,798.8 | 467 |
| 2002 | FC | 42.2 | 176.8 | 1,013.7 | 15.8-18,217.7 | 360 |
| 2002 | SH | 39.7 | 138.0 | 367.8 | 12.2-4,034.2 | 459 |

When we compared the rates at which salmon and steelhead passed through overflow weirs downstream from the Bradford Island counting window with rates through the Bradford Island vertical-slot weirs, we found the passage rates through the nine vertical-slot weirs were approximately twice those through the overflow weirs based on mean values and 50-67% higher based on median values (Table 3).

Counting Windows and Vertical-slot Weirs Combined

Spring−summer Chinook salmon had the highest median passage times in both fishways and during both years while fall Chinook salmon tended to have to lowest times (Figure 4).

### *Passage Times as Proportions of Total Dam Passage Times*

Counting Windows

Based on median values, counting window passage times accounted for ≤1% of the total dam passage times (Table 5). On average, counting window passage times accounted for <7% of total dam passage times and were typically in the 3 to 4% range. The highest median and mean values were for spring−summer Chinook salmon at the Bradford Island counting window in 2001. For some fish, the counting window passage time accounted for almost 98% of their total dam passage time.

Table 3. Median, mean, standard deviation of the mean, and sample sizes for overflow weir and vertical-slot weir passage rates for radio-tagged spring−summer Chinook salmon (CK), fall Chinook salmon (FC), and steelhead (SH) at Bradford Island fishway at Bonneville Dam, 2001-2002.

| | | Overflow Weirs | | | | Vertical-slot Weirs | | | |
|---|---|---|---|---|---|---|---|---|---|
| Year | Species | Med. (min/weir) | Mean (min/weir) | S.D. | N | Med. (min/weir) | Mean (min/weir) | S.D. | N |
| 2001 | CK | 2.3 | 3.8 | 4.6 | 323 | 3.5 | 6.3 | 12.5 | 317 |
| 2001 | FC | 2.1 | 2.6 | 2.2 | 196 | 3.5 | 6.9 | 12.6 | 199 |
| 2001 | SH | 2.2 | 3.6 | 5.0 | 284 | 3.5 | 6.7 | 13.1 | 289 |
| 2002 | CK | 2.2 | 3.7 | 4.6 | 337 | 3.7 | 6.8 | 13.0 | 356 |
| 2002 | FC | 2.0 | 2.6 | 2.7 | 241 | 3.2 | 5.6 | 12.0 | 275 |
| 2002 | SH | 2.0 | 3.0 | 7.4 | 334 | 2.9 | 7.3 | 28.5 | 366 |

