Passage Behavior and Survival for Hatchery Yearling Chinook Salmon at Lower Monumental Dam, 2004

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EXECUTIVE SUMMARY

In 2004, NOAA Fisheries Service conducted research to evaluate passage behavior and estimate relative survival for radio-tagged, river-run hatchery yearling Chinook salmon at Lower Monumental Dam on the Snake River. Fish were collected, surgically tagged with a radio transmitter, and PIT tagged at Lower Monumental Dam. The treatment group was comprised of 1,916 radio-tagged fish released 7 km upstream from Lower Monumental Dam. The reference group was comprised of 2,019 radio-tagged fish released into the tailrace of Lower Monumental Dam.

Releases occurred during both daytime and nighttime operations for 25 d from 30 April to 26 May. Project operations during the evaluation included bulk spill 24-h per day for the initial 13 d followed by no spill during the final 12 d of the study. During bulk spill operations, mean passage conditions were as follows: 72 kcfs river flow, 38% spill (as a percent of total project discharge), spillway gate opening of 6 stops, and 440 ft msl tailwater elevation. During no spill operations, average passage conditions were 78 kcfs river flow and 441 ft msl tailwater elevation.

Median forebay residence time was significantly longer during no spill than during bulk spill (1.10 vs. 0.09 d; $P < 0.001$). During bulk spill, 92% of test fish first approached the spillway portion of the dam. During no spill periods, fish approached the spillway and powerhouse in similar proportions. During both bulk spill and no spill, greater than a third of the fish approached the middle of the dam in the vicinity of spillbays 7 and 8. Passage-route distribution during bulk spill was 87% through the spillway, 7% through the juvenile bypass system, 2% through turbines, and 4% through undetermined routes.

Within the spillway, the majority (62%) passed through either spillbay 3 or 7. Passage-route distribution during no spill was 72% through the juvenile bypass system and 28% through the turbines. Within the powerhouse the majority (43%) passed the dam by entering turbine intake 1 or 4.

For fish with a known passage route, fish guidance efficiency was 81.7% during bulk spill and 72.1% during no spill. Fish passage efficiency was 98.4% during bulk spill and 72.1% during no spill. Median tailrace egress was 10 min for bulk spill and 8 min for no spill. Spill efficiency during bulk spill was 89.3%, and spill effectiveness was 2.33 to 1.

Relative survival was estimated from detections of treatment and reference groups at a series of downstream telemetry transects between Lower Monumental Dam on the lower Snake River and John Day Dam on the lower Columbia River. Pooled relative dam survival was significantly higher during bulk spill (0.919; 95% CI, 0.882-0.956) than during no spill (0.750; 95% CI, 0.699-0.802, $z = 5.20$; $P < 0.001$). Estimated spillway survival during bulk spill was 0.961 (95% CI, 0.924-0.999). During no spill, relative survival was estimated at 0.911 (95% CI, 0.857-0.965) for fish passing through the powerhouse (turbines and juvenile bypass system combined), 0.922 (95% CI, 0.862-0.983) for fish passing via the bypass system, and 0.881 (95% CI, 0.789-0.973) for fish passing turbines at Lower Monumental Dam.

CONTENTS

EXECUTIVE SUMMARY. iii

INTRODUCTION. 1

METHODS. 3
- Study Area. 3
- Fish Collection, Tagging, and Release.. 3
- Data Processing and Analysis. 6
  - Forebay Residence Time. 6
  - Approach and Passage Distribution. 8
  - Fish Passage Performance Metrics. 10
  - Tailrace Egress. 10
  - Survival Estimates. 10

RESULTS. 13
- Fish Collection, Tagging, and Releases. 13
- Project Operations. 13
- Forebay Residence Time. 21
- Approach and Passage Distribution. 23
- Fish Passage Performance Metrics. 27
- Tailrace Egress. 27
- Survival Estimates. 28
  - Dam Survival. 28
  - Route-Specific Survival. 28
  - Avian Predation. 28

DISCUSSION. 30

RECOMMENDATIONS. 35

ACKNOWLEDGMENTS. 35

REFERENCES. 37

APPENDIX A: Evaluation of Study Assumptions. 45

APPENDIX B: Ice Harbor Dam Arrival Distributions for Treatment and Reference Release Groups with Significantly Different Travel Timing. 55

APPENDIX C: Telemetry Data processing and Reduction Flowchart. 63

INTRODUCTION

The Columbia and Snake River Basins have historically produced some of the largest runs of Pacific salmon *Oncorhynchus* spp. and steelhead *O. mykiss* in the world (Netboy 1980). More recently, however, some stocks have decreased to levels that warrant listing under the U.S. Endangered Species Act of 1973 (NMFS 1991, 1992, 1998, 1999). Factors associated with human activities that have contributed to the decline and loss of some salmonid stocks include overfishing, hatchery practices, logging, mining, agricultural practices, and dam construction and operation (Nehlsen et al. 1991). A primary focus of recovery efforts for depressed stocks has been assessing and improving fish passage conditions at dams.

The spillway has long been considered the safest passage route for migrating juvenile salmonids at Columbia and Snake River dams. Holmes (1952) reported survival estimates of 96 (weighted average) to 97% (pooled) for fish passing Bonneville Dam spillway during the 1940s. A review of 13 estimates of spillway mortality published through 1995 concluded that the most likely mortality rate for fish passing standard spillbays ranges from 0 to 2% (Whitney et al. 1997). Similarly, recent survival studies on juvenile salmonid passage through various routes at dams on the lower Snake River have indicated that survival was highest through spillways, followed by bypass systems, then turbines (Iwamoto et al. 1994; Muir et al. 1995a,b, 1996, 1998, 2001; Smith et al. 1998). Pursuant to the National Marine Fisheries Service (NMFS) 2000 Biological Opinion (NMFS 2000), project operations at Lower Monumental Dam have relied on a combination of voluntary spill and collection of fish for transportation to improve hydrosystem-passage survival for migrating juvenile salmonids.

The current spill program at Lower Monumental Dam calls for voluntary spill to achieve goals for both fish passage efficiency and total dissolved gas levels. In 2002, the U.S. Army Corps of Engineers (USACE) modified the spillway at Lower Monumental Dam by adding flow deflectors to the end bays in conjunction with a contract to repair damage to the stilling basin. With the addition of end-bay flow deflectors, new spill patterns using all eight bays were developed prior to the 2003 juvenile salmonid migration. In 2003, after construction of end-bay deflectors at Lower Monumental Dam, a radiotelemetry study was initiated to further investigate spillway survival (Hockersmith et al. 2004).

The spill pattern was distributed uniformly among spill bays, and the spill cap was generally found to be 25-40 kcfs (often on the basis of not exceeding the total dissolved gas (TDG) limit of 120% in the tailrace of Lower Monumental Dam or 115% in the forebay of Ice Harbor Dam). This spill discharge range remained relatively constant

throughout the evaluation. Between the first half and the second half of the study, average total river flow doubled, powerhouse discharge increased threefold, and tailwater elevation increased by 4 feet, whereas the volume spilled and spillway gate openings remained relatively constant. In 2003, Hockersmith et al. (2004) observed significantly higher spillway survival (0.987 vs. 0.834) during periods of higher total river flow, powerhouse discharge, and tailwater elevation at Lower Monumental Dam. This suggests that even though spill discharge per bay did not change appreciably, tailwater elevation appeared to influence spillway survival.

Coupled with contrasting spillway survivals of 0.978 in 2000 and 0.895 in 2002 for yearling Chinook at Ice Harbor Dam (Eppard et al. 2002, 2005a), it has become increasingly apparent that spillway survival for fish passing spill bays with deflectors can be high or low, depending on tailwater elevation and other factors. Due to the relatively low spillway passage survivals observed when project discharge is low, a new spill pattern, hereafter referred to as bulk spill, was developed for Lower Monumental Dam in 2004. By increasing the volume spilled in each spillbay, the bulk spill pattern increases submergence of the flow deflectors, creating a condition analogous to increased tailwater elevation. In general, for a given volume of spill, bulk spill patterns reduce the number of individual spillbays used and increase the discharge per bay.

The proposed study design was to examine smolt passage and survival at Lower Monumental Dam during voluntary spill under two different spill patterns. The spill patterns would alternate between a flat spill pattern and a bulk spill pattern for 25 days using a randomized 4-day block design. However, due to low flows in the Snake River, voluntary spill at Lower Monumental Dam was limited to the first half of the study. Therefore, the study design was changed to examine smolt passage and survival during early periods of bulk spill and later periods of no spill. The partitioned nature of project operations at Lower Monumental Dam may have affected the results of comparisons between the two spill conditions, because a randomized experimental design was not possible. Results of this study will be used to inform management decisions to optimize survival for juvenile salmonids arriving at the dam. This study addressed research needs outlined in SPE-W-00-1 of the USACE, Northwestern Division, Anadromous Fish Evaluation Program.

METHODS

Study Area

The study area included a 135-km river reach from Lower Monumental Dam on the lower Snake River to Irrigon, OR on the lower Columbia River (Figure 1). Lower Monumental Dam, the second dam above the mouth of the Snake River, is located 67 km above the confluence of the Snake and Columbia Rivers.

Fish Collection, Tagging, and Release

Radio tags were purchased from Advanced Telemetry Systems Inc.,[1] had a user-defined shut-off after 10 d, and were pulse-coded for identification of individual fish. Each radio tag measured 16 mm in length by 6 mm in diameter and weighed 1.3 g in air.

River-run, hatchery yearling Chinook salmon were collected at the Lower Monumental Dam smolt collection facility from 29 April to 25 May. We used only hatchery-origin yearling Chinook salmon that were not previously PIT tagged, that had no visual signs of disease or injury, and that were 15 g or larger. Fish were anesthetized with tricaine methanesulfonate (MS-222) and sorted in a recirculating anesthