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Fish Ecology Division

Northwest Fisheries Science Center

National Marine Fisheries Service

Seattle, Washington

by
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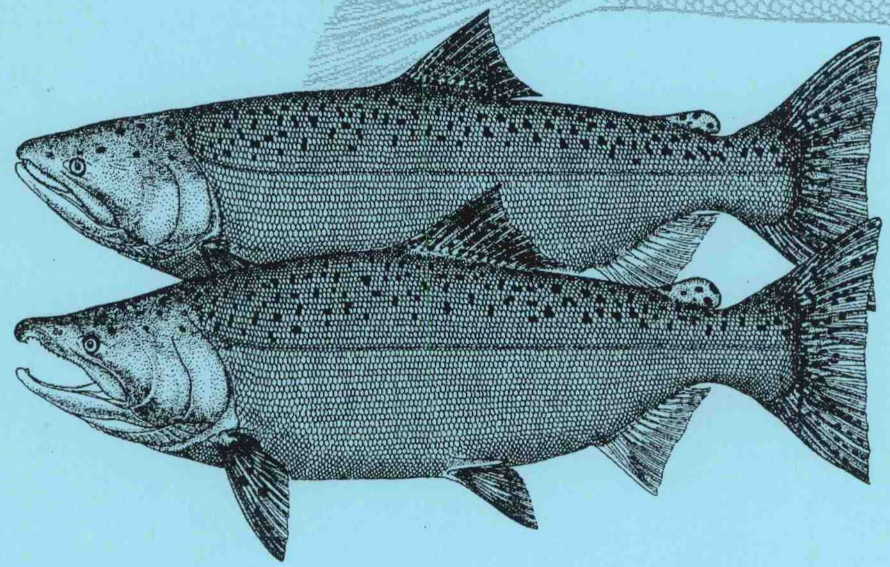
May 2008



Adult Fall Chinook Salmon Passage through Fishways at Lower Columbia River Dams, 2002-2005

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Projects ADS-00-1 through 5 and ADS-00-12

May 2008

EXECUTIVE SUMMARY

Radiotelemetry tags were gastrically implanted in fall Chinook salmon *Oncorhynchus tshawytscha* to examine behavior trends at hydropower dams from 2002 to 2005. Movements were monitored as fish migrated upstream using radiotelemetry receivers placed along the Columbia River, at the mouths of most tributaries, and throughout fishways at four lower Columbia River dams (Bonneville, The Dalles, John Day, and McNary Dams). Results were examined for interannual and interdam differences, and compared to fall Chinook salmon movements from previous years (Burke et al. 2005). Striking consistencies in fish behavior at individual dams were observed between years.

Passage efficiency at dams on the lower Columbia River ranged from 89.3 to 97.3% during the four years and was relatively stable through time. Similarly, differences in dam passage durations were greater among dams than among years (medians ranged from 12 to 23.5 h across all dams and years). Fish passed McNary Dam more quickly than the other dams in each year, though between dam comparisons are tricky due to the unique structure design and receiver configuration at each project. While fishway use patterns were dam-specific, strong preferences were observed for individual fishways at each dam (like the John Day Dam south fishway). Entrance efficiencies ranged from 66.5 to 96.5%. Once fish entered a fishway, it was generally used for a passage attempt, except at McNary Dam where fish approached and entered primarily at the south ladder, but often abandoned it and later used the for north ladder.

When time at the dam was analyzed by segment, fall Chinook salmon appeared to spend the majority of their time in the tailrace and at the base of the dams, and this occurred both before and after making attempts to pass the dam. Within fishways fish spent the most time in ladders. Total time spent in the collection channel and transition pool segments was relatively low, but these areas were common turn-around points for fish that failed to pass a dam. Turn-arounds were observed in all segments of the fishways at each dam examined. However, the median number of attempts made at a segment was consistently low. Fish at John Day Dam made the most turn-arounds prior to dam passage.

Fallback rates varied among dams and ranged from 7.0 to 10.5% of the fish that passed. Most fallback events occurred more than 24 h after fish had cleared the dams, supporting volitional returns rather than unintentional fallbacks. However, for fallbacks within 24 h of passage, the rate was often dependent on the fishway used to ascend, particularly at The Dalles and John Day Dams.

CONTENTS

INTRODUCTION

An important aspect of the adult Pacific salmonid *Oncorhynchus* spp. radiotelemetry research project is describing how fish move past dams in the lower Columbia and Snake Rivers. Monitoring the fishway entrance use and movements within the fishways of adult salmon and steelhead at all four of the lower Snake River dams began in spring 1993 and continued through 1994. Antennas connected to SRX/DSP receivers were placed near entrances to fishways, within fishways, and at the top of the ladders at these dams. Coverage was later expanded to include the four dams on the lower Columbia River, major tributary mouths, and some passage routes at dams in the middle Columbia River.

With this telemetry system, we monitored movements of individual radio-tagged fish as they approached entrances to fishways, and identified fishway openings used by fish to enter and exit. We also documented movements within fishways, and assessed the time required for fish to pass the dams. Radiotelemetry has also allowed documentation of system-wide timing and movements (Keefer et al. 2004), fishway use and passage in years prior to 1998, and for other runs and species (Bjornn et al. 1995, 1998a, Keefer et al. 2003a, and Naughton et al. (2005)). Detailed information on fishway use and passage for fall Chinook in 1998 through 2001 was reported by Burke et al. (2005). The study described here continues these analyses and compares results obtained in 2002 to 2005 to results in Burke et al. (2005).

The objectives relating to the movement of fall Chinook salmon tagged from 2002 through 2005 included, but were not limited to, monitoring fishway entrance use, measuring movements and turn-arounds in the fishways, examining delay and passage times at lower Columbia and Snake River dams, and determining routes and rates of fallback events.

TAGGING METHODS

Fall Chinook salmon (mean length = 81.5 cm, range 51 to 109.5 cm; Figure 1) were collected in the Washington shore adult fish facility (AFF) at Bonneville Dam on the mainstem Columbia River (river kilometer (rkm) 235.1; Table 1). Here, they were outfitted with radio transmitters via intragastric insertion (Mellas and Haynes 1985). Sampling started in early August and ran into October, and coincided with the fall Chinook run (Table 1; Figure 2). The median size and length distribution of fish tagged in 2003 and 2004 were similar to previous years (Burke et al. 2005); fish tagged in 2002 and 2005 were slightly smaller. The number of fish tagged on each day was roughly proportionate to their abundance based on longer-term averages of run size (Figure 2). To maximize sample sizes across the lower Columbia River hydropower projects, upriver bright fall Chinook were selected when possible. In general, tules, fish that spawn in tributaries of the lower Columbia River, were not selected.

Fixed Lotek[1] SRX receivers detected radio-tagged fish in and around dam structures at each of the four lower Columbia River dams. These receivers were used to determine when a fish approached a dam, entered a fishway, moved within the fishway, and exited the fishway (See Appendix for dam-specific maps of antenna locations). Bjornn et al. (2000) and Keefer et al. (2004) provide a detailed description of tagging and monitoring methods used throughout the basin. Methods and results for individual analyses in this report are given in the following sections.

Table 1. Number of fish released above and below Bonneville Dam (BO) and dates of release in each year.

	2002 1 Aug-15 Oct	2003 1 Aug-15 Oct	2004 17 Aug-3 Oct	2005 24 Aug-1 Oct
Total Number Tagged	1066	666	606	600
Released Downstream of BO	755	665	571	0
Released into BO ladder	1	1	35	600
Released Upstream of BO	310	0	0	0

[1] Use of trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

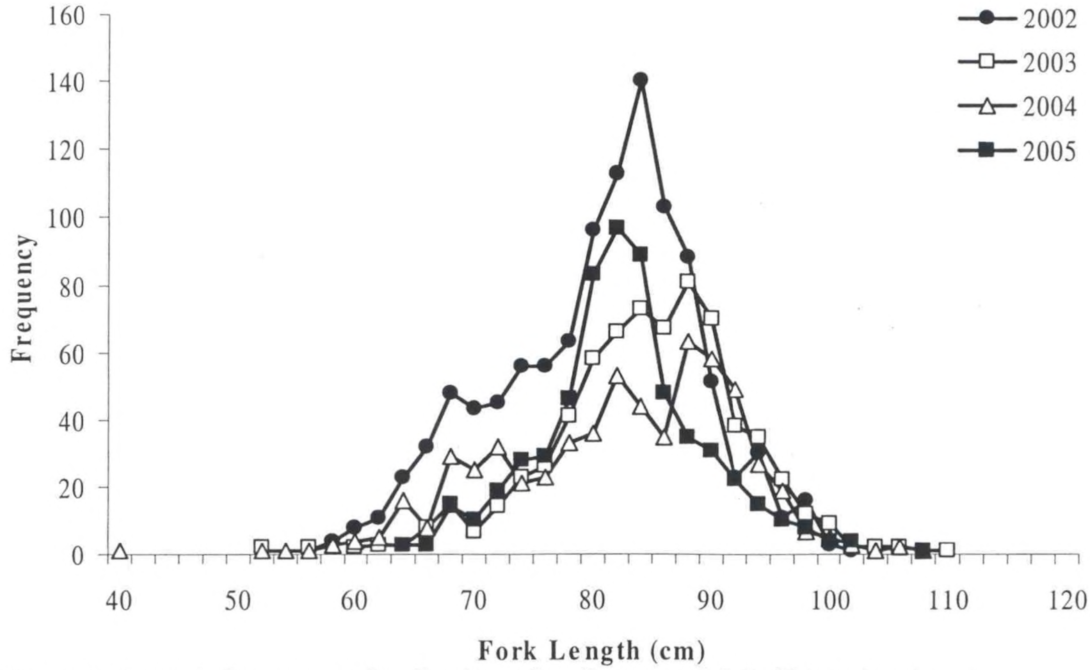


Figure 1. Length frequency distribution of radio-tagged fall Chinook salmon.

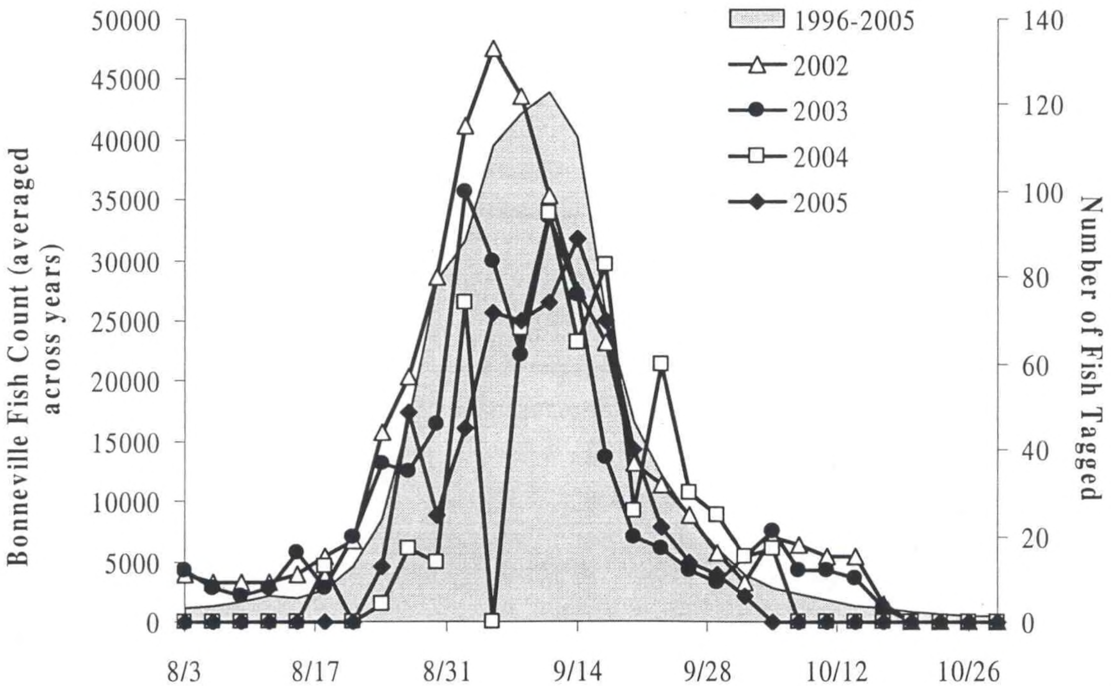


Figure 2. Average count of fall Chinook salmon at Bonneville Dam from 1996 to 2005 and the number radio-tagged fish (summed over 3 day intervals) in our study.

PASSAGE EFFICIENCY

Methods

Passage efficiency was defined as the number of fish passing a dam divided by the number of fish that had an opportunity to pass. The opportunity to pass was determined two ways: 1) using all fish that were detected at the dam, and 2) using only fish that entered a fishway at that dam. Fish released directly into the ladder system or upstream from a given dam (primarily occurring at Bonneville Dam) were excluded from the passage efficiency analysis at that dam. Passage efficiency was calculated for each of the four lower Columbia River dams.

Increased energy expenditure and reduced escapement to spawning grounds can result from fallback events at dams (Boggs et al. 2003). We indirectly tracked fallbacks, which were identified by detections downstream from a dam that occurred after a fish passed that dam. For fish that fell back at a dam, we only included records occurring before the fallback event in our analysis of dam passage time and passage efficiency. We also calculated passage efficiency on subsequent attempts for those fish that fell back over a dam, including only records occurring after the fallback event in this analysis.

Results

Passage efficiency (before fallback) for fish detected anywhere at these four dams in 2002 through 2005 ranged from 89.3 to 97.3% (Table 2). Using only fish that entered a fishway, passage efficiency increased to between 91.8 and 99.4%. As in past years (Burke et al. 2005), passage efficiency at John Day Dam was slightly different in both magnitude and variability from the other three lower Columbia River dams. At John Day Dam, passage efficiency was variable among years and increased monotonically from 2002 to 2005. It should be noted however, that passage efficiency at John Day Dam in 2001, a low-flow year, was greater than 3 of the 4 years reported here (excepting 2005, which had the lowest flow of this study period). At Bonneville, The Dalles, and McNary Dams, passage efficiency (for fish detected anywhere at the dam) differed relatively little between years, and did not provide evidence of clear trends. The passage efficiencies for each dam in these years are similar to those reported in Burke et al. (2005). However, passage efficiency was generally higher at The Dalles Dam in 2002-2005.

Successful dam passage on attempts following fallback events (reascension rates) was much lower than passage efficiencies of fish making their first ascent. Rates ranged from 11.1% at John Day Dam (2005) to 52.9% at The Dalles Dam (2005) for fish detected anywhere at the dam. However, once fish re-entered a fishway on subsequent attempts, their passage efficiencies were higher in all cases (although sample sizes were very low) and approached those of first passage attempts. While passage efficiency after fallback was generally higher for fish that entered a fishway, passage efficiency was still notably low at McNary Dam in 2002. Low passage efficiency after fallback was also seen at John Day Dam in previous years (Burke et al. 2005), but was not apparent between 2002 and 2005. See Boggs et al. (2004) for additional information on reascension rates.

Table 2. Passage efficiency at Bonneville (BON), The Dalles (TDD), John Day (JDD), and McNary (MCN) Dams. The first panel represents passage efficiency before any fallback events; the second represents passage efficiency after a fallback.

	Number of fish															
	2002				2003				2004				2005			
	BON	TDD	JDD	MCN	BON	TDD	JDD	MCN	BON	TDD	JDD	MCN	BON	TDD	JDD	MCN
Before Fallback																
Released below dam	755	1066	1066	1066	665	666	666	666	571	606	606	606	0	600	600	600
Recorded at dam[a]	718	815	638	487	618	482	391	301	526	452	387	292	0	464	367	272
Recorded approaching dam	697	792	627	483	603	468	384	297	512	441	382	288	0	444	363	270
Recorded entering fishway	687	780	621	482	594	464	376	296	507	435	375	285	0	434	356	269
Number passed	676	744	570	479	583	453	350	293	496	426	349	275	0	420	342	263
Passage Efficiency[a]	*94.2*	*91.3*	*89.3*	*98.4*	*94.3*	*94.0*	*89.5*	*97.3*	*94.3*	*94.2*	*90.2*	*94.2*	*0.0*	*90.5*	*93.2*	*96.7*
Passage Efficiencyb[b]	*98.4*	*95.4*	*91.8*	*99.4*	*98.1*	*97.6*	*93.1*	*99.0*	*97.8*	*97.9*	*93.1*	*96.5*	*0.0*	*96.8*	*96.1*	*97.8*
After Fallback																
Released below dam	28	66	10	17	23	43	7	8	18	40	11	6	0	23	10	2
Recorded at dam[a]	28	62	9	16	23	40	7	7	18	40	10	5	0	17	9	2
Recorded approaching dam	21	29	5	10	14	14	1	3	10	18	4	1	0	9	4	1
Recorded entering fishway	16	28	5	8	9	13	1	3	6	16	4	1	0	9	1	1
Number passed	14	25	3	3	6	11	1	2	6	12	3	1	0	9	1	1
Passage Efficiency[a]	*50.0*	*40.3*	*33.3*	*18.8*	*26.1*	*27.5*	*14.3*	*28.6*	*33.3*	*30.0*	*30.0*	*20.0*	*0.0*	*52.9*	*11.1*	*50.0*
Passage Efficiency[b]	*87.5*	*89.3*	*60.0*	*37.5*	*66.7*	*84.6*	*100*	*66.7*	*100*	*75.0*	*75.0*	*100*	*0.0*	*100*	*100*	*100*

[a] detected anywhere
[b] fish that entered

PASSAGE DURATION

Methods

For passage duration calculations, we defined the timing of three events for each fish released at sites downstream from each dam:

1) Arrival in the tailrace area: the first detection of a fish at a tailrace receiver (located 1.8 and 3.2 km downstream from each dam).
2) First entrance into a fishway: the first detection at a receiver just inside a fishway entrance.
3) Dam passage: the last detection at the top of a ladder.

Using these data, we calculated the time from arrival in the tailrace to first entrance, the time from first entrance to dam passage, and the total passage time from arrival in the tailrace to dam passage. Some fish were not detected at one or more of these endpoints and were not included in this analysis.

The same passage metrics were calculated for fish that fell back over a dam to determine whether fish performed differently on their second ascension. In the case of fish with multiple fallbacks, only the data recorded during the first re-ascension were used in this analysis.

Results

As in fall Chinook monitored in 1998–2001 (Burke et al. 2005), a distinct diel effect was apparent in the passage duration data. Techniques are available to elucidate these diel trends (Moser et al. 2004; Naughton et al. 2005; Caudill et al. *In Press*), though in-depth analyses of timing are beyond the scope of this report. However, diel trends are even evident in simple counts of coded records (Figure 3). Since a coded record is always the first of a block of records at a particular site (for a given fish), the timing of coded records usually represents arrival at a particular area, and therefore indicates fish movement. Timing of coded records clearly indicated that most salmon activity occurred between 0600 and 1800 hours (daylight). Most behaviors we monitored occurred during the day, though arrival and departure from the areas downstream of the dam (F1 and L1 in Figure 3) comprised a larger proportion of the nighttime movements we observed. Passage events (denoted by LT, or last top) were notably absent during the early morning hours, but continued later into the night than other behaviors as fish pushed to ascend the dams.

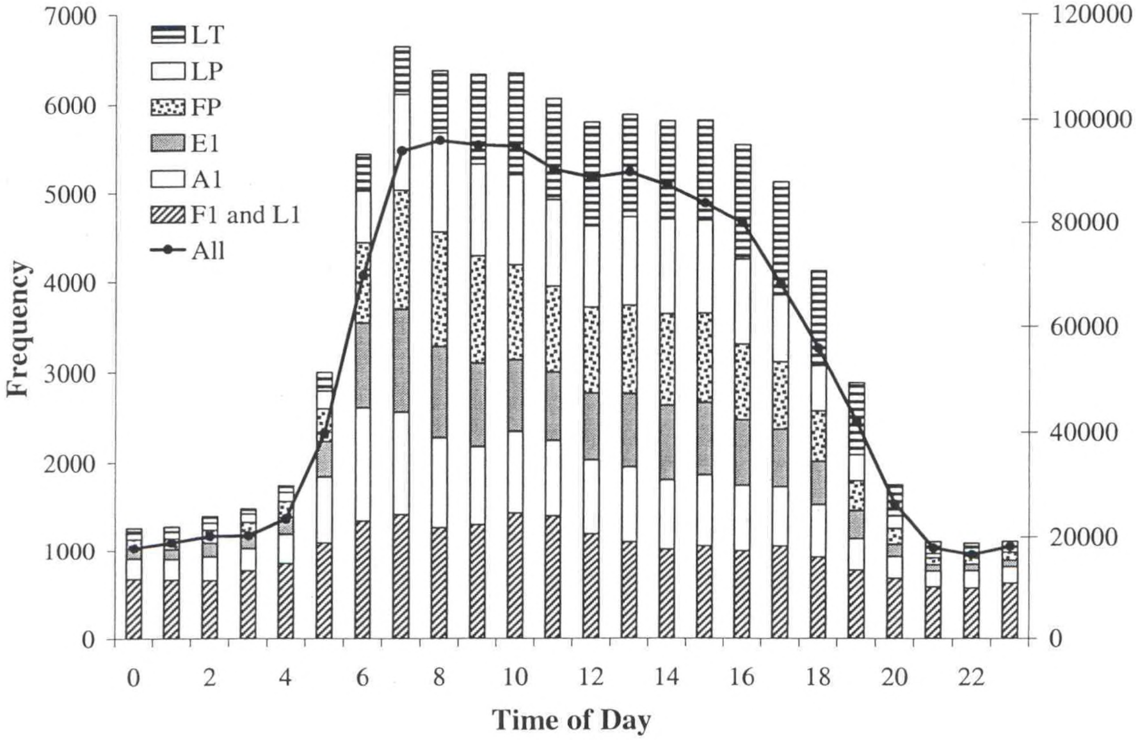


Figure 3. Frequency of coded records per hour of the day for 2002. LT = last top, LP = last pool, FP = first pool, E1 = first entrance into fishway, A1 = first approach to fishway, F1 and L1 = first approach and last departure from downstream areas, All = all coded records for fall Chinook in 2002 (right axis).

Passage duration sample size ranged from 23 to 691 fish (Table 3). With few exceptions, differences in passage duration were greater among dams than among years (Figures 4-6). In all cases, the distribution of times to pass a dam (whether measured from arrival downstream or first entrance) was highly skewed with long tails created by fish slow to pass (see Figure 5 as example). Therefore, we tested for differences using non-parametric comparisons of passage time distributions. At Bonneville Dam, for example, the cumulative distribution of first to last detection passage times (Figure 6) indicated a bimodal distribution of passage times, where the 80th percentile was much larger than that for The Dalles Dam. This bimodal pattern reflects diel patterns of fish activity.

For time from tailrace arrival to first entrance, median salmon passage times ranged from 2.0 (John Day Dam, 2004) to 8.3 h (Bonneville Dam, 2002). This included travel time from tailrace receivers, milling behavior while searching for entrances, and the decision to enter the fishway. All of these behaviors are strongly dependent on time of day. As in past studies (Burke et al. 2005) the time from tailrace arrival to activity at the base of the dam tended to be longest at John Day Dam (Table 3). However, fish at John Day Dam did not exhibit the longest times for passage duration for every metric. Times from fish detection at the tailrace receivers to first entrance were shorter than at any other dam for any individual year. Times for first entrance to passage were shorter at The Dalles Dam than any others (except McNary Dam in 2003).

When calculating passage time from first entrance to passage, the duration represents time spent in passing through fishways, including time spent during multiple passage attempts made after the first entrance detection. Median passage duration from first entrance to passage ranged from 3.8 (The Dalles Dam, 2004) to 21.4 h (John Day Dam, 2002; Figure 5). John Day Dam had consistently longer passage time distributions than the other lower Columbia River dams in every year (Wilcoxon Rank Sum test, $P < 0.0001$). At Bonneville, John Day, and McNary Dams, passage duration was consistently longest in 2002 (Wilcoxon Rank Sum test, $P < 0.05$). The only exception to this was at John Day Dam, where passage duration in 2003 was not significantly different from 2002 ($P > 0.05$). At The Dalles Dam, passage duration was longest in 2003 (Wilcoxon Rank Sum test, $P < 0.0001$).

When we examined the time from tailrace arrival to passage, which encompasses all behaviors in the vicinity of the dam structure, both the median values and the cumulative proportion values (Figure 6) tended to be lowest in 2004 in all cases. The overall range was 12.0 (McNary Dam, 2003) to 23.4 h (John Day Dam, 2003). Fish at John Day Dam consistently took the longest to pass, but this was not as pronounced as for duration from first entrance to passage. The long entrance to passage time was mediated by a shorter duration from tailrace arrival to entrance. The passage times for tailrace arrival to dam passage that are reported here are consistent with those in previous work (Burke et al. 2005) except for the times at John Day Dam. Here, the times were substantially shorter than previously reported for all years except for 2002. Of the median passage times in each report, the higher flow years (2000 and 2002) always had the longest passage times at Bonneville, The Dalles, and John Day Dams. The other metrics cannot be directly compared, as they use approach time instead of entrance time in their calculations.

Due to small sample sizes, only median values of post-fallback passage time (fish that fell back and attempted to pass again) are reported (Table 3). We report the same metric used as with pre-fallback passage times: tailrace arrival to first entrance of the dam, first entrance to dam passage, and tailrace arrival to dam passage. Median passage times across the three metrics ranged from 2.2 to 436.7 h ($n = 1$ in both cases). In all cases, post-fallback median passage times were either longer or not significantly different from pre-fallback median passage times (Table 3).

Table 3. Median passage duration (h) and sample size (in parentheses) for distinct areas at all four lower Columbia River dams. Upper panel represents fish before any fallback events; lower panel represents passage efficiency after a fallback event. Shaded cells indicate a significant difference (increases in nearly all cases) between pre- and post-fallback passage times (Wilcoxon rank sum test, $P < 0.05$). No fish were released below Bonneville Dam in 2005; thus no pre-fallback results are available.

	Bonneville				The Dalles				John Day				McNary			
	2002	2003	2004	2005	2002	2003	2004	2005	2002	2003	2004	2005	2002	2003	2004	2005
	Passage duration (h) before fallback															
Arrival in the area to first entrance at a dam	8.3 (503)	3.3 (389)	4.0 (244)	N/A	5.5 (374)	5.0 (270)	6.6 (211)	7.7 (5.3)	2.4 (334)	3.1 (212)	2.0 (223)	2.2 (145)	2.7 (235)	3.6 (98)	3.1 (97)	2.5 (32)
First entrance at a dam to dam passage	8.7 (574)	8.2 (498)	7.9 (327)	N/A	6.0 (639)	6.6 (424)	3.8 (363)	4.4 (365)	21.4 (373)	15.9 (317)	10.4 (320)	8.9 (322)	7.1 (375)	6.1 (234)	5.3 (218)	6.6 (185)
Arrival in the area to dam passage	21.0 (567)	20.3 (424)	19.8 (329)	N/A	16.7 (411)	16.1 (276)	15.4 (234)	16.0 (51)	23.4 (415)	19.1 (214)	15.8 (222)	15.8 (144)	12.8 (286)	12.0 (286)	13.0 (106)	15.9 (23)
	Passage duration (h) after fallback															
Arrival in the area to first entrance at a dam	20.2 (32)	39.5 (7)	22.4 (4)	19.6 (3)	13.3 (15)	15.1 (11)	24.6 (10)	18.4 (4)	18.3 (4)	N/A (0)	318.4 (2)	416.1 (1)	172.4 (5)	150.5 (5)	94.7 (1)	N/A (0)
First entrance at a dam to dam passage	8.8 (36)	9.5 (5)	2.7 (5)	34.9 (2)	6.8 (20)	2.5 (11)	3.2 (9)	2.9 (7)	27.5 (2)	2.2 (1)	24.5 (2)	20.6 (1)	18.5 (2)	4.9 (2)	4.3 (1)	6.8 (1)
Arrival in the area to dam passage	24.5 (32)	22.2 (4)	26.4 (5)	30.8 (3)	39.7 (16)	69.2 (10)	35.8 (11)	39.4 (5)	77.4 (2)	N/A (0)	133.6 (2)	436.7 (1)	41.8 (1)	155.4 (2)	99.0 (1)	N/A (0)

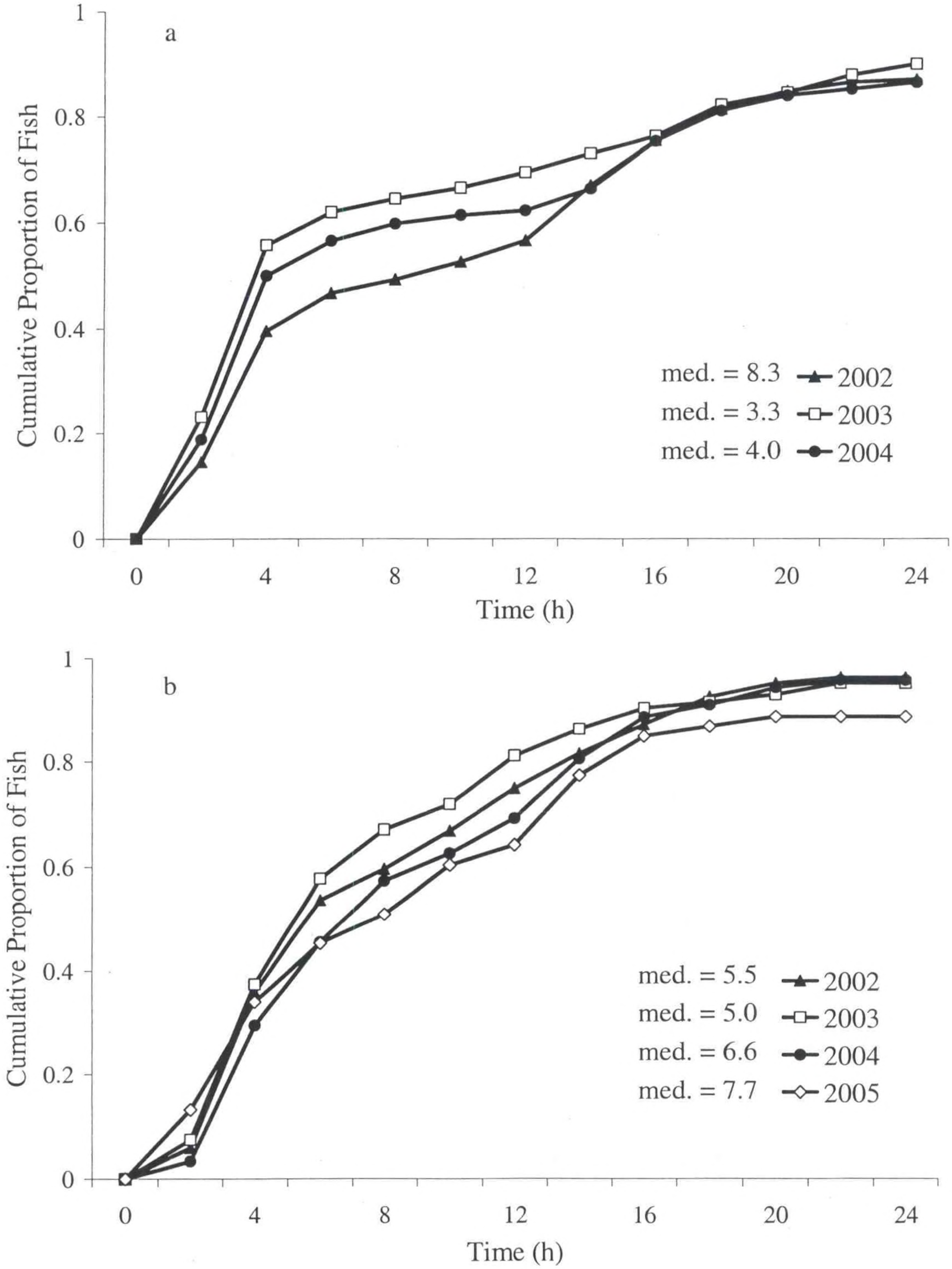
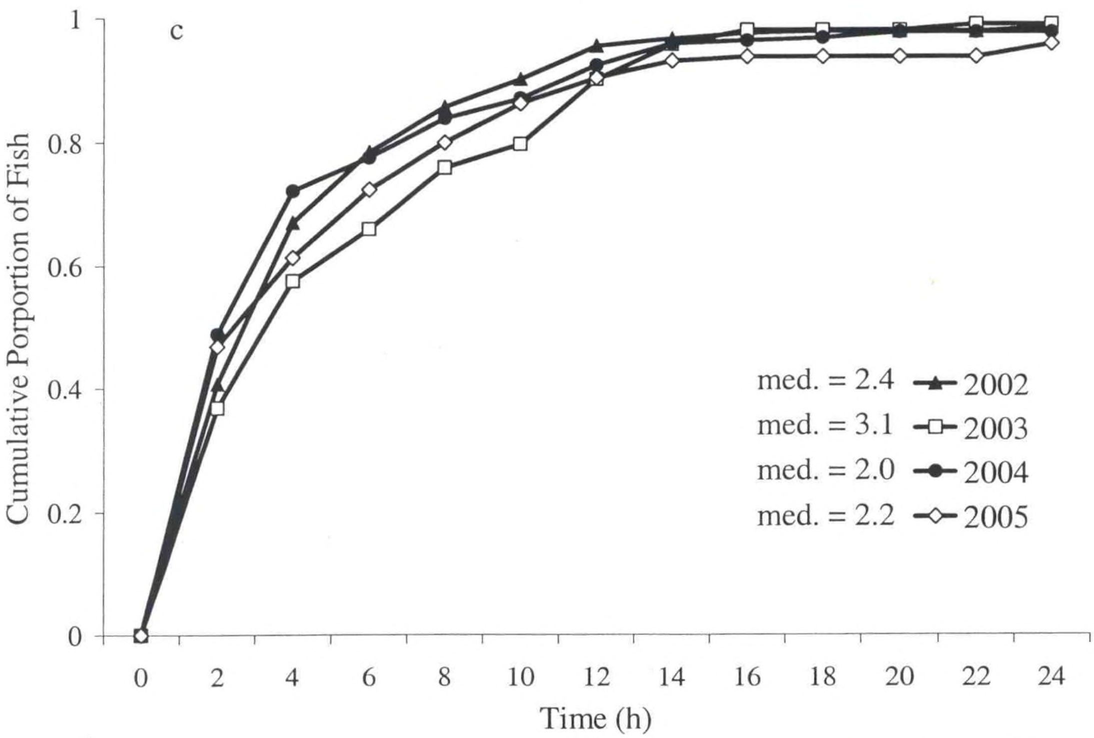


Figure 4a. Cumulative proportion of fish as a function of duration from the first detection downstream from a dam to the first entrance at Bonneville Dam (a) and The Dalles Dam (b). Median passage times are also shown.



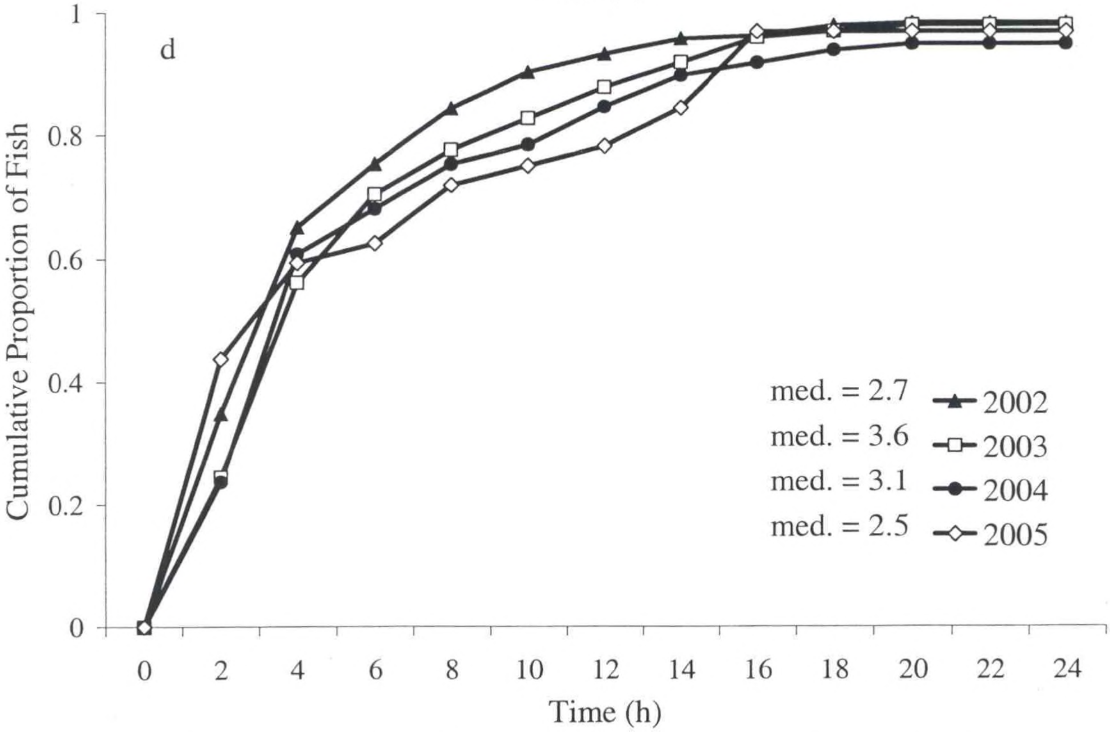


Figure 4b. Cumulative proportion of fish as a function of duration from the first detection downstream from a dam to the first entrance at John Day Dam (c) and McNary Dam (d). Median passage times are also shown.

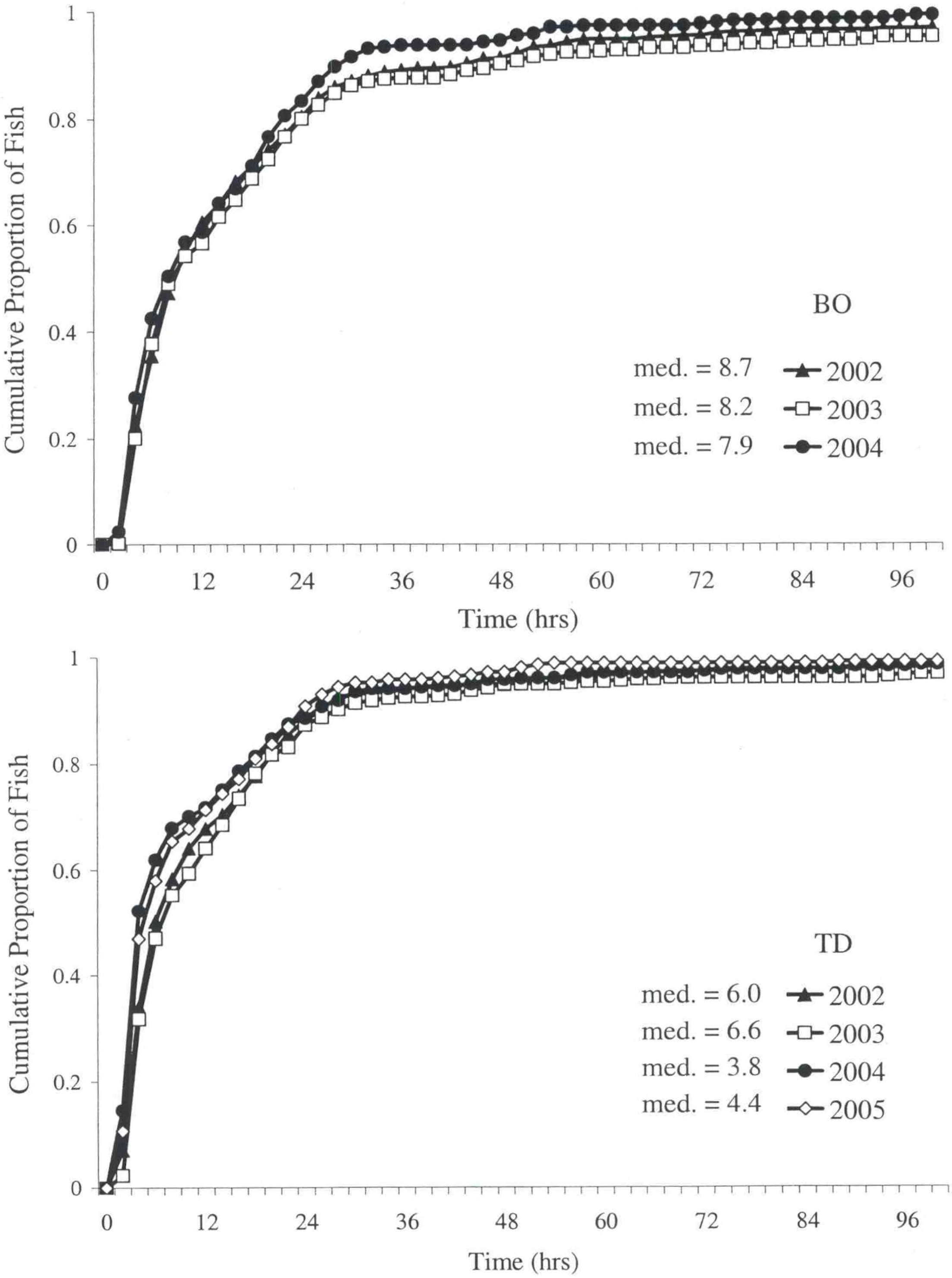
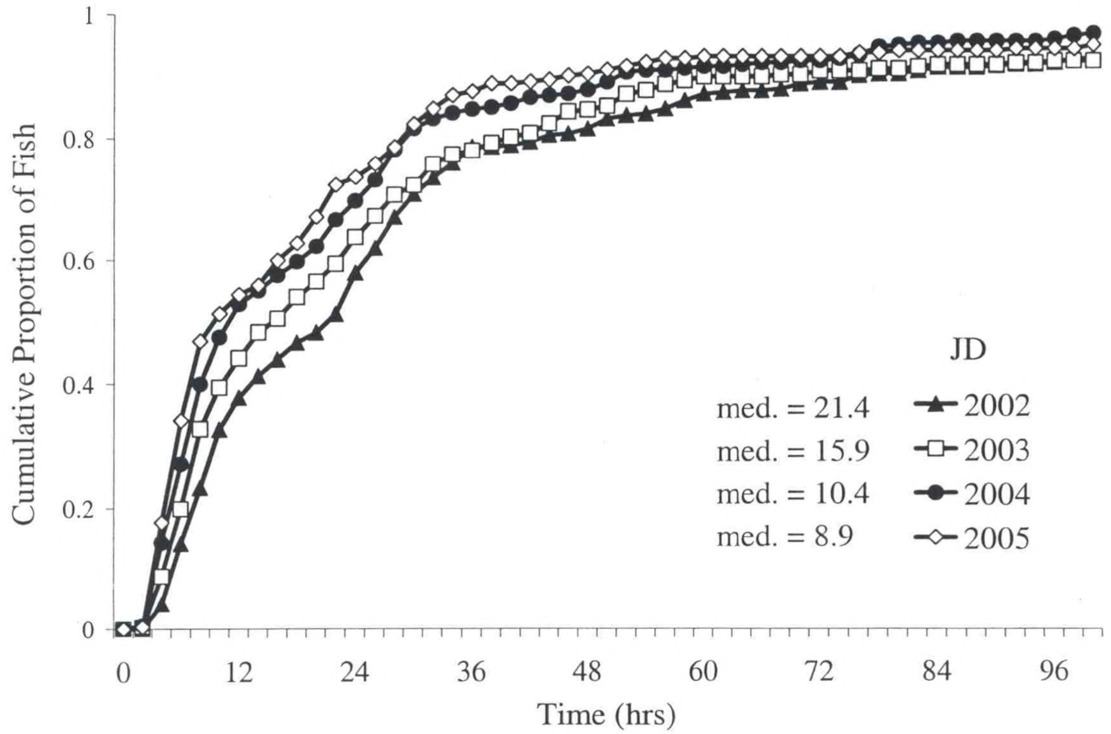


Figure 5a. Cumulative proportion of fish as a function of duration from the first entrance at a dam to the last detection at the top of the ladder at Bonneville Dam (BO) and The Dalles Dam (TD). Median passage times are also shown.



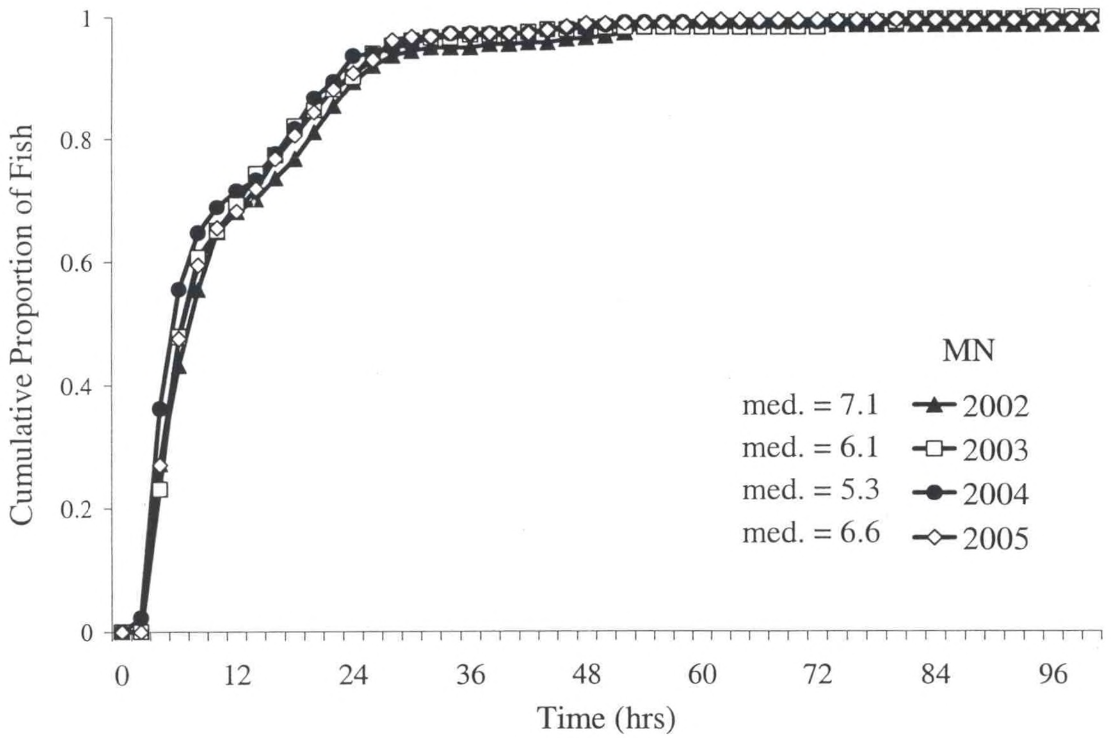


Figure 5b. Cumulative proportion of fish as a function of duration from the first entrance at a dam to the last detection at the top of the ladder at John Day Dam (JD) and McNary Dam (MN). Median passage times are also shown.

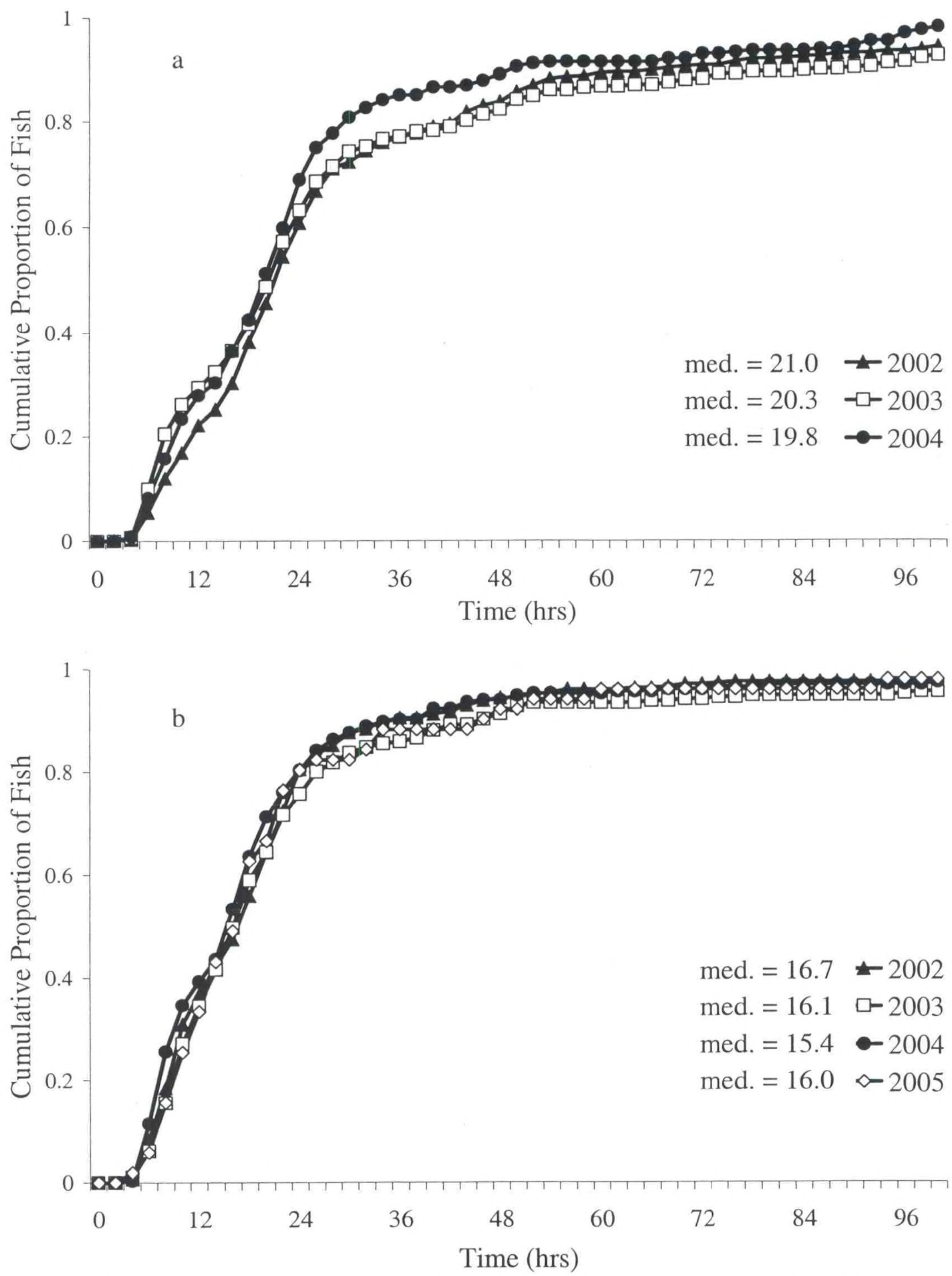


Figure 6a. Cumulative proportion of fish as a function of duration from the first detection downstream from a dam to the last detection at the top of the ladder at Bonneville Dam (a) and The Dalles Dam (b). Median passage times are also shown.

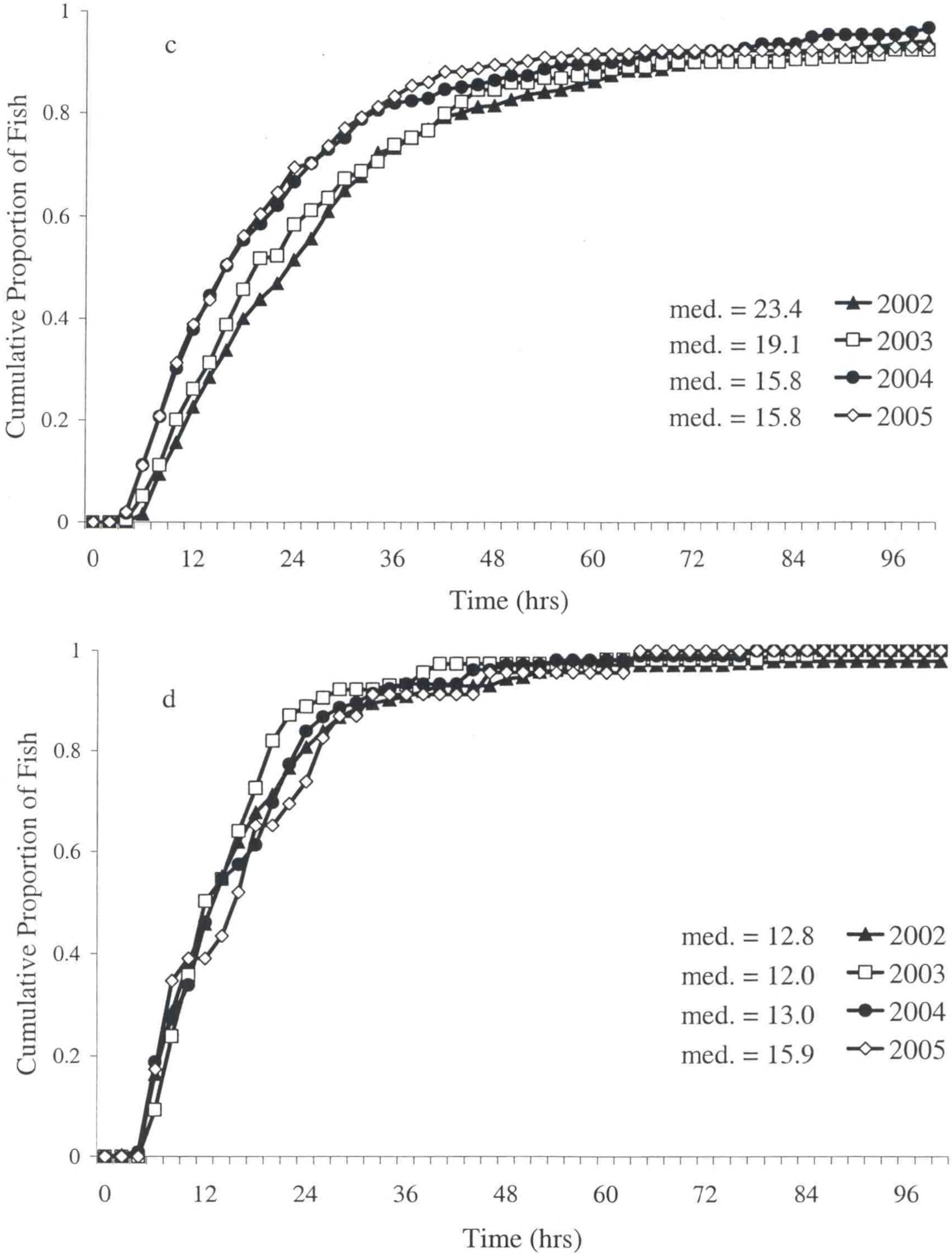


Figure 6b. Cumulative proportion of fish as a function of duration from the first detection downstream from a dam to the last detection at the top of the ladder at John Day Dam (c) and McNary Dam (d). Median passage times are also shown.

FISHWAY USE AND BEHAVIOR

Radio receivers were set up strategically within each fishway to ensure adequate coverage for determining fish behavior. In addition to passage efficiency and duration, the placement of these receivers enabled us to follow fish movement in and around entrances to the various fishways. We examined behavior within the fishways both in terms of how long fish spend in various segments of each fishway and how often fish change direction within a fishway.

Approaches, Entrances, and Exits into/from Fishways

Methods

For each dam, we analyzed the number of times that adult fall Chinook salmon passed through individually monitored entrances. We computed first approaches (the first fishway entrance approached by an individual fish), and all approaches (all approaches, including first approaches, made at a given entrance) at each dam. An approach was defined as the detection of a radio-tagged fish at an antenna positioned outside an entrance. After their first approach, fish often approached repeatedly and at multiple entrances. Occasionally, a fish was detected inside the fishway without being detected outside the entrance. These were termed "unknown approaches." Based on the entrance used, data were assigned to the fishway system in question (e.g., Washington-shore fishway).

Similarly, we reported first entrances (the first fishway entrance used by an individual fish), and all entrances (all entrances, including first entrances) for each fishway. An entrance was defined as the detection of a transmitter by an antenna positioned inside a fishway. If the entrance location was not clear, the passage could still be assigned to the fishway system ("unknown entrance"). Entrance efficiency was calculated by fishway as the number of first entrances divided by the number of first approaches.

Results

In general, interannual variability in entrance use was low for the lower Columbia River Dams. However, there were distinct use patterns for fall Chinook salmon at each dam. These results focus on fishway entrance usage during dam passage attempts prior to fallback events. Fishway entrance usage for all events directly correlated with usage for first approaches.

Bonneville Dam—Fish made approaches more often at powerhouse 2 (PH2) than at powerhouse 1 (PH1). Greater use of the Washington shore ladder was evident for first approaches and first entrances as well as all approaches and entrances (Table 4).

The Dalles Dam—As in previous years (Burke et al. 2005), fish tended to use the east ladder entrance (Table 4). Entrance efficiency at this location was high, at over 90% in all years. At the north ladder, more fish made a first entrance at the north entrance than made their first approach at this location in 2004 and 2005. Relatively few fish used the north shore fishway for approaches, entrances, or passage.

John Day Dam—Similar to The Dalles, there was little use of the north ladder entrance at John Day Dam (Table 4). Despite low usage and potentially incomplete receiver coverage, entrance efficiency for fish that used the north ladder at John Day Dam was exceptionally high. The south ladder had higher use, but intermediate entrance efficiencies. This finding is also consistent with previously reported patterns of John Day ladder use (Burke et al. 2005).

McNary Dam—As at the other dams, interannual variability in entrance use was low at McNary Dam, and there were consistent patterns of ladder usage. Overall, more fish were detected using the south ladder. Fewer fish were detected entering the south end of the powerhouse than approaching it. However, more fish first entered the north ladder entrance than made their first approach there, and more fish passed via the north ladder than first approached or first entered that ladder (Table 4). In other words, migrating fish moved into the north ladder to pass after entering elsewhere. This pattern has also been observed in previous studies of fall Chinook salmon in the Columbia River (Burke et al. 2005).

Apparent entrance efficiency differed depending on the side of the river and the dam in question, ranging from 66.5% (Oregon shore of Bonneville Dam in 2004) to 96.5% (Washington shore of The Dalles Dam in 2002). In general, proportional use of entrances was not different between the first entrance and all subsequent entrances.

Table 4. Number of radio-tagged adult Chinook salmon known to make approaches, entrances, and pass via each of two ladders or the navigation lock. First approaches and first entrances, as well as all approaches and all entrances (in parentheses) are reported for each dam.

		Bonneville Dam			The Dalles Dam			John Day Dam			McNary Dam		
		WA shore	OR shore	Nav lock	North	East	Nav lock	North	South	Nav lock	North	South	Nav lock
2002	Approaches	534	220	0	114	656	0	21	572	0	74	408	0
		(8,021)	(6,571)		(536)	(3,101)		(916)	(11,347)		(710)	(2,741)	
	Entrances	450	186	0	110	593	0	30	401	0	102	290	0
		(1,526)	(575)		(409)	(1,433)		(616)	(3,939)		(484)	(958)	
	Passage	404	301	13	84	688	0	75	470	0	229	242	1
2003	Approaches	410	202	0	71	400	0	9	375	0	55	238	0
		(6,204)	(1,470)		(247)	(1,985)		(577)	(27,784)		(389)	(1,521)	
	Entrances	382	149	0	60	392	0	23	320	0	59	194	0
		(1,373)	(455)		(172)	(1,022)		(391)	(3,384)		(269)	(514)	
	Passage	368	208	5	13	448	0	34	314	2	124	159	0
2004	Approaches	330	173	0	27	392	0	8	377	0	71	217	0
		(4,412)	(1.098)		(157)	(1,488)		(467)	(18,278)		(424)	(1,143)	
	Entrances	239	115	0	32	354	0	28	321	0	92	149	0
		(726)	(347)		(107)	(769)		(381)	(2,917)		(265)	(341)	
	Passage	363	159	4	25	411	0	23	325	3	135	125	0
2005	Approaches	1	15	0	49	371	0	11	354	0	35	233	0
		(143)	(112)		(160)	(1,324)		(345)	(8,716)		(381)	(1,225)	
	Entrances	1	3	0	49	337	0	17	320	0	53	201	0
		(48)	(27)		(129)	(651)		(257)	(2.573)		(226)	(591)	
	Passage	574	7	0	11	418	0	5	337	1	73	122	0

Duration in Fishway Segments

Methods

To determine the total amount of time fish spent in various stretches of the fishway and tailrace (duration), we first divided the area around each dam into 5 segments, defined as follows:

1) Tailrace: from the downstream antennas (1.8 to 3.2 km downstream from each dam) to the area of detection at the base of the powerhouses or spillways.
2) Base of the dam: the area of detection at the base of the powerhouses and spillways but outside of the actual fishway.
3) Collection channel: from just inside the various fishway entrances to either the confluence of the various channels or the first submerged weir, depending on the design of the fishway.
4) Transition pool: from the end of the collection channel to the first emerged weir.
5) Ladder: from the first emerged weir to the top of the fishway, including the ladder exit.

Analyses for duration in fishway segments were conducted for 2002 through 2004; 2005 results were not analyzed due to changes in receiver configuration that did not provide the level of detail necessary to perform these analyses. Specifically, the transition pool segment was not defined or monitored with the antenna array in 2005, thus impacting our ability to differentiate between any of the in-fishway segments.

We calculated the time from the first record in any given section to the first record in any other section. Thus, we inherently assumed that fish remained in the section where they were last detected until we had evidence that they were somewhere else. However, three factors affect the accuracy of this determination: differences in receiver coverage between dams, distance between receivers in some locations, and the fact that detection probability is not 100%. Receiver coverage evaluations have been done and have shown that segment time results were not affected by the presence/absence of some receivers (Burke et al. 2005). The possibility of mis-assignment remains, particularly when distinguishing between the tailrace and the base of the dam. Thus, these results should be viewed as estimates of time spent in each segment and not absolute durations.

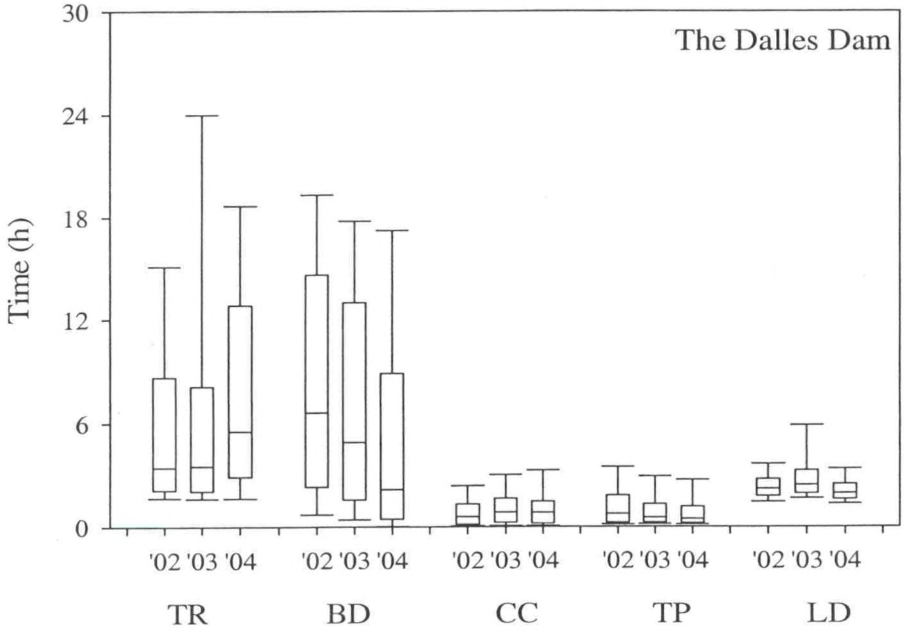
We calculated duration in each segment for each time the fish entered it, since fish tended to enter a particular segment more than once. All durations in a particular segment were then summed, regardless of how many times the fish entered and exited that segment. Fish that were not detected in a segment were not included in the calculation for that segment.

Results

Segment times ranged widely, and the distributions were highly skewed (Table 5, Figures 7-8). Median times and ranges were also dam-dependent. Overall, fish consistently spent less time in the collection channel and the transition pool than in other sections of the fishways (Table 5, Figures 7-8). In most cases, over 90% of the fish spent less than 2 h in each of these sections. The median range for the collection channel was 0.4 (Bonneville Dam, 2002 and McNary Dam, 2003) to 2.6 h (John Day Dam, 2002), while that for the transition pool was 0.2 (McNary Dam, 2003) to 2.0 h (McNary Dam, 2004; Table 5). The amount of time spent in the other segments varied widely among dams, but the tailrace and base of the dam segments consistently had the longest durations (medians ranged from 1.8 to 11.9 h).

Table 5. Median total time (h) in each segment of the fishways for radio-tagged adult fall Chinook salmon.

	Median time (h)				
	Tailrace	Base of the dam	Collection channel	Transition pool	Ladder
Bonneville Dam					
2002	11.9	3.4	0.4	0.4	3.2
2003	11.0	2.8	0.5	0.6	3.1
2004	9.0	3.2	0.5	0.5	3.9
The Dalles Dam					
2002	3.4	6.6	0.6	0.8	2.2
2003	3.5	4.9	0.8	0.5	2.4
2004	5.5	2.2	0.8	0.4	1.9
John Day Dam					
2002	6.5	7.8	2.6	0.6	3.0
2003	6.5	7.6	2.5	0.5	3.0
2004	3.8	5.0	2.3	0.4	2.7
McNary Dam					
2002	1.8	3.8	0.5	0.5	2.7
2003	1.9	3.8	0.4	0.2	2.9
2004	2.2	3.3	2.0	2.0	0.7



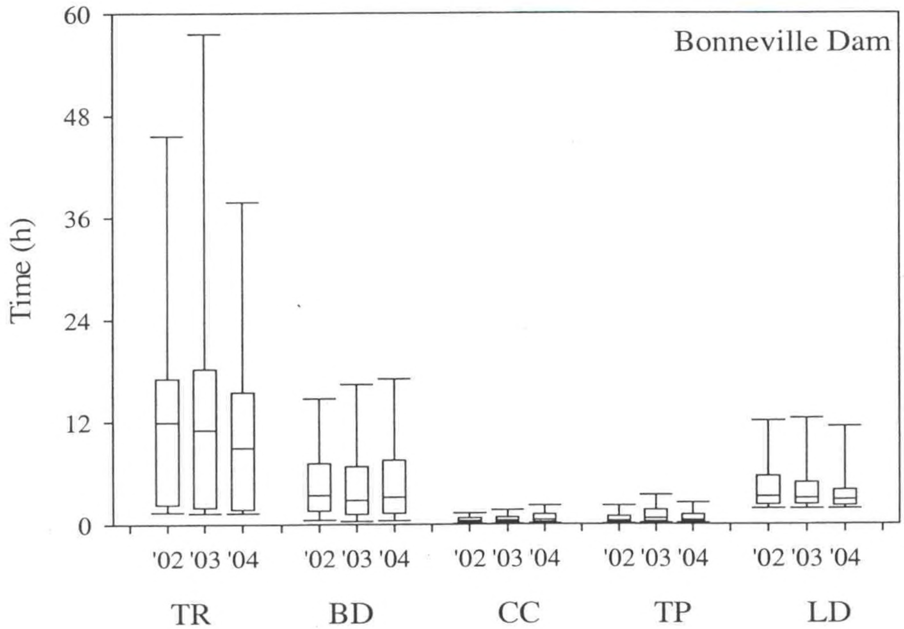
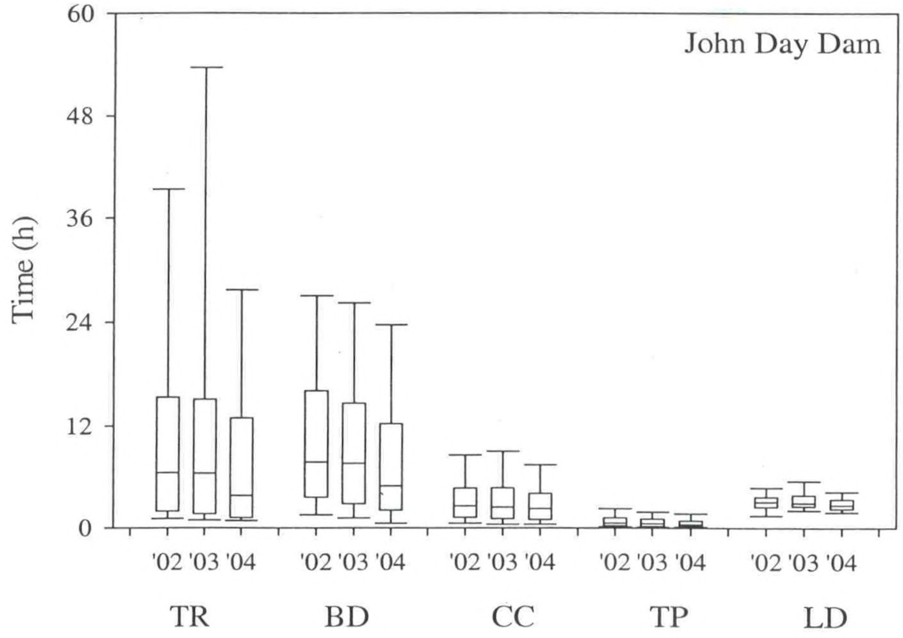


Figure 7. Median (bar) amount of total time fish spent in each of five fishway segments at Bonneville and The Dalles Dams, 2002-2005. Whiskers represent 10^{th} and 90^{th} percentiles, boxes represent 25^{th} and 75^{th} percentiles. TR = tailrace, BD = base of dam, CC = collection channel, TP = transition pool, LD = ladder.



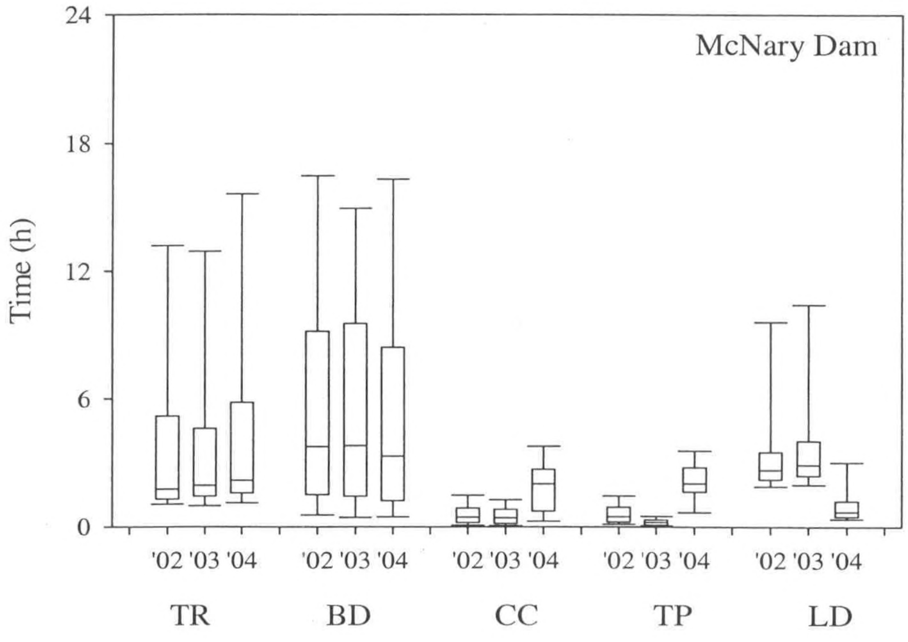


Figure 8. Median (bar) amount of total time fish spent in each of five fishway segments at John Day and McNary Dams, 2002-2005. Whiskers represent 10^{th} and 90^{th} percentiles, boxes represent 25^{th} and 75^{th} percentiles. TR = tailrace, BD = base of dam, CC = collection channel, TP = transition pool, LD = ladder.

At Bonneville Dam, fish spent more time in the ladder than in the collection channel or the transition pool. The amount of time spent in the ladder was similar to that for the tailrace segment, but less than time spent at the base of the dam. This pattern was also observed at Bonneville Dam in 1998 and 2001 (Burke et al. 2005). At The Dalles and John Day Dams, fish spent more time in the ladder than in the collection channel and transition pools, and there was much less variability than observed for the downstream and tailrace segments. Fish collectively spent more time in the collection channel at John Day Dam than in other collections channels, as shown by the broader distribution of times (Figure 8), a pattern also observed by Burke et al. (2005). At McNary Dam, fish spent relatively little time in all segments, though their times had wide ranges and were highly skewed, especially for tailrace and ladder segments.

Among-year differences for each dam were minor. The notable exception was for segment times at McNary Dam in 2004. In this case, fall Chinook salmon spent considerably more time in the collection channel and transition pool segments, and less time in the ladder than in 2002 and 2003. We found that fish held in these segments longer in 2004 than in other years (rather than visited them more often), which represents different behavior than has been observed at this dam in the past. We are unaware of any changes to the dam structure or operations to explain this change.

Turn-Arounds

Methods

We determined how many times each fish reversed direction within the fishways by dividing each fishway into five segments, as in the previous analysis. Because the five segments are spatially sequential, we were able to determine which direction a fish was traveling by marking detections in one segment followed by detections in a separate segment (either upstream or downstream from the first segment). We then counted changes in direction for each fish. Direction reversals were assigned to the segment where the terminal detection occurred. For example, if a fish was detected in the collection channel and then detected in the transition pool, we determined that it was swimming upstream. If that fish was next detected in the collection channel, we assigned a turn-around (from upstream to downstream) to the transition pool segment.

In addition, we examined how far downstream fish retreated after turning around by noting the segment where the fish was when it started moving upstream following a turn-around event. A fish that turned around in the ladder and retreated downstream and out of the fishway was assigned a turn-around in the ladder and an exit to the base of the dam. Turn-arounds are reported for each section and are summarized based on how far the fish retreated. Only fish that eventually passed the dam were included in the analysis presented here. As with other analyses, if a fish fell back at a dam, only behavior before that fallback event was included. Data for fish that were detected at the dam but failed to pass were also examined (3-32 fish in each dam/year combination), but yielded qualitatively similar patterns of turn around behavior.

In some instances, fish were not detected in a particular segment, even though they did swim through it (based on detections on either side of the segment). By definition, not being detected in a segment would preclude a determination of reversing direction in that segment. Hence, there was the potential for bias against segments with low detection probability. This was especially true of the north fishway collection channels at The Dalles and McNary Dams, where the length of the collection channel segment depended on the tailwater level and the position of the receivers resulted in minimal coverage. However, evaluation of this bias has indicated that it is small (Burke et al. 2005).

Results

Across all dams and years, 82.2 to 90% of the fish reversed direction at least once while heading upstream. Turn-arounds occurred in all fishway segments at each dam examined (Table 6). Many fish that reversed direction did so more than once; individual fish reversed direction from 0 to 111 times for a single fishway segment. However, the median number of attempts to pass through any section was between 0 and 4 (Table 6).

Relatively few direction reversals occurred at The Dalles and McNary Dams (Figures 9 and 10); the median number of turn-arounds in each of the fishway segments and in each year was less than or equal to 1 and the 90^{th} percentile was less than or equal to 4. Similarly, at Bonneville Dam fish exhibited relatively few turn-arounds.

Table 6. Percent of radio-tagged adult fall Chinook salmon that reversed direction at least once per fishway segment within Bonneville, The Dalles, John Day, and McNary Dams in 2002, 2003, and 2004 for passage events prior to fallback. The median number of turn-arounds per fish is shown in parentheses.

	Proportion (%) and median number of turn-arounds		
	Collection channel	Transition pool	Ladder
Bonneville Dam			
2002	55.3 (1)	59.8 (1)	24.1(0)
2003	45.3 (0)	60.2 (1)	13.4 (0)
2004	37.9 (0)	59.3 (1)	8.9 (0)
The Dalles Dam			
2002	26.6 (0)	53.2 (1)	18.4 (0)
2003	28.5 (0)	45.7 (0)	19.2 (0)
2004	16.4 (0)	44.8 (0)	9.2 (0)
John Day Dam			
2002	90.0 (4)	85.6 (3)	15.4 (0)
2003	83.1 (4)	82.0 (3)	12.6 (0)
2004	80.8 (3)	82.2 (3)	4.0 (0)
McNary Dam			
2002	66.4 (1)	54.5 (1)	23.8 (0)
2003	50.5 (1)	34.1 (0)	17.4 (0)
2004	58.2 (1)	25.1 (0)	4.7 (0)

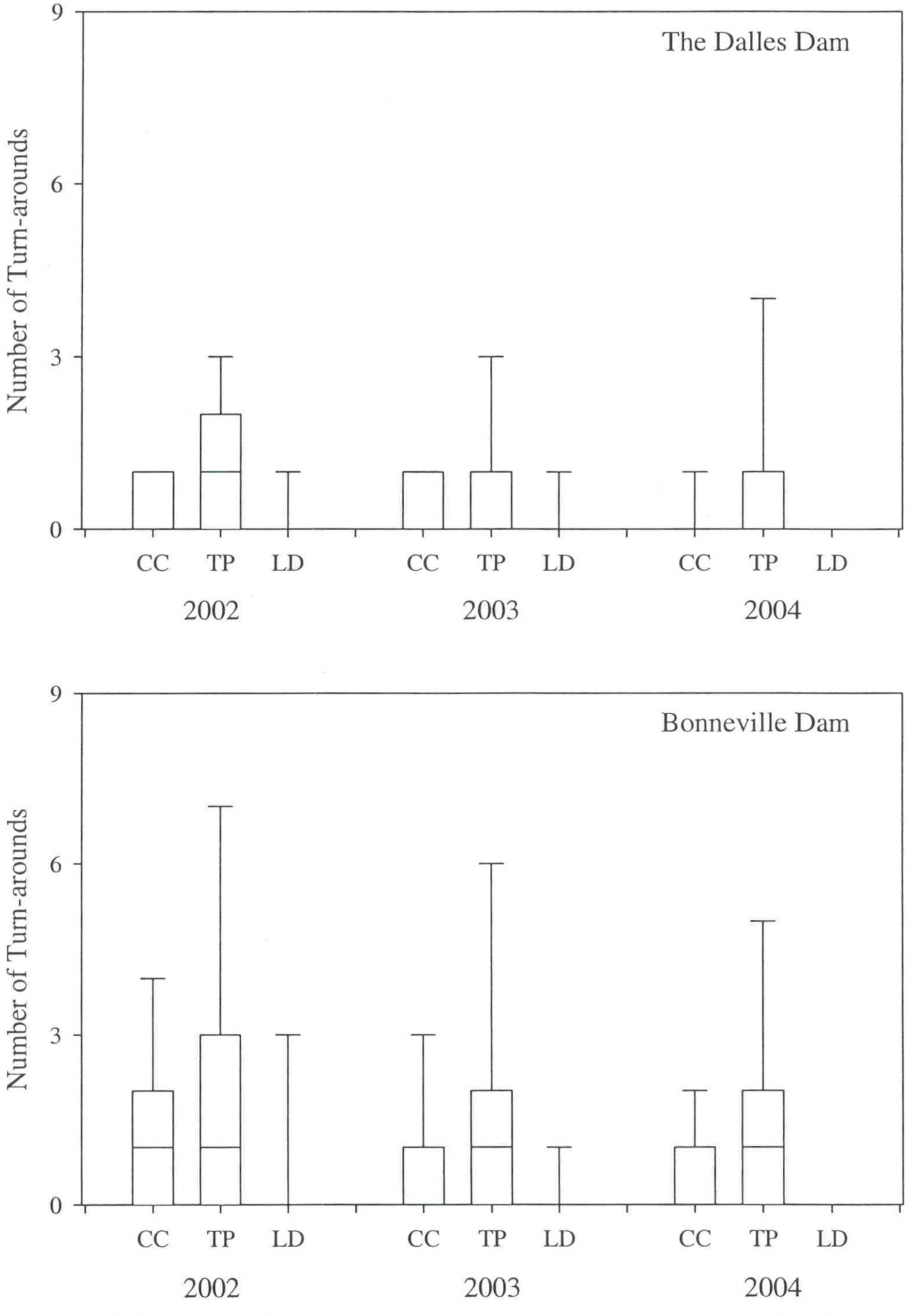
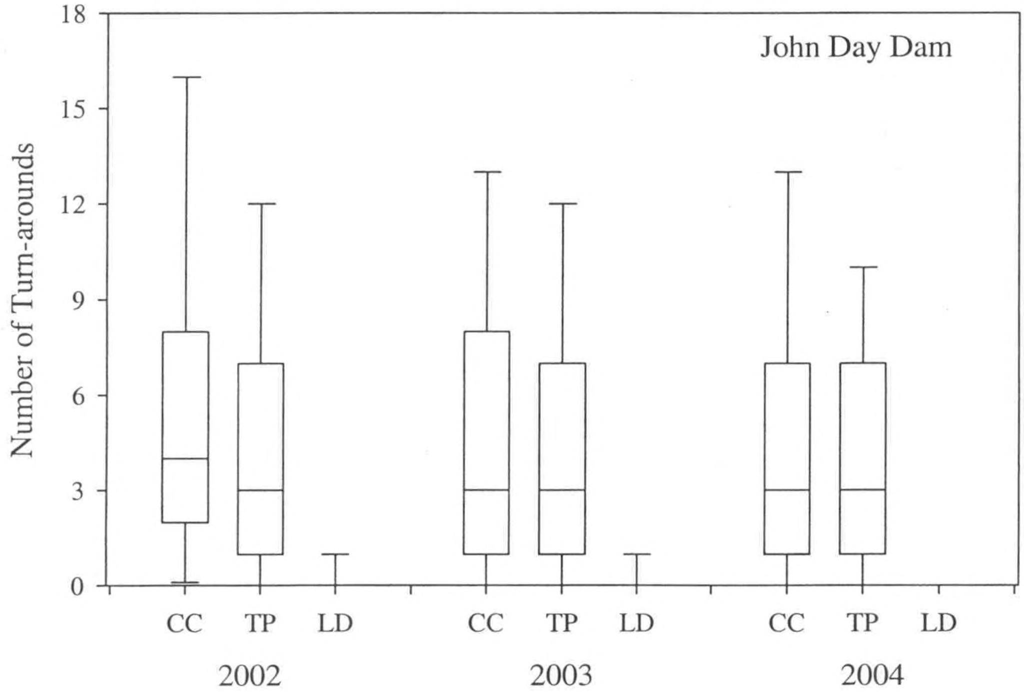


Figure 9. Median (bar) number of times fish reversed direction while heading upstream at Bonneville and The Dalles Dams. Whiskers represent 10th and 90th percentiles, boxes represent 25th and 75th percentiles for each fishway segment: CC = collection channel, TP = transition pool, and LD = ladder.



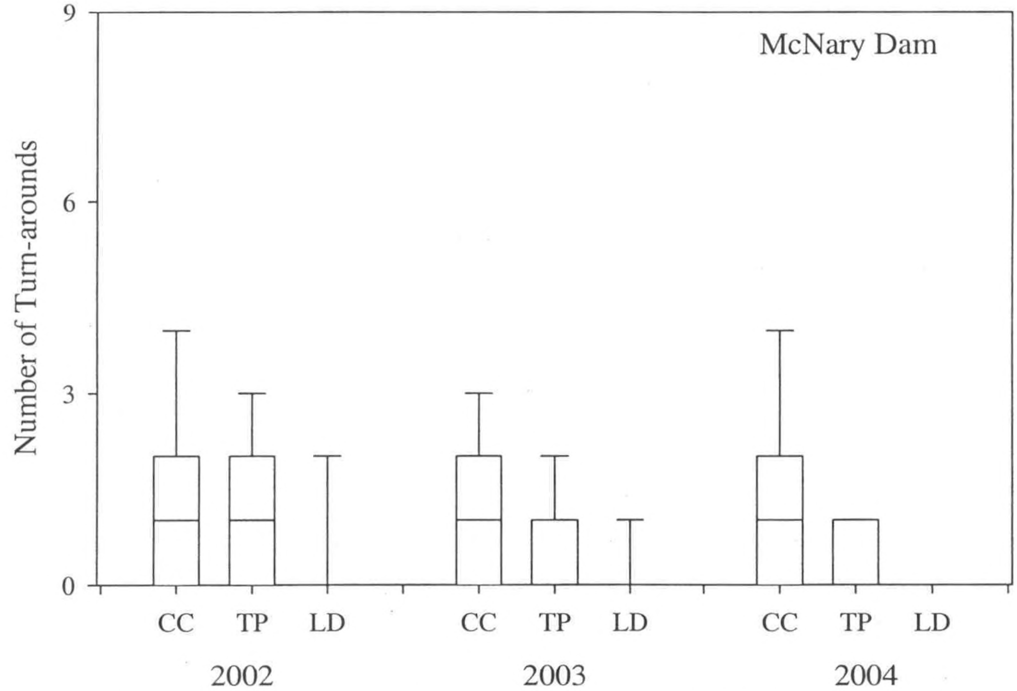


Figure 10. Median (bars) number of times fish reversed direction while heading upstream at John Day and McNary Dams. Whiskers represent 10th and 90th percentiles, boxes represent 25th and 75th percentiles for each fishway segment: CC = collection channel, TP = transition pool, and LD = ladder.

However, the 90th percentile at Bonneville was higher than at The Dalles and McNary Dams (Figures 9 and 10). At Bonneville and The Dalles Dams, the transition pool segment consistently had the widest range of turns per segment, even when the median number of turns in the segment was low. At John Day Dam, there was a wide range of turns per segment, indicating that some fish made many turns in this section.

John Day Dam stood out from the other dams in that most fish made large numbers of turn-arounds in both the collection channel and the transition pool in all 3 years (Figure 10). The medians were consistently and significantly higher than the other three dams in all years for both of these fishway segments (Wilcoxon Rank Sum test, $P < 0.05$). Over 90% of turn-arounds in these segments at John Day Dam occurred in the south fishway. For fish that turned around, the south fishway had a median of 7 attempts per fish for the collection channel and 4 for the transition pool across all years (all other sections and dams had 1 to 2 attempts per fish on median across all years). Unlike the collection channel and transition pool, the number of turn-arounds per fish in the ladder segment of John Day Dam was comparable to the other dams, even in the south fishway. Additionally, fewer fish turned around in the ladder segment of the fishway at John Day Dam than at the other dams or at other sections of the fishway.

The patterns in turn-around behavior for fall Chinook salmon in 2002-2004 were amazingly similar to those seen in 1998, 2000, and 2001 (Burke et al. 2005). This lack of interannual variability indicates that environmental conditions have less to do with these behaviors than the dam structures and flow patterns within them, things that have not changed over the course of this study.

Following a turn around, we determined the segment to which fish retreated before turning around and heading back upstream. These "retreat" segments were mostly in areas outside of the dam fishways. However, fish turning around in the ladders often retreated only to the transition pools before progressing upstream again. Retreat segment analyses provided more specific fish movement and behavior data related to turn around behavior.

These results varied by dam and allowed us to identify the proportion of times fish that entered a section successfully passed through it. In cases of turn-arounds, these data also show the section to which fish retreated following a turn-around, and the total number of attempts at each section (Figures 11-14). When fish turned around within the fishways, most individuals consistently retreated to the base of the dam at The Dalles, John Day, and McNary Dams (Figures 12-14). At Bonneville Dam, retreats were spread more evenly between the tailrace, the base of the dam, and the collection channel

(Figure 11). However, at all dams, retreat distances varied greatly for each segment and differed among dams, fishways, and years (Figures 11-14).

The percentages of fish that successfully passed through the collection channel and transition pool segments were highly variable. Success rates for the ladder segments were generally lowest at Bonneville Dam and the north fishway of The Dalles Dam. Fish turning around in the ladder section often retreated only to the transition pool segment of the fishway. However, if they continued downstream, they completely exited the dam structure. The interannual and dam-specific patterns of retreat were notably similar to those previously reported for fall Chinook salmon in the lower Columbia River (Burke et al. 2005).

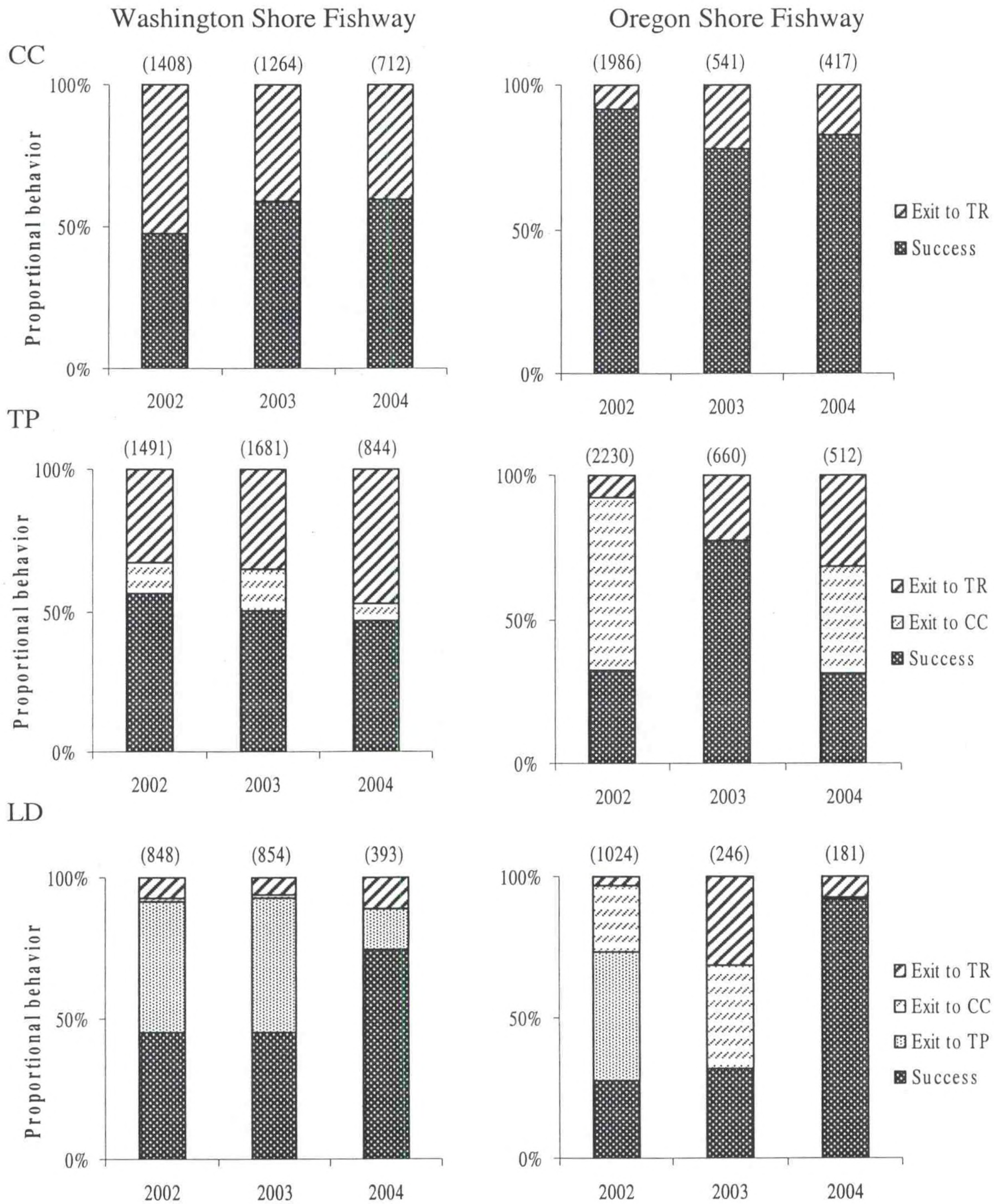


Figure 11. Proportion of attempts to pass through Bonneville Dam collection channel (CC), transition pool (TP), and ladder (LD) that were either successful or resulted in a turn-around. Turn-arounds were divided up based on how far fish retreated to the tailrace (exit to TR), the collection channel (exit to CC), or the transition pool (exit to TP). Numbers in parentheses indicate total number of attempts made by radio-tagged fish.

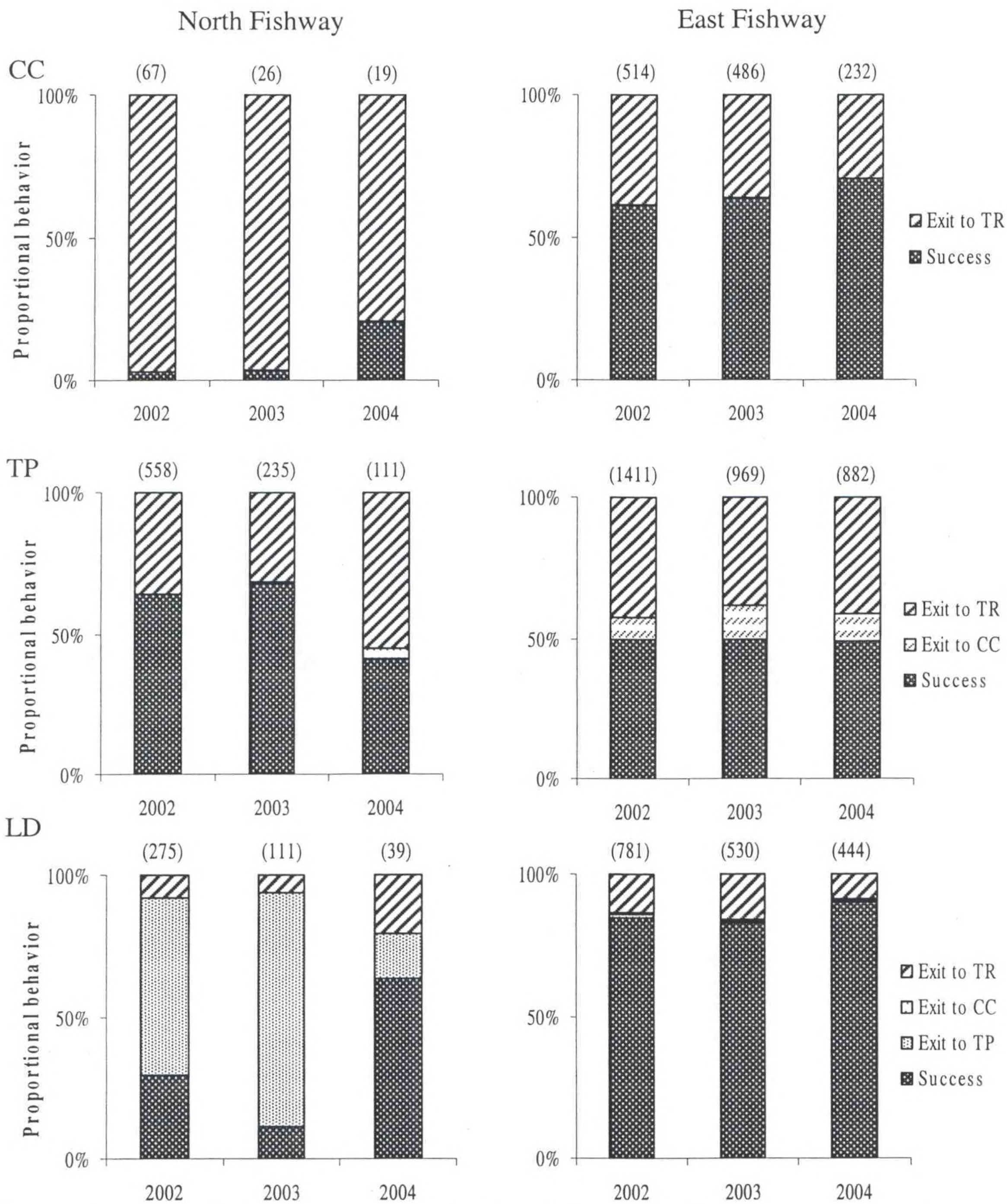


Figure 12. Proportion of attempts to pass through The Dalles Dam collection channel (CC), transition pool (TP), and ladder (LD) that were either successful or resulted in a turn-around. Turn-arounds are divided up based on how far the fish retreated: to the tailrace (exit to TR), the collection channel (exit to CC), or the transition pool (exit to TP). Numbers in parentheses indicate the total number of attempts made by radio-tagged fish.

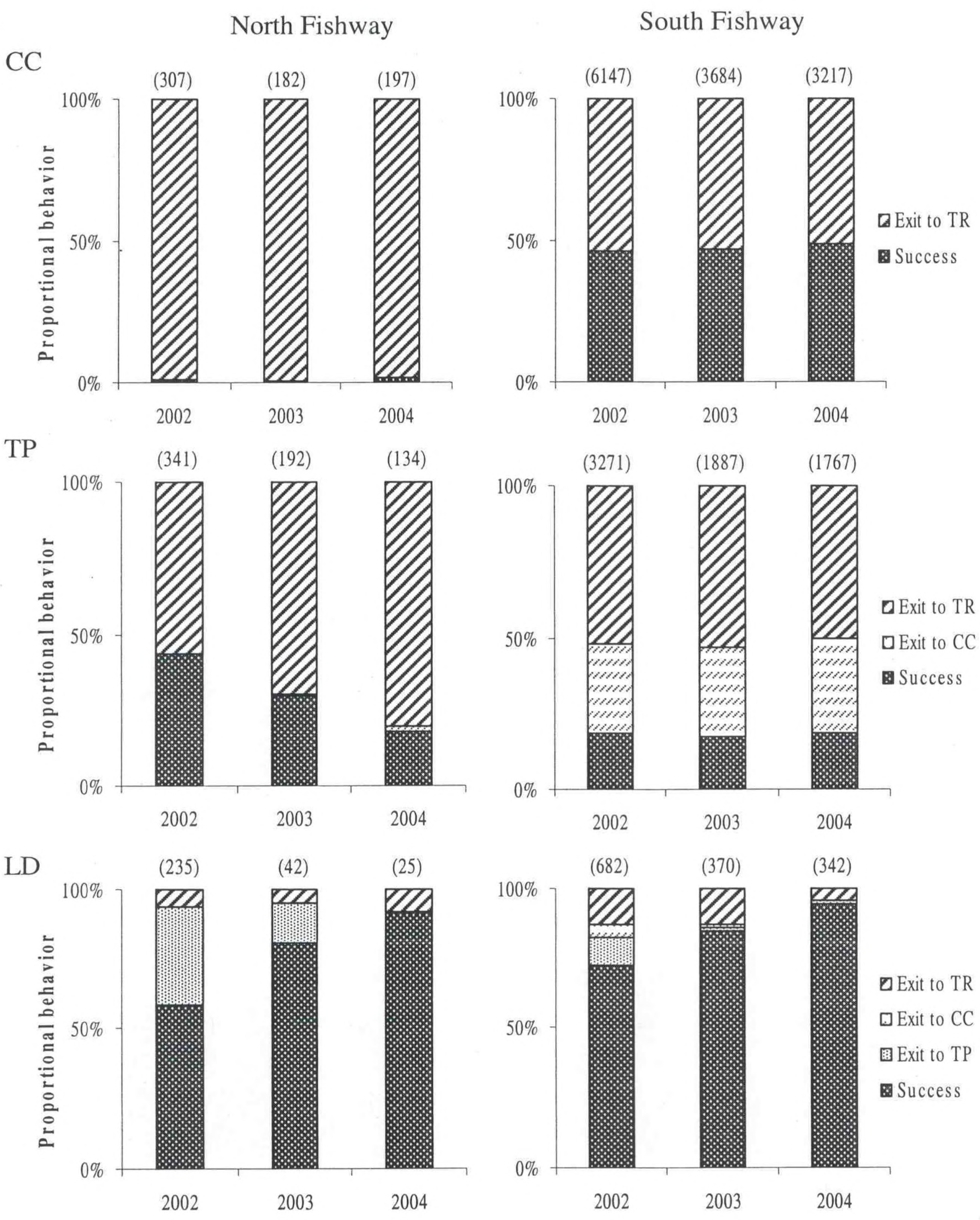


Figure 13. Proportion of attempts to pass through the John Day Dam collection channel (CC), transition pool (TP), and ladder (LD) that were either successful or resulted in a turn-around. Turn-arounds are divided up based on how far the fish retreated: to the tailrace (exit to TR), the collection channel (exit to CC), or the transition pool (exit to TP) segment. Numbers in parentheses indicate the total number of attempts made by radio-tagged fish.

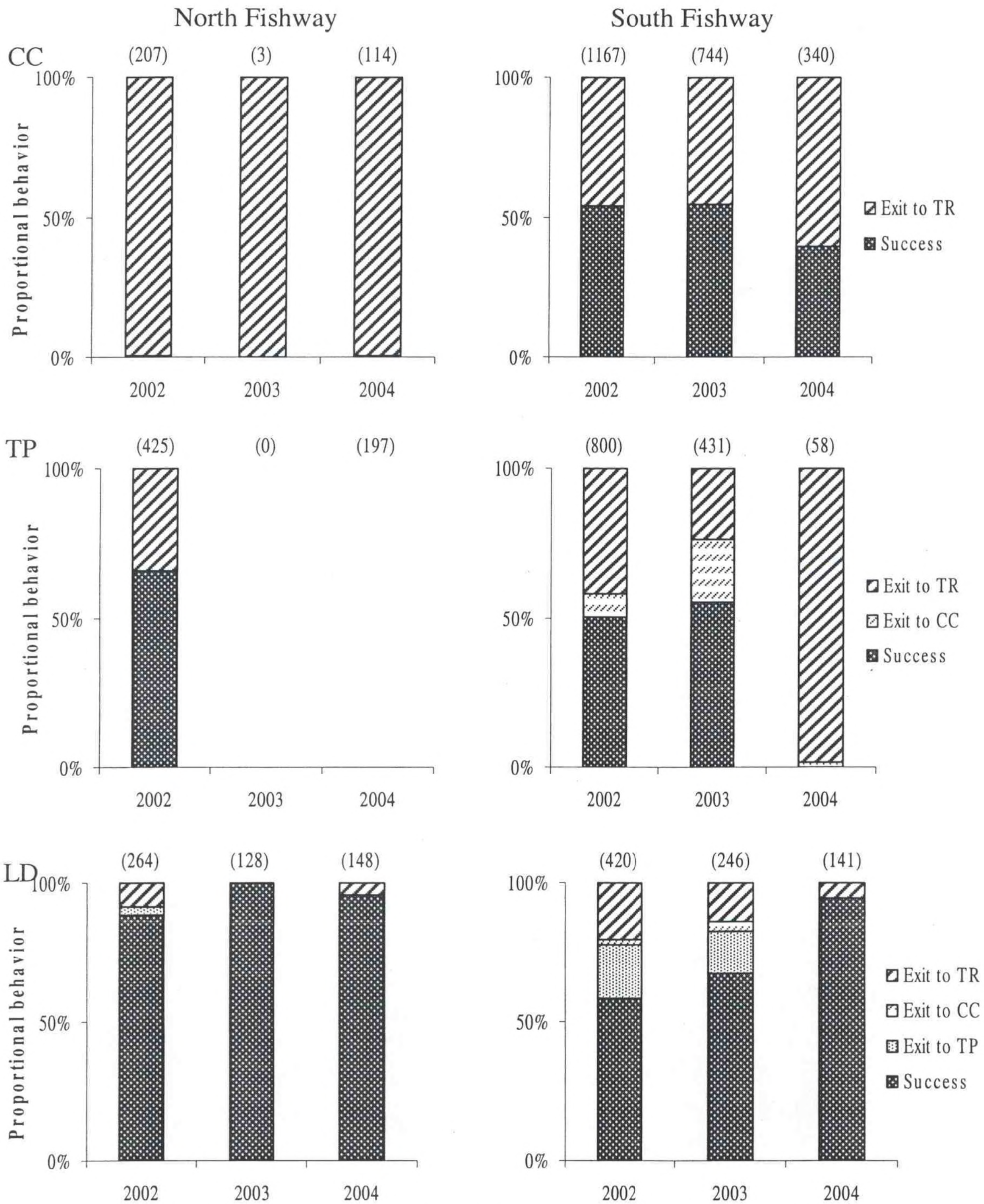


Figure 14. Proportion of attempts to pass through the McNary Dam collection channel (CC), transition pool (TP), and ladder (LD) that were either successful or resulted in a turn-around. Turn-arounds are divided up based on how far the fish retreated: to the tailrace (exit to TR), the collection channel (exit to CC), or the transition pool (exit to TP) segment. Numbers in parentheses indicate the total number of attempts made by radio-tagged fish.

Fallback Fish

Methods

We first counted the number of individual fish that fell back at each dam, and then calculated the proportion of fish that passed that exhibited fallback behaviors (fallback rate). Some fish fell back more than once, so we also counted both the number of times each fish fell back and the total number of fallback events at each dam. In 2002 (as in 2000 and 2001, Burke et al. 2005), some fish were released upstream from Bonneville Dam to examine fallback rates based on release location in the forebay. We considered fallbacks for these fish at Bonneville Dam separately.

The probability of falling back over a dam can be influenced by the route fish used to ascend a fishway (Reischel and Bjornn 2003). For each fallback event, we determined the ladder from which the fish exited immediately before falling back. Fallbacks were divided into those that occurred within 24 h of passage and those occurring after more than 24 h. If a fish passed a dam via an unknown route, the ladder was assigned a null value. A more detailed analysis of fallback events can be found in Boggs et al. (2003; 2004).

Results

Fall Chinook salmon fell back at each of the lower Columbia River dams. Rates ranged from 0.8 (McNary Dam, 2005) to 9.5% (The Dalles Dam, 2003) for fish released below a dam (Table 7). Relatively few fish fell back over an individual dam more than once (range = 0.0 to 1.5%). The highest percentage of fish falling back more than once occurred at Bonneville and The Dalles Dams, particularly in 2003: 1.0% at Bonneville Dam for fish released downstream, and 1.5% at The Dalles Dam.

In 2002, when fish were released both downstream and upstream of Bonneville Dam, fallback rates at that dam were highly dependent on where fish were released. For fish released downstream, the fallback rate at the dam was 4.1% (Table 7). For fish released upstream from Bonneville Dam, the fallback rate was 14.2%. Fish released upstream of Bonneville Dam in previous years had similarly high rates of fallback (Burke et al. 2005).

For fish released downstream of the dam being analyzed, fallback rates were highest at The Dalles Dam, followed by Bonneville Dam (same pattern as in previous years). Fallback rates varied among years at some dams (Table 7). For example, at The

Table 7. Number of fall Chinook salmon that fell back over the dams and the number of repeat fallbacks. The percentage of fish that fell back of those that passed the dam is in parentheses (for Bonneville Dam, upstream-released fish, percentage value is for all fish released upstream from Bonneville Dam).

	Number and percentage of fallbacks			
	2002	2003	2004	2005
Bonneville Dam (downstream-released)				
Total number of fish	28 (4.1)	23 (3.9)	18 (3.4)	27 (4.6)
Total number of fallback events	33	28	25	31
Number that fell back once	23 (3.4)	19 (3.3)	13 (2.4)	23 (3.9)
Number that fell back twice	5 (0.7)	6 (1.0)	3 (0.6)	4 (0.7)
Number that fell back three times	0 (0.0)	1 (0.2)	2 (0.4)	0 (0.0)
Number that fell back more than three times	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Bonneville Dam (upstream-released)				
Total number of fish	44 (14.2)			
Total number of fallback events	50			
Number that fell back once	38 (12.3)			
Number that fell back twice	6 (1.9)			
Number that fell back three times	0 (0.0)			
Number that fell back more than three times	0 (0.0)			
The Dalles Dam				
Total number of fish	66 (8.9)	43 (9.5)	40 (9.4)	23 (5.5)
Total number of fallback events	76	50	44	26
Number that fell back once	57 (7.7)	36 (7.9)	36 (8.5)	21 (5.0)
Number that fell back twice	8 (1.1)	7 (1.5)	4 (0.9)	1 (0.2)
Number that fell back three times	1 (0.1)	0 (0.0)	0 (0.0)	1 (0.2)
Number that fell back more than three times	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
John Day Dam				
Total number of fish	10 (1.8)	7 (2.0)	10 (2.9)	10 (2.9)
Total number of fallback events	10	7	10	10
Number that fell back once	10 (1.8)	7 (2.0)	10 (2.9)	10 (2.9)
Number that fell back twice	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Number that fell back three times	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Number that fell back more than three times	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
McNary Dam				
Total number of fish	17 (3.5)	8 (2.7)	6 (2.2)	2 (0.8)
Total number of fallback events	17	12	7	2
Number that fell back once	17 (3.5)	6 (2.0)	5 (1.8)	2 (0.8)
Number that fell back twice	0 (0.0)	1 (0.3)	1 (0.4)	0 (0.0)
Number that fell back three times	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Number that fell back more than three times	0 (0.0)	1 (0.3)	0 (0.0)	0 (0.0)

Dalles Dam, fallback rates decreased substantially in 2005 (down to 5.5% from around 9% in previous years). A decrease in fallback rate was also observed at McNary Dam (from 3.5 to 0.8% across the study years). However, the opposite occurred at John Day Dam, where fallback rate increased from 1.8 to 2.9%. At both John Day and McNary Dams, total numbers of fallbacks were much lower than at Bonneville and The Dalles Dams, ranging from 1 to 3.5% in the 4 years.

Most fallback events occurred more than 24 hours after fish passed a dam, regardless of the passage route used. For fish that fell back within a day of passing a dam, almost 90% had used an Oregon-shore ladder (averaged over all four dams, Table 8). Although more fish used Oregon shore ladders, particularly at The Dalles and John Day Dams (Table 4), fish using the Oregon shore route also fell back at higher frequencies. The only cases in which the fallback percentages were higher for a Washington shore ladder were at John Day Dam in 2002 and The Dalles Dam in 2005 (Table 8); however, numbers available for these calculations were low in both cases.

Table 8. The number of Chinook salmon that fell back within 24 hours of passage (<24 h), and over 24 h after passage (>24h) after using is the number of fish that fell back after passing via each route divided by the total number that passed by that route. Nav = Navigation Lock, Unkn = unknown ladder.

	Ladder							
	WA		%	OR		%	Nav	Unkn
	<24 h	>24 h		<24 h	>24 h			
Bonneville Dam								
2002	0	7	1.7	0	29	9.6	2	1
2003	0	4	1.1	1	22	11.1	1	1
2004	0	8	2.2	1	12	8.2	4	0
2005	0	30	5.2	0	1	14.3	0	2
The Dalles Dam								
2002	2	6	9.5	6	62	9.9	0	0
2003	0	1	7.7	6	43	10.9	0	1
2004	0	1	4.0	7	36	10.5	0	1
2005	0	1	9.1	4	21	6.0	0	0
John Day Dam								
2002	0	2	2.7	2	6	1.7	0	0
2003	0	0	0.0	2	5	2.2	0	0
2004	0	0	0.0	3	8	3.4	0	0
2005	0	0	0.0	3	7	3.0	0	1
McNary Dam								
2002	2	5	3.1	0	9	3.7	0	1
2003	0	2	1.6	0	10	6.3	0	2
2004	0	1	0.7	0	6	4.8	0	1
2005	0	0	0.0	0	0	0.0	0	2

DISCUSSION

Upriver-migrating adult salmon show varied responses to obstacles such as dams, depending on the structure itself and its operation, as well as the environmental conditions at the time it is encountered. Despite the variability in stimuli and individual fish responses, radiotelemetry techniques applied over multiple seasons can reveal trends in fish behavior interactions. With seven years of fall Chinook salmon passage behavior and fishway use available in the lower Columbia River, it is the consistency of fish response to the dams regardless of environmental factors that stands out.

The ability of fall Chinook salmon to traverse fishways at hydropower dams is of utmost importance in the impounded Columbia River. Passage efficiency of adult salmon must be high for populations to persist. Of the four dams on the lower Columbia River, McNary Dam hindered the fewest fish; passage efficiency averaged over 96% in this study and in previous years (Burke et al. 2005). Likewise, passage efficiencies were consistently high at Bonneville Dam, averaging just over 94% during this study and previous work (Burke et al. 2005). John Day Dam posed the biggest challenge to passage, with efficiencies under 90% in two of the four years we examined. There was relatively small variability among years at all lower Columbia River dams.

Passage efficiency values were higher and interannual variability decreased when only fish that actually entered a fishway were used. Passage efficiencies were over 95% at Bonneville, The Dalles, and McNary Dams for these fish; the same patterns were observed for fall Chinook salmon at these dams in previous years (Burke et al. 2005). Variation in attraction to the fishways between years, or the ability of fish to locate and enter fishways, may be the most important source of interannual variation that affects passage efficiency. Therefore, external factors such as dam operations and environmental conditions would have the most impact on passage efficiency while fish are in the tailrace. Additional factors resulting in decreased passage efficiency for fish that did not enter fishways are: 1) harvest below the dams, and 2) fish that approach dams after overshooting a downstream tributary and turning around before entering a fishway (Keefer et al. 2006a).

Passage efficiency patterns for fish at John Day Dam were notably different than at the other dams. Interannual variability at this dam was not dependent on fish entering the fishway, indicating that factors affecting passage occurred within the fishway at this dam, instead of in the tailrace. The large number of turn-arounds per fish gives us another indication of trouble in the John Day Dam fishways. Unfortunately, turn-around data is not available for 2005, a year when we observed higher passage efficiency than any previous years. Fall Chinook salmon are not the only migrating fish that change their behavior at John Day Dam. Elevated temperatures within the dam fishways have increased exit rates of steelhead (Keefer et al. 2003b) at this dam. Factors other than temperature (i.e. flow, turbidity, oxygen levels, corner angle, or construction) may also impact passage efficiency of fall Chinook salmon and warrant additional directed research at John Day Dam.

After fallback events, overall passage efficiencies were much lower than on initial attempts. Some portion of this is explained by fish intentionally moving downstream after overshooting their natal tributary and not attempting to reascend (see Boggs et al. 2003). If fish re-entered the fishways after a fallback, passage was slower on subsequent attempts, and efficiencies were similar but still lower than for fish that made only one attempt. Additionally, passage efficiency on reascension was lower for fall Chinook salmon than comparable rates for spring/summer Chinook salmon and steelhead (Boggs et al. 2004). While passage efficiency at John Day Dam has historically been low on reascension even for fish re-entering the fishway (Burke et al. 2005; Boggs et al. 2004), that was not the case in our study. Sample sizes were small, but fish that entered the fishway following a fallback typically ascended the entire fishway, even at John Day Dam. For the large number that failed to re-enter the fishways, many were last detected in the Deschutes, White Salmon, or Klickitat Rivers, supporting the idea that these fish overshot their destinations.

Differences in size, structure, operation, and receiver configurations among dams resulted in wide variation in the passage time estimates we computed at each structure. For the total passage from arrival at the dam base to fishway exit at the top, fall Chinook salmon consistently passed McNary Dam much faster than the other dams. Possible reasons include: 1) fish learned from passages at downstream fishways, 2) they had higher motivation as a result of being closer to spawning grounds, or 3) they encountered more favorable environmental conditions later in the season. However, the passage at McNary Dam covers a relatively short distance from downstream receivers to the dam structure, and involves negotiating a smaller, less complex fishway than at many of the other dams.

Overall passage times at all dams were generally longest in 2002, the year with the highest flow of those examined, and one in which tagged fish were smaller than in other years. While swimming speed may increase with body size (Brett 1995), the likelihood of passing is inversely related to size (Caudill et al. in press). We did not see a change in passage efficiency with the smaller fish in 2002, only in passage time. The correlation of high flow and longer passage times is expected based on risk analyses (Caudill et al. in press) and was also noted in previous years (Burke et al. 2005).

Dam passage time can be divided into: 1) time spent below the dam and 2) time spent negotiating fishways. Fish at John Day Dam had high median passage times overall, but time spent below the dam was shorter than at other dams. So, fish entered the dam readily and the difference in passage time between John Day Dam and the other dams occurred after fish were in the fishways. John Day Dam also had the slowest median passage times for both steelhead and spring/summer Chinook salmon (Keefer et al. 2002; Bjornn et al. 2000). Temperature differentials between the forebay and the ladder at John Day Dam, as well as warm water temperatures within the Oregon shore ladder have been correlated with poor performance at this dam (Keefer et al. 2003b).

After fish entered the fishways, the time from first entrance to dam passage was shortest at The Dalles Dam. While fall Chinook salmon may have experienced delays finding or entering the fishways, their upstream passage through the fishways was most direct at this dam. Fishway passage time at McNary Dam was also short. Similarly, steelhead passed McNary Dam quickly (Keefer et al. 2002), and spring/summer Chinook salmon passed most rapidly at Bonneville and The Dalles Dams (Bjornn et al. 2000). It is impossible to directly compare these passage times with past reports, as they have reported time from first approach to dam passage rather than first entrance. We found that using the fishway entrances reduces some of the dependence of data on receiver locations and eliminates counting fish swimming past a receiver as a relevant behavior. This calculation eliminates time between approach and entrance, which is often artificially long as fish are deemed approaching when they are in fact milling at the base of the dam.

Interannual variability in passage duration was low at all dams except for John Day Dam, where median passage time was 8h longer in 2002 than in 2004 and 2005. While the majority of fall Chinook salmon passed each of the four dams in less than 24h, at John Day Dam in 2002 only 51% passed within this time. The 2002 passage time numbers are similar to those previously reported (Burke et al. 2005), so passage times in 2003-2005 were considerably faster than in previous years. Collection channel turn-arounds were more prevalent at John Day Dam in 2002, and the ladder section presented more difficulties than in the other years examined.

Passage times following fallback events were substantially longer than on first attempts. The difference was significant despite sample size limitations. This was most apparent when the time analyzed incorporated re-approach and milling behaviors below the dam. Each additional attempt requires more energy expenditure and may result in slower passage times. Alternatively, fallback fish may represent those that are poor navigators and thus move in a less directed and circuitous manner. While the amount of fallbacks, reascension times, and overshoot behavior have been examined (Boggs et al.

2004, Keefer et al. 2006b), effects of cumulative stress and the resulting impact on fall Chinook salmon fitness has not been adequately assessed.

At Bonneville Dam, most fall Chinook salmon used powerhouse entrances to fishways which are closer to the shores along which fish migrate (Dawm and Osborne 1998; Hinch et al. 2002) as opposed to spillway entrances near the middle of the river. Entrances at the other dams are all shoreline oriented, but there were distinct preferences for entering the Oregon shore fishways at The Dalles, John Day, and McNary Dams. If fall Chinook salmon sampled were largely destined for right-hand exiting tributaries, they might show such preference (Keefer et al. 2006b), but the severity of the disparate use and the strength of the Hanford Reach population in the fall Chinook run implicate additional factors.

All entrances were used at Bonneville Dam, but fall Chinook salmon disproportionately used the Washington shore fishway. Except for the fall of 2000, the Washington shore ladder has consistently been preferred by these fish (Burke et al. 2005). Fish tagged at Bonneville Dam were captured from the fishway on the Washington shore, so there may have been a bias towards its use. Despite the same potential bias, spring/summer Chinook salmon undergoing the same tag and release regime did not show a preference on re-approach at Bonneville Dam (Keefer et al. 2006b). Moreover, fall Chinook salmon, preferences in fishway use at Bonneville Dam have been inconsistent in previous years (Burke et al. 2005). Powerhouse priority was at PH2 during this study, and this, along with environmental conditions, may have influenced fishway use at Bonneville Dam more than fish origin or experience. The position of open orifice gates has not affected entrance use in past studies (Burke et al. 2005), so was not considered here.

The proportional relationship between approaches, entrances, and passage events appeared consistent for each fishway examined. At Bonneville, John Day, and The Dalles Dams, the number of approaches, entrances, and passage within a year were similar, indicating that after a fish chose a fishway, it proceeded all the way through it on that attempt. While entrance efficiency varied, it was generally highest at these three dams and fish usually entered upon approach.

At McNary Dam, the fish exhibited a different pattern of use. At the south ladder overall use was higher than the north ladder. However, more fish approached the south ladder than successfully entered it, and more entered it than passed all the way through it. After approaching, and even entering, many fall Chinook salmon at McNary Dam exited from the south ladder and moved to the north ladder to pass the dam. Apparently there is some impediment to completely navigating the south ladder at this dam. This is a longstanding pattern, as it was visible for fall Chinook salmon at McNary Dam in Burke et al. (2005) as well.

Fall Chinook salmon passing over The Dalles Dam had the greatest likelihood of falling back downstream (5.5-9.5%) of the dams examined (as in Burke et al. 2005). All four dams had different fallback rates, but they were remarkably consistent among years. The most notable difference was for fish that were released above Bonneville Dam in that they fell back downstream at much higher rates than fish released below the dam. This may have been in response to initial disorientation upon release, or entrainment in forebay flows different from those acting upon fish exiting the ladders.

Most fish only fell back once at a given dam. For those released downstream of a dam, at most 1.5% (The Dalles Dam, 2003) fell back more than once. Even the group of fish released above Bonneville Dam had low secondary fallback rates, 1.9%, this suggests that fallback behavior in these fish is related more to overshoot behavior or temporary disorientation than to dam-induced disruption of migration.

The majority of fallback events occurred more than 24 h after fish passed a dam, further indicating large scale orientation and homing/searching movements (Keefer et al. 2006a, Boggs et al. 2004). Yet, the particular fishway used to pass a dam can influence fallback rates for shorter time frames (Reischel and Bjornn 2003). For fish that fell back soon after passing, fish fell back more at Bonneville and McNary Dams after passing through the Oregon shore ladders, and at The Dalles and John Day Dams after using Washington shore ladders. A similar pattern was noted by Burke et al. (2005).

The highest fallback rates we recorded for fish released below a dam were in 2005 at Bonneville Dam. Fish exiting from the Bradford Island fishway are in the forebay of the spillway, resulting in higher fallback rates (Reischel and Bjornn 2003). Releases directly into the forebay further demonstrate this propensity. With respect to McNary Dam, fall Chinook salmon exhibited an apparent tendency to overshoot their natal stream, leading to fallbacks at this dam (Boggs et al. 2003). These were often associated with Oregon shore passage due to heavier use of that fishway, but may also relate to potential impediments to McNary Dam south ladder passage. Slow passage times affect spawning success (Caudill et al. in press), and fallbacks exacerbate this problem for anadromous salmonids.

Fall Chinook salmon spent most of their time at a project below the dam structure rather than within the fishway proper at all dams. Holding below the dam leaves fish particularly vulnerable to predation, especially for spring/summer Chinook salmon exposed to sea lions at Bonneville Dam. Finding entrances and moving into fishways may not be the whole problem; time below the dam may be exacerbated by diel behaviors in which some fish exit fishways at night (see Naughton et al. 2005 for similar behavior in sockeye salmon).

Within the fishways, cumulative time spent in the ladder segment was typically longer than time in the collection channel and transition pool segments. However, at John Day Dam, where time from first entrance to passage was particularly long, time in the collection channel was long relative to analogous segments at other dams. Interannual variability in time spent at each segment was generally low. However, at McNary Dam in 2004 fish spent much more time in the collection channels and transition pools than in other years and exhibited quick passage through the ladder segment. Higher flow out of the Snake River may have disproportionately affected McNary Dam passage in that year.

While fall Chinook salmon generally hold position more within the ladder segment than in other fishway sections, the locations of turn-arounds provides some additional insight into the reason fish take longer to pass a given segment of the fishway. Only rarely do fish pass straight through all segments of a fishway on a given passage attempt. As was seen by Burke et al. (2005), total time spent in the collection channel and transition pool segments was low, but there are also more direction reversals in these segments than in other segments. The transition pool has previously been implicated as a common turn around point (Bjornn et al. 1998b, Keefer et al. 2003, Naughton et al. 2007). This was particularly true at John Day Dam. However, the median number of times a fish turned around per section at this dam that we reported was lower than previously reported (Burke et al. 2005).

Two possible explanations for turning behavior are lack of attractant flow (Naughton et al. 2007) or large temperature differentials between segments (Peery et al. 2003). Fish tend to turn around at the downstream end of pools rather than at the transition between segments, suggesting that lack of attractant flow may contribute most to this behavior in the collection channel and transition pool segments (Naughton et al. 2007).

Passage success through the ladder segment at all dams was typically high, particularly in 2004. However, at The Dalles Dam north fishway, it was substantially lower than in previous years (Burke et al. 2005), with success as low as 12% (in 2003). We are not aware of any changes made to the north fishway in that year. Conversely, success rates through the ladder segment of the south fishway at McNary Dam increased relative to previous years (Burke et al. 2005).

This report highlights the differences in behavior of fall Chinook salmon during these years versus those previously reported (Burke et al. 2005), but the consistency of behavior among all years is remarkable. From timing of passage to the locations of turn arounds within fishways, responses were often consistent despite environmental fluctuation and sampling variation. Previous work has been done to improve passage for adult salmonids; however, more recent changes to the dam structures have focused on improving juvenile salmonid passage. The work presented here identifies a few key areas where additional structural or operational modifications to fishways could improve the rate and efficiency of adult fall Chinook salmon passage at Lower Columbia River dams.

ACKNOWLEDGEMENTS

We thank Steve Lee and his crew for tagging the Chinook salmon at Bonneville Dam. Thanks to Ken Tolotti and Carol Morat for maintaining and downloading hundreds of receivers throughout Washington, Oregon, and Idaho. Thanks to Mike Jepson and his crew for interpreting the telemetry data, fish by fish. This project would not have been possible without the economic support of the U.S. Army Corps of Engineers. We thank Doug Dey, David Clugston, and Marvin Shutters for technical and adminstrative help.

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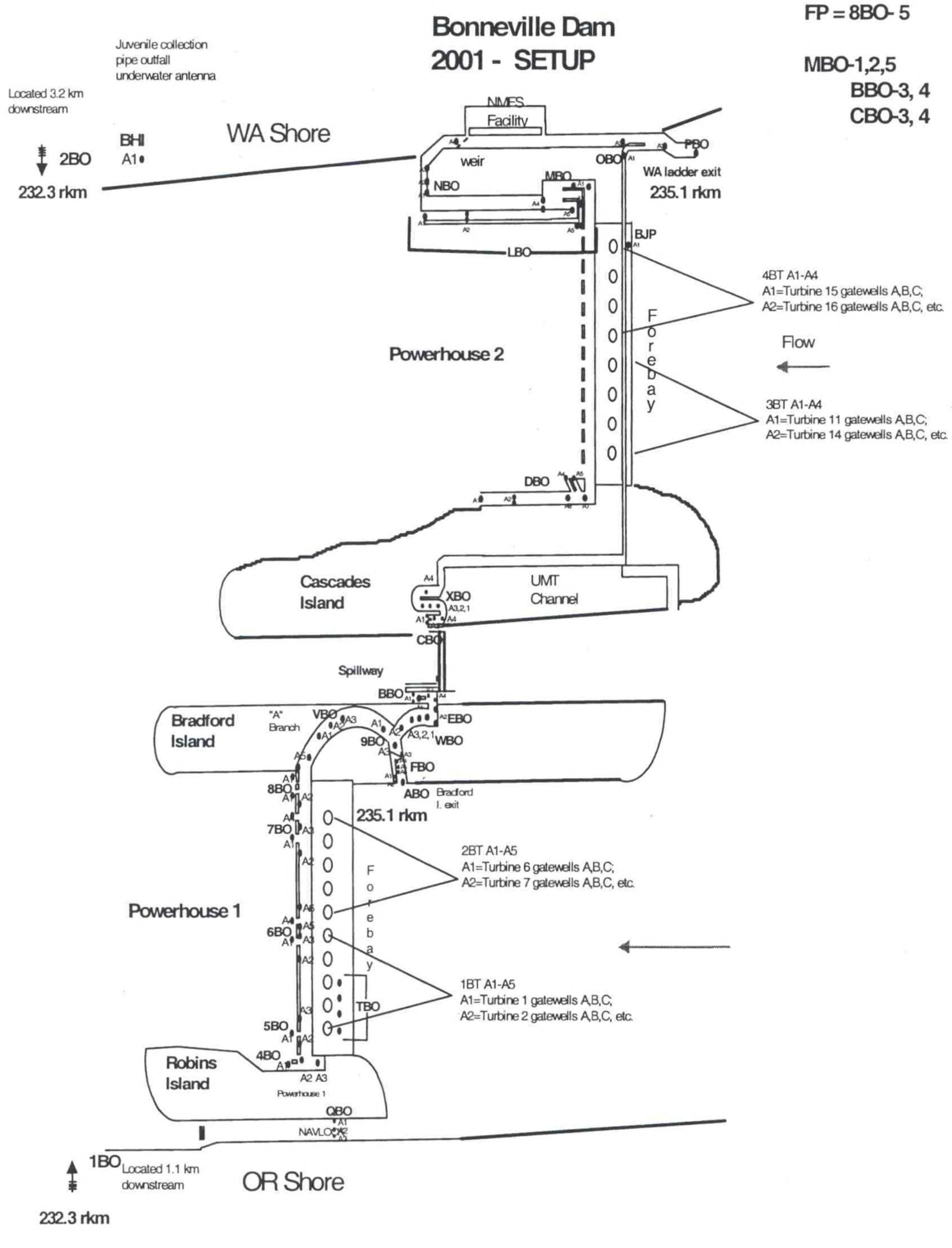
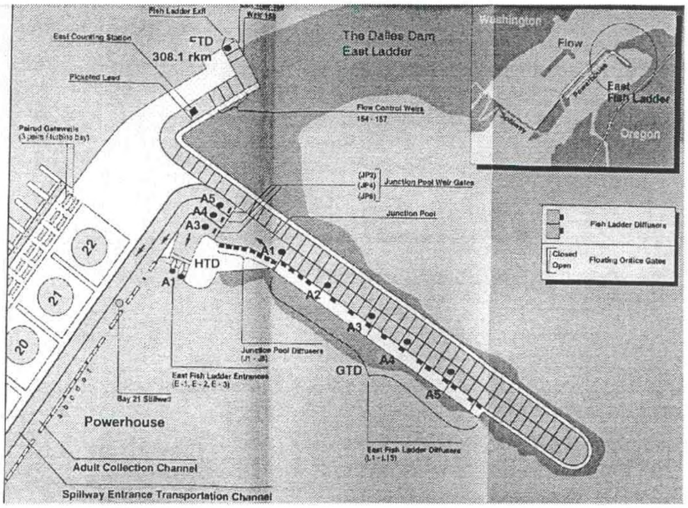
APPENDIX: 2001 Dam Antenna Locations



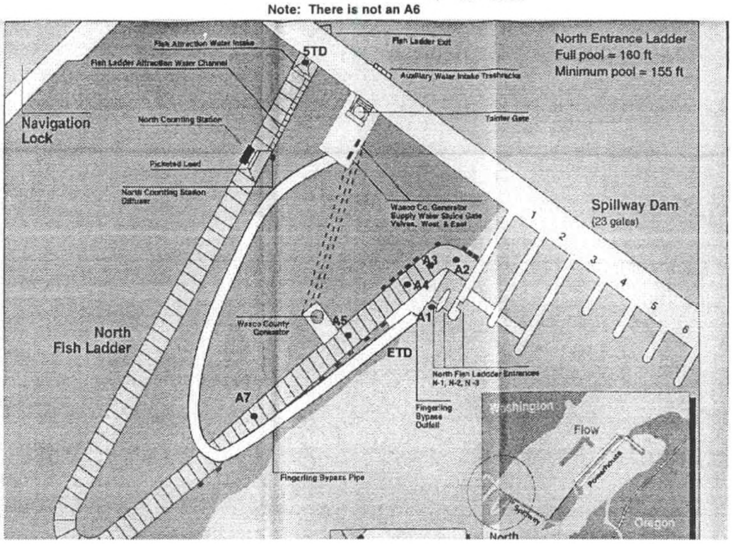
Bonneville Dam antenna setup.

The Dalles Dam - 2001 setup FP = HTD-3, 4, or 5
Note: orifice gates are closed

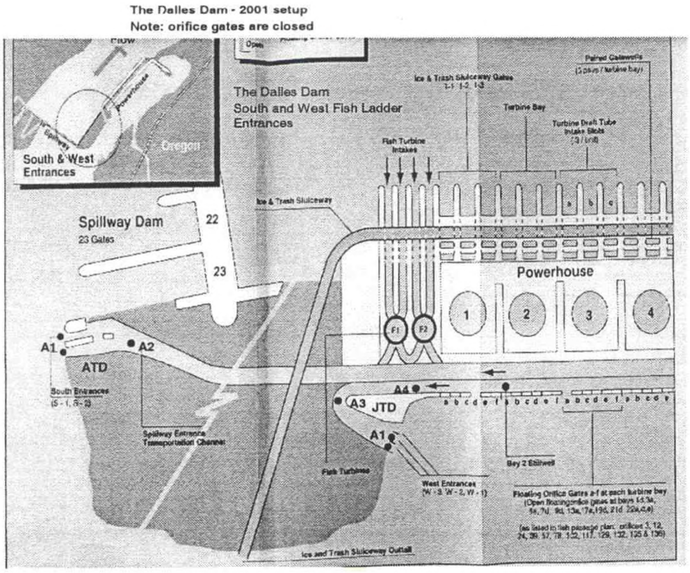


The Dalles Dam East Ladder

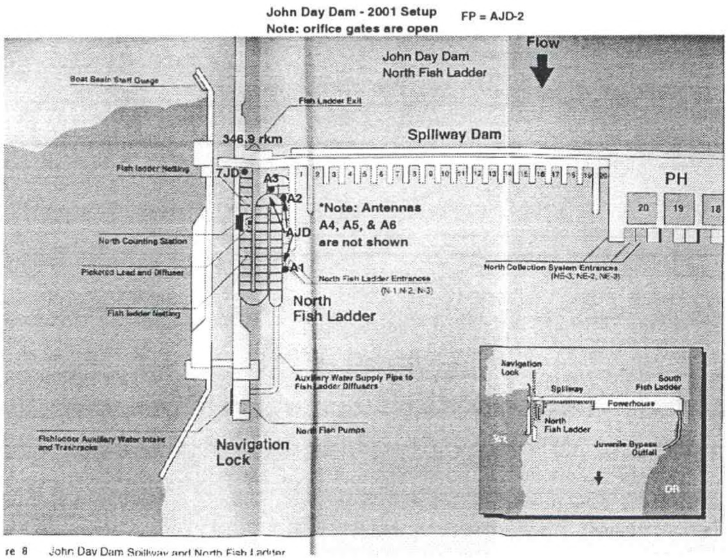
The Dalles Dam - 2001 Setup FP = ETD-2
Note: There is not an A6



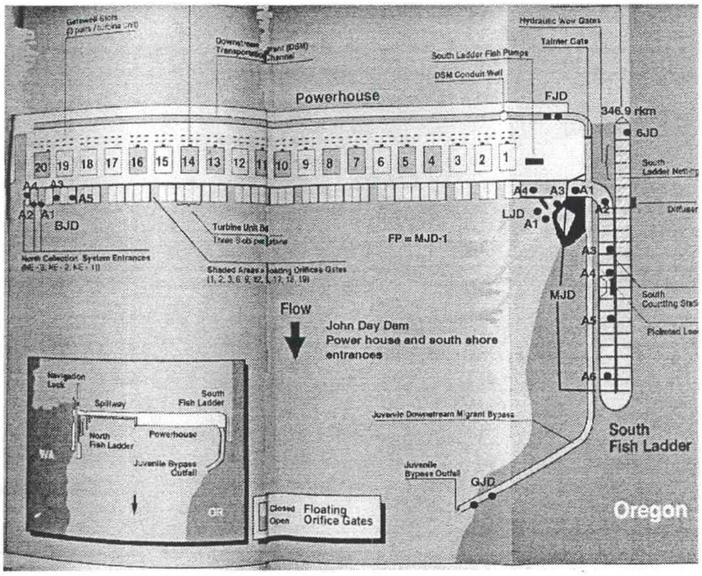
The Dalles Dam Spillway



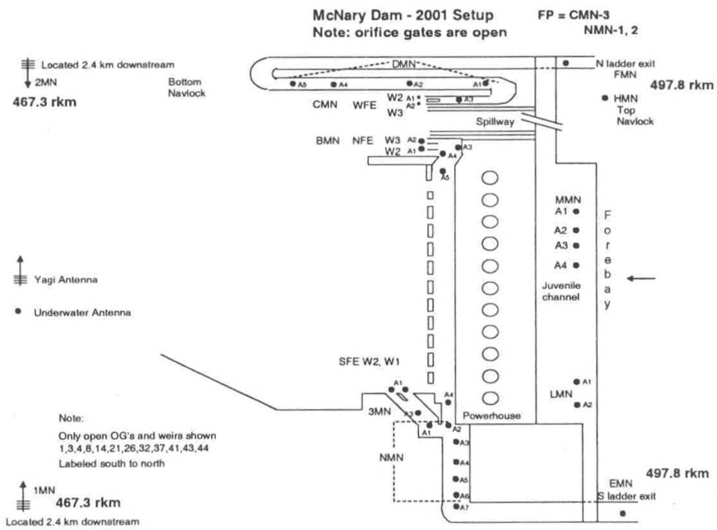
The Dalles Dam South and West Ladder Entrances



John Day Dam North Ladder



John Day Dam South Ladder



McNary Dam