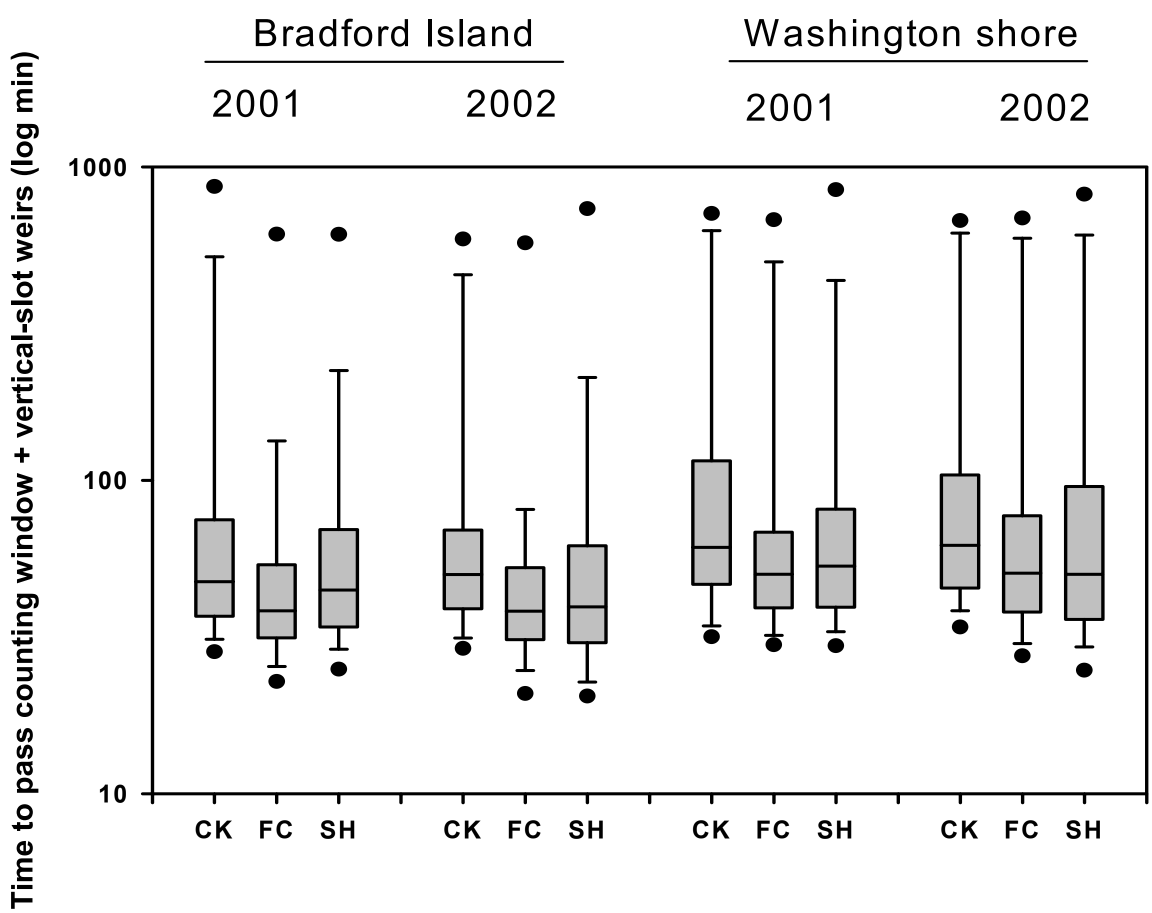


Figure 4. Median, quartile, 5th, 10th, 90th and 95th percentile counting window and vertical-slot weir (combined) passage times (min) for Bradford Island and Washington shore fishways at Bonneville Dam, 2001-2002. (CK = spring−summer Chinook salmon, FC = fall Chinook salmon, and SH = steelhead). Sample sizes are given in Table 4.

Table 4. Median, mean, standard deviation of the mean, range, and sample sizes for counting window to ladder exit passage times for radio-tagged spring−summer Chinook salmon (CK), fall Chinook salmon (FC), and steelhead (SH) at Bradford Island and Washington shore fishways at Bonneville Dam, 2001-2002.

| | | Bradford Island | | | | |
|---|---|---|---|---|---|---|
| Year | Species (Run) | Median (min) | Mean (min) | S.D. (min) | Range (min) | N |
| 2001 | CK | 47.5 | 169.8 | 438.6 | 20.2-5,823.7 | 327 |
| 2001 | FC | 38.4 | 165.3 | 861.8 | 17.4-9,904.2 | 203 |
| 2001 | SH | 44.6 | 250.8 | 1,788.3 | 12.2-28,908.3 | 294 |
| 2002 | CK | 50.1 | 186.4 | 944.2 | 19.1-15,795.2 | 361 |
| 2002 | FC | 38.3 | 102.5 | 435.3 | 12.4-6,918.7 | 277 |
| 2002 | SH | 39.5 | 144.3 | 445.1 | 13.1-4,909.3 | 369 |
| | | Washington Shore | | | | |
| Year | Species (Run) | Median (min) | Mean (min) | S.D. (min) | Range (min) | N |
| 2001 | CK | 61.2 | 202.8 | 409.4 | 23.6-5,101.8 | 410 |
| 2001 | FC | 50.2 | 136.7 | 358.0 | 17.6-5,204.2 | 292 |
| 2001 | SH | 53.3 | 192.4 | 553.4 | 21.3-7,798.1 | 436 |
| 2002 | CK | 62.0 | 216.1 | 627.5 | 19.1-8,885.8 | 463 |
| 2002 | FC | 50.6 | 198.6 | 1,026.4 | 16.2-18,369.0 | 358 |
| 2002 | SH | 50.2 | 324.5 | 1,826.3 | 14.5-34,277.0 | 457 |

Table 5. Median, mean, standard deviation of the mean, range, and sample sizes for percentages of total passage times used by radio-tagged spring−summer Chinook salmon (CK), fall Chinook salmon (FC), and steelhead (SH) to pass a counting window after initially being recorded downstream from the Bradford Island or Washington shore counting windows at Bonneville Dam, 2001-2002.

| | | Bradford Island | | | | |
|---|---|---|---|---|---|---|
| Year | Species | Median (%) | Mean (%) | S.D. (%) | Range (%) | N |
| 2001 | CK | 1.0 | 6.7 | 15.2 | <0.1-85.3 | 297 |
| 2001 | FC | 0.6 | 3.1 | 10.9 | <0.1-77.7 | 187 |
| 2001 | SH | 0.9 | 4.9 | 11.9 | <0.1-97.7 | 278 |
| 2002 | CK | 0.8 | 3.9 | 10.8 | <0.1-86.0 | 321 |
| 2002 | FC | 0.7 | 3.1 | 10.3 | <0.1-96.1 | 236 |
| 2002 | SH | 0.7 | 4.7 | 13.2 | <0.1-93.2 | 340 |

Table 5 Cont.

| Year | Species | Washington shore | | | | |
|---|---|---|---|---|---|---|
| | | Median (%) | Mean (%) | S.D. (%) | Range (%) | N |
| 2001 | CK | 0.5 | 2.6 | 7.6 | <0.1-65.8 | 385 |
| 2001 | FC | 0.2 | 2.7 | 10.9 | <0.1-78.6 | 264 |
| 2001 | SH | 0.7 | 5.3 | 14.9 | <0.1-95.7 | 420 |
| 2002 | CK | 0.2 | 2.2 | 8.1 | <0.1-80.8 | 379 |
| 2002 | FC | 0.3 | 2.5 | 9.2 | <0.1-97.7 | 296 |
| 2002 | SH | 0.6 | 4.2 | 12.8 | <0.1-84.6 | 413 |

Vertical-slot Weirs

Vertical-slot weir passage times comprised <5% of total dam passage times based on median values and ≤9% based on mean values (Table 6). In all cases, fish used higher proportions of total dam passage times to pass vertical-slot weirs than to pass counting windows based on both median and mean values.

Table 6. Median, mean, standard deviation of the mean, range, and sample sizes for percentages of total passage times used by radio-tagged spring−summer Chinook salmon (CK), fall Chinook salmon (FC), and steelhead (SH) to pass vertical-slot weirs after initially being recorded downstream from the Bradford Island or Washington shore vertical-slot weirs at Bonneville Dam, 2001-2002.

| Year | Species | Bradford Island | | | | |
|---|---|---|---|---|---|---|
| | | Median (%) | Mean (%) | S.D. (%) | Range (%) | N |
| 2001 | CK | 2.4 | 4.6 | 8.7 | 0.1-85.6 | 293 |
| 2001 | FC | 3.4 | 7.1 | 12.0 | 0.2-79.2 | 188 |
| 2001 | SH | 3.8 | 7.6 | 13.5 | 0.1-97.9 | 278 |
| 2002 | CK | 1.7 | 3.3 | 4.6 | 0.1-49.3 | 318 |
| 2002 | FC | 2.4 | 5.1 | 9.6 | 0.1-79.0 | 234 |
| 2002 | SH | 2.0 | 4.9 | 10.2 | 0.1-93.4 | 338 |
| | | Washington Shore | | | | |
| Year | Species | Median (%) | Mean (%) | S.D. (%) | Range (%) | N |
| 2001 | CK | 3.6 | 6.6 | 10.3 | 0.1-88.4 | 389 |
| 2001 | FC | 4.8 | 9.0 | 13.2 | 0.2-72.0 | 263 |
| 2001 | SH | 3.9 | 8.6 | 14.7 | 0.1-95.7 | 420 |
| 2002 | CK | 2.5 | 6.2 | 11.2 | 0.2-81.4 | 382 |
| 2002 | FC | 3.7 | 8.8 | 14.6 | 0.2-97.2 | 298 |
| 2002 | SH | 2.9 | 8.6 | 15.6 | 0.0-87.9 | 415 |

Counting Windows and Vertical-slot Weirs Combined

With both fishways and years included, the combined passage of count windows and vertical-slot weirs at the termini of the Bonneville fishways accounted for 6.9 -11.8% of total dam passage times based on mean values and 2.8 - 5.6% based on median values (Table 7).

Table 7. Median, mean, standard deviation of the mean, range, and sample sizes for percentages of total passage times used by radio-tagged spring−summer Chinook salmon (CK), fall Chinook salmon (FC), and steelhead (SH) to pass from counting windows to ladder exits of the Bradford Island or Washington shore at Bonneville Dam, 2001-2002.

| | | Bradford Island | | | | |
|---|---|---|---|---|---|---|
| Year | Species | Median (%) | Mean (%) | S.D. (%) | Range (%) | N |
| 2001 | CK | 4.3 | 10.2 | 15.6 | 0.2-86.5 | 297 |
| 2001 | FC | 4.3 | 8.8 | 14.1 | 0.2-79.5 | 187 |
| 2001 | SH | 5.2 | 10.6 | 15.7 | 0.2-98.1 | 278 |
| 2002 | CK | 2.8 | 6.9 | 11.9 | 0.1-88.1 | 321 |
| 2002 | FC | 3.6 | 7.8 | 13.6 | 0.1-96.7 | 236 |
| 2002 | SH | 3.4 | 8.4 | 14.7 | 0.1-93.8 | 340 |
| | | Washington Shore | | | | |
| Year | Species | Median (%) | Mean (%) | S.D. (%) | Range (%) | N |
| 2001 | CK | 5.0 | 9.0 | 12.6 | 0.2-88.4 | 385 |
| 2001 | FC | 5.6 | 11.0 | 15.8 | 0.2-79.0 | 264 |
| 2001 | SH | 5.1 | 11.8 | 17.5 | 0.1-96.0 | 420 |
| 2002 | CK | 3.1 | 7.6 | 12.4 | 0.2-88.2 | 379 |
| 2002 | FC | 4.4 | 10.5 | 16.2 | 0.3-98.0 | 296 |
| 2002 | SH | 4.3 | 11.4 | 17.9 | 0.1-88.3 | 413 |

***Correlation Analyses – Dam Passage Times and Window or Weir Passage Times***

Because time to pass count windows is a component of total dam passage time, the two parameters are not independent. The same is true for vertical-slot weir passage time. However, if counting windows or vertical-slot weirs at Bonneville Dam were impediments to adult salmon and steelhead passage during 2001-2002, we would predict that high counting window (or vertical-slot weir) passage times would have been associated with high total dam passage times. Conversely, if fish with high total dam passage times had low counting window or vertical-slot weir passage times, the strength of the relationship between counting window passage time and total dam passage time would be diminished.

When we combined data from all runs and both years, we found a positive correlation between total dam passage times and counting window or vertical-slot weir passage times for the two fishways but the $r^2$ values were ≤ 0.05 (Figure 5). This suggests that while fish with high counting window or vertical-slot weir passage times tended to have high total dam passage times, the relationship was weak.

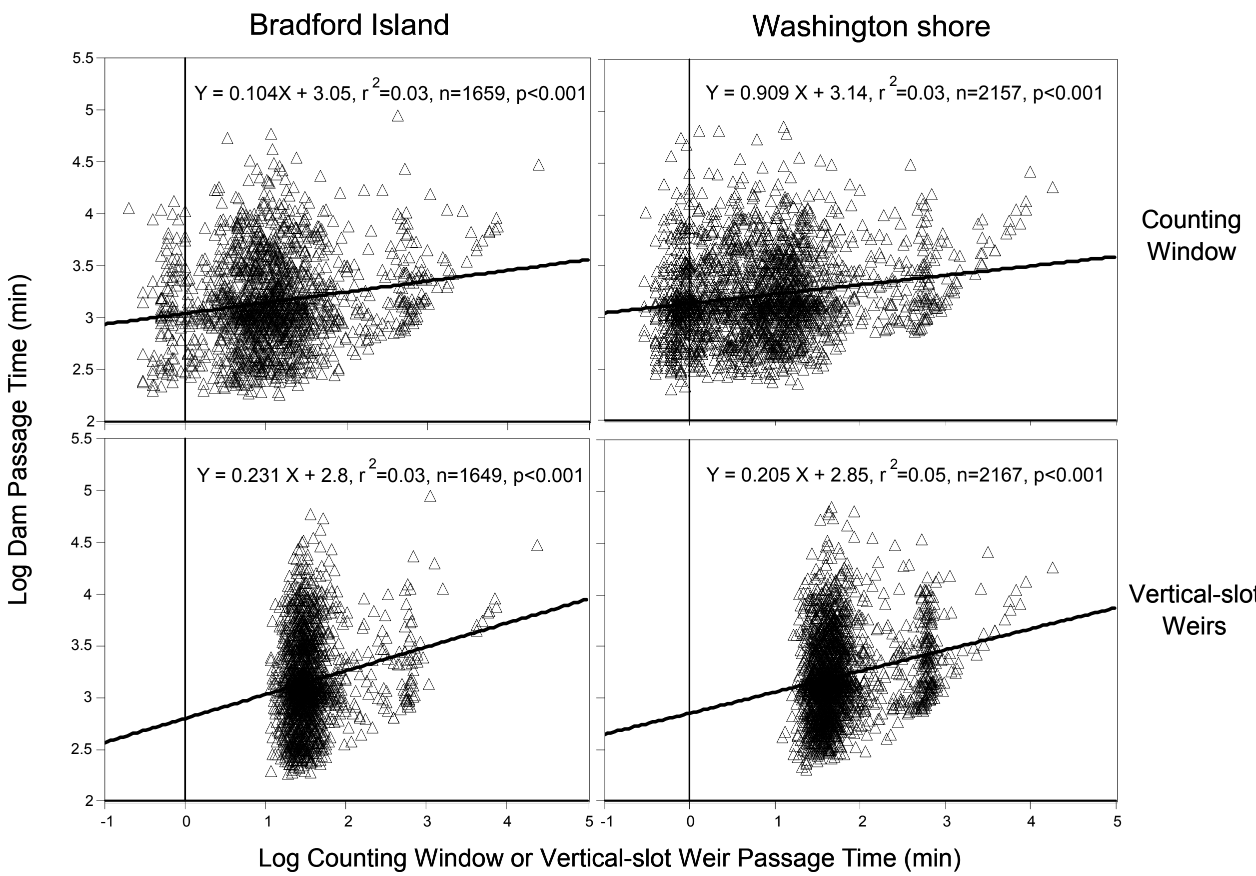


Figure 5. Linear correlation models of log-transformed counting window or vertical-slot weir passage times with log-transformed total dam passage times for spring−summer and fall Chinook salmon, and steelhead in the Bradford Island and Washington shore fishways at Bonneville Dam, 2001-2002.

### *Regression Analyses – Effects of Fish Counts on Window and Weir Passage Times*

Among the twelve run/year/fishway combinations, only one regression model for counting window passage times produced a slope significantly different from zero

(Table 8). Generally, little variation in counting window passage times was explained by the fish count data. Specifically, nine of the twelve models had $r^2$ values less than 0.11. The lone model producing a significant, non-zero slope was for steelhead in the Bradford Island ladder during 2001. There were four radio-tagged steelhead recorded during each of the first two weeks/blocks with steelhead and they had median counting window passage times of 73 and 42 minutes, respectively. These passage times coincided with high fish counts, most notably American shad, which averaged over 60,000 shad per day in the Bradford Island ladder during this two week interval (27 May – 9 June, 2001).

Two of the twelve models associated with vertical-slot weir passage times produced slopes significantly different from zero, both for steelhead. They were associated with different fishways and different years, however. As with counting window regression models, little variation in vertical-slot weir passage times was explained by the fish count data. Ten of the twelve models had $r^2$ values less than 0.15.

Over half the models for windows and weirs produced negative slopes (although not significantly different from zero), which on their face, suggest that high fish counts catalyze the movements of radio-tagged fish past the windows and weirs. On balance, we believe that steelhead were slightly more likely to have increased passage times during periods of high fish counts than Chinook salmon but any effects of high fish counts on counting window or vertical-slot weir passage times were small.

***Salmon and Steelhead Swimming to Transition Pools after Being Recorded at Counting Windows or in Vertical-slot Weirs***

The maximum proportion of any group recorded swimming to a transition pool after being recorded downstream from a counting window was 2.4% for spring−summer Chinook salmon at Bradford Island fishway in 2001 (Table 10). Values for all other groups were approximately 1% or less. Overall, slightly more than 0.5% (*n*= 4,277) of the radio-tagged fish initially recorded downstream from a counting window swam downstream to a transition pool. The median time to pass a counting window for all fish recorded swimming to a transition pool from a counting window was 1,797 minutes, or approximately 30 h (*n*=24).

As with the counting windows, relatively few fish were recorded swimming to a transition pool after being recorded in the vertical-slot weirs. The maximum proportion of any group recorded swimming to a transition pool after being recorded in the vertical-slot weirs was 2.4% for fall Chinook salmon in the Bradford Island fishway in 2001 (Table 11). Overall, approximately 0.7% (*n*=4,253) of the radio-tagged fish recorded in the vertical-slot weirs of Bonneville Dam during both study years swam downstream to a transition pool and their median vertical-slot weir passage time was 5,719 min, or about 4 days (*n*=22).

Table 8. Regression coefficients and significance levels for weighted regression models where median weekly counting window passage times were dependent and mean daily fish count within weeks/blocks (all species summed) were predictors. All models were weighted by the number of radio-tagged fish in each week/block.

| Year | Species (Run) | Bradford Island | | | | |
|---|---|---|---|---|---|---|
| | | $r^2$ | *P* | *Slope* | *Intercept* | *df* |
| 2001 | CK | 0.19 | 0.08 | 0.00035 | 13.7 | 16 |
| 2001 | FC | 0.08 | 0.40 | -0.00035 | 7.8 | 10 |
| 2001 | SH | 0.53 | <0.01 | 0.00062 | 7.4 | 20 |
| 2002 | CK | 0.00 | 0.86 | -0.00003 | 18.7 | 18 |
| 2002 | FC | 0.09 | 0.32 | -0.00125 | 16.6 | 12 |
| 2002 | SH | 0.00 | 0.91 | -0.00011 | 20.0 | 22 |
| Year | Species (Run) | Washington Shore | | | | |
| | | $r^2$ | *P* | *Slope* | *Intercept* | *df* |
| 2001 | CK | 0.16 | 0.09 | 0.00031 | 7.6 | 17 |
| 2001 | FC | 0.11 | 0.28 | -0.00009 | 4.5 | 11 |
| 2001 | SH | 0.01 | 0.69 | -0.00007 | 9.7 | 21 |
| 2002 | CK | 0.02 | 0.61 | -0.00008 | 8.2 | 17 |
| 2002 | FC | 0.00 | 0.90 | 0.00001 | 5.0 | 11 |
| 2002 | SH | 0.00 | 0.98 | -0.00001 | 9.6 | 19 |

Some fish that approached or even passed a counting window swam downstream and ultimately did not pass the dam. In each of the two study years, two fall Chinook salmon and one steelhead did not pass the dam after being recorded on antennas upstream from the counting window. Of the 4,277 radio-tagged fish recorded downstream from a counting window, 4,271 (99.9%) of them ultimately passed the dam.

### *Up-and-back Behavior*

Some fish were detected upstream of a counting window and then downstream of a counting window, an event we termed up-and-back behavior. Of the 4,277 unique fish recorded downstream from a counting window during the two study years, 272 (6.4%) exhibited up-and-back behavior at a counting window.

Based on the counting window where fish were initially detected, steelhead consistently exhibited the greatest proportions of up-and-back behavior during both study years (*range* = 7.6-11.8%; Table 12). Spring−summer Chinook salmon exhibited slightly higher proportions of up-and-back behavior than fall Chinook salmon. Generally, we observed the behavior less at the Washington shore counting window than the Bradford Island counting window.

Table 9. Regression coefficients and significance levels for weighted regression models where median weekly vertical-slot weir passage times were dependent and mean daily fish count within weeks/blocks (all species summed) were predictors. All models were weighted by the number of radio-tagged fish in each week/block.

| | | Bradford Island | | | | |
|---|---|---|---|---|---|---|
| Year | Species (Run) | $r^2$ | *P* | *Slope* | *Intercept* | *df* |
| 2001 | CK | 0.09 | 0.23 | -0.00009 | 32.8 | 16 |
| 2001 | FC | 0.15 | 0.23 | 0.00056 | 29.5 | 10 |
| 2001 | SH | 0.28 | 0.01 | 0.00122 | 26.6 | 20 |
| 2002 | CK | 0.03 | 0.49 | -0.00008 | 36.0 | 18 |
| 2002 | FC | 0.05 | 0.46 | -0.00311 | 50.6 | 12 |
| 2002 | SH | 0.00 | 0.98 | -0.00003 | 34.8 | 22 |
| | | Washington Shore | | | | |
| Year | Species (Run) | $r^2$ | *P* | *Slope* | *Intercept* | *df* |
| 2001 | CK | 0.02 | 0.62 | -0.00152 | 73.6 | 17 |
| 2001 | FC | 0.01 | 0.77 | 0.00007 | 44.0 | 11 |
| 2001 | SH | 0.01 | 0.60 | 0.00012 | 41.6 | 21 |
| 2002 | CK | 0.08 | 0.24 | -0.00037 | 56.4 | 17 |
| 2002 | FC | 0.00 | 0.96 | -0.00009 | 44.9 | 11 |
| 2002 | SH | 0.49 | <0.01 | 0.00094 | 32.2 | 19 |

Table 10. Frequency, percentage, median passage time, and sample size of radio-tagged spring−summer Chinook salmon (CK), fall Chinook salmon (FC), and steelhead (SH) recorded swimming to a transition pool after being recorded downstream from a counting window in the Bradford Island or Washington shore fishways at Bonneville Dam, 2001-2002.

| | | Bradford Island | | | Washington shore | | |
|---|---|---|---|---|---|---|---|
| Year | Species | Frequency | Percent | N | Frequency | Percent | N |
| 2001 | CK | 8 | 2.4 | 340 | 1 | 0.2 | 410 |
| 2001 | FC | 1 | 0.5 | 206 | 1 | 0.3 | 293 |
| 2001 | SH | 1 | 0.3 | 296 | 2 | 0.5 | 438 |
| 2002 | CK | 4 | 1.1 | 361 | 0 | 0.0 | 464 |
| 2002 | FC | 2 | 0.7 | 279 | 0 | 0.0 | 360 |
| 2002 | SH | 2 | 0.5 | 370 | 2 | 0.4 | 460 |

Table 11. Frequency, percentage, median vertical-slot weir passage time, and sample sizes of radio-tagged spring−summer Chinook salmon (CK), fall Chinook salmon (FC), and steelhead (SH) recorded swimming to a transition pool after being recorded in the vertical-slot weirs of the Bradford Island or Washington shore fishways at Bonneville Dam, 2001-2002.

| | | Bradford Island | | | Washington Shore | | |
|---|---|---|---|---|---|---|---|
| Year | Species | Frequency | Percent | N | Frequency | Percent | N |
| 2001 | CK | 2 | 0.6 | 322 | 0 | 0.0 | 415 |
| 2001 | FC | 5 | 2.4 | 206 | 0 | 0.0 | 291 |
| 2001 | SH | 5 | 1.7 | 295 | 3 | 0.7 | 436 |
| 2002 | CK | 1 | 0.3 | 357 | 2 | 0.4 | 467 |
| 2002 | FC | 2 | 0.7 | 277 | 2 | 0.6 | 360 |
| 2002 | SH | 2 | 0.5 | 368 | 4 | 0.9 | 459 |

Table 12. Frequency, percentage, and sample sizes of radio-tagged spring−summer Chinook salmon (CK), fall Chinook salmon (FC), and steelhead (SH) recorded upstream and then downstream from a counting window in the Bradford Island or Washington shore fishway at Bonneville Dam, 2001-2002. Groupings are based on counting windows where fish were initially detected.

| | | Bradford Island | | | Washington shore | | |
|---|---|---|---|---|---|---|---|
| Year | Species | Frequency | Percent | N | Frequency | Percent | N |
| 2001 | CK | 19 | 5.6 | 340 | 13 | 3.2 | 410 |
| 2001 | FC | 12 | 5.8 | 206 | 7 | 2.4 | 293 |
| 2001 | SH | 35 | 11.8 | 296 | 40 | 9.1 | 438 |
| 2002 | CK | 23 | 6.4 | 361 | 21 | 4.5 | 464 |
| 2002 | FC | 17 | 6.1 | 279 | 13 | 3.6 | 360 |
| 2002 | SH | 37 | 10.0 | 369 | 35 | 7.6 | 460 |

Of the 272 fish that exhibited up-and-back behavior, 30 (11.0%) swam downstream to a transition pool. By subtraction, 242 (89%) of the fish exhibiting up-and-back behavior swam upstream and passed the dam via the same counting window/fishway where they were initially recorded. The median time to pass a counting window for these 242 fish was 31.2 min, approximately 23 min higher than the median counting window passage time for all fish during both years (8.5 min, *n*=4,271). The median counting window passage time for all 272 fish that exhibited up-and-back behavior was 43.1 min.

Of the 30 fish that exhibited up-and-back behavior and swam to a transition pool, 28 (93%) exhibited up-and-back behavior and then swam to a transition pool while two (7%) approached a counting window, swam to a transition pool, and then exhibited the behavior at a counting window.

Because some fish used different routes to pass a counting window, we examined the frequencies of up-and-back behavior based on where the behavior occurred (Table 13). The frequencies were largely unchanged from Table 9 because a small proportion of fish that exhibited up-and-back behavior swam to a transition pool. The median time to pass a counting window for fish that exhibited up-and-back behavior and swam to a transition pool was 5,232 min ($n$=24), or 3.6 days. Six fish exhibited up-and-back behavior, swam to a transition pool, and did not pass the dam.

Table 13. Frequencies of radio-tagged spring−summer Chinook salmon (CK), fall Chinook salmon (FC), and steelhead (SH) recorded upstream and then downstream from a counting window at the Bradford Island or Washington shore fishway at Bonneville Dam, 2001-2002. Groupings are based on where up-and-back behavior occurred.

| | | Bradford Island | Washington shore | Bradford Island and Washington shore |
|---|---|---|---|---|
| Year | Species | Frequency | Frequency | Frequency |
| 2001 | CK | 18 | 14 | 0 |
| 2001 | FC | 11 | 7 | 1 |
| 2001 | SH | 35 | 39 | 1 |
| 2002 | CK | 23 | 21 | 0 |
| 2002 | FC | 17 | 12 | 1 |
| 2002 | SH | 37 | 35 | 0 |

## Diel Effects on Counting Window Passage Times

We compared the counting window passage times of salmon and steelhead that were first detected downstream from a counting window during the day (0500 to 2100) and night. Relatively few salmon and steelhead were initially recorded downstream of a counting window at night but those that were generally had higher median and mean counting window passage times (Table 14).

# Discussion

For the majority of radio-tagged adult salmon and steelhead, the counting windows and vertical-slot weirs were not an impediment to passing Bonneville Dam during 2001 or 2002. This assertion is based on the small proportions of total dam passage times counting window (≤1% *median*, <7% *mean*) and vertical-slot weir (<5% *median*, ≤ 9% *mean*) passage times comprised. While the proportion of total dam passage time is a relative measure, we believe it offers some insight into how much time fish used to pass

Table 14. Median, mean, and sample sizes for counting window passage times based on day or night arrivals for radio-tagged spring−summer Chinook salmon (CK), fall Chinook salmon (FC), and steelhead (SH) at Bradford Island (BI) and Washington shore (WA) counting windows at Bonneville Dam, 2001-2002.

| Year | Fishway | Species (Run) | Night | | | Day | | |
|---|---|---|---|---|---|---|---|---|
| | | | Med. (min) | Mean (min) | N | Med. (min) | Mean (min) | N |
| 2001 | BI | CK | 566.2 | 637.7 | 14 | 10.8 | 97.0 | 326 |
| 2001 | BI | FC | 670.7 | 670.7 | 2 | 5.8 | 103.8 | 202 |
| 2001 | BI | SH | 7.9 | 212.9 | 8 | 9.8 | 96.5 | 287 |
| 2002 | BI | CK | 526.4 | 536.4 | 19 | 13.7 | 111.3 | 342 |
| 2002 | BI | FC | 6.6 | 156.6 | 11 | 7.6 | 53.0 | 266 |
| 2002 | BI | SH | 569.3 | 424.7 | 11 | 9.8 | 95.6 | 358 |
| 2001 | WA | CK | 588.5 | 612.5 | 17 | 9.3 | 38.8 | 393 |
| 2001 | WA | FC | 576.3 | 551.7 | 8 | 1.9 | 33.4 | 285 |
| 2001 | WA | SH | 439.1 | 1,342.5 | 7 | 8.2 | 101.7 | 431 |
| 2002 | WA | CK | 564.4 | 833.2 | 22 | 5.9 | 49.6 | 442 |
| 2002 | WA | FC | 237.6 | 285.7 | 6 | 4.6 | 90.2 | 354 |
| 2002 | WA | SH | 6.3 | 14.8 | 3 | 8.0 | 226.4 | 457 |

these segments of the dam. In absolute terms, 75% of all fish recorded passing a counting window (independent of fishway) did so in < 20 min. For vertical-slot weirs, the upper quartiles for all run/year groups initially recorded in the Washington shore and Bradford Island fishways were < 66 min and < 41 min, respectively. Moreover, the relationship between counting window or vertical-slot weir passage times and total dam passage times was weak, suggesting high dam passage times were not directly related to the attributes of the counting windows or the vertical-slot weirs.

The high passage efficiency of salmon and steelhead recorded downstream of a counting window (99.9%) also suggests that the counting windows were not a major impediment to most adult salmon and steelhead passage. In contrast, Ocker et al. (2001) suggested counting windows/vertical slot segments of fishways at Bonneville Dam consistently obstructed the passage of (adult) radio-tagged lamprey in 1998 and 1999 and cited counting window passage efficiencies of 78% (*n*=49) and 63% (*n*=59), respectively.

Fish that swam downstream to transition pools consistently had the highest counting window and vertical-slot weir passage times. However, these fish comprised a small proportion of all fish recorded at a counting window or in the vertical-slot weirs (~0.5%, *n*=4,277). Similarly, fish that exhibited up-and-back behavior had high median counting window passage times, especially if they also swam to a transition pool. Most fish (89%, *n*=272) exhibiting up-and-back behavior did not swim to a transition pool, however.

While the median counting window passage times for the Bradford Island fishway were higher than those for the Washington shore fishway, the differences were on the order of minutes.  The energetic costs associated with passing each counting window, however, may have varied significantly.  Brown et al. (2002) found the median total energy used by spring Chinook salmon per meter length of fishway to be ~10 times higher near the Bradford Island counting window than the Washington shore counting window during April - June, 2001.

Brown et al. (2002) also found the median total energy used by spring Chinook salmon per meter length of fishway to be higher through vertical-slot weirs than overflow weirs in the Bradford Island fishway.  This is consistent with our finding that passage rates through the vertical-slot weirs of the Bradford Island fishway were higher than those through the overflow weirs based on both mean and median values.  Based on these faster rates alone, replacing the vertical-slot weirs of Bonneville Dam with overflow weirs with submerged orifices may catalyze adult salmon and steelhead passage.

Annual differences among counting window and vertical-slot weir passage times in the two fishways were small.  Water temperatures are typically cooler during the migration of spring−summer Chinook salmon and this may explain the higher median counting window and vertical-slot weir passage times as compared to fall Chinook salmon and steelhead.

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