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FISHWAY ENTRANCE USE AND PASSAGE TIMES OF ADULT SPRING–SUMMER CHINOOK SALMON AT LOWER MONUMENTAL DAM, WITH AN EMPHASIS ON EFFECTS OF SPILLWAY DEFLECTORS: 2000-2004

by

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Preface

Managers of Columbia River basin salmonids *Oncorhynchus* spp. are interested in the circumstances of adult migrants that fail to pass dams, as well as why some fish experience passage delay, particularly if passage delay can be linked to dam operations or fishway configurations. In this report, we present summary information on fishway entrance use and passage times of radio-tagged adult spring–summer Chinook salmon at Lower Monumental Dam from 2000-2004. Additional emphasis has been placed on the effects of end-bay spill deflectors, which were installed in the winter of 2002-2003.

This and related reports from this research project can be downloaded from the website: http://www.uidaho.edu/cnr/ferl/publications

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Executive Summary

We monitored the passage behaviors of 1,679 radio-tagged adult spring–summer Chinook salmon at Lower Monumental Dam from 2000-2004. Over the five years, 99.7% of the monitored fish successfully passed the dam. Under most conditions, the majority of tagged fish passed via the north-shore ladder.

Passage times at the dam (annual medians) ranged from 1.4 to 2.2 h from time of tailrace entry to first approach a fishway, from 1.5 to 3.5 h from first approach to first fishway entry, and from 9.2 to 13.3 h to pass the dam. Ladder ascension times were rapid, with relatively little variability among years (medians 3.5-3.7 h). In all passage environments, salmon slowed upstream migration at night.

Full-dam passage times were only weakly correlated with environmental conditions, including flow, spill, and water temperature. In general, passage times were longer during higher flow and spill and when water temperatures were either relatively high (> 17º C) or low (< 10º C). Full-dam passage times were more strongly correlated with fishway use behaviors: times were longer when fish approached fishway entrances multiple times and when fish entered and exited the fishway more than once. Numbers of approaches and entries were correlated, indicating these measures were inter-related. Times also varied somewhat with where fish first approached and entered fishways, possibly reflecting differences in fishway entrance configurations and/or the ease of use.

Orifice gates were closed in all study years. Use of the south-shore, south-powerhouse, and north-shore entrances varied significantly among years. Patterns were related, at least in part, to environmental conditions fish encountered. Use of the south-shore entrance, adjacent to the spillway, increased as flow and spill increased, presumably because attraction flows to this side of the river were greater at higher discharge. Ratios of fishway approaches to fishway entries also varied among years, and there was some evidence that conditions near some fishway entrances (especially the south-powerhouse entrance) became more difficult for adult fish to negotiate during periods of higher flow and spill.

Particular attention was given to the effects of spillway deflectors, which were installed in the Lower Monumental end bays in the winter of 2002-2003. Previous hydraulic modeling had indicated that deflectors may increase turbulence near adult fishway entrances. In general, however, there was limited evidence that deflectors had a negative impact on adult spring–summer Chinook passage at the dam. Deflectors were associated with some possible shifts in fishway use patterns, but overall dam passage metrics indicated that negative effects were limited. Given below-average flow and spill conditions in the study years, further evaluation of deflector effects is recommended during years with higher discharge.

Introduction

An important aspect of the adult salmon and steelhead *Oncorhynchus* spp. passage project has been to describe how fish move past dams in the lower Columbia and Snake rivers. With receivers and antennas placed near entrances to fishways, within fishways, and at the tops of ladders, we have monitored movements of individual fish outfitted with transmitters as they approached entrances to fishways, determined openings used by fish to enter and exit fishways, documented their movements within fishways, and assessed the time fish require to pass the dams.

Reducing passage 'delay' at dams has been a management priority, as there is mounting evidence that slow passage at dams translates to reduced migration success (Geist et al. 2000; Brown et al. 2002; Caudill et al. *in review* a). We have reported detailed information on fishway use and passage times for adult salmon and steelhead in multi-year and multi-species assessments at the four lower Columbia River dams (Keefer et al. *in review a,b,c*; Burke et al. 2005). Similar evaluations were conducted for Snake River dams and are reported in Bjornn et al. (1995; 1998a,b); and Keefer et al. (2003a). A more general comparison of full-dam passage times for adult fish from all runs at all lower Columbia and lower Snake River dams is reported in Keefer et al. (2004a). In this report, we present details of fishway entrance use and passage times for spring–summer Chinook salmon at Lower Monumental Dam. Particular attention is given to the effects of recently-installed spill deflectors on entrance use and passage times. Analyses were restricted to spring–summer Chinook salmon because almost all steelhead and fall Chinook salmon pass the dam during zero-spill conditions.

Spill is a management issue at lower Snake River dams in part because it can result in total high dissolved gas (TDG) supersaturation in tailraces and other areas downstream, increasing mortality and injury risks for juvenile and adult migrants as well as resident fish (Weitkamp and Katz 1980; Backman and Evans 2002), and possibly altering adult migration behaviors (e.g., Johnson et al. 2005). However, routing juvenile fish over spillways also provides survival benefits relative to passing through turbines. Efforts to balance the survival benefits of spill for juveniles with juvenile and adult risks associated with TDG included the installation of spillway deflectors at Lower Granite, Little Goose, and Lower Monumental dams in the 1970's. Deflectors reduce TDG by limiting water from plunging deep into the stilling basins below spillways. Spill deflectors were installed in most, but not all, spillbays during this period. At Lower Monumental Dam, for example, deflectors were installed in spillbays 2-7, but not in the end bays 1 and 8.

The 2000 Biological Opinion (NMFS 2000) recommended that additional efforts be made to ameliorate TDG supersaturation. In response, spillway deflectors were installed in end spillbays 1 and 8 at Lower Monumental Dam in the winter of 2002-2003. Concern for adult migrants arose after hydraulic models evaluated by USACE indicated that deflectors in the end bays might increase turbulence and alter hydraulic conditions near the adjacent adult fishway entrances. Turbulent conditions have the potential to delay or disorient upstream-migrating adult salmon and steelhead. Therefore, we evaluated the effects of end-bay spill deflectors using adult radiotelemetry data collected in years before and after deflector installation. Fishway use patterns and passage time metrics for spring–summer Chinook salmon migrating during 2000-2002 (pre-installation) were compared to behaviors for salmon migrating in 2003-2004 (post-installation).

Methods

***Study area**.* – Lower Monumental Dam is located at river km 67 (mile 41.6) on the lower Snake River. Construction details of the dam, powerhouses, spillway, and spilling basin are described at http://www.nww.usace.army.mil/html/pub/pertdata/lomopert.htm.

Radio-tagged salmon were monitored with two aerial antennas in the Lower Monumental tailrace and a series of underwater antennas at each open fishway entrance and at the tops of each ladder (Figure 1). Antennas on the outside wall of the north-shore, south-powerhouse, and south-shore entrances recorded fish approaches to these sites. Antennas on the inside of the fishways near each entrance recorded fishway entries, and the combination of antenna sites were used to identify when fish exited from a fishway back into the tailrace. Orifice gate entrances were closed and unmonitored in all study years.

Spillway deflectors were installed in spillbays 1 and 8 in winter 2002-2003 (Figure 2). A concrete wall separates the spilling basin from the area immediately adjacent to the south-powerhouse fishway entrance site, whereas the south-shore entrance has more direct exposure to spillway turbulence (Figure 2).

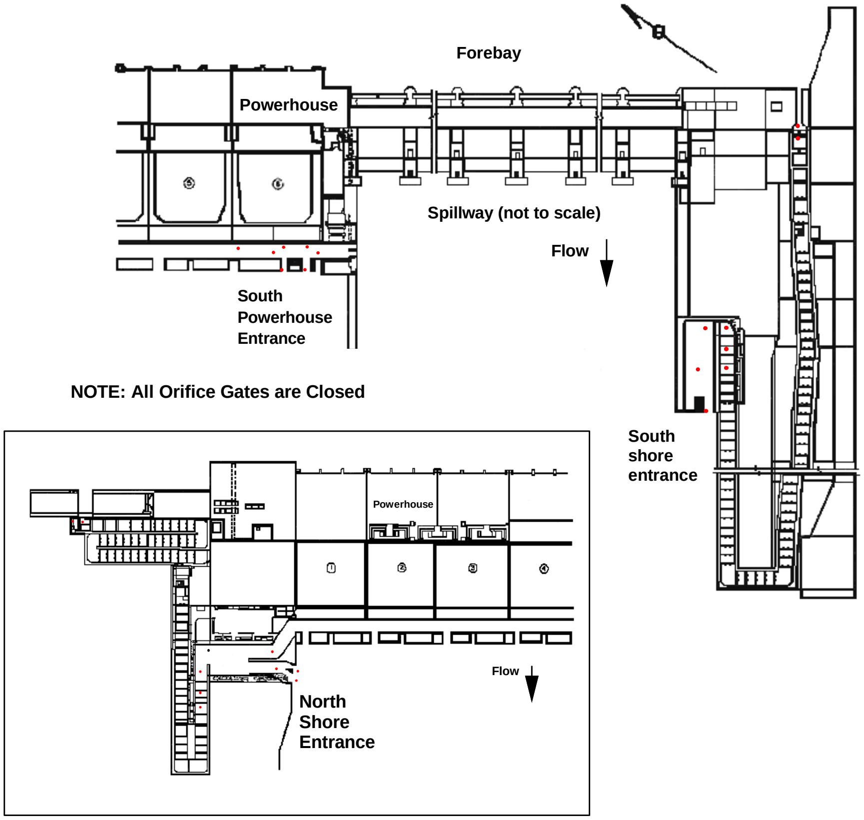

Figure 1. Schematic map of Lower Monumental Dam, with locations of underwater antennas (red circles) used to monitor fish passage and behaviors. Orifice gates were closed during all study years. Two aerial antennas, one on each shoreline about 1 km downstream from the dam, were used to monitor the tailrace.

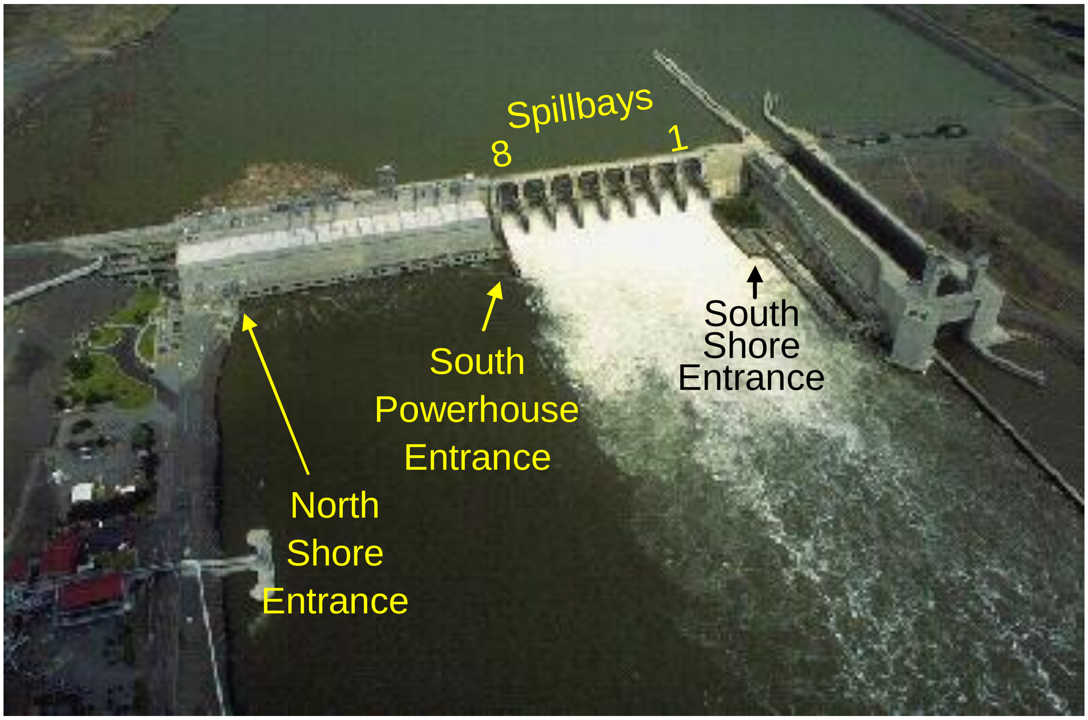

Figure 2. An aerial photo showing the main adult fishway entrances and spillbays (1 and 8) where spill deflectors were installed in winter 2002-2003 at Lower Monumental Dam.

Fish collection and radio-tagging. – Spring–summer Chinook salmon used for the study were collected and intragastrically outfitted with radio transmitters at the adult fish facility at Bonneville Dam on the Columbia River (river kilometer 235.1). Tagging and fish collection methods are described in Keefer et al. 2004b and Bjornn et al. 2000. Spring Chinook were tagged in April and May, while summer-run fish were tagged in June and July using run-separation dates established by USACE. Sampling was in approximate proportion to the runs at large passing Bonneville Dam, although we tended to undersample during peak counts and oversample during low counts in an effort to tag fish from all portions of the runs. Selection for salmon that had been PIT-tagged as juveniles led to slight oversampling of Snake River salmon relative to other populations in the basin. See Keefer et al. 2004c for a more complete assessment of the overall sampling effort for spring–summer Chinook salmon.

Passage distributions for radio-tagged fish at Lower Monumental Dam spanned the migration season in each year (Figure 3). As with the total sample, radio-tagged fish somewhat under-represented the runs during passage peaks and over-represented the run when counts were low. The largest departure from representative sampling was in 2001, when the overall spring run was exceptionally large and also arrived very early. Sample sizes at Lower Monumental ranged from 178 fish in 2004 to 553 fish in 2001. Overall, 99.7% of the fish recorded at the dam eventually passed the dam.

River environment. – Total river flow at Lower Monumental Dam during the study years ranged from < 20 kcfs to about 200 kcfs (Figure 4). The 2001 migration was characterized by near-record low flow, while most other years were near average. Runoff peaks typically occurred in late May or early June, though secondary peaks occurred in mid-April, particularly in 2000 and 2002. Discharge approached base flows near late June or early July (Figure 4).

Spill levels were somewhat more variable between years (Figure 5). Spill was nearly continuous between 20 and 50 kcfs from April through mid-June in 2000 and 2003, with similar timing for peak spill. However, much higher spill (~80 kcfs) was recorded briefly in 2003. No-spill conditions persisted through all of 2001 and most of 2002. Two periods of spill occurred in 2004, one in late April to early May and a second time in early June (Figure 5).

The distribution of spill among spillbays was available for 2003 and 2004 (provided by Karen Zelch, USACE). When spill occurred in 2003, some discharge typically passed through each spillbay (Figures 6-8). Spill from end bays 1 and 8 averaged between 3-5 kcfs in each month of 2003, though at times discharge from these bays was as high as 15 kcfs. Discharge through the end bays in 2003 was typically higher than, or similar to, discharge from spillbays 2 through 7. In 2004, spillbays 2, 4, 5, 6, and 8 were used relatively infrequently. Spillbay 1 was used on most days when there was spill, with discharge typically between 6-10 kcfs. During portions of the year, both spillbays 1 and 8 were used in patterns similar to those in 2003.

Water temperatures followed predictable warming trends throughout each migration year (Figure 9). The spring of 2004 was characterized by warm temperatures, while the spring of 2002 was typically coolest. Warmer than average periods were recorded in late May and early June of both 2000 and 2001, coincident with the lower runoff peaks in those years.

***Statistical analyses*. –** Two objectives were considered in the analyses of the fishway use and passage time data: 1) general summaries of the fish behaviors at the dam, independent of the question of spillway deflectors, and 2) the effects of spillway deflectors on fish behaviors. For the most part, summaries for the effects of spillway deflectors excluded fish that approached a fishway, entered a fishway, or entered a passage segment (for passage time analyses) during days with no reported spill. This excluded all fish in 2001 and large proportions of the fish in 2002 and 2004. We did not attempt to identify fish that initially experienced zero-spill conditions but then encountered spill before passing the dam (i.e., those that experienced ‘treatment’ switching). Given the spill patterns in the study years (spill mostly continuous when it was occurring) only a small proportion of the study fish likely experienced such switches.

The vast majority of salmon approaches and entries at fishways were clearly coded with regard to approach and entry location. However, a small number of events were ambiguous with regards to exact time, and these were coded ‘unknown’. This typically occurred when a fish was detected at an antenna inside a fishway but not at a fishway entrance antenna. Unknown actions were excluded from summaries of fish behaviors that were location-specific (e.g., the distribution of approaches among fishway entrance locations). Similarly, when a fish’s first tailrace entry, fishway approach, or fishway entry was ‘unknown’ with regards to location or time, the passage time for that fish was not included for the passage segment affected. Unknown actions were included in summaries of total approaches and entries when they were not location specific.

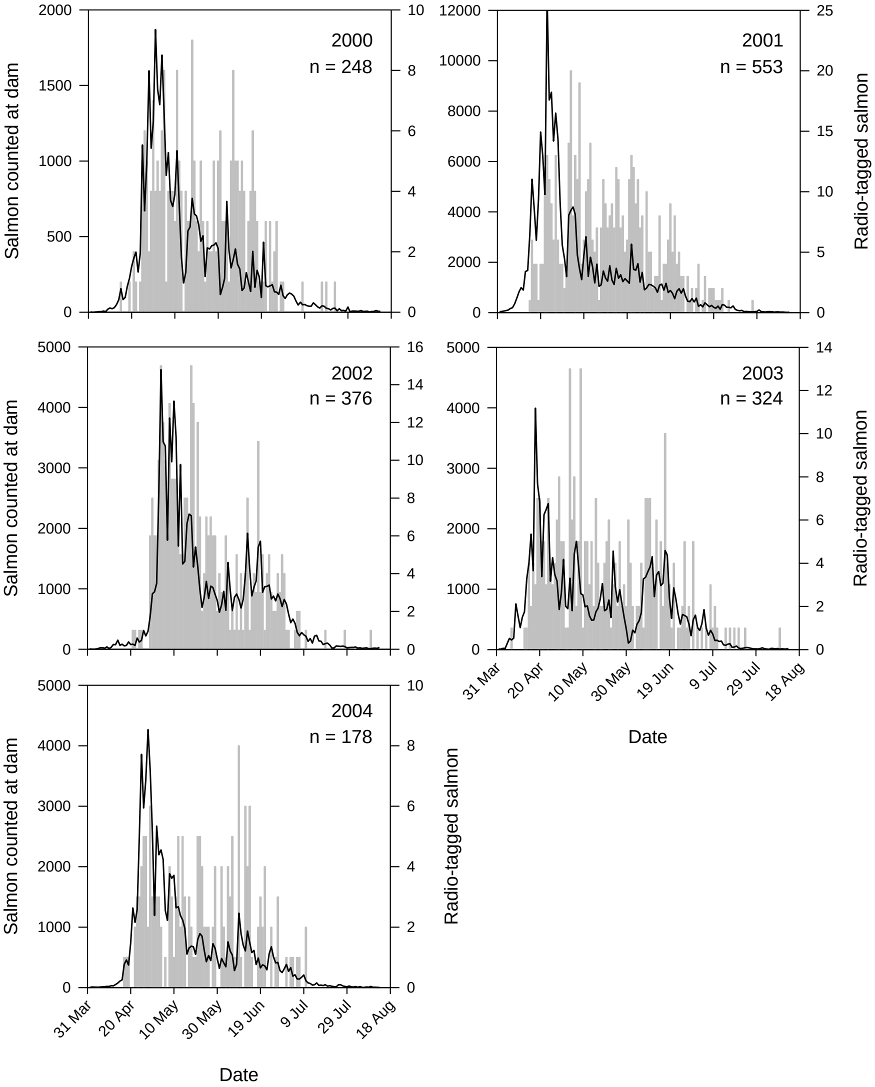

Figure 3. Numbers of spring–summer Chinook salmon counted passing (solid black lines) and the number of unique radio-tagged salmon detected (gray bars) each day at Lower Monumental Dam.

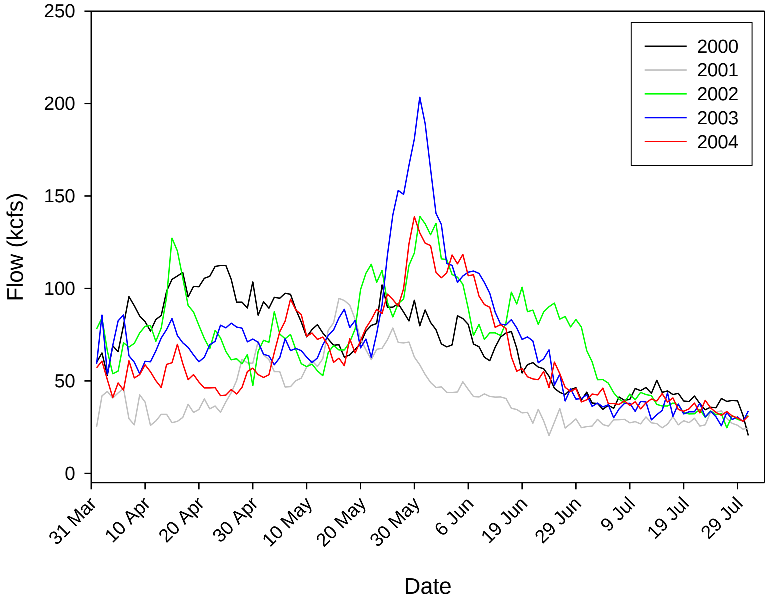

Figure 4. Total mean daily discharge (kcfs) at Lower Monumental Dam, 2000-2004.

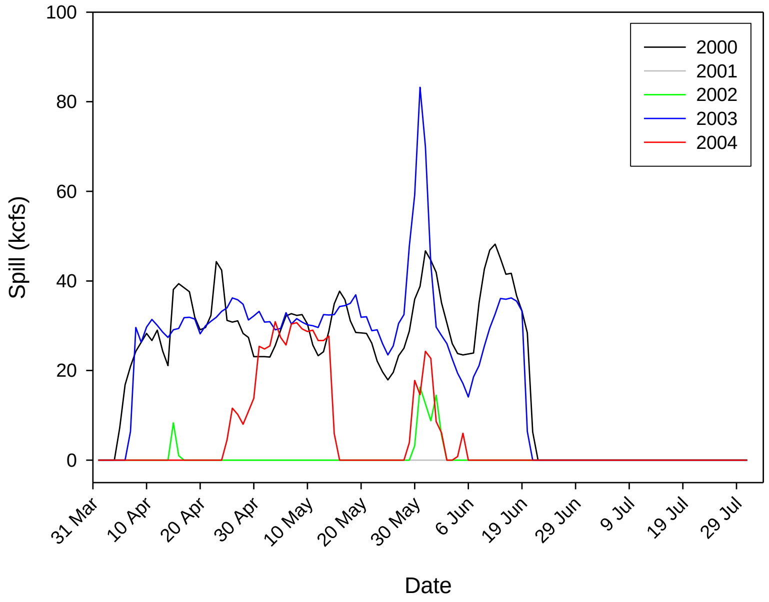

Figure 5. Total mean daily spill (kcfs) at Lower Monumental Dam, 2000-2004.

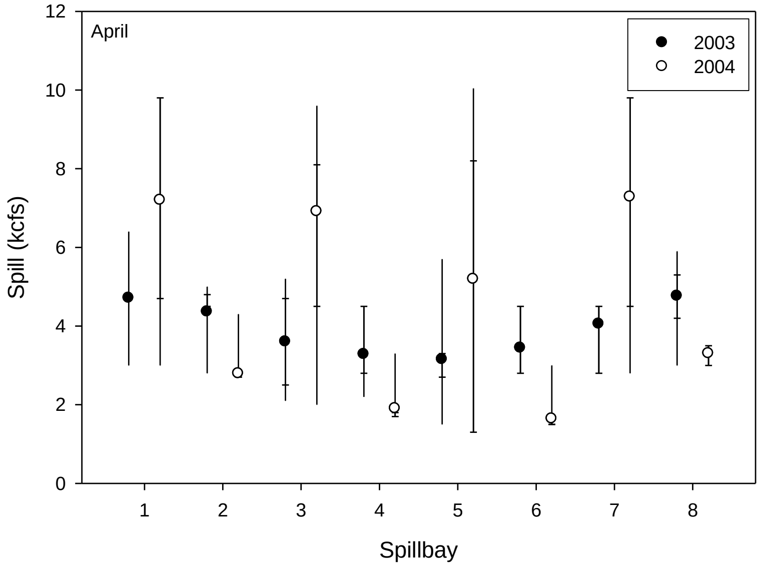

Figure 6. Mean, quartile, and 5th and 95th percentiles of spill recorded passing through each spillbay in April of 2003 and 2004. Spill occurred during 75-77% of possible 5-minute periods for each spillbay in 2003 and during <1-12% of periods in 2004.

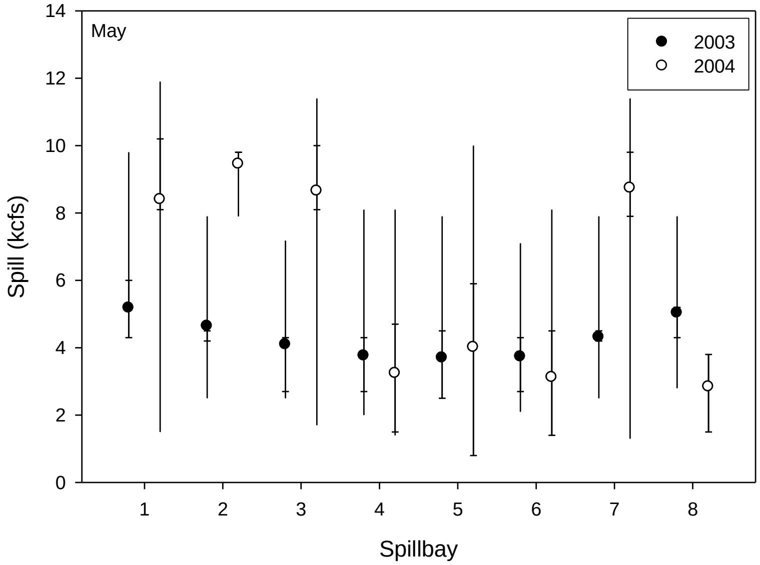

Figure 7. Mean, quartile, and 5th and 95th percentiles of spill recorded passing through each spillbay in May of 2003 and 2004. Spill occurred during 96-99% of possible 5-minute periods for each spillbay in 2003 and during 6-49% of periods in 2004.

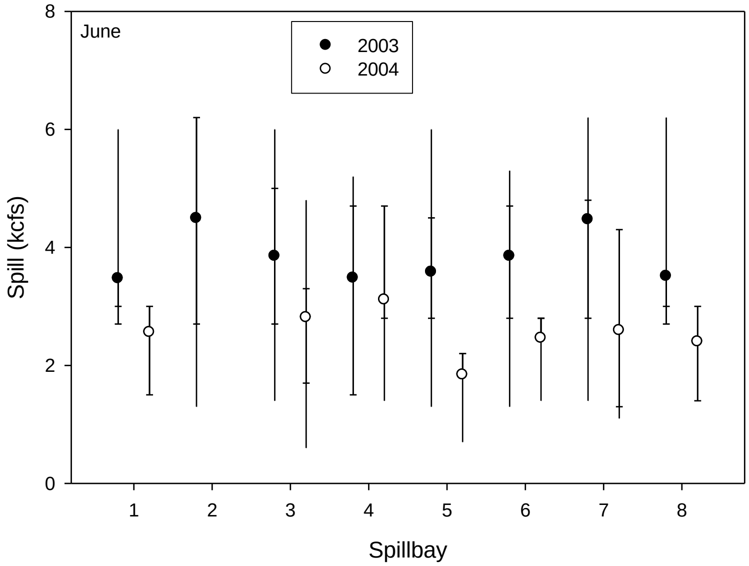

Figure 8. Mean, quartile, and 5th and 95th percentiles of spill recorded passing through each spillbay in June of 2003 and 2004. Spill occurred during 61-64% of possible 5-minute periods for each spillbay in 2003 and during 0-3% of periods in 2004.

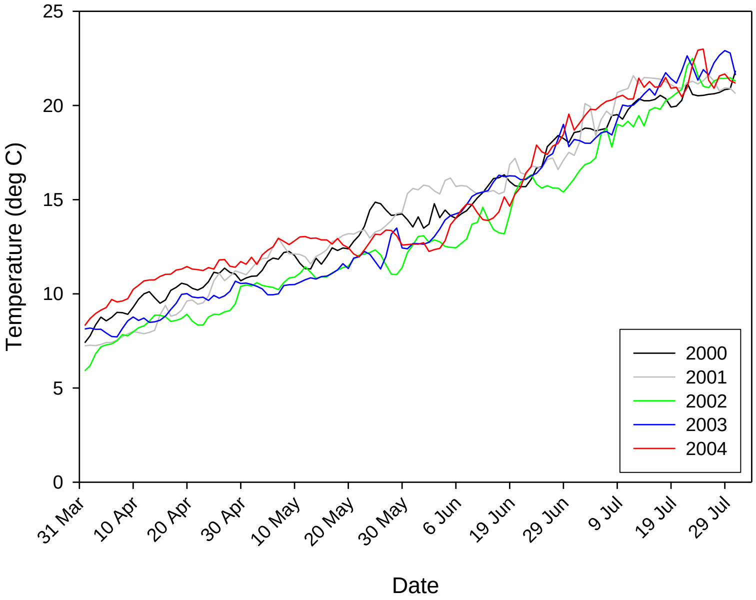

Figure 9. Mean daily water temperature (deg C) at Lower Monumental Dam, 2000-2004.

Passage times were calculated for three passage segments: 1) from first tailrace record to first approach at a fishway entry, 2) from first fishway approach to first fishway entry, and 3) from first tailrace record to exit from the top of a fish ladder. The first metric best summarizes the time fish initially spent in the tailrace before approaching the dam. The second metric includes the time fish spent approaching one or more fishway entrances as well as time that elapsed while fish were in the tailrace after first approaching the dam. The final, full-dam, metric included all fish behaviors at the dam, including exits from and re-entries into fishways. Only first dam passage events were considered; records after fish fell back were excluded. Mean and median passage times are reported, though in general medians are a better indicator of central tendency for passage time data, which tends to be right-skewed (Keefer et al. 2004a; 2004d). Additional, fine-scale passage details in and near the north-shore counting window at Lower Monumental Dam are reported in Jepson et al. 2006.

Distributions of first and total fishway approaches and entries were compared using Pearson χ^2 tests and multiple logistic regression. Linear regression, analysis of variance (ANOVA) and general linear models that included both categorical and continuous predictor variables (GLM, Allison 1999) were used to evaluate passage times (SAS 2000). Passage times were $\log_e$ transformed in all models to improve the normality of error terms. Because any fish response to spillway deflectors would occur only during spill, most analyses related to deflector effects were restricted to fish that entered passage segments on days with spill.

Results

***Fishway approaches and entries**.* – In all study years, radio-tagged Chinook salmon were most likely to first approach the Lower Monumental fishways at the north-shore entrance (Table 1). However, the distribution of first fishway approaches among entrance locations differed significantly among years (*df* = 8, χ^2 = 110.3, *P* < 0.001, Pearson χ^2 test). First approaches were most frequent at the north-shore entrance in 2003 and 2004 and were least frequent at the south-powerhouse entrance in those same years (Table 1). Comparison of first approach distributions during no-spill conditions before and after spillway deflector installation (see Table 2 for sample sizes) produced a generally similar pattern: in the post-deflector period (2003-2004), more fish first approached at the north-shore entrance (68% vs. 56%), fewer first approached at the south-powerhouse entrance (8% vs. 15%), and slightly more first approached at the south-shore entrance (24% vs. 29%) (*df* = 2, χ^2 = 15.6, *P* < 0.001). These shifts may have been a result of spill deflectors or (more likely) from deflectors and a combination of environmental differences between years.

When all approaches were combined, the south-powerhouse entrance was the most approached in all years except 2004, when the north-shore entrance was approached most (Table 1). Again, significant year effects were detected (*df* = 8, χ^2 = 822.4, *P* < 0.001). Results were also significant when only fish that approached during days with spill were included: in the post-deflector period, more fish approached at the north-shore entrance (33% vs. 22%), similar percentages approached at the south-powerhouse entrance (59% vs. 59%), and fewer approached at the south-shore entrance (7% vs. 18%) (*df* = 2, χ^2 = 428.3, *P* < 0.001).

Table 1. Numbers of first and total fishway approaches at Lower Monumental Dam and the percentages that were recorded at each major fishway entrance site, by year and summed for the pre- and post-spillway deflector installation periods.

	First fishway approaches				Total fishway approaches			
Year	*n*	NSh	SPh	SSh	*n*	NSh	SPh	SSh
2000	242	40.5%	26.9%	32.6%	3405	25.4%	60.3%	14.2%
2001	552	61.4%	27.9%	10.7%	14088	25.2%	61.8%	13.0%
2002	375	58.7%	26.7%	14.7%	8045	25.4%	59.7%	14.9%
Total	**1,169**	**56.2%**	**27.3%**	**16.5%**	**25,538**	**25.3%**	**60.9%**	**13.8%**
2003	317	69.7%	10.1%	20.2%	7,275	33.4%	60.6%	6.1%
2004	170	65.9%	14.1%	20.0%	1,818	42.2%	37.2%	20.6%
Total	**487**	**68.4%**	**11.5%**	**20.1%**	**9,093**	**35.1%**	**55.9%**	**9.0%**

Table 2. Spill conditions when radio-tagged Chinook salmon first entered the tailrace and at the time of first and total fishway approaches and entries at Lower Monumental Dam. Years 2000-2002 were before spillway deflectors were installed in end spillbays.

		Spill conditions			
		Spill > 0		Zero spill	
	Years	*n*	%	*n*	%
First tailrace entry	2000-2002	237	22%	832	78%
	2003-2004	342	73%	129	27%
First fishway approaches	2000-2002	513	35%	944	65%
	2003-2004	355	73%	132	27%
Total fishway approaches	2000-2002	4,535	17%	22,686	83%
	2003-2004	7,316	80%	1,777	20%
First fishway entries	2000-2002	238	21%	898	79%
	2003-2004	337	73%	122	27%
Total fishway entries	2000-2002	467	13%	3,206	87%
	2003-2004	468	47%	538	53%

Distributions of first fishway entries among entrance sites differed between years (*df* = 8, χ^2 = 57.3, *P* < 0.001) (Table 3). The south-shore entrance had the most first entries in 2000 and 2001, the north-shore entrance had the most in 2002 and 2004, and the south-powerhouse had the most in 2003. When only fish that first entered during spill were included, fewer fish first entered at the south-shore entrance in the post-deflector period (34% vs. 42%), more first entered at the south-powerhouse entrance (31% vs. 25%), and similar percentages first entered at the north-shore entrance (35% vs. 32%). These differences were not significant (*df* = 2, χ^2 = 5.1, *P* = 0.080). When all fishway entries were considered, the north-shore entrance was used most in all years except 2002 (south-powerhouse), and the south-shore or south-powerhouse entrances were used least (*df* = 8, χ^2 = 91.5, *P* < 0.001). Results were non-significant (*df* = 2, χ^2 = 2.4, *P* = 0.298) when all entries that occurred during days with spill were compared for pre- and post-deflector periods.

Table 3. Numbers of first and total fishway entries at Lower Monumental Dam and the percentages that were recorded at each major fishway entrance site, by year and summed for the pre- and post-spillway deflector installation periods.

	First fishway entries				Total fishway entries			
Year	*n*	NSh	SPh	SSh	*n*	NSh	SPh	SSh
2000	232	34.1%	23.3%	42.7%	550	41.5%	24.2%	34.4%
2001	539	33.6%	31.2%	35.3%	2249	46.4%	26.6%	27.0%
2002	365	40.8%	40.6%	18.6%	874	38.9%	41.0%	20.1%
Total	**1,136**	**36.0%**	**32.6%**	**31.4%**	**3,673**	**43.9%**	**29.6%**	**26.5%**
2003	307	30.9%	34.9%	34.2%	586	39.9%	29.9%	30.2%
2004	152	45.4%	29.0%	25.7%	420	43.3%	32.1%	24.5%
Total	**459**	**35.7%**	**32.9%**	**31.4%**	**1,006**	**41.4%**	**30.8%**	**27.8%**

In a multiple logistic regression model with all fish included, the distribution of first fishway approaches was significantly associated with the interaction term deflector×spill ($\chi^2 = 13.95$, $P < 0.005$) and migration date ($\chi^2 = 4.03$, $P = 0.045$) (Table 4). (note: year was not included as a predictor variable in any multiple regression or GLM models.) The interaction term likely reflects differences in spill patterns during the pre- and post-deflector installation period (e.g., no spill in 2001), as well as the shift away from the south-powerhouse entrance to the north-shore entrance summarized in Table 1. The increased preference for the north-shore entrance as a first approach site was consistent across most flow and spill conditions (Figures 10 and 11), as well as through the migration seasons (Figure 12). The date effect probably reflected the general decline in first approaches at the south-shore entrance as seasons progressed as well as mid-season changes in approach distributions likely related to flow and spill patterns (Figure 12). Results differed somewhat when only fish that first approached during spill were included, with more significant terms (Table 4, in parentheses). The deflector term was significant in the reduced model ($P = 0.048$), but explained a relatively small proportion of the variability.

The multiple logistic regression model for total fishway approaches for all fish included many more significant terms (Table 4). Date, flow×date, deflector, and deflector×flow variables were all significant at $P < 0.001$. Under most conditions, total approaches increased at the north-shore entrance after deflector installation (Figures 13-15). There was a greater range of flow conditions in the two years after installation, and total approaches at the south-shore entrance increased at the higher flow levels, while relative use at the south-powerhouse entrance declined. There was also a tendency for reduced approaches at the south-powerhouse entrance late in the migration season, particularly after deflector installation.

With all fish included, the distribution of first fishway entries was significantly ($P \leq 0.005$) associated with deflector, flow, date, and flow×date terms (Table 5). In general, first fishway entries were lowest at the north-shore entrance during high flow (Figure 17) and mid-migration (Figure 18). Use of the south-powerhouse entrance increased with flow prior to deflector installation, while use of the south-shore entrance increased with flow after deflector installation. Results were comparable when only fish that first entered during spill were included (Table 5, in parentheses). The multiple logistic regression model for total fishway entries (all fish) produced results very similar to the one for first fishway entries (Table 5, Figures 19-21). Results were also generally similar when only fishway entries that occurred during spill were included, except that spill terms became more significant.

Table 4. Results of multiple logistic regression analyses of the distributions of first and total fishway approaches at Lower Monumental Dam. χ^2 and *P* values are for Type III analyses of effects. Results in parentheses are for fish that approached on days with spill.

		First fishway approaches		Total fishway approaches	
Variable	*df*	χ^2	*P*	χ^2	*P*
Deflector	1	0.51 (3.44)	0.475 (0.064)	0.71 (3.91)	0.400 (0.048)
Flow	1	0.48 (0.01)	0.489 (0.938)	0.17 (10.43)	0.677 (0.001)
Spill	1	0.08 (0.00)	0.781 (0.996)	21.10 (19.24)	<0.001 (<0.001)
Date	1	4.03 (0.02)	0.045 (0.887)	69.36 (0.00)	<0.001 (0.990)
Deflector×Flow	1	2.80 (6.50)	0.094 (0.011)	4.20 (10.87)	0.040 (0.001)
Deflector×Spill	1	13.95 (0.56)	<0.001 (0.456)	6.23 (0.11)	0.013 (0.738)
Deflector×Date	1	0.01 (0.43)	0.927 (0.513)	10.56 (5.15)	0.001 (0.023)
Flow×Spill	1	1.98 (1.55)	0.159 (0.213)	1.24 (17.36)	0.265 (<0.001)
Flow×Date	1	1.86 (0.04)	0.173 (0.848)	2.57 (17.97)	0.109 (<0.001)
Spill×Date	1	0.15 (0.01)	0.697 (0.912)	29.06 (16.77)	<0.001 (<0.001)

With all fish included, the distribution of first fishway entries was significantly (*P* ≤ 0. There was a tendency for salmon to first enter fishways at the entrance where they first approached, but large proportions entered at sites other than first approach sites (Figure 22). Tailrace crossing was very common. On average, 33% of the fish that first approached at the south-shore entrance made their first entry at the north-shore entrance and 29% that first approached at the north-shore entrance and 25% that first approached at the south-powerhouse entrance made first entries at the south-shore.

Table 5. Results of multiple logistic regression analyses of the distributions of first and total fishway entries at Lower Monumental Dam. χ^2 and *P* values are for Type III analyses of effects. Results in parentheses are for fish that entered on days with spill.

		First fishway entries		Total fishway entries	
Variable	*df*	χ^2	*P*	χ^2	*P*
Deflector	1	11.56 (10.10)	<0.001 (0.002)	13.41 (16.68)	<0.001 (<0.001)
Flow	1	10.55 (5.03)	0.001 (0.025)	9.46 (7.08)	0.002 (0.008)
Spill	1	3.43 (7.98)	0.064 (0.005)	1.81 (8.64)	0.178 (0.003)
Date	1	8.07 (0.08)	0.005 (0.780)	23.65 (0.57)	<0.001 (0.449)
Deflector×Flow	1	5.11 (1.48)	0.024 (0.232)	10.96 (2.81)	<0.001 (0.094)
Deflector×Spill	1	0.29 (2.12)	0.593 (0.145)	1.14 (3.91)	0.286 (0.048)
Deflector×Date	1	7.66 (7.87)	0.006 (0.005)	9.66 (13.27)	0.002 (<0.001)
Flow×Spill	1	0.05 (1.14)	0.823 (0.286)	0.32 (0.05)	0.569 (0.831)
Flow×Date	1	15.23 (4.23)	<0.001 (0.040)	21.46 (8.00)	<0.001 (0.005)
Spill×Date	1	3.21 (8.26)	0.073 (0.004)	0.93 (7.06)	0.336 (0.008)

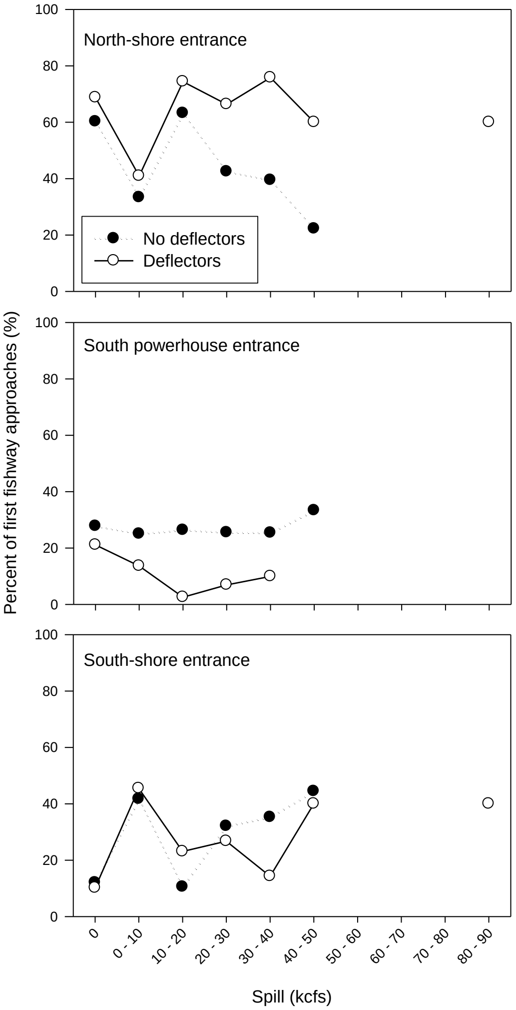

Figure 10. Percentages of first fishway approaches as distributed among fishway entrances, by spill and presence or absence of spill deflectors.

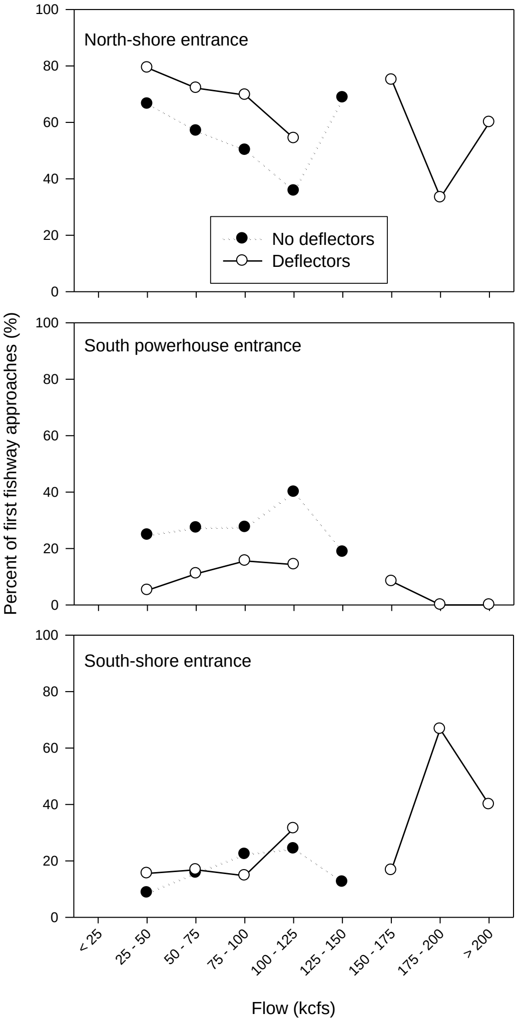

Figure 11. Percentages of first fishway approaches as distributed among fishway entrances, by flow and presence or absence of spill deflectors.

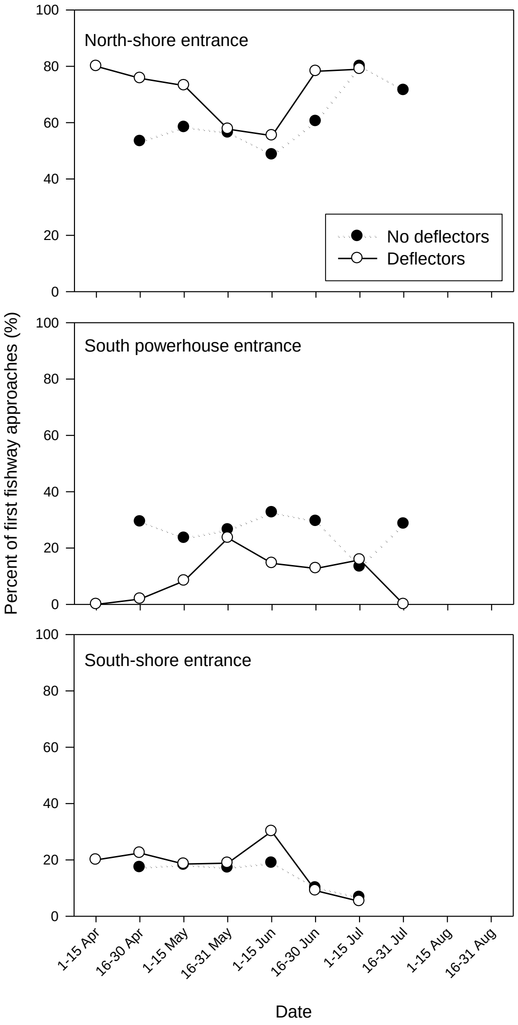

Figure 12. Percentages of first fishway approaches as distributed among fishway entrances, by date and presence or absence of spill deflectors.

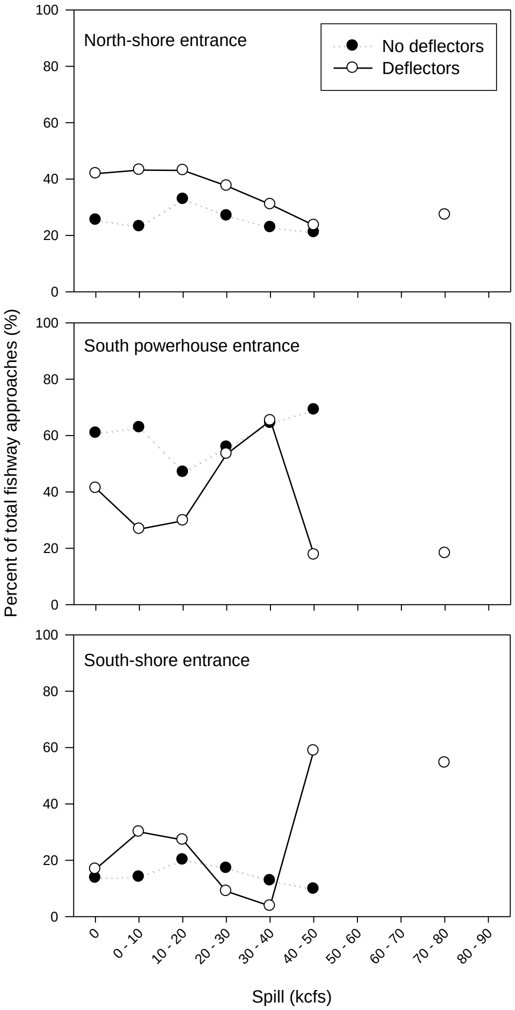

Figure 13. Percentages of total fishway approaches as distributed among fishway entrances, by spill and presence or absence of spill deflectors.

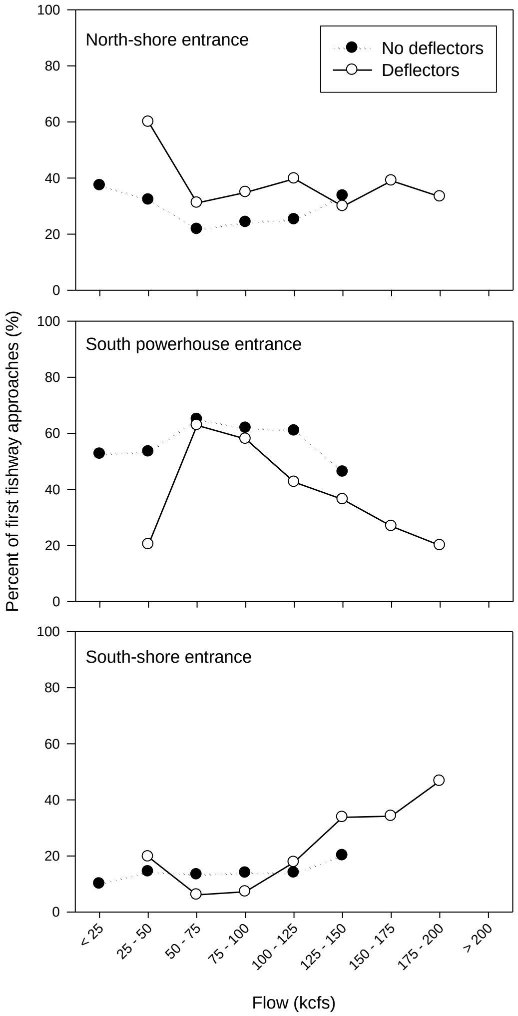

Figure 14. Percentages of total fishway approaches as distributed among fishway entrances, by flow and presence or absence of spill deflectors.

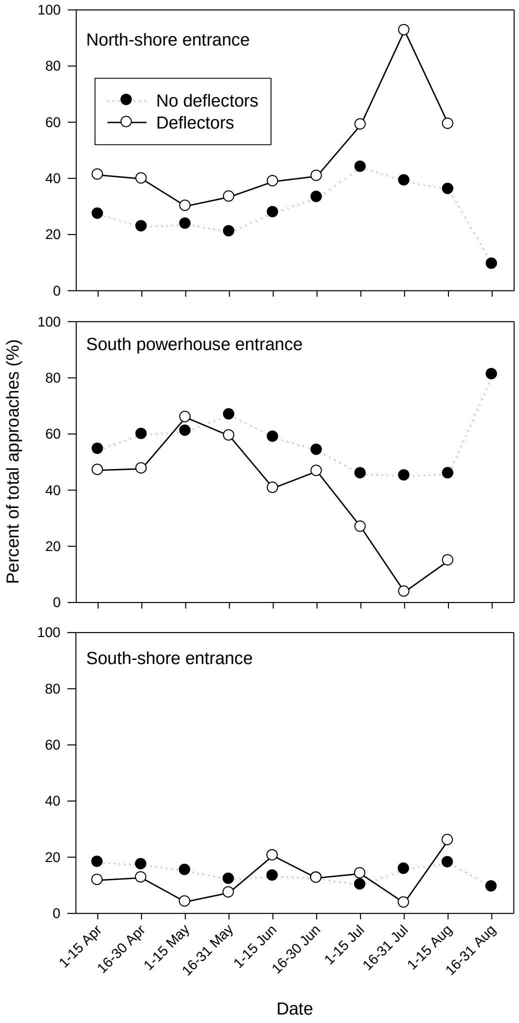

Figure 15. Percentages of total fishway approaches as distributed among fishway entrances, by date and presence or absence of spill deflectors.

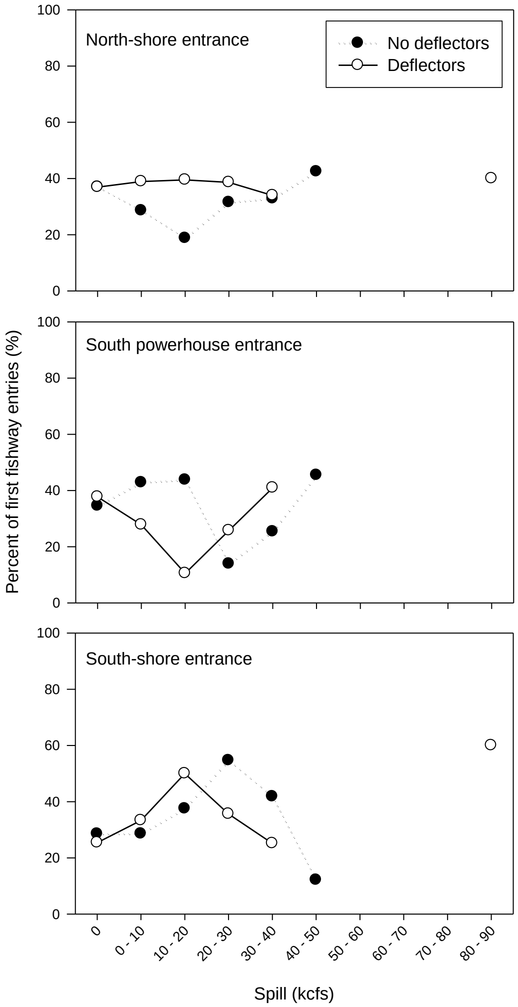

Figure 16. Percentages of first fishway entries as distributed among fishway entrances, by spill and presence or absence of spill deflectors.

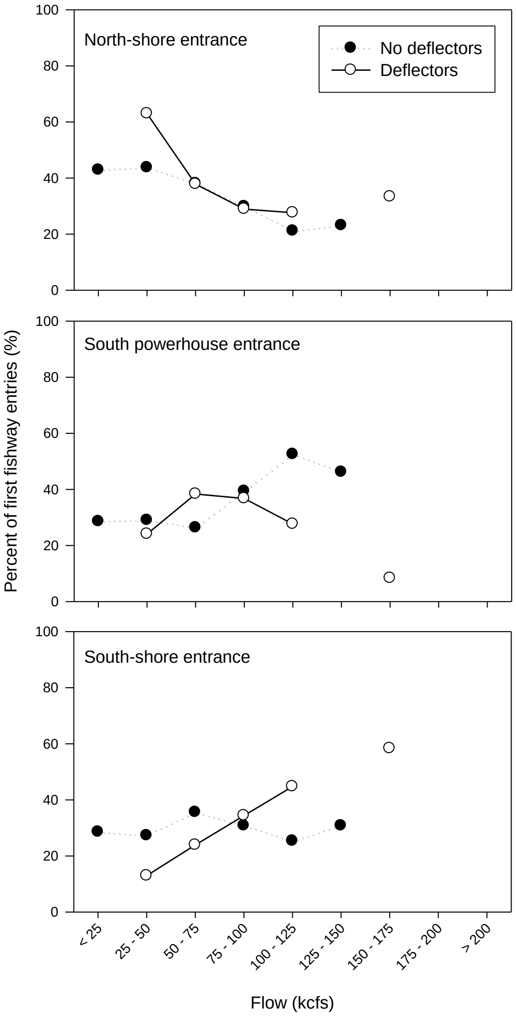

Figure 17. Percentages of first fishway entries as distributed among fishway entrances, by flow and presence or absence of spill deflectors.

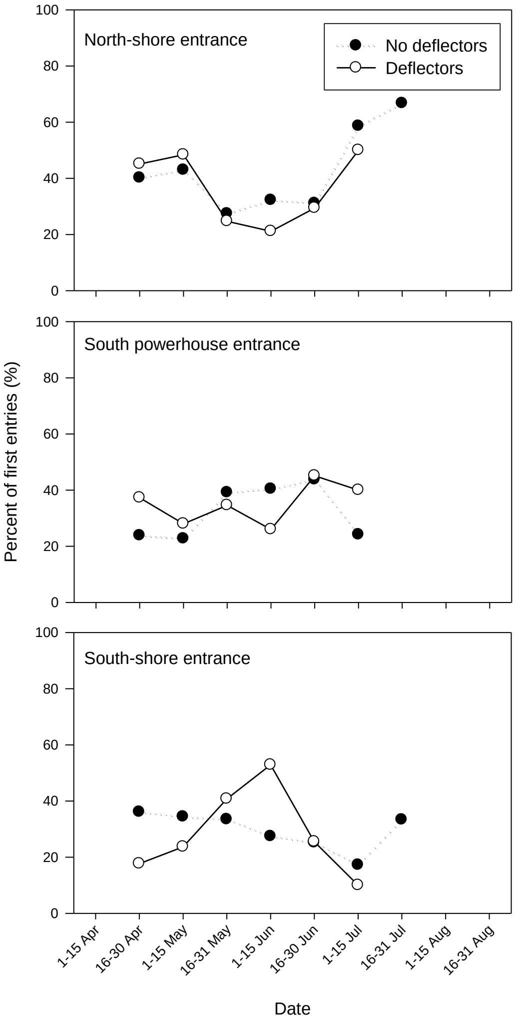

Figure 18. Percentages of first fishway entries as distributed among fishway entrances, by date and presence or absence of spill deflectors.

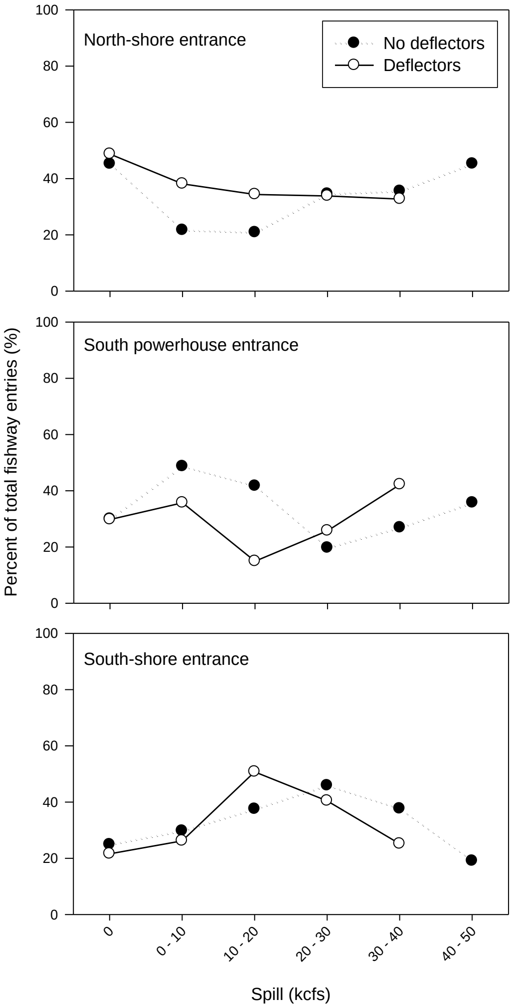

Figure 19. Percentages of total fishway entries as distributed among fishway entrances, by spill and presence or absence of spill deflectors.

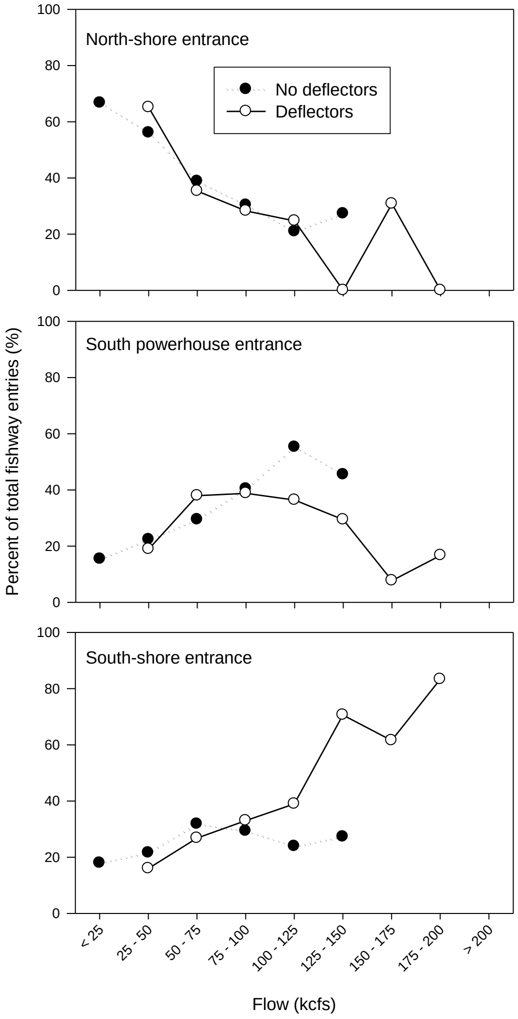

Figure 20. Percentages of total fishway entries as distributed among fishway entrances, by flow and presence or absence of spill deflectors.

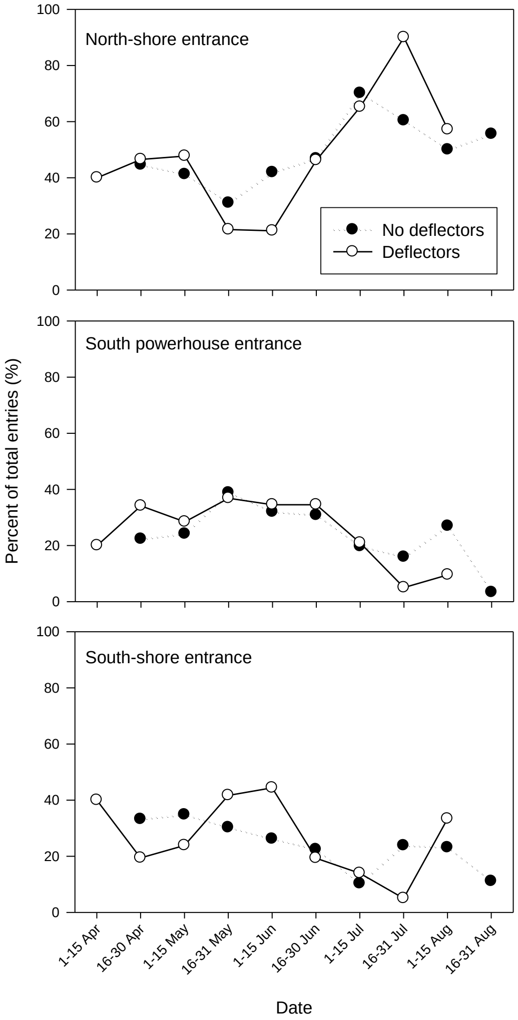

Figure 21. Percentages of total fishway entries as distributed among fishway entrances, by date and presence or absence of spill deflectors.

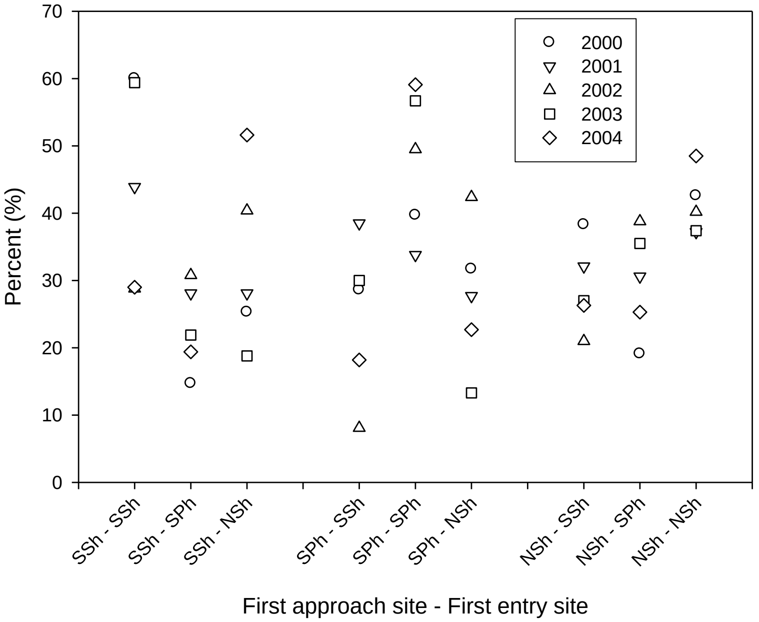

Figure 22. Locations of first fishway entrances used by Chinook salmon in relation to locations of first fishway approaches, by year.

***Fishway approach:Fishway entry ratios**.* – The ratios of total fishway approaches: total fishway entries indicated that salmon approached fishway entrances multiple times per entry at all sites (Table 6). In both pre- and post-deflector periods, the south-shore entrance had the lowest approach:entry ratio (3.61 pre-installation and 2.92 post-installation), while the south-powerhouse entrance had the highest ratios (14.30 and 16.40, respectively). The north-shore entrance had the largest relative change in the approach:entry ratio, from 4.01 in the pre-deflector period to 7.68 in the post-deflector period (Table 6). As the vicinity of the north-shore entrance should have been least affected by spillway deflectors, it is unlikely that this ratio change was a result of the deflector installation.

When only fishway approaches and entries on days with spill were included, approach:entry estimates were higher at all sites (Table 6), suggesting that entering fishways was more difficult due to spill or to the higher flow and/or tailwater elevations associated with spill. Ratios in the post- deflector period were approximately double those in the pre- deflector period at north-shore and south-powerhouse entrances, while the ratio was lower at the south-shore entrance in the post-deflector period. However, the difference can be attributed almost entirely to the 2003 migration, which had very high ratios at the north-shore and especially the south-powerhouse entrance (Table 6). Ratios in 2004 were similar to or lower than those from pre-deflector years.

Approach:entry ratios at the south-shore entrance were remarkably consistent throughout the migration seasons, both pre- and post-deflector installation, and under a variety of flow and spill conditions (Figures 23-25). In contrast, ratios were much more variable at the north-shore and south-powerhouse entrances. At the north-shore entrance, ratios increased as spill increased and under moderate flows in the post-deflector period. Ratios at the south-powerhouse entrance also increased with increased spill after installation, and were higher in mid-season in both periods (Figures 23-25), coincident with runoff peaks.

Table 6. Ratios of the total number of fishway approaches: the total number of fishway entries at each major fishway entrance location at Lower Monumental Dam, by year and summed for the pre- and post-spillway deflector installation periods. Estimates in italics are with all approaches and entries during zero spill excluded. *n* = the number of entries at that site.

	North Shore		S. Powerhouse		South Shore		Total	
Year	*n*	Apps:Ents	*n*	Apps:Ents	*n*	Apps:Ents	*n*	Apps:Ents
2000	228	3.80	133	15.44	189	2.57	550	6.19
2001	1044	3.40	597	14.58	608	3.02	2,249	6.26
2002	340	6.02	358	13.41	176	6.80	874	9.20
Total	**1,612**	**4.01**	**1,088**	**14.30**	**973**	**3.61**	**3,673**	**6.95**
***Total*[1]**	***163***	***6.26***	***128***	***20.95***	***176***	***4.73***	***467***	***9.71***
2003	234	10.37	175	25.18	177	2.50	586	12.41
2004	182	4.21	135	5.01	103	3.64	420	4.33
Total	**416**	**7.68**	**310**	**16.40**	**280**	**2.92**	**1,006**	**9.04**
***Total*[1]**	***154***	***15.90***	***150***	***28.99***	***164***	***3.16***	***468***	***15.63***

[1] with all approaches and entries during zero spill excluded

At the individual fish scale, the numbers of fishway approaches/fish and fishway entries/fish were right-skewed in all years, with some fish approaching and entering many times. Median numbers of fishway approaches were 16 times/fish in the years before deflectors were installed, versus 7 times/fish in the years after installation (χ^2 = 114.4, $P < 0.001$, Kruskal-Wallis test; Table 7). Median numbers of fishway entries per fish were 2.0 before deflectors and 1.0 after deflectors (χ^2 = 52.8, $P < 0.001$). Both of the latter were not corrected for days with no-spill conditions, and the 2001 migration was particularly influential -- the number of fishway entries per fish in 2001 was nearly double what was recorded in other years.

Table 7. Mean and median numbers of fishway approaches and entries per salmon at Lower Monumental Dam, by year and summed for the pre- and post-spillway deflector installation periods. *n* = the number of unique fish with known approaches or entries.

	Fishway approaches			Fishway entries		
Year	*n*	Mean	Median	*n*	Mean	Median
2000	244	14.0	8.0	239	2.4	1.0
2001	553	25.5	19.0	551	4.2	2.0
2002	375	21.5	17.0	374	2.4	1.0
Total	**1,172**	**21.9**	**16.0**	**1,164**	**3.3**	**2.0**
2003	318	23.0	9.0	318	1.9	1.0
2004	172	10.8	6.0	172	2.7	1.0
Total	**490**	**18.7**	**7.0**	**490**	**2.2**	**1.0**

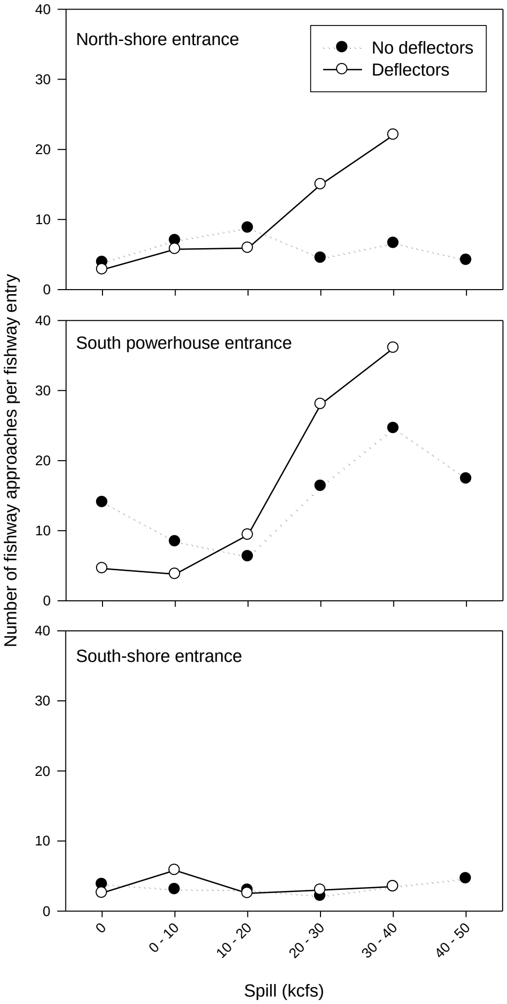

Figure 23. Ratios of fishway approaches:fishway entries, by spill, entrance location and presence or absence of spill deflectors.

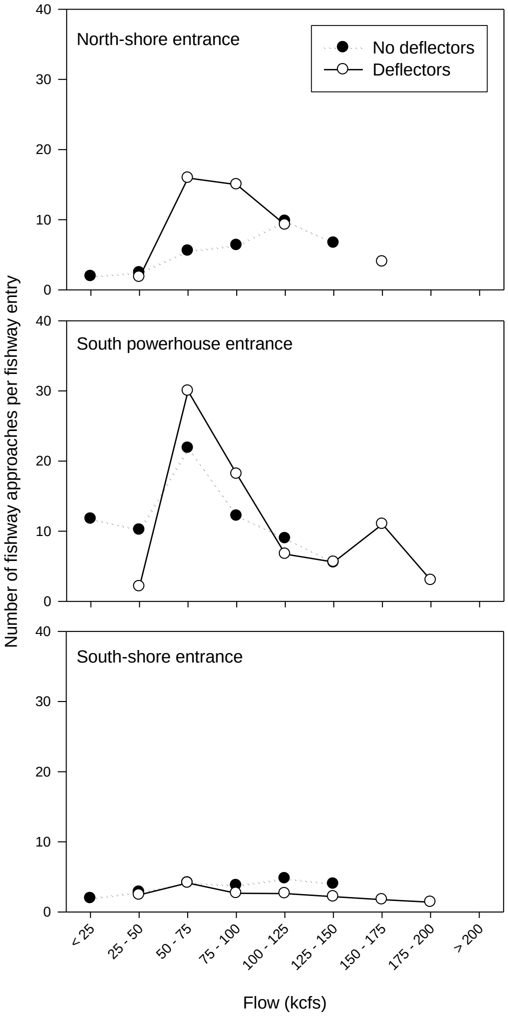

Figure 24. Ratios of fishway approaches:fishway entries, by flow, entrance location and presence or absence of spill deflectors.

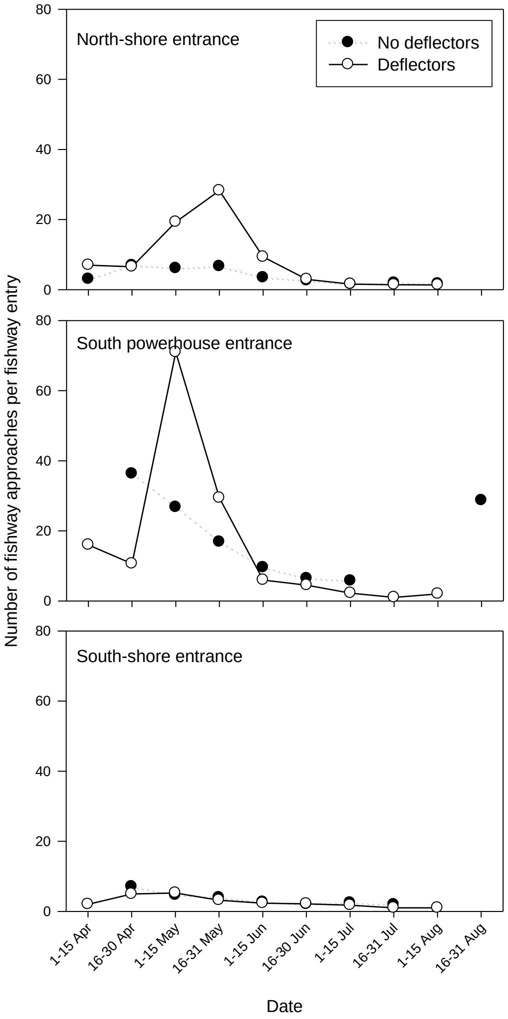

Figure 25. Ratios of fishway approaches:fishway entries, by date, entrance location and presence or absence of spill deflectors.

Ladder passage. – In all years, majorities of the radio-tagged salmon passed via the north-shore ladder (Table 8). Use of the south-shore ladder was highest in 2000 (37%) and 2003 (32%), the two years with relatively high and constant spill. Use of the south-shore ladder was also higher when only fish that entered the tailrace on days with spill were considered (Table 8). On days with spill, use of the south-shore ladder was lower (28% vs. 38%) in the post-deflector period.

Table 8. Percentages of radio-tagged Chinook salmon that passed the north- and south-shore ladders at Lower Monumental Dam. Numbers in italics are with all fish that entered the tailrace during zero spill excluded.

	North ladder (%)	South ladder (%)	Unknown (%)
2000	147 (60%)	91 (37%)	8 (3%)
2001	465 (84%)	82 (15%)	4 (1%)
2002	354 (93%)	20 (5%)	6 (2%)
Total	**966 (84%)**	**193 (17%)**	**18 (2%)**
Total[1]	***143 (62%)***	***86 (38%)***	***0 (0%)***
2003	214 (66%)	104 (32%)	5 (2%)
2004	162 (91%)	8 (4%)	9 (5%)
Total	**376 (75%)**	**112 (22%)**	**14 (3%)**
Total[1]	***244 (72%)***	***96 (28%)***	***1 (<1%)***

[1] fish that entered the tailrace during zero spill excluded

Passage time introduction. – A variety of passage time metrics are useful for evaluating potential sources of passage delay at dams. Figure 26 shows seven partially overlapping metrics we considered for this analysis, of which three are described in detail in the following sections. The tailrace entry to first fishway approach metric (Metric 1) best summarizes the time fish initially spent in the tailrace before approaching the dam and was useful for interpreting whether fish had difficulty initially locating fishway entrances. The first approach to first fishway entry metric (Metric 2) represents the time fish took to enter a fishway once they had approached the dam and should be useful in determining if fish had difficulty initially entering fishways. The tailrace to pass dam metric (Metric 3, full-dam passage) incorporates all behaviors at the dam, and is useful for general comparisons across years and dams.

The four metrics that were not considered in detail were: tailrace entry to first fishway entry (equivalent to Metric 1 + Metric 2); first fishway approach to pass dam (equivalent to Metric 3 - Metric 1); first entry to pass the dam (equivalent to Metric 3 - Metric 2 - Metric 1); and last fishway entry to pass the dam. This last metric measured time to pass through fishways and up ladders on each fish's final attempt. Relatively little variability was observed for this metric (annual means = 3.56-3.73 h, annual medians = 2.57-2.95 h), and we did not consider it further.

Time to first approach a fishway. – Median salmon passage times from the time of tailrace entry to the first recorded approach at a fishway entrance ranged from 1.41 to 2.24 h across years, with all fish included (Table 9). Medians were slightly lower for the pre-installment period (1.59 h) than the post-installment period (1.67 h) (Figure 27). Mean values (*range* = 1.94 to 3.57 h) showed similar patterns. When passage times were $\log_e$ transformed to improve normality, a 1-way ANOVA indicated that passage times differed significantly among years (*df* = 4, *F* = 35.02, *P* < 0.001). Similarly, $\log_e$ transformed times differed by the fishway entrance first approached (*df* = 2, *F* = 7.28, *P* < 0.001), with longer times for fish that first approached at the south-shore entrance (Figure 27). Salmon that arrived during night (1800-0600) passed more slowly than those that arrived during the day (0600-1800) (*df* = 1, *F* = 128.09, *P* < 0.001) (Figure 27). When only fish that first approached during days with spill were included, times did not differ for pre- and post-deflector periods (*F* = 2.89, *P* = 0.090); times did differ by first fishway approach site (longest times for those that first approached the south-shore entrance, *F* = 4.20, *P* = 0.015). Those that entered the tailrace at night again had longer passage times (*F* = 67.65, *P* <0.001).

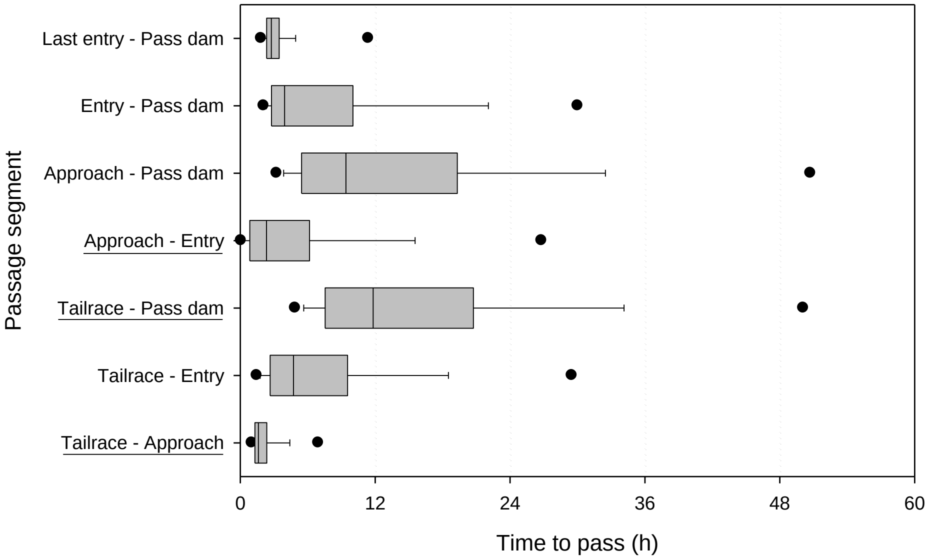

Figure 26. Passage times (median, quartile, 10th, 90th, 5th, and 95th percentiles) of all radio-tagged spring–summer Chinook salmon at Lower Monumental Dam, 2000-2004. Tailrace = tailrace entry; Approach = first fishway approach; Entry = first fishway entry; Last entry = last fishway entry before passing dam; Pass dam = exit from the top of a fish ladder. The passage segments in the figure overlap and only the underlined segments are discussed in detail.

Univariate linear regression models of the continuous variables flow, spill, and water temperature were also each significant (*P* < 0.001) with all fish included, though these variables explained only small percentages of the variance in $\log_e$ transformed tailrace to first fishway approach passage times ($0.03 \leq r^2 \leq 0.14$). Passage times tended to increase with flow and spill volume (Figures 28 and 29) and to decrease as temperatures increased (Figure 30). Patterns were similar when limited to fish that entered the tailrace during spill, except that temperature was not significant (*P* > 0.05).

A multiple regression model that included all six independent variables (year not included) explained about 27% of the variability in tailrace to first fishway approach passage times (Table 10). Time of tailrace entry (*F* = 228.09) and spill (*F* = 211.83) explained the most variability, followed by temperature, presence of spillway deflectors, and total flow. Inclusion of interaction terms only modestly improved overall model fit (max r^2 ~ 0.31), and so these terms were excluded. The largest differences between the deflector ‘treatments’ occurred during periods of low water temperature and high flow or spill. During the post-deflector period, times were also longer for fish that first approached the south-shore entrance and those that entered the tailrace at night. It is notable, however, that under most conditions, passage times through this migration segment were similar with and without spill deflectors (Figures 27-30). Results were not substantively different when limited to fish that entered the tailrace during spill.

Appendix Table 1 includes passage times for spring–summer Chinook salmon radio-tagged in 1993 and 1997, years with above average flow and spill levels. Passage times from tailrace to first fishway approach in 1997 were considerably longer than in any study year (*median* = 3.09 h, *mean* = 8.67 h, *n* = 302). It should be noted, however, that orifice gates were open (and unmonitored) in earlier years, and so direct comparisons with the 2000-2004 results may not be advisable.

Table 9. Mean and median passage times for radio-tagged Chinook salmon from entry into the tailrace to first recorded approach at a fishway entrance at Lower Monumental Dam. Estimates in italics are for fish that entered the tailrace during spill.

	Year	*n*	Mean	Median	% > 24 h
Tailrace - First approach	2000	225	3.57	2.24	1.3%
	2001	468	2.01	1.53	0.0%
	2002	374	1.94	1.54	0.0%
	Total	**1,067**	**2.31**	**1.59**	**0.3%**
	Total[1]	***235***	***3.56***	***2.26***	***1.3%***
	2003	297	3.39	1.87	0.7%
	2004	170	2.05	1.41	0.6%
	Total	**467**	**2.90**	**1.67**	**0.6%**
	Total[1]	***339***	***3.39***	***1.89***	***0.9%***

[1] fish that entered the tailrace during zero spill excluded

Table 10. Results of the general linear model (GLM): $\log_e$ (passage time from tailrace entry to first fishway approach) = flow + spill + temperature + time of day (day, night) + location of first approach (north-shore, south-powerhouse, south-shore) + deflector (yes, no) + error. All fish included.

Variable	*df*	Type III SS	MS	*F*	*P*
Deflector	1	3.61	3.61	13.88	<0.001
Approach site	2	1.25	0.62	2.41	0.090
Time of day	1	59.28	59.28	228.09	<0.001
Flow	1	2.36	2.36	9.08	0.003
Spill	1	55.05	55.05	211.83	<0.001
Temperature	1	8.46	8.46	32.57	<0.001
Model r^2 = 0.27; F = 80.32; $P < 0.001$					

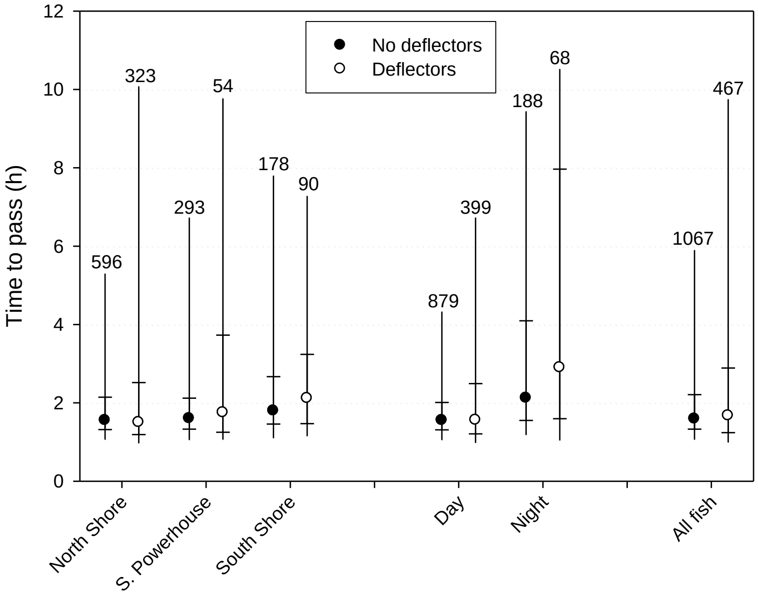

Figure 27. Median, quartile, and 5th and 95th percentiles of Chinook salmon passage times from tailrace entry to first recorded approach at a fishway entry. Categories are location of first approach, day vs. night, and all fish during the pre- and post-spillway deflector periods.

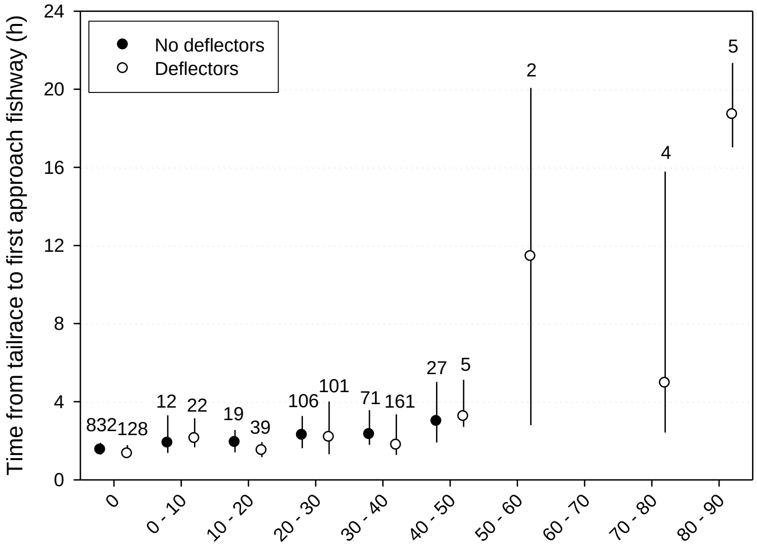

Figure 28. Median and quartiles of Chinook salmon passage times from tailrace entry to first recorded approach at a fishway entry. Categories are 10-kcfs intervals of spill during the pre- and post-spillway deflector periods.

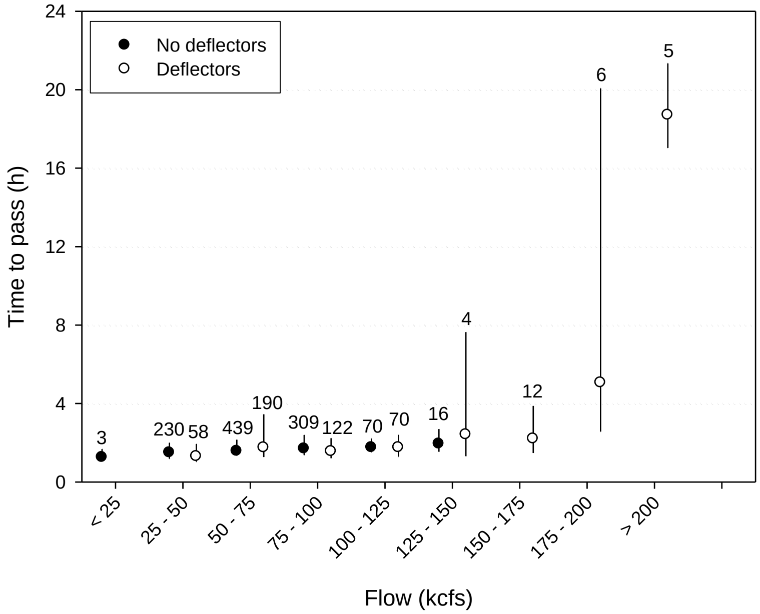

Figure 29. Median and quartiles of Chinook salmon passage times from tailrace entry to first recorded approach at a fishway entry. Categories are 25-kcfs intervals of total flow during the pre- and post-spillway deflector periods.

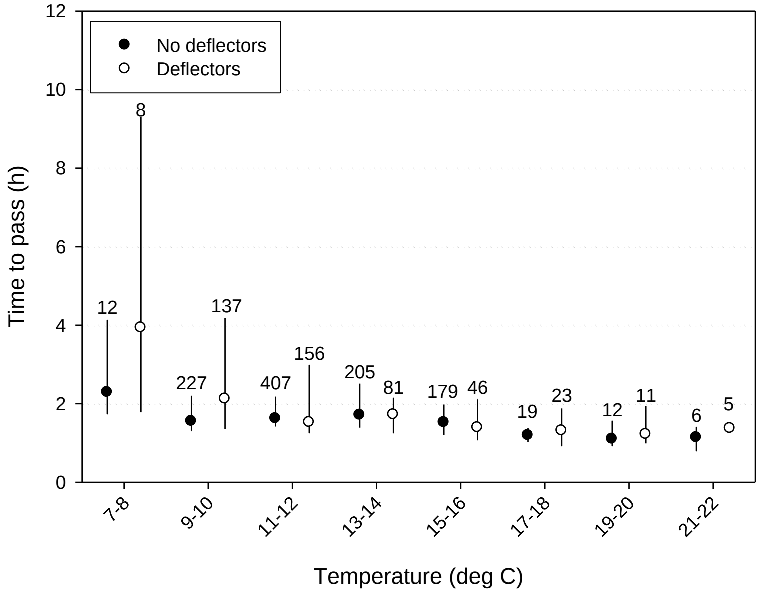

Figure 30. Median and quartiles of Chinook salmon passage times from tailrace entry to first recorded approach at a fishway entry. Categories are 2º C intervals during the pre- and post-spillway deflector periods.

Time from first approach to first enter a fishway. – Median passage times from the time of first fishway approach to the first recorded entry into a fishway ranged from 1.53 to 3.48 h across years (Table 10). Medians in the years after deflector installment included both the highest (3.48 h) and lowest (1.53 h) annual medians in the study. Overall, medians were lower for the pre-installment period (2.19 h) than the post-installment period (2.89 h) (Figure 31). Mean values (*range* = 3.52 to 14.59 h) were more variable, reflecting the right-skewed distributions. A 1-way ANOVA of $\log_e$ transformed times indicated passage times differed significantly among years ($df = 4$, $F = 13.65$, $P < 0.001$). Similarly, $\log_e$ transformed times differed by the fishway entrance first approached ($df = 2$, $F = 7.41$, $P < 0.001$), with longer times for those that first approached at the north-shore entrance (Figure 31). Salmon that first approached a fishway during night (1800-0600) passed more slowly that those that arrived during the day (0600-1800) ($df = 1$, $F = 13.39$, $P < 0.001$), (Figure 31). When only fish that first approached during days with spill were included, times were longer in the post-deflector period ($F = 4.71$, $P = 0.030$); times also differed by first fishway approach site (longest times for those that first approached the north-shore entrance, $F = 7.13$, $P < 0.001$). Those that first approached at night had passage times similar to those that first approached during the day ($F = 2.19$, $P = 0.140$).

Univariate linear regression models of the continuous variables flow, spill, and water temperature were also each significant ($P < 0.001$) with all fish included, though these variables explained only small percentages of the variance in $\log_e$ transformed tailrace to first fishway approach passage times ($0.01 \leq r^2 \leq 0.07$). Passage times tended to increase with flow and spill volume (Figures 32 and 33) and to decrease as temperatures increased (Figure 34). Results were similar when limited to fish that first approached during spill, except that flow was not significant ($P > 0.05$).

A multiple regression model that included all six independent variables explained about 12% of the variability in first fishway approach to first fishway entry passage times (Table 12). Temperature ($F = 107.11$) and spill ($F = 42.29$) explained the most variability, followed by time of day and first approach site. Notably, spill deflectors and flow were not significant ($P > 0.05$). Inclusion of interaction terms only modestly improved overall model fit (max $r^2 \sim 0.16$), and so these terms were excluded. Differences in passage times were not clearly related to the deflector ‘treatments’. During the post-deflector period, times tended to be longer for fish that first approached at low to moderate spill (< 30 kcfs) and at intermediate flow levels. Under most conditions, however, median passage times through this migration segment were similar with and without spill deflectors (Figures 32-34). Patterns were similar when only fish that approached on days with spill were included, except that time of day and temperature were not significant for the reduced sample.

In 1997, passage times from first fishway approach to first fishway entry were much longer than in any study year (*median* = 4.53 h, *mean* = 40.94 h, $n = 271$) (Appendix Table 1).

Table 11. Mean and median passage times for radio-tagged Chinook salmon from first approach at a fishway entrance to first fishway entry at Lower Monumental Dam. Estimates in italics are for fish that first approached a fishway during spill.

	Year	*n*	Mean	Median	% > 24 h
First approach - First entry	2000	232	10.39	2.74	12.9%
	2001	539	3.52	1.66	1.1%
	2002	365	5.36	2.68	3.8%
	Total	**1,136**	**5.51**	**2.19**	**4.4%**
	***Total*[1]**	***238***	***10.43***	***2.74***	***13.0%***
	2003	307	14.59	3.48	13.0%
	2004	152	4.63	1.53	3.3%
	Total	**459**	**11.29**	**2.89**	**9.8%**
	***Total*[1]**	***336***	***14.36***	***3.67***	***12.8%***

[1] fish that first approached a fishway during zero spill excluded

Table 12. Results of the general linear model (GLM): $\log_e$ (passage time from first fishway approach to first fishway entry) = flow + spill + temperature + time of day (day, night) + location of first approach (north-shore, south-powerhouse, south-shore) + deflector (yes, no) + error. All fish included.

Variable	*df*	Type III SS	MS	*F*	*P*
Deflector	1	8.45	8.45	2.73	0.099
Approach site	2	72.60	36.30	11.73	<0.001
Time of day	1	92.40	92.40	29.87	<0.001
Flow	1	1.54	1.54	0.50	0.481
Spill	1	130.85	130.85	42.29	<0.001
Temperature	1	331.39	331.39	107.11	<0.001
Model $r^2 = 0.12$; $F = 30.21$; $P < 0.001$					

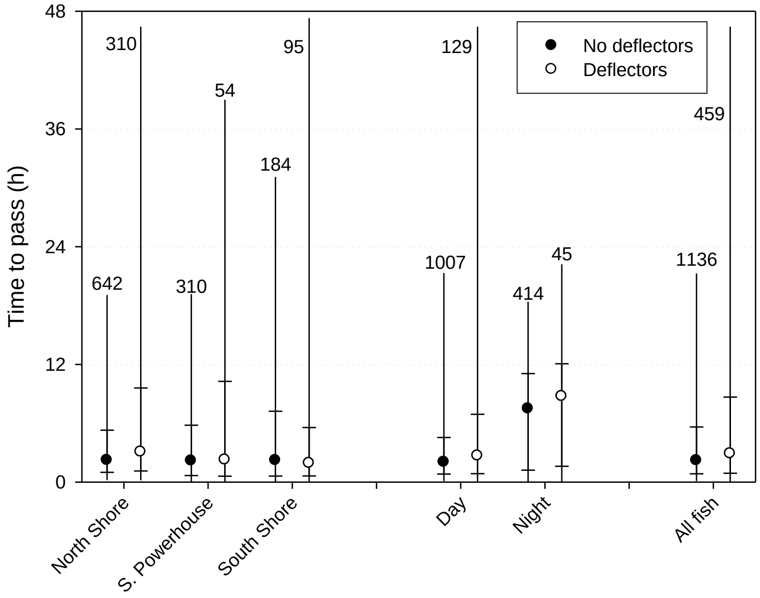

Figure 31. Median, quartile, and 5th and 95th percentiles of Chinook salmon passage times from first recorded fishway approach to first fishway entry. Categories are location of first approach, day vs. night, and all fish during the pre- and post-spillway deflector periods.

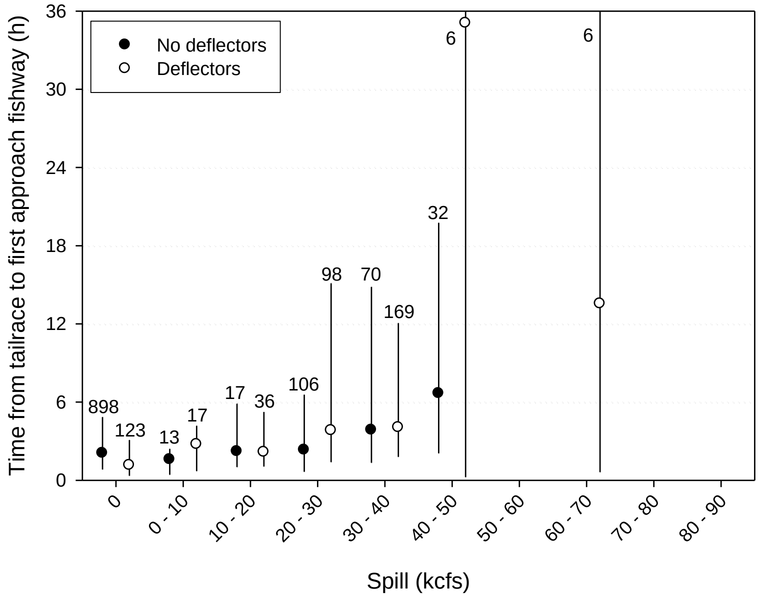

Figure 32. Median and quartiles of Chinook salmon passage times from first recorded fishway approach to first fishway entry. Categories are 10-kcfs intervals of spill during the pre- and post-spillway deflector periods.

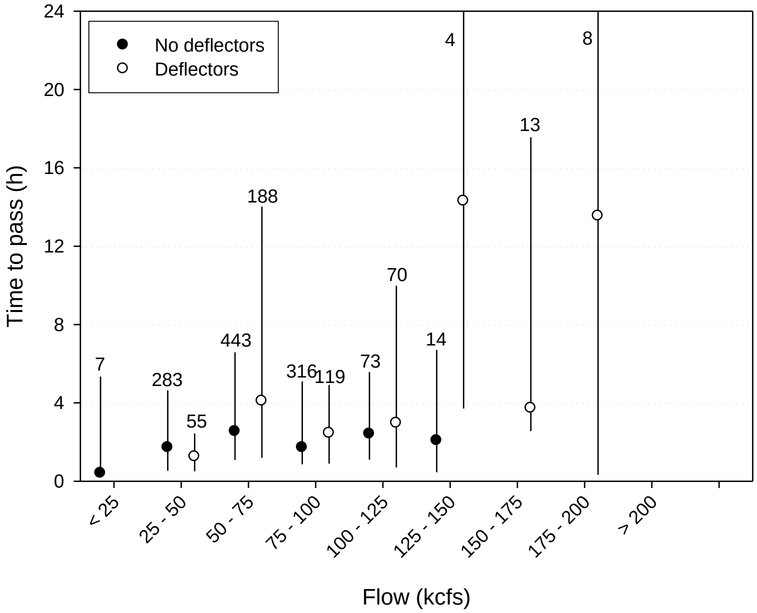

Figure 33. Median and quartiles of Chinook salmon passage times from first recorded fishway approach to first fishway entry. Categories are 25-kcfs intervals of total flow during the pre- and post-spillway deflector periods.

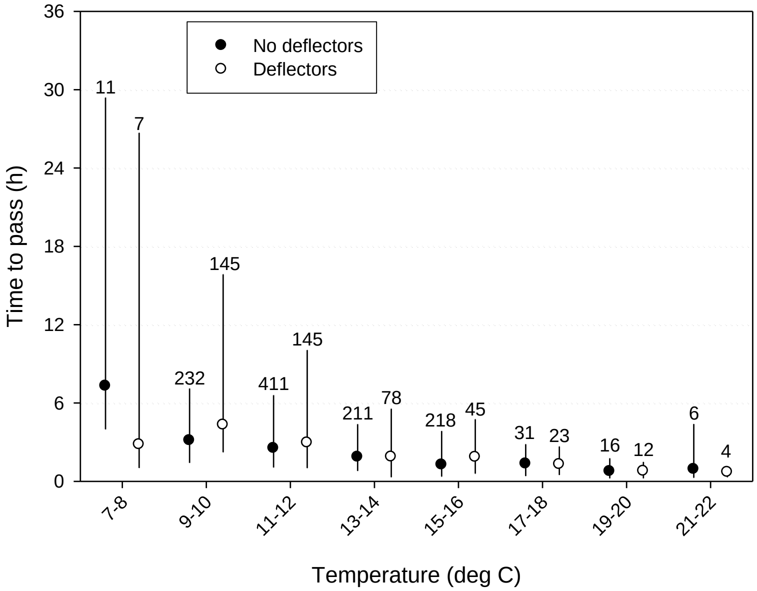

Figure 34. Median and quartiles of Chinook salmon passage times from first recorded fishway approach to first fishway entry. Categories are 2º C intervals during the pre- and post-spillway deflector periods.

Total time to pass dam. – Median full-dam passage times, from the time of first tailrace record to exit from the top of a fish ladder, ranged from 9.23 to 13.33 h across years (Table 13). Overall, medians were slightly lower for the post-deflector installment period (11.44 h) than the pre-installment period (11.88 h) (Figure 35). Mean values were more variable, and overall means were slightly longer in the post-installment period (Table 13). Log_e transformed times differed significantly among years ($df = 4$, $F = 11.31$, $P < 0.001$) and by the location of the first fishway entry (Figure 35), with longer times for those that first entered the south-shore entrance and shorter times for those that first entered at the north-shore entrance ($df = 2$, $F = 3.93$, $P = 0.020$). Fish that passed the dam via the south-shore ladder had longer passage times than those that passed via the north ladder ($df = 1$, $F = 6.03$, $P = 0.014$). In contrast, $\log_e$ transformed times did not differ by the fishway entrance first approached ($df = 2$, $F = 0.44$, $P = 0.646$).

Both the number of fishway approaches (Figure 36) and the number of fishway entries (Figure 35) per fish had relatively large effects on full-dam passage times. The number of approaches per fish ($\log_e$ transformed to improve normality) explained 29% of the variability in passage times ($r^2 = 0.29$, $F = 587.91$, $P < 0.001$). Log transformation did not produce normality for the number of fishway entries per fish, and a categorical variable was created instead (1 entry, 2-5 entries, > 5 entries). More fishway entries (and therefore exits back into the tailrace) was strongly associated with longer full-dam passage time ($df = 2$, $F = 57.21$, $P < 0.001$). Increasing numbers of fishway entries per fish was associated with warmer water temperatures (Figure 38), and was especially prevalent in 2001, the low-flow, no-spill year.

In contrast to other passage segments, full-dam passage times did not differ by arrival time (coded day vs. night) in the tailrace ($df = 1$, $F = 0.03$, $P = 0.863$). However, there was a clear pattern of longer (though still very variable) passage time for fish that arrived late in the day when time was treated as a continuous variable ($r^2 = 0.04$, $F = 68.61$, $P < 0.001$), indicating that most fish stopped upstream migration at the dam during darkness (Figure 37). The fastest passage tended to be by fish that entered the tailrace near sunrise.

Univariate linear regression models of the continuous variables flow, spill, and water temperature had mixed results. Passage times increased with increasing spill ($df = 1$, $F = 41.63$, $P < 0.001$, Figure 39), but not flow ($df = 1$, $F = 1.99$, $P = 0.159$, Figure 40). No linear relationship was observed for temperature ($df = 1$, $F = 0.02$, $P = 0.880$). However, passage times tended to be fastest at intermediate temperatures (Figure 41), and the relatively small numbers of fish that encountered temperatures > ~17º C had among the longest passage times. This likely was related to the higher numbers of fishway entries and exits by fish migrating at the warmer temperatures (Figure 38), and may indicate unattractive temperature conditions inside fishways. Nonetheless, none of these environmental variables explained much of the overall variability in full-dam passage times.

A multiple regression model that included all ten independent variables explained about 43% of the variability in full-dam passage times (Table 14). The number of fishway approaches ($F = 630.10$) and spill ($F = 145.33$) explained the most variability. Spill deflectors were not significant ($P = 0.47$). Inclusion of interaction terms only modestly improved overall model fit. Many predictor variables were at least partially correlated (e.g., flow and spill, entries and approaches). As a result, a reduced model that included only total approaches and spill also had comparable predictive power, with an $r^2 = 0.40$.

All of the above univariate and multiple regression models were also run for the reduced sample of those fish that entered the tailrace only during days with spill. In univariate models, spill deflectors, first approach site, first entry site, ladder passed, and temperature were all non-significant ($P > 0.05$). Significant variables included: the $\log_e$ of total fishway approaches ($df = 1$, $F = 276.34$, $P < 0.001$), spill ($df = 1$, $F = 43.62$, $P < 0.001$), the number of fishway entries ($df = 2$, $F = 20.17$, $P < 0.001$), and flow ($df = 1$, $F = 14.77$, $P < 0.001$). A multiple regression model that included all variables had an $r^2 = 0.47$; the number of fishway approaches, flow, and spill were most significant.

The median full-dam passage time in 1997 (23.77 h, $n = 289$) was almost double the medians for 2000-2004, and the 1997 mean (66.22 h) was about triple the means in 2000-2004 (Appendix Table 1). Tailrace and top-of-ladder antennas were also in place during the 1993 and 1998 spring–summer Chinook salmon migrations, and both the medians (18.00 h in 1993, 18.24 h in 1998) and means (30.75 h in 1993, 41.34 h in 1998) were longer than in 2000-2004 (Appendix Table 1). Figure 42 shows the full-dam passage times for all years (except 1993), as well as the greater variability and generally longer passage during high-flow conditions.

Table 13. Mean and median passage times for radio-tagged Chinook salmon from first tailrace record to exit from the top of a ladder at Lower Monumental Dam. Estimates in italics are for fish that first entered the tailrace during days with spill.

	Year	*n*	Mean	Median	% > 24 h
Tailrace - Pass dam	2000	216	22.40	12.85	29.2%
	2001	354	17.30	13.33	20.1%
	2002	372	15.47	10.95	12.9%
	Total	**942**	**17.75**	**11.88**	**19.3%**
	Total[1]	***227***	***21.91***	***12.59***	***28.6%***
	2003	297	23.77	12.69	23.2%
	2004	169	13.30	9.23	7.7%
	Total	**466**	**19.97**	**11.44**	**17.6%**
	Total[1]	***338***	***22.26***	***12.18***	***20.7%***

[1] fish that first entered the tailrace during zero spill excluded

Table 14. Results of the general linear model (GLM): $\log_e$ (passage time from tailrace entry to exit from a ladder) = flow + spill + temperature + time of day (day, night) + location of first approach (north-shore, south-powerhouse, south-shore) + location of first entry (north-shore, south-powerhouse, south-shore) + $\log_e$ (number of approaches) + number of entries (1, 2-5, >5) + deflector (yes, no) + error. All fish included.

Variable	*df*	Type III SS	MS	*F*	*P*
Deflector	1	0.16	0.16	0.52	0.472
First approach site	2	1.71	0.57	1.82	0.141
First entry site	2	4.86	1.62	5.19	0.001
Log$_e$ approaches	1	196.72	196.72	630.10	<0.001
Entries	2	10.87	5.43	17.41	<0.001
Ladder passed	1	1.82	1.82	5.82	0.016
Time of day	1	0.02	0.02	0.06	0.803
Flow	1	2.42	2.42	7.77	0.005
Spill	1	45.37	45.37	145.33	<0.001
Temperature	1	0.35	0.35	1.12	0.289
Model $r^2 = 0.40$; $F = 70.18$; $P < 0.001$					

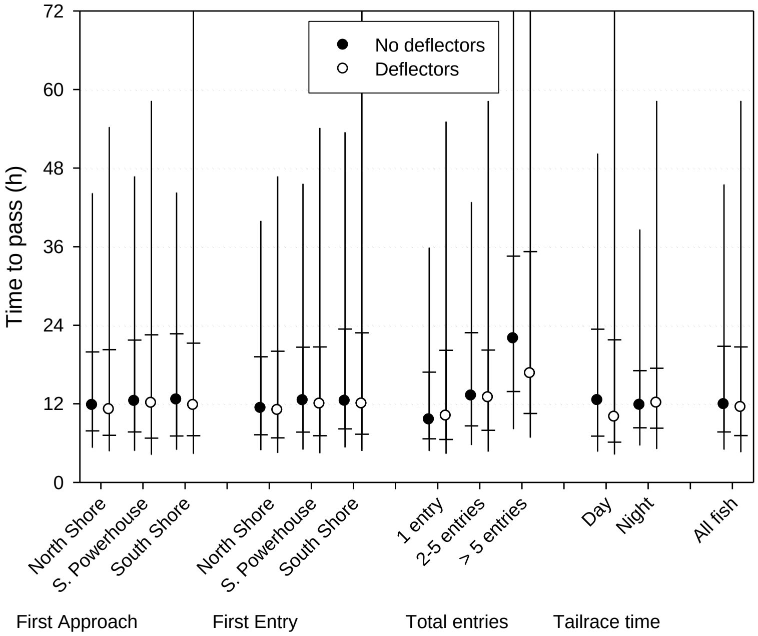

Figure 35. Median, quartile, and 5th and 95th percentiles of Chinook salmon passage times from tailrace entry to exit from the top of a fish ladder. Categories are location of first approach and entry, number of fishway entries, day vs. night, and all fish during the pre- and post-spillway deflector periods.

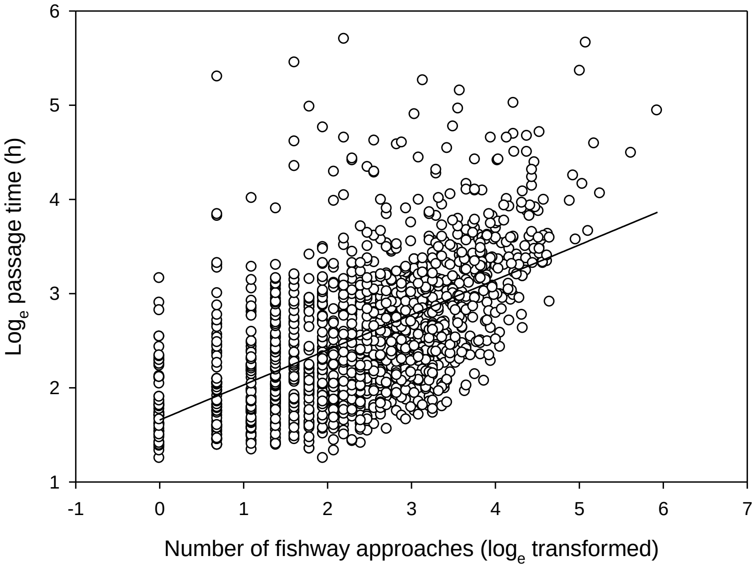

Figure 36. Log$_e$ transformed relationship between the number of fishway approaches and full-dam passage times at Lower Monumental Dam, 2000-2004.

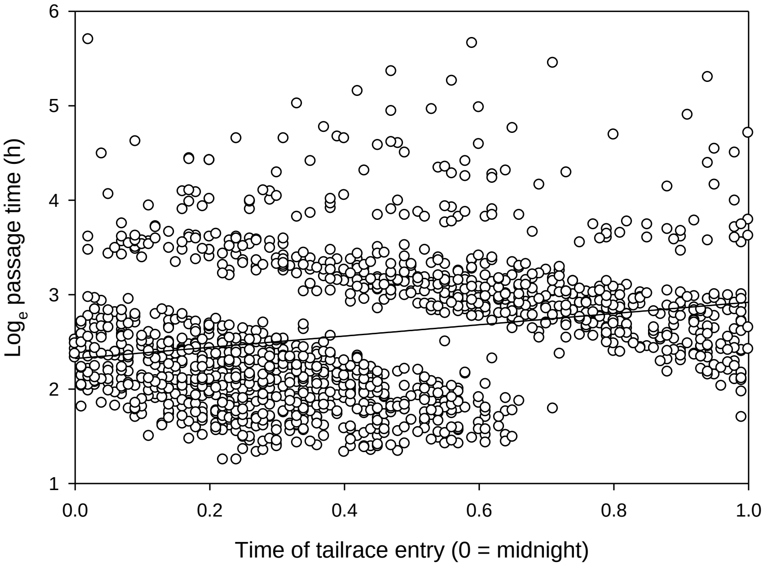

Figure 37. Relationship between the time of tailrace entry and $\log_e$ transformed full-dam passage times at Lower Monumental Dam, 2000-2004.

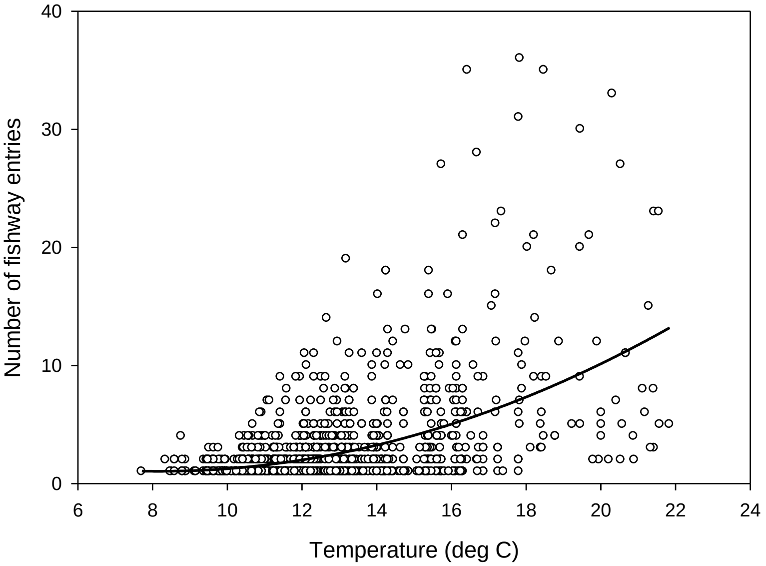

Figure 38. Relationship between water temperature at the time of tailrace entry and the number of fishway entries per salmon at Lower Monumental Dam, 2000-2004.

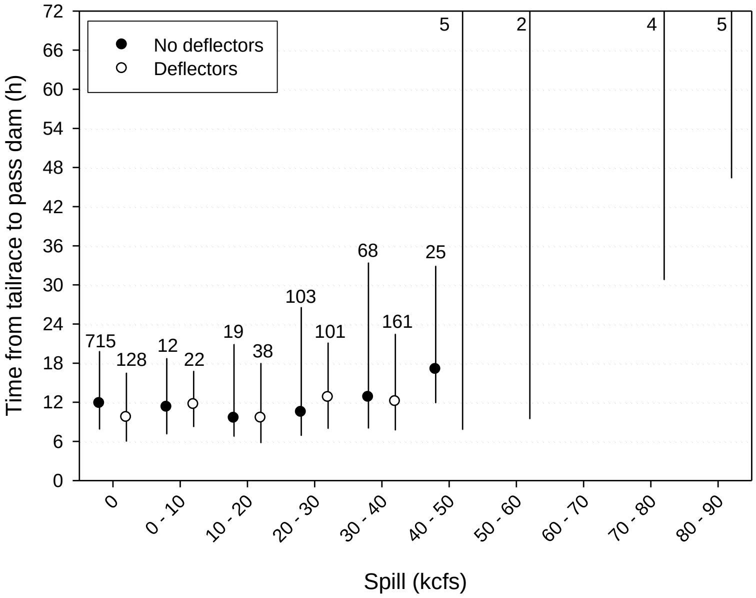

Figure 39. Median and quartiles of full-dam Chinook salmon passage times. Categories are 10-kcfs intervals of spill during the pre- and post-spillway deflector periods.

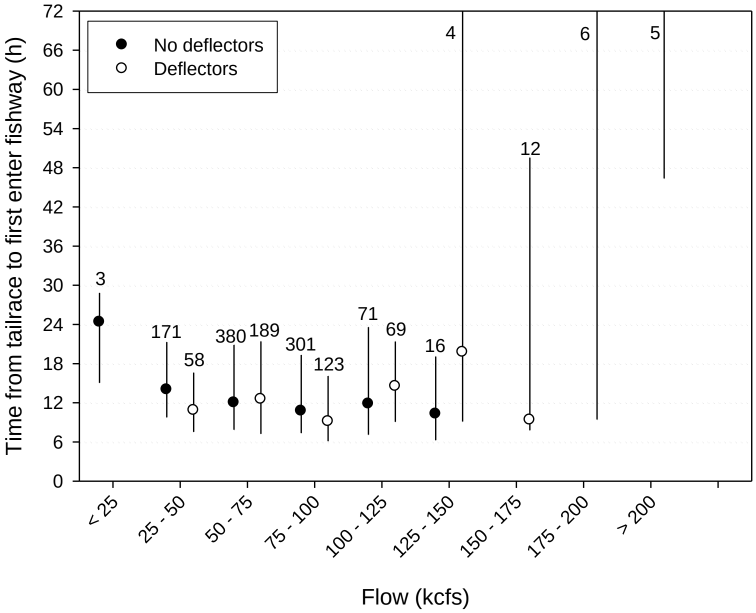

Figure 40. Median and quartiles of full-dam Chinook salmon passage times. Categories are 25-kcfs intervals of total flow during the pre- and post-spillway deflector periods.

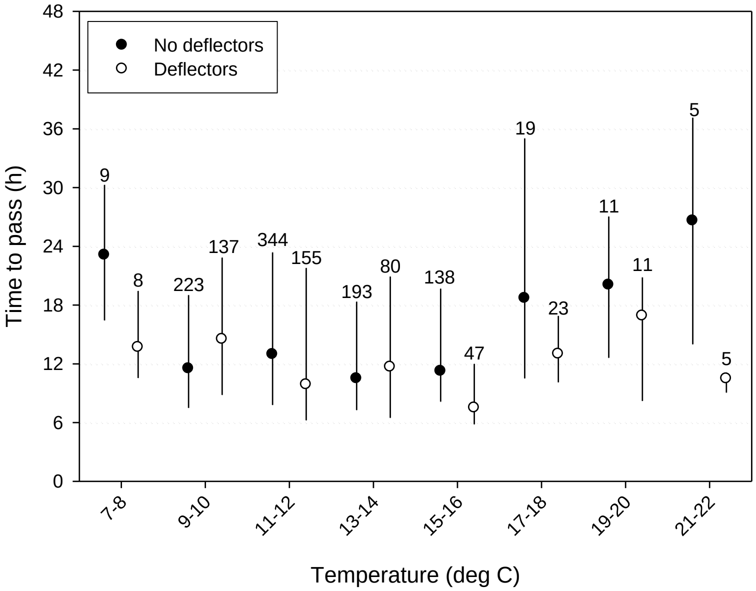

Figure 41. Median and quartiles of full-dam Chinook salmon passage times. Categories are 2 ºC intervals of water temperature during the pre- and post-spillway deflector periods.

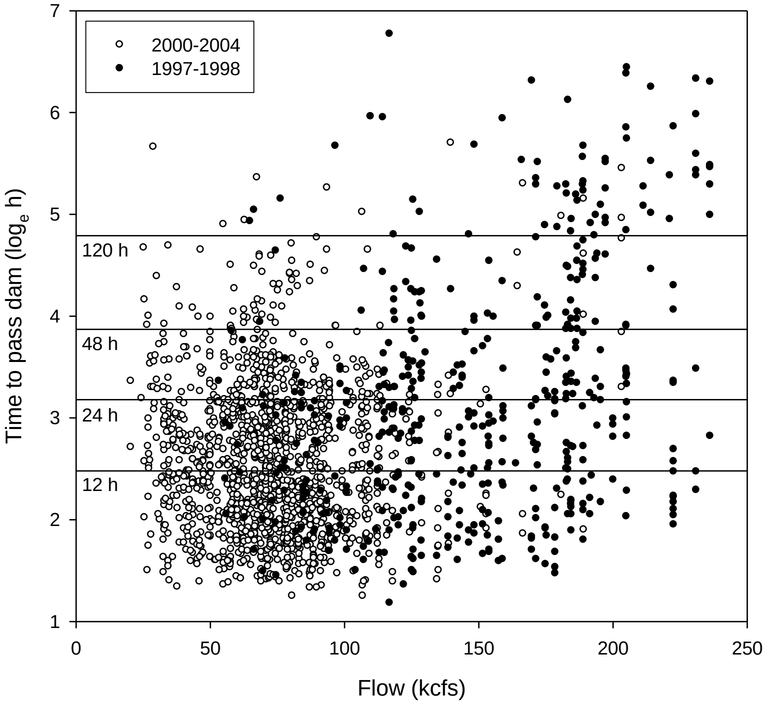

Figure 42. Relationship between mean daily flow at the time of tailrace entry and $\log_e$ transformed full-dam passage times for spring–summer Chinook salmon at Lower Monumental Dam, 1997-1998 (*n* = 483) and 2000-2004 (*n* = 1,408).

Discussion

Passage times. -- Most radio-tagged spring–summer Chinook salmon efficiently passed Lower Monumental Dam during the five study years. About half the fish in the sample passed the dam in 12 hours or less, and more than 80% passed in less than 24 hours. In general, full-dam passage times reported here were comparable to those for spring–summer Chinook salmon at other lower Snake River dams from 1996-2001 and were faster than passage times recorded at Bonneville, The Dalles, and John Day dams (Keefer et al. 2003a; 2004a; *in review* a,b,c).

As at most other studied dams, adult Chinook salmon took longer to pass Lower Monumental Dam when they arrived in the tailrace late in the day or at night, and if they approached fishways or entered and exited fishways multiple times. The diel pattern is consistent with many observations that adult salmonids stop or slow migration in turbulent or confusing environments during darkness (e.g., Naughton et al. 2005). We have also observed longer passage following fishway exit to the tailrace for all runs and at all of the dams studied in the adult radiotelemetry project. In general, most additional passage time accrues in the tailrace or further downstream after fish exit fishways, and relatively little time is spent inside fishways (see Burke et al. 2005). Time spent in tailrace areas can be energetically expensive (Brown et al. 2002), and reducing fishway fallout would both reduce passage times and theoretically be less costly for upstream migrants.

Increasing flow and spill were also associated with longer full-dam passage times, though these environmental data were only weakly correlated with individual fish passage times. Low correlations may have been due, at least in part, to the substantial variability associated with diel patterns and fishway behaviors. These factors may mask the effects of environmental variables, particularly in these years when flow and spill were at or below average for the majority of the study. There is evidence, however, that higher flow/spill can have a larger effect on salmon passage times at Lower Monumental Dam. Data for spring–summer Chinook salmon tagged in 1993 (Bjornn et al. 1995) and 1997-1998, three years with higher flow and spill than the study years evaluated here, indicated much greater variability in passage times as well as longer mean and median times at high flow. Full-dam passage times in 1993 and 1997-1998 were substantially longer than in 2000-2004, and we doubt that open orifice gates in earlier years account for the differences. High flow and spill create greater turbulence, perhaps making it more difficult for adults to locate and enter fishways. Alternately, the higher turbidity and tailwater elevations associated with high flows may present confusing cues to adults. High tailwater elevations inundate the lower fishways and transition pools, potentially changing hydraulic conditions and reducing attraction flows through submerged orifices. This type of passage ‘delay’ mechanism appears to occur at Bonneville Dam’s Washington-shore fishway (Keefer et al. *in review* a) and possibly other sites. At Lower Monumental Dam, passage times during the period of highest flow (180-200 kcfs) and spill (50-80 kcfs) in this study (late May 2003) were among the longest recorded during 2000-2004. Spill from the end spillbays was periodically 10-15 kcfs during this time, the highest reported levels for 2003-2004.

The effects of water temperature on full-dam passage times were somewhat mixed, and were difficult to separate from flow, spill, and fish passage behaviors. Passage was most efficient (rapid) at moderate temperatures, with slower full-dam passage at both low and high temperatures. The number of fish ‘delayed’ at higher temperatures was relatively small because most fish had already passed the dam by the time water temperatures exceeded about 17º C. In similar findings, Peery et al. (2003) reported delayed migration timing and slower passage times for adult salmon and steelhead through the lower Snake River at higher temperatures. In the current results, later migrants (mostly summer-run fish) were much more likely to enter and exit fishways multiple times, and this behavior was associated with longer passage times. Multiple-entry behavior is consistent with fish behaviors we have observed at other dams at higher temperatures, and appears to occur when fishway temperatures exceed those of the tailwater (Keefer et al. 2003b; Caudill et al. *in review*). The multiple-entry behavior at Lower Monumental Dam may counteract the more general pattern we have observed of faster passage for spring–summer Chinook salmon as water temperatures increase (Keefer et al. 2004a; 2004d). The ‘delays’ associated with high temperatures in this study typically occurred during periods of zero spill and low flow and it is possible that a combination of temperature and other conditions (including fish condition) produced the recorded behaviors.

Passage times in the tailrace section of the dam, both from first tailrace entry to first fishway approach and from first approach to first fishway entry, tended to decrease as water temperature increased. This is consistent with observations at other dams and with other species. Times through these sections also tended to be longer during higher flow and spill conditions, though again variability was quite high and correlations were low. Where fish first approached or first entered a fishway did affect passage times. Salmon that first approached at the south-shore entrance tended to have longer times to first approach, perhaps because some of these fish were directly exposed to turbulent conditions from the spillway. In contrast, those that first entered the north-shore entrance had longer passage times between first approach and first entry. This may have been related to the proportions of fish crossing the tailrace between first approach and first entry, or to the number of approaches per entry, which were higher at the north-shore entrance than at the south-shore entrance.

Fishway use patterns. -- Where fish approached and entered fishways varied among years, and differences in use patterns were at least partially related to environmental conditions. Fish favored the north-shore entrance as a first approach site, while overall the south-powerhouse entrance was approached most. Fish were more likely to approach at the north-shore entrance when spill was low, more likely to approach the south-powerhouse entrance when flow was low, and more likely to approach the south-shore entrance when flow was high.

The most-used location for first fishway entries differed in almost each year. Generally, salmon were less likely to enter the south-shore entrance at zero spill, perhaps because there was relatively little attraction flow to that side of the river under zero-spill conditions. Discharge from the powerhouse would tend to draw fish towards the north-shore entrance, and possibly the south-powerhouse entrance. Use of the south-shore as an entrance site increased with spill, particularly in 2003-2004. In all years, use of the north-shore entrance decreased as flow increased, again likely reflecting the greater attraction flows to the south-shore and south-powerhouse when flow and spill were higher.

Ratios of fishway approaches to fishway entries were quite variable across years and entrance sites. Ratios were highest in 2003, the year with the period of highest spill and flow. The south-powerhouse entrance appeared to be the least efficient at passing fish, as measured by approach:entry ratios. With the exception of 2004, ratios were 13-25 approaches per entry for this site in each year, and were considerably higher than that during periods of spill. The general pattern at the south-powerhouse entrance suggests that conditions near this site may be less attractive for adult Chinook salmon than at other entrances. It is possible that turbulence from the spillway makes it more difficult to locate this entrance, despite the concrete wall that separates the fishway from the spill basin. Detection ranges for the underwater antennas located on the outside of fishway entrances are typically < 10 m, and it is possible that fish following attraction flows along the current seam downstream from the wall were detected as they neared the wall's end. In any case, the telemetry data clearly suggest that the south-powerhouse is a relatively difficult entry site, particularly during high flow/spill conditions.

In contrast, approach:entry ratios at the south-shore entrance changed little as flow and spill increased. The size and discharge from the south-shore site may make this entrance easier for adult fish to enter. It is also possible that the south-shore entrance has fewer negative effects from spill, perhaps because turbulence patterns in the entrance vicinity are less confusing. The north-shore entrance should be relatively unaffected by spill levels. However, approach:entry ratios did fluctuate at this site, and were typically higher during higher flow/spill conditions. From the telemetry data alone, it is not clear what the mechanism for variable ratios at this site is, though discharge patterns from the powerhouse are a possible factor. To better understand the observed behaviors at these sites, further evaluation of the hydraulic conditions near all fishway entrances—and especially the south-powerhouse entrance—is recommended.

Effects of spillway deflectors. -- The principal challenge in our retrospective analyses of how the installation of spillway deflectors affected adult salmon passage was identifying periods with similar background environmental conditions in pre- and post-installation years. In terms of spillway discharge, the 2002 and 2004 migrations were each characterized by relatively limited spill, but only a few days in late May and early June were similar enough for good between-year comparisons and sample sizes of radio-tagged fish were quite small on these days. Spill conditions were more similar throughout the 2000 and 2003 migrations, but flow patterns in these years were considerably different (high peak flows in late May-early June of 2003 versus moderate but extended peak flows in April of 2000). Given these patterns, we visually examined behaviors using groups of fish that encountered similar environmental (e.g., flow, spill, temperature) conditions before and after deflector installation. We also used multiple regression models that included spill deflectors as a 'treatment' variable. Most of these analyses indicated that spill deflectors likely had a relatively limited effect on spring–summer Chinook salmon behaviors at the dam, though among-year environmental variability across years may have masked some potential effects.

One behavioral difference that did appear to be related to the installation of spill deflectors, was the distribution of where salmon approached Lower Monumental Dam. After installation, there was a shift away from the south-powerhouse entrance toward the north-shore entrance, and this shift appeared to be consistent across flow and spill conditions. Notably, however, some measures of fishway use indicated that this shift occurred even during periods of zero spill, suggesting some effect other than spillway deflectors. In contrast to patterns of fishway approaches, the distribution of fishway entries appeared to be relatively unaffected by the installation. There was some evidence that more fish entered at the south-shore entrance during higher flow conditions, but this seems more likely to be related to increased attraction flows than to the effects of deflectors per se.

Ratios of approaches to entries were higher in the post-deflector years, especially at the south-powerhouse and north-shore entrances during higher spill. It is possible that increased ratios at the south-powerhouse entrance were a response to the deflector installation, but the fact that ratios similarly increased at the north-shore entrance raises some doubt. Ratios were consistent at the south-shore entrance with and without spillway deflectors. There was also some limited evidence that salmon were less likely to use the south ladder after deflector installation during periods of spill, but again this may have been related more to general environmental conditions than to the deflectors.

In almost all multivariate analyses, the presence/absence of spill deflectors was at best a minor explanatory variable, while flow, spill, temperature, and especially fish behaviors (numbers of entries and approaches) were considerably more predictive. Tailrace passage times (from first tailrace record to approach a fishway) and full-dam passage times (tailrace to exit from the top of a ladder) were similar under most conditions pre-and post-installation. Times to pass from first approach to first fishway entry were longer in the post-installation years, but multiple regression results suggest this pattern was largely a function of environmental conditions. It is plausible that spillway deflectors altered the distribution of approaches as well as the ratio of approaches to entries, but if so, these changes did not result in longer passage times.

In conclusion, it is possible that spillway deflectors may adversely affect adult fish passage behaviors at some threshold spill level. As has been suggested by hydraulic modeling by the USACE, prohibitively turbulent conditions may develop at high spill near the fishway entrances adjacent to the spillway. During 2000-2004, however, spill was only rarely greater than 40 kcfs, and difficult passage conditions did not appear to be a widespread problem for Chinook salmon at and below these levels. Future evaluations in years with higher flow and spill would help identify if adverse conditions develop at some threshold levels.

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Appendix

Appendix Table 1. Mean and median passage times for spring–summer Chinook salmon at Lower Monumental Dam in 1993, 1997 and 1998. Orifice gates were open and unmonitored in 1997. Only tailrace and top-of-ladder sites were monitored in 1998. 1993 data from Bjornn et al. 1995.

	Year	*n*	Mean	Median	% > 24 h
Tailrace - First approach	1993	277	4.32	1.92	n/a
	1997	302	8.67	3.09	5.6%
	1998	n/a	n/a	n/a	n/a
First approach - First entry	1997	271	40.94	4.53	31.0%
	1998	n/a	n/a	n/a	n/a
Tailrace - Pass dam	1993	281	30.75	18.00	n/a
	1997	289	66.22	23.77	49.1%
	1998	194	41.34	18.24	37.6%