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IDAHO COOPERATIVE FISH AND WILDLIFE RESEARCH UNIT

EXPERIMENTAL EVALUATION OF FISHWAY MODIFICATIONS ON THE PASSAGE BEHAVIOR OF ADULT CHINOOK SALMON AND STEELHEAD AT LOWER GRANITE DAM, SNAKE RIVER 2000-2002

A report for Project ADS-00-2

by

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Abstract

In 2000, the five downstream weirs in the transition pool at Lower Granite Dam were modified so that a 0.3 m (1ft) head could be maintained at each weir to increase velocities through submerged orifices. We hypothesized that with higher flows through the underwater orifices, fish would more readily locate the submerged orifices and move into the ladder without delay. A framework for vertical panels was added, allowing for the addition of panels as needed to reduce the width of the overflow section.

It is unclear however, if faster passage times in 2000 were related to the weir modifications or to better flow and passage conditions (lower and less turbid flow). Therefore, in 2001 and 2002, we conducted an experiment to determine if the faster transition pool times we found in 2000 were due to modification of the panels in the transition pool. In 2001 and 2002, we manipulated the slotted aluminum panels of the first two downstream weirs in the fish ladder by alternately raising (control) and lowering (treatment) panels to manipulate flow through the weirs.

During the experiment we monitored radio-tagged adult Chinook salmon and steelhead to determine passage routes and times through the transition pool. The weir treatment increased the number of spring–summer Chinook salmon passing straight through the transition pool compared to those exiting the transition pool to the collection channel or tailrace. Mean passage times through the transition pool differed among routes and were significantly lower during treatment periods for the exit-to-collection channel route in spring–summer Chinook salmon, but not for other routes. Passage times among routes differed in steelhead, but there was no evidence of treatment effects on route use or passage time. Fall Chinook exhibited similar trends in route use and passage time to spring–summer Chinook, but differences were not significant, perhaps because of relatively small sample size. Total dam passage times did not differ by treatment or route for any run. Fish depth during passage of the transition pool suggested that most fish passed through submerged orifices and supported the hypothesis that increased water velocity through these orifices caused the increase in straight-through passage in spring–summer Chinook. Collectively, the results suggested the weir modifications provided improvement to passage through the transition pool for spring–summer Chinook and no evidence of negative effects on other runs. The results from this study were used to develop new design criteria and modifications of the Lower Granite Dam fishway.

Introduction

Hydroelectric dams on the Snake River in the Columbia River basin have been implicated in a basin-wide decline of wild anadromous salmonids *Oncorhynchus* spp. during the latter 20th Century (Raymond 1988; McClure et al. 2003). Currently, twelve Columbia basin salmon and steelhead evolutionarily significant units that are listed as endangered or threatened under the U.S. Endangered Species Act (NMFS 2000) must pass as many as nine mainstem dams during their upstream migration. Hence, there is concern that dams may slow migration and may subsequently reduce escapement to spawning grounds and population viability (Quinn et al. 1997; Dauble and Mueller 2000).

The transition pool is one area at Columbia and Snake River dams where salmon and steelhead seem to have difficulty passing. The transition pool is the portion of fishway just downstream from the first weir in the fish ladder where the main fishway entrance and powerhouse collection channel join the fish ladder. Bjornn et al. (1998) observed steelhead (*O. mykiss*) turning around and moving downstream in the fishway after reaching transition pool areas, and in some cases, exiting the fishway to the tailrace. They reported that steelhead that exited from the transition pool to the tailrace had significantly longer dam passage times than steelhead not exhibiting this behavior. Peery et al. (1998) and Keefer et al. (2003) reported similar behavior patterns for Chinook salmon at lower Snake and Columbia River dams.

It is unknown why some fish hesitate in or leave transition pools before successfully passing dams, but hydraulic conditions likely play a role (Bunt et al. 1999; Bunt et al 2001; Bunt 2001). Transition pools in Columbia River dams are areas of variable and non-uniform flows, where discharge originating from forebay surface waters are augmented by water pumped in from the tailrace. However, as tailwater elevations fluctuate, weirs at the bottoms of fish ladders may be submerged and become part of transition pools. We hypothesized that most fish orient towards the bottom of fishways and pass though the submerged orifices in ladder weirs rather than passing over weir crests. When weirs are submerged, most flow occurs near the surface, with little or no attracting flow passing through the submerged orifices because there is little difference in water elevation head. Without such attracting flow at orifices, we hypothesized some fish would approach the first submerged weir but not identify the fish ladder as an upstream passage route. Fish would then move back downstream in search of an alternate passage route with more attraction cues, potentially slowing migration. Transition pools may also contain potentially deterring temperature gradients during summer, when warm water from the forebay surface moves down ladders and meets the cooler water that is pumped into the lower portions of ladders from tailraces (i.e. turbine discharge).

Fish managers have made continual structural and operational modifications at dams with the aim of improving fish passage (Monk et al. 1989; Odeh 1999; Clay 1995). As part of these efforts, we tested prototype weir modifications at the Lower Granite Dam transition pool designed to test the hypothesis that increasing hydraulic head at transition pool weirs and increasing flow through weir orifices would improve fish passage efficiency and reduce fish passage times. Here, we present the results of a randomized block test of the effects of the modified weirs on the behavior of upstream migrating adult Chinook salmon and steelhead. We examined two aspects of passage behavior: first, we examined treatment effects on the path or route taken by fish through the transition pool, focusing on whether the treatments reduced the probability that fish would exit the transition pool compared to passing straight through on the first attempt. Second, we examined the influence of weir treatments on mean passage times through the transition pool and on total dam passage times, defined as tailrace entrance to ladder exit.

Study Site

Lower Granite Dam is located at river kilometer (rkm) 694.6 on the Snake River in the northwestern United States (Figure 1). The Snake River is the largest tributary of the Columbia River and has a mean annual discharge of approximately 1,400 $m^3 \bullet s^{-1}$ ranging from 544 to 3,503 $m^3 \bullet s^{-1}$at Lower Granite Dam, (means 1991-2000; Columbia River DART, 2001) with peaks generally occurring in May and June. Average discharge at Lower Granite Dam during the study period was 1,314 $m^3 \bullet s^{-1}$ in 2000, 1,065 $m^3 \bullet s^{-1}$ in 2001 and 1,337 $m^3 \bullet s^{-1}$ in 2002. Lower Granite Dam is the furthest upstream dam on the Snake River that allows upstream fish passage.

Methods

Fish trapping and tagging

Adult Chinook salmon and steelhead were trapped for intragastric radio-tagging (Mellas and Haynes, 1985) during 2000-2002 in the adult fish facility, adjacent to the Washington-shore ladder at Bonneville Dam, and were implanted with radio-transmitters using the techniques described in Keefer et al. (2004a). We tagged all fish regardless of minor injury or fin clip. Fish with severe injuries (e.g., gashes penetrating to the coelomic cavity or those that affected swimming performance) accounted for less than 1% of all fish trapped, and were not tagged. While we selected fish haphazardly and tagged them in approximate proportion to the number passing the dam each day, the samples were not truly random because only fish passing through one of the two Bonneville ladders were sampled. Further, the proportion sampled each day varied slightly, and we did not sample at night because few adult salmon and steelhead pass dams at night (Robards and Quinn 2002; Keefer et al. 2004b; Naughton et al. 2005).

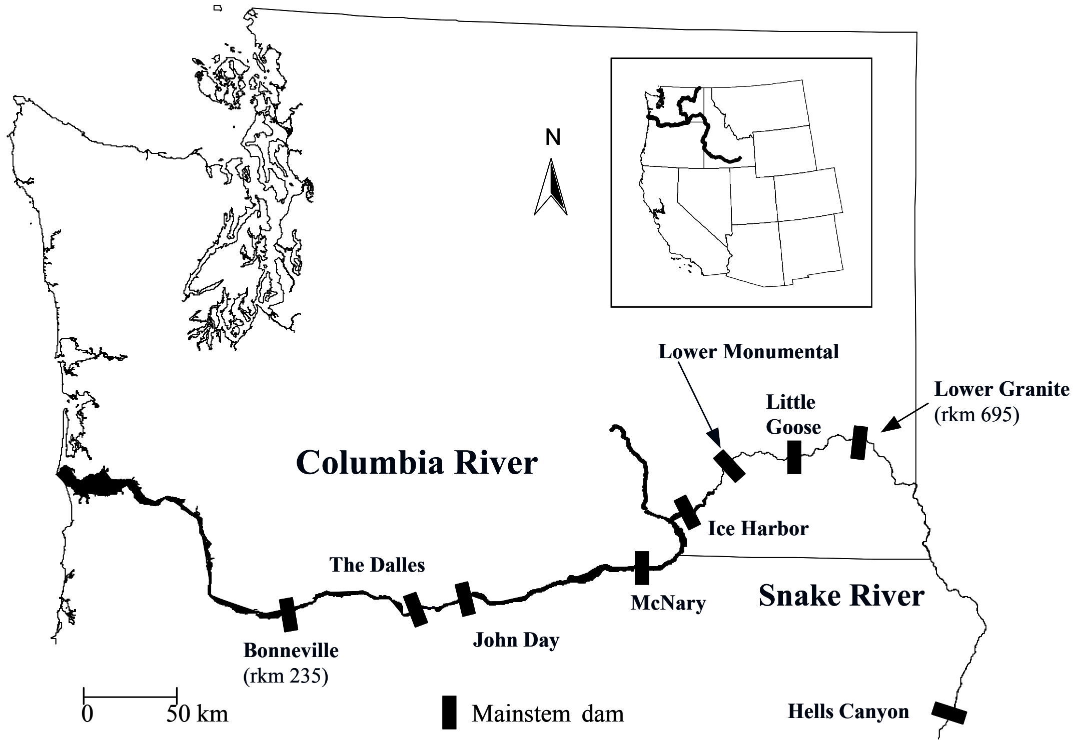

Figure 1. Lower portions of the Columbia and Snake rivers, with locations of main-stem dams. Adult Chinook salmon and steelhead were fitted with radio transmitters at Bonneville Dam and Lower Granite Dam.

During the three-year study, transmitters were placed in 3,412 Chinook salmon and steelhead in 2000, 3,355 fish in 2001 and 3,555 fish in 2002. Fish were radio-tagged using 3- and 7-volt radio transmitters (Lotek Wireless, Inc., Newmarket, Ontario) that emitted a unique, digitally coded signal every 5 s. Three-volt tags weighed 11 g in air (4.3 by 1.4 cm), 7-volt tags were 29 g (8.3 by 1.6 cm) and combination acoustic radio transmitters (CART) tags were 28 g (6.0 by 1.6 cm). All transmitters were cylindrical with 43-47 cm antennas. After tagging, fish were moved to a 2,275 L oxygenated, insulated transport tank and were then at locations 9.5 km downstream from Bonneville Dam on both sides of the river. An additional 84 adult Chinook salmon and steelhead (72 spring-summer chinook, 7 steelhead, 5 fall Chinook) were trapped in the Lower Granite Dam fishway and tagged with a 3-volt (9.0 by 2.0 cm; 34 g in air) radio data storage transmitter (RDST) that recorded temperature at 1-min intervals and pressure at 5-s intervals for up to 40 d. Fish with RDSTs were released in the Lower Granite Dam tailrace but were not used in passage time calculations or route analysis. Pressure measurements from these fish were used to determine the depths that Chinook salmon and steelhead used as they passed through the transition pool and fish ladder (estimated accuracy was +/- 0.5 m, Lotek Wireless).

Telemetry monitoring

We assessed movements and passage rates of radio-tagged fish with fixed radio telemetry sites. We used SRX/DSP receivers/processors (Lotek Wireless) connected to nine-element aerial Yagi and underwater antennas to determine when a fish approached a fishway entrance, entered a fishway, moved within the fishway, and exited the fishway (Figure 2). The SRX/DSP combination was used to simultaneously monitor several frequencies on multiple antennas. Telemetry data were downloaded every 1-2 weeks.

Fishway modification

In the first year of the study (2000) the five downstream weirs in the transition pool at Lower Granite Dam were modified by mid-May 2000 to produce a 0.3 m (1ft) head and a velocity of 2.4 $m \cdot s^{-1}$ through the weir orifices. An aluminum plate was added to the center non-overflow section of the first five weirs to prevent water from flowing over that portion of the weir. Prior to 12 May, only the central portion of the modified weirs was in place. A two-level catwalk system was built for adding and removing weir panels. Slotted aluminum panels that were 20.3

cm (8 in) wide and varied from 4.6-5.8 m long were used as stop-logs to control flow through the overflow portion of the modified weirs. Each panel added to a weir increased the head by about 3 cm (0.1 ft). Data were summarized for the two periods (i.e., 21 April through 12 May, and 13 May to 19 Dec) and compared to data from 1996 which were the only telemetry data available. Head differences were measured with a gauging stick each time the weir panels were changed (resolution .03 cm (0.01 ft)).

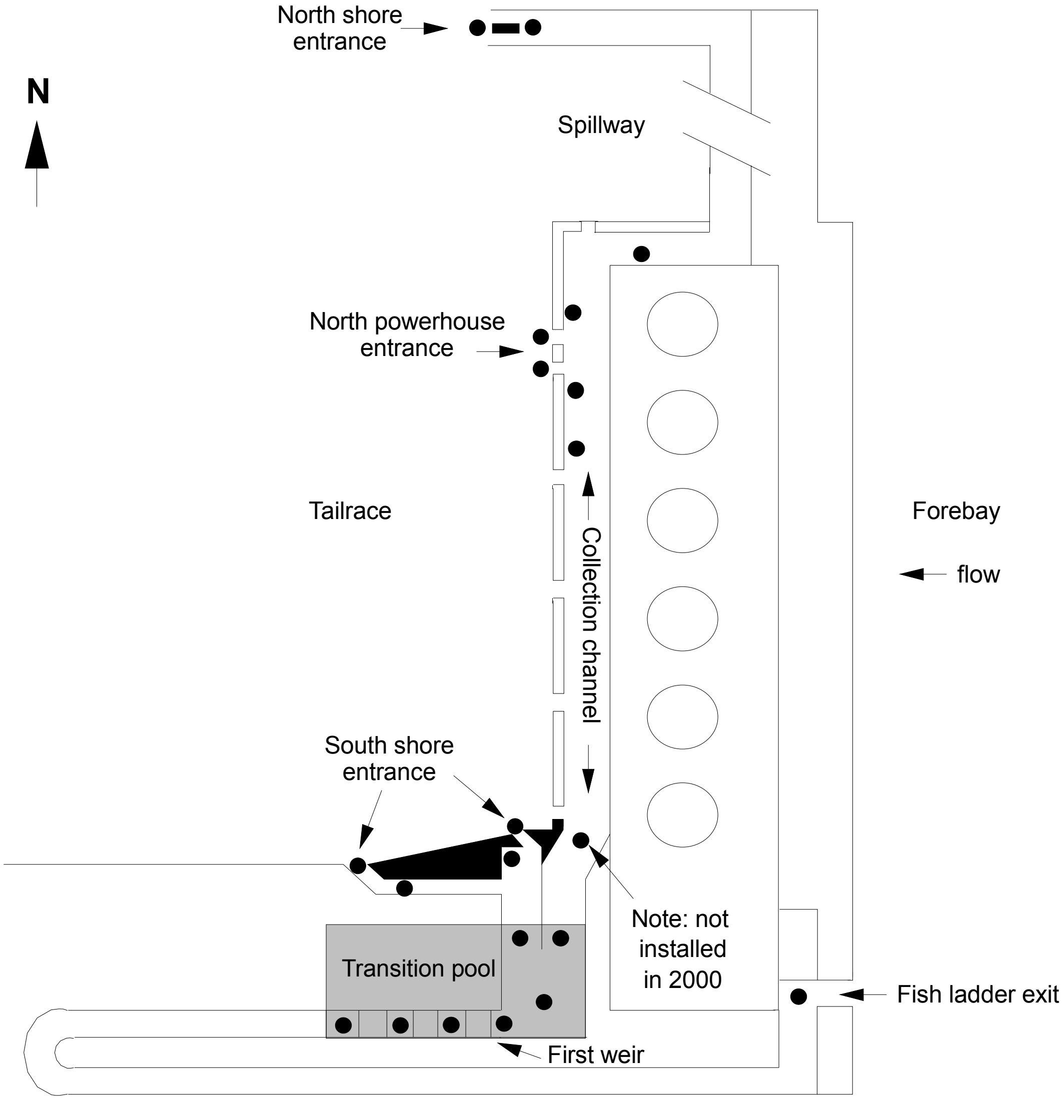

Figure 2. Locations of antennas (solid circles) and potential transition pool area depending on tailwater elevation at Lower Granite Dam in 200-2002.

In 2001 and 2002, we modified the two most downstream weirs in the fish ladder at Lower Granite Dam (Figure 3) to produce a 30 cm head and a predicted velocity of 2.4 m•s^{-1} (Clay 1995; Sean Milligan, U.S. Army Corps of Engineers, personal communication) through the weir orifices. Seven pairs of slotted aluminum panels that were 20.3 cm wide were used to

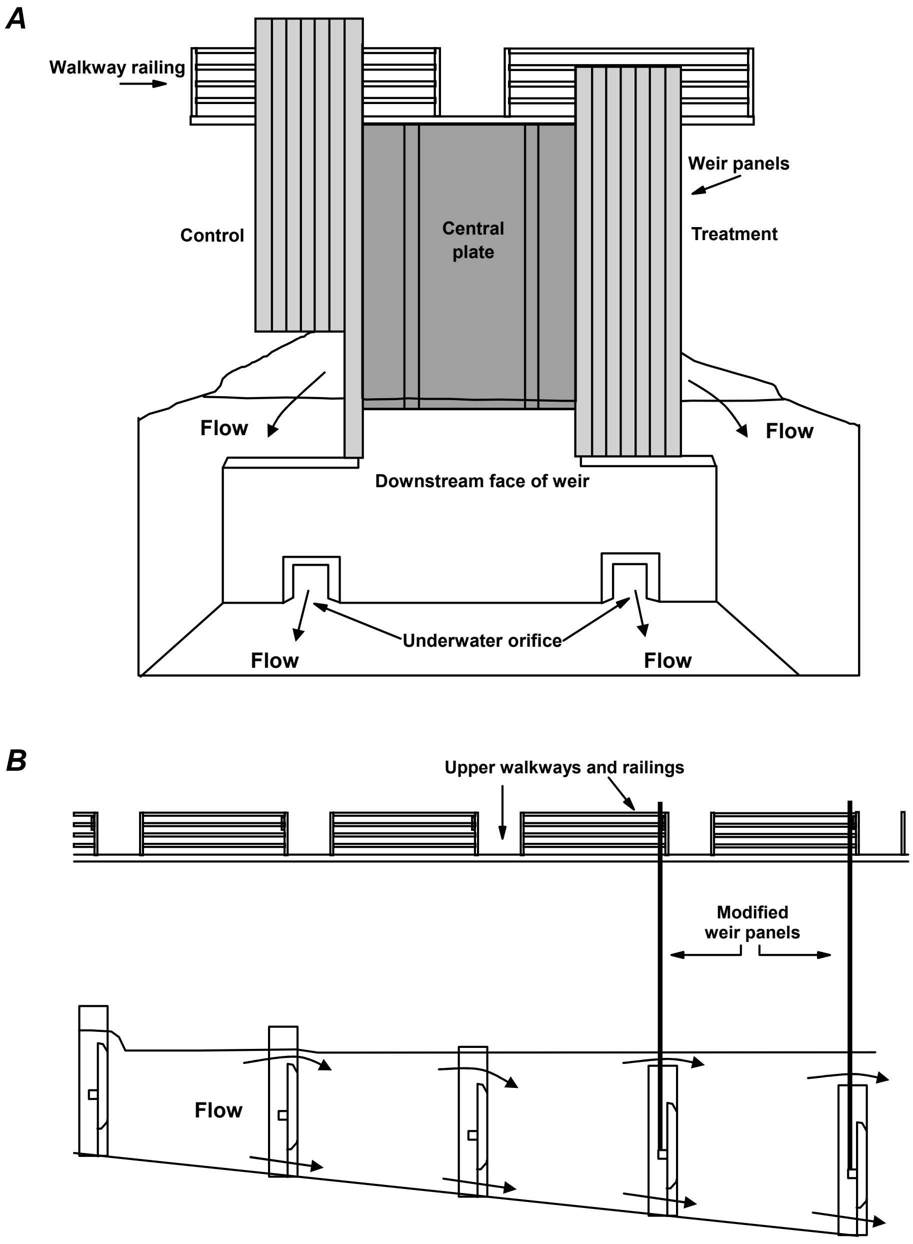

Figure 3. Diagram of a modified weir in the Lower Granite Dam fishway (A). The slotted vertical panels on the first two weirs were raised and lowered to restrict flows through the overflow portion of the weir. Side view of the modified weirs (B)

restrict the flow through the overflow portion of the modified weirs. Each pair of panels added to a weir increased the head by about 3 cm. All 14 weir panels in place produced about a 30 cm head differential at the two modified weirs. Head differences were measured with a gauging stick each time the weir position was changed. Pool depths upstream from each of the two weirs were maintained at a minimum of 2.1 m regardless of weir position. We calculated flow velocity through weir orifices using the following equation (Clay 1995):

$$V = \sqrt{2gh}$$

where h is the head and g is the acceleration of gravity.

Experimental Design

In 2001 and 2002, we compared paired treatment blocks to determine if passage times were significantly different between transition pool treatments. Treatment conditions were defined as control (two panels down) or treatment (all 14 panels down) on each of the first two weirs. Treatment condition sequence was randomly assigned within each block. We attempted to maintain each treatment condition until at least ten tagged fish of any species had passed through the transition pool, as indicated by an automated passive integrated transponder tag (PIT-tag) detection system (McCutcheon et al. 1994) or by examination of downloaded radio-telemetry data. However, due to receiver outages, some blocks had fewer than ten fish. Individual treatments ranged from 1-18 d in 2001 and 1-12 d in 2002 (Figure 4). To minimize any effects of raising and lowering panels on passage behavior, the panels were raised or lowered at night because few adult salmonids pass at night (Robards and Quinn 2002; Keefer et al. 2004b; Naughton et al. 2005). The experimental periods were from 18 April to 15 October in 2001 and from 10 May to 20 November in 2002.

Data processing

Downloaded data files were electronically transferred to the National Marine Fisheries Service office in Seattle, WA for initial processing. Each file was screened and obvious errors and records produced from electronic background noise were removed. Screened files were then transferred to the University of Idaho for coding. Coding involved inspecting all records for each fish and assigning a code to records that defined the behavior of those fish (e.g. first passage of the tailrace receiver, entrance or exit from a fishway). Coding was facilitated by using a semi-automated program developed with Arcview (V 2.0 for Windows). Coded data were used to identify and summarize movements of radio-tagged fish.

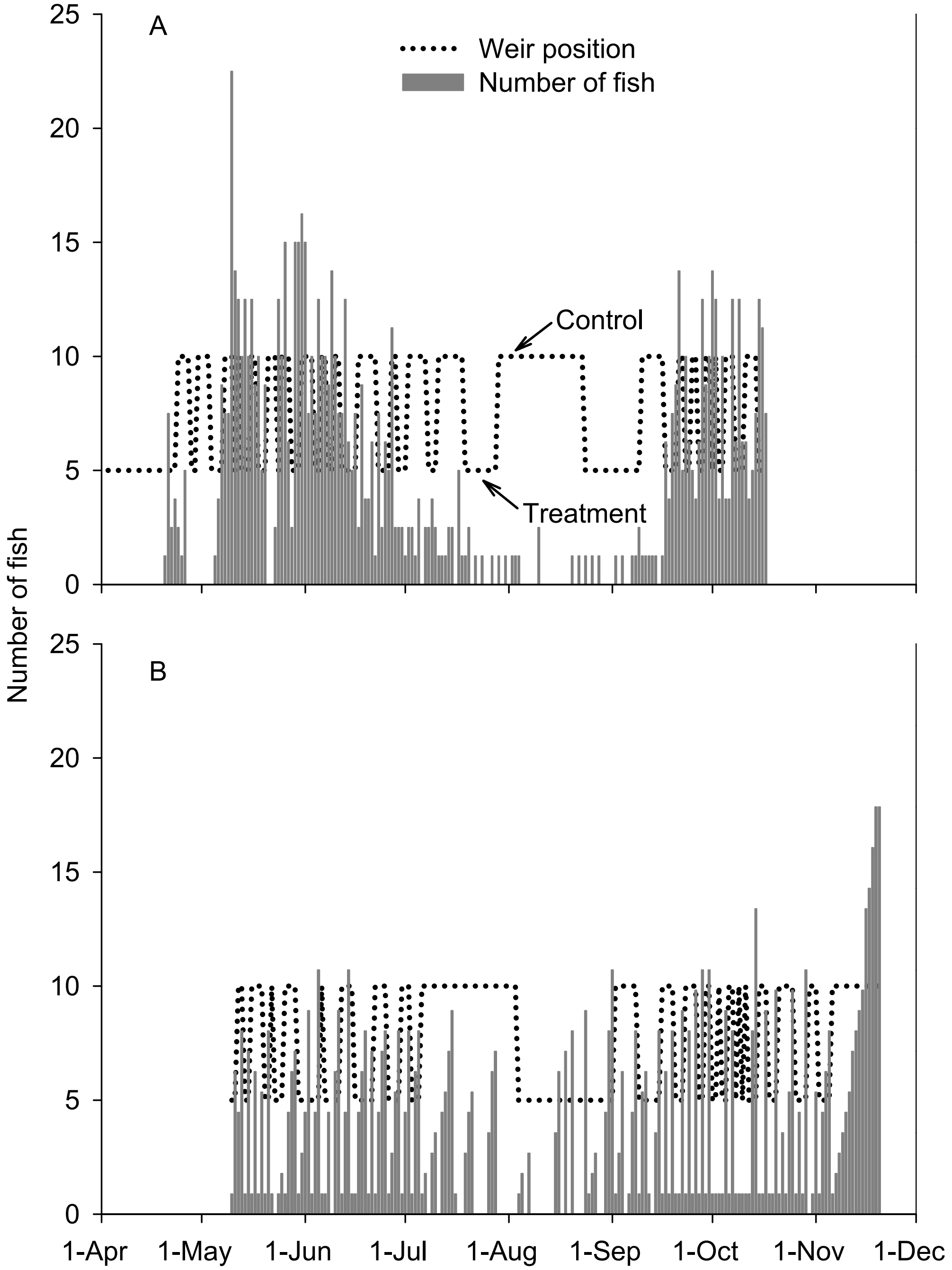

Figure 4. The number of radio-tagged fish passing the transition pool and treatment periods at Lower Granite Dam in 2001 (A) and 2002 (B).

Passage time calculations

We calculated passage times for radio-tagged adult salmon and steelhead at Lower Granite Dam for two segments: (1) the transition pool passage time, the first record in the transition pool (FP) to the last record in the transition pool (LP) and (2) total dam passage time, the first record at the tailrace site (F1) to the last record at the top-of-the-ladder site (LT). We limited the analysis to only the transition pool (FPLP) and total passage (F1LT) times because FPLP most directly estimated the effects of the treatment on passage rate through the transition pool while F1LT estimated any effect of changes in transition pool passage rate on overall passage times. Some fish entered the transition pool and migrated back out to the tailrace, a behavior we believe was related to route searching, and transition pool passage times included this time. Data associated with reascension events by fish that had fallen back (downstream movement through turbines, juvenile bypass facilities, fish ladders, navigation locks or over spillways (Reischel and Bjornn 2003; Boggs et al. 2004) were excluded from the analysis.

Route selection and migration depth

Because passage times could be affected by the route of passage, we classified the route taken by each fish into one of three categories using the telemetry records: (1) passed straight through the transition pool on the first attempt, (2) exited the transition pool into the collection channel or (3) exited the transition pool into the tailrace. All fish eventually passed the dam.

Mean migration depths in the transition pool were estimated from RDST transmitter data by matching time-stamps on transition pool telemetry records and RDST records. Sample sizes were reduced compared to passage times because the RDSTs recorded depth every 5 seconds while telemetry records occurred only as fish passed antennas. Consequently, telemetry and depth records could not be reliably matched in many cases.

Statistical analyses

In 2001 and 2002, we used a multinomial logit analysis, an extension of binary logistic regression for response variables with more than two categories (Allison 1999), to test treatment effects on route selection by adult Chinook salmon and steelhead. The logit model was used to estimate the odds of adult fish (1) passing straight through the transition pool versus exiting to the tailrace (2) passing straight through the transition pool versus exiting to the collection channel, and (3) exiting to the collection channel versus exiting to the tailrace. Predictor variables were year, treatment, and the interaction of year and treatment. Calculated odds ratios express the probability of the selected route being chosen during the treatment versus control condition. All analyses were conducted with the CATMOD procedure in SAS v.9.1 (SAS Institute Cary, NC). The year × treatment interaction could not be evaluated for fall Chinook salmon because of missing cells (Allison 1999).

We were also interested in whether there were treatment effects on passage time within groups of fish using the same route. We tested for the effects of weir treatment and route on passage time with multivariate analysis of variance (MANOVA) using the MANOVA model: FPLP + F1LT = route + treatment + year + route × treatment + block (treatment) + route × block (treatment) + error followed by univariate analysis of variance (ANOVA) for those response variables with MANOVA $P \leq 0.05$. The number of fish within blocks varied among treatment periods (2001 *range* = 2-31; 2002 *range* = 3-24) and the number of blocks varied by species. Overall sample sizes were 418 spring–summer Chinook salmon, 173 steelhead, and 55 fall Chinook salmon in 2001 and 260 spring–summer Chinook salmon, 344 steelhead, and 31 fall Chinook salmon in 2002. All treatment effects were tested using the block (treatment) error term. Passage times were $\log_e$ transformed to reduce variance heterogeneity and normalize the distributions. All analyses were conducted with the General Linear Model procedure in SAS v.9 (SAS Institute, Cary NC).

Results

Passage times and route selection in 2000

In 2000, with modifications to the weirs in place, spring and summer Chinook salmon moved through the transition pool at Lower Granite Dam faster (median of 0.60 h) than during 1996 (4.10 h; with no modifications). Passage time through the transition pool was also faster for steelhead in 2000 (median of 0.26 h) compared to 1996 (0.88 h). Total median time to pass Lower Granite Dam for spring and summer Chinook salmon was faster in 2000 (18.3 h) than during 1996 (38.0 h) before weirs were modified. However, median passage times through the transition pool for spring-summer Chinook salmon were slightly longer after the weir modification (0.60 h) than before the modification (0.42 h) in 2000 (Table 1). Passage time through the transition pool in 2000 for fall Chinook salmon after the weir modification was the slowest at 3.91 h, however this may have been due to small sample size (n=18).

Table 1. Median times (h) for radio-tagged Chinook salmon and steelhead to pass different segments at Lower Granite Dam in 1996 and 2000 before and/or after the weir modification. Sample sizes are in parentheses.

	Passage Segment				
Species	TR-AP	AP-EN	FP-LP	LP-FT	TR-LT
Spring/summer Chinook[1]	1.66 (76)	3.10 (88)	4.10 (24)	8.77 (72)	38.07 (63)
Spring/summer Chinook[2]	1.00 (67)	3.81 (55)	0.42 (39)	4.56 (30)	12.32 (38)
Spring/summer Chinook[3]	1.09 (134)	4.08 (110)	0.60 (154)	6.74 (102)	18.27 (97)
Fall Chinook[3]	3.48 (10)	1.93 (8)	3.91 (18)	7.91 (25)	28.86 (13)
Steelhead[1]	2.03 (159)	0.73 (157)	0.88 (177)	7.35 (181)	25.86 (157)
Steelhead[3]	1.92 (204)	1.17 (156)	0.26 (319)	4.80 (271)	22.51 (174)

[1] Data at Lower Granite Dam in 1996
[2] Before the weir modification April - 11 May 00
[3] After the weir modification 12 May - October 00

Differences existed in spring and summer Chinook salmon route selection where a slightly greater proportion of fish passed straight through the transition pool and smaller proportion exited to the collection channel after the weir modification in 2000 (Table 2). We observed a similar pattern with steelhead in 2000 with a greater proportion of fish passing straight through the transition pool and a smaller proportion of fish exiting to the collection channel and tailrace compared to steelhead behavior in 1996.

Fishway modification in 2001 and 2002

Weir modifications were effective in achieving our target of a 30 cm head at the first two weirs in 2001, but were slightly less effective in 2002 (Table 3). The increase in hydraulic head produced higher flow velocities through orifices in both weirs. Mean calculated orifice flow velocities through the first weir during treatments were more than double those during control periods in 2001 and 2002 (Table 3). Compared to control periods, mean flow velocity through the second weir orifice during treatments was approximately 90% higher in 2001 and more than 100% higher in 2002.

Table 2. Proportion and median times (h) of Chinook salmon and steelhead passing straight through transition pool or exiting to collection channel or tailrace at Lower Granite Dam in 2000 before and/or after the weir modification. Sample size is in parentheses.

	Behavior		
Proportion	Straight through	Exit to collection channel	Exit to Tailrace
Spring/summer Chinook[1]	0.28(11)	0.59 (23)	0.13 (5)
Spring/summer Chinook[2]	0.29 (45)	0.36 (55)	0.35 (54)
Fall Chinook[2]	0.20 (6)	0.38 (12)	0.42 (13)
Steelhead[3]	0.25 (44)	0.27 (48)	0.48 (85)
Steelhead[2]	0.48 (153)	0.20 (63)	0.32 (101)
Median time (h)			
Spring/summer Chinook[1]	0.17	0.45	4.07
Spring/summer Chinook[2]	0.08	0.53	8.11
Fall Chinook[2]	0.18	0.54	27.72
Steelhead[3]	0.12	0.33	10.40
Steelhead[2]	0.10	0.35	14.68

[1] Before the weir modification April - 12 May 00
[2] After the weir modification 12 May - October 00
[3] Steelhead data from 1996 at Lower Granite Dam

Table 3. Mean head differentials and calculated water velocities through orifices at the most downstream weirs in the Lower Granite Dam fishway.

		Mean head differential, m (SD)		Mean velocity through orifice, m•s^{-1} (SD)	
Year	Treatment condition	Weir 1	Weir 2	Weir 1	Weir 2
2001	Control	0.07 (0.05)	0.10 (0.08)	1.17 (0.99)	1.40 (1.25)
	Treatment	0.30 (0.04)	0.32 (0.07)	2.43 (0.89)	2.51 (1.17)
2002	Control	0.07 (0.21)	0.04 (0.07)	1.17 (2.03)	0.89 (1.17)
	Treatment	0.28 (0.05)	0.22 (0.05)	2.34 (0.99)	2.08 (0.99)

Route selection in 2001 and 2002

Spring–summer Chinook salmon were 1.80 times more likely ($P<0.001$) to pass straight through the transition pool than to exit to either the collection channel or tailrace during the treatment compared to the control condition (Table 4), corresponding to a 16.6-26.4% increase in the number of spring–summer Chinook salmon passing straight through the transition pool (Table 5). The significant year × treatment interaction effect for spring-summer Chinook was due to the stronger treatment effect in 2001 than 2002. The smaller sample of fall Chinook salmon exhibited similar, but not significant ($P > 0.05$) patterns in route selection. Steelhead exhibited no differences in route use between treatment and control conditions.

Passage times in 2001 and 2002

The response of passage time to treatments differed by run and route within run. Generally, passage times among Chinook salmon were variable, ranging from minutes to more than 8 days for the transition pool and 3.3 hours to more than 9 days to pass the dam. Minimum times for steelhead were similar, but maximum times were greater than 63 days. Mean spring–summer Chinook salmon passage times through the transition pool ranged from about 0.1 h for fish that passed straight through during control and treatments to > 5 h for fish that exited to the tailrace under control conditions (Figure 5). Similarly, mean steelhead passage times ranged from about 0.2 h for fish that passed straight through the transition pool to > 4 h for fish that exited to the tailrace for control and treatment conditions.

Overall, the passage times were not strongly related to treatment once accounting for route effects. The relationship between route and mean transition pool passage times were similar among runs, though the level of statistical significance varied. Among spring–summer Chinook salmon, route had a large and significant effect on the transition pool passage time (Table 6, Figure 5) because times were several times greater for individuals exiting to either the collection channel or tailrace than for those passing straight through. Transition pool passage times in steelhead were significantly related to route, while fall Chinook salmon exhibited similar, but not significant, trends (Table 6; Figure 5).

Table 4. Results of multinomial logit analysis of treatment effects on route selection by spring–summer Chinook salmon. *Note*: Odds ratios expressed as the probability of the selected route being chosen in 2002 compared to 2001 and during the treatment versus control condition.

		Route Selection		
Run	Parameter	Straight through vs. exit to collection channel	Straight through vs. exit to tailrace	Exit to collection channel vs. exit to tailrace
Spring–summer Chinook	Intercept	1.35 *	1.33 **	1.81 ***
	Year	2.83 ***	1.39 **	2.03 ***
	Treatment	1.80 ***	1.79 ***	1.01
	Year × treatment	1.23	1.29 *	1.04
Fall Chinook[1]	Intercept	1.41	2.31	3.26*
	Year	1.51	1.63	1.08
	Treatment	1.12	1.50	1.68
Steelhead	Intercept	3.83***	1.03	3.97***
	Year	1.16	1.27*	1.09
	Treatment	1.19	1.13	1.05
	Year × treatment	1.16	1.12	1.16

*$P<0.05$, **$P<0.01$, ***$P<0.001$

[1] Year × last pool treatment interaction could not be evaluated because of missing cells

Treatment effects within route depended on both run and route. Shorter mean passage times during treatment periods by spring–summer Chinook salmon that exited to the collection channel resulted in a significant treatment × route interaction but no overall treatment effect (Table 6). Neither fall Chinook salmon nor steelhead exhibited evidence of treatment effects on mean passage time. The lack of significant relationships between passage time and treatment or route for fall Chinook salmon may have resulted from lower sample size, splitting treatments among a large number of blocks and routes, and the large variability in fish passage behavior. The observed route and treatment effects on passage time in the transition pool did not have a detectable effect on total passage times for any run (Table 6).

Table 5. Percentages of fish passing during each treatment condition for different routes selected in the transition pool at Lower Granite Dam. Percentages using each route are for the first passage attempt only.

					Percent (*n*) using each route		
Run	Year	Treatment condition	N	%	Straight through	Exit to collection channel	Exit to tailrace
Spring–summer Chinook	2001	control	209	50.1	10.1 (21)	43.1 (90)	47.9 (98)
		treatment	208	49.9	36.5 (76)	29.3 (61)	34.1 (71)
	2002	control	114	43.9	36.8 (42)	49.1 (56)	14.0 (16)
		treatment	146	56.1	53.4 (78)	37.0 (54)	9.6 (14)
Fall Chinook	2001	control	18	32.7	33.3 (6)	55.6 (10)	11.1 (2)
		treatment	37	67.3	37.8 (14)	40.5 (15)	21.6 (8)
	2002	control	7	22.6	0.0	85.7 (6)	14.3 (1)
		treatment	24	77.4	25.0 (6)	50.0 (12)	25.0 (6)
Steelhead	2001	control	80	46.2	48.8 (39)	40.0 (32)	11.3 (9)
		treatment	93	58.8	49.5 (46)	39.8 (37)	10.8 (10)
	2002	control	170	49.4	32.4 (55)	54.1 (92)	13.5 (23)
		treatment	174	50.6	44.3 (77)	46.0 (80)	9.8 (17)

Migration depth

Information from the RDSTs indicated fish passed the transition pool near the bottom, which was at least 2.1 m deep throughout the experiment. The average depth among fish recorded at one or more of the five underwater antennas during treatments was 2.0 to 2.1 m and 1.9 to 2.2 during control periods. The shallowest a fish was recorded at while passing through the transition pool was 0.3 m and the deepest was 3.4 m.

Table 6. Results of MANOVA (A) and univariate ANOVA tests (B) of the effects treatment and route on mean transition pool and total dam passage times for spring–summer Chinook salmon, fall Chinook salmon, and steelhead at Lower Granite Dam, Snake River.

A) MANOVA Run	Factor	Wilk's lambda	df	*F*	*P*
Spring–summer Chinook	Treatment	0.965	2,58	1.05	0.357
	Route	0.235	4, 116	30.83	<0.001
	Route × treatment	0.848	4, 116	2.49	0.0470
Fall Chinook	Treatment	0.907	2,12	0.62	0.555
	Route	0.602	4,24	1.73	0.175
	Route × treatment	0.731	4,24	1.02	0.417
Steelhead	Treatment	0.995	2,57	0.14	0.872
	Route	0.496	4,114	11.98	<0.001
	Route × treatment	0.912	4,114	1.35	0.257

B) ANOVA	Source	MS	df	*F*	*P*
Spring–summer Chinook					
Transition pool passage time	Treatment	4.713	1	1.99	0.164
	Route	184.944	2	77.31	<0.001
	Route × treatment	9.793	2	4.09	0.022
Total dam passage time	Treatment	0.412	1	0.29	0.590
	Route	5.070	2	1.81	0.173
	Route × treatment	0.126	2	0.04	0.956
Steelhead					
Transition pool passage time	Treatment	0.480	1	0.19	0.667
	Route	109.721	2	21.31	<0.001
	Route × treatment	5.364	2	2.08	0.134
Total dam passage time	Treatment	0.236	1	0.27	0.606
	Route	2.959	2	1.69	0.194
	Route × treatment	0.984	2	1.12	0.332

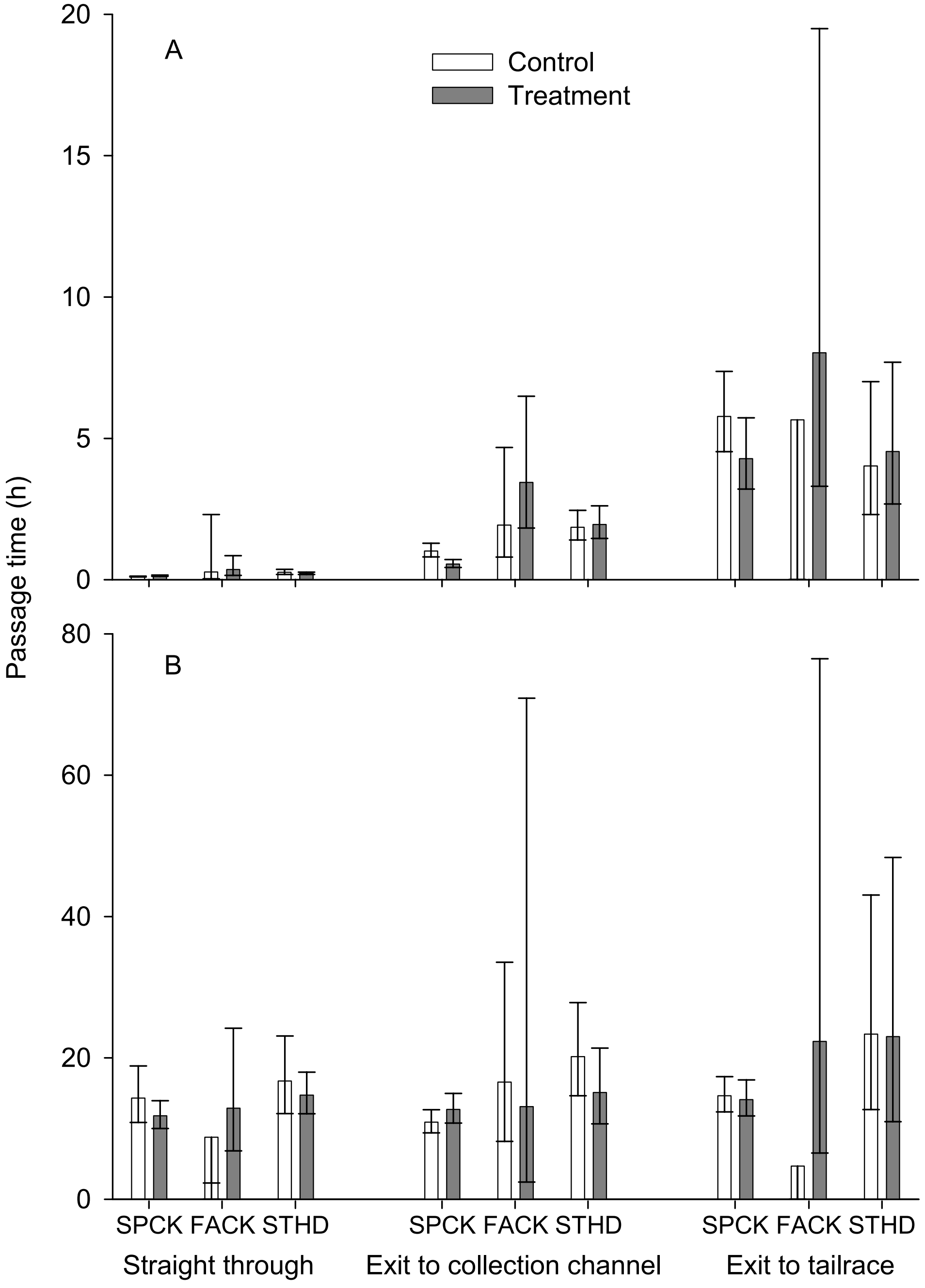

Figure 5. Mean transition pool (A) and total dam passage times (B) with 95% confidence intervals by route and treatment for spring-summer Chinook salmon (SPCK), fall Chinook salmon (FACK) and steelhead (STHD) in 2001-2002. Sample sizes are presented in Table 2.

Discussion

After modifying all five weirs in 2000 by adding and removing weir panels, we observed faster passage times through the transition pool compared to previous data at Lower Granite Dam from 1996. However, passage times for spring and summer Chinook salmon were slightly longer after the weir modification (0.60 h) versus before the modification (0.42 h) in 2000. Thus, it was unclear whether manipulation of the weir panels was responsible for faster transition pool times. Therefore, in 2001 and 2002 we only modified the first two weirs in an experiment with either the weir panels up or down. This allowed us to determine that the faster passage times and changes in fish behavior, with a greater proportion of fish moving through the transition pool on their first attempt, was due to our manipulation of the transition pool.

Weir modifications appeared effective in reducing the frequency of downstream exits out of the transition pool back to the collection channel or tailrace for spring–summer Chinook salmon at Lower Granite Dam in 2001 and 2002, and the other two runs exhibited similar, though not statistically significant responses. Overall, passage time appeared to be related primarily to the route taken through the fish passage facility. Transition pool passage times were much longer for fish that exited the transition pool, and in spring–summer Chinook salmon the probability of exiting was markedly reduced under treatment conditions. Therefore, the treatment appeared to indirectly reduce passage times in spring-summer Chinook salmon by increasing the frequency of straight through passage. Notably, passage time differences within treatment, once controlling statistically for route, were not detected or were minimal. The limited number of treatment blocks, variable field conditions, and especially the large variability in passage times within treatment may have limited our ability to detect treatment effects and potentially to detect the effects of the treatment on overall passage times.

Mean transition pool passage times for fish that exited to the tailrace were 4-8 h longer than for fish that passed straight through and 1-3 h longer for fish exiting to the collection channel regardless of treatment condition. Fish that exited to the collection channel were still "within" the dam fishway and may have required less time to relocate and pass the transition pool compared to fish exiting to the tailrace. Interestingly, neither treatment condition nor route had a detectable effect on total dam passage time, an observation that was probably primarily related to the large variability in passage behavior, much of which is associated with the time spent in the tailrace and presumably represents time spent searching for fishway entrances. Modifications of the transition pool that reduce exits and increase passage rates may be especially important during summer when water temperature at the top of the ladder may be 5˚C or more warmer than the bottom of the ladder at Lower Granite Dam (USACE 2004). Ladder passage times were significantly longer and exits from the transition pool were more frequent for summer and fall Chinook salmon and steelhead when such temperature differences were greater than 1 to 2 ˚C (C. C. Caudill unpublished data). Importantly, these temperature differences were most common at temperatures thought to be stressful to salmonids (≥18˚C; Richter and Kolmes 2005).

Consequently, the weir modifications should reduce the potential for cumulative or interactive effects of poor hydraulic conditions and poor thermal conditions at the transition pool that slow passage through the transition pool and lead to thermal stress. Such improvements may be especially important given the known sublethal and lethal effects of high temepratures on salmonid fishes (reviewed in Richter and Kolmes 2005). Regardless of temperature, salmon that do not rapidly pass dams frequently spend many additional hours in the tailrace (Bjornn et al. 1995, 1998) and passage of the tailrace appears to be energetically costly compared to passage of other segments (Brown et al. 2006). For instance, Brown et al. (2002) found that 81% of the energy used by spring Chinook salmon during passage of Bonneville dam was expended in the tailraces while only 18% and 1.5% were used in the fishways and forebays, respectively. Consequently, the effect of the modificaitons on route use may have had greater energetic and physiological consequences than effects on passage time *per se*. Additionally, while the observed effects on passage time were small in magnitude, some evidence suggests that longer migration times across multiple dams and reservoirs is significantly associated with unsuccessful migration (Naughton et al. 2005; C. C. Caudill unpublished data), suggesting the potential for cumulative effects across dams.

The shorter transition pool passage times and lower number of transition pool exits were probably the result of increased water flow at submerged weir orifices. Pacific salmon spend little time near the surface during upstream migration (Daum and Osborne 1998; Johnson et al. 2005), including when in pool and weir fish ladders (e.g. Monk et al. 1989), and would therefore be more likely to encounter and be attracted to flow through submerged orifices than surface flow over the weir crests. Information from the RSDTs directly supported our hypothesis that Chinook salmon and steelhead traveled near the bottom of the transition pool. This behavior was evident during treatment and control periods and suggests that fish migrating near the bottom of the transition pool were more likely to perceive an increase in attraction flows from weir orifices.

Such mechanistic understanding of migration behavior is critical when designing fish passage facilities for adult anadromous salmonids. Concern over migratory delay at Columbia and Snake River dams has prompted the National Marine Fisheries Service to call for operational changes at dams (NMFS 2000). In response, the U. S. Army Corps of Engineers has made many structural changes to fishways, collection channels, and ladders to improve passage conditions for juvenile and adult salmonids, however, few studies have provided information that allows mechanistic evaluation of those modifications. Furthermore, design and operation criteria for adult fishways are often based on controlled laboratory conditions which are not representative of field conditions at passage structures (Haro et al. 2004). The results of this study demonstrated that evaluation of fishway modifications can be conducted using an experimental approach and under realistic field conditions. Future modifications should strive to use a similar mechanistic approach to efficiently design or modify existing fish passage structures.

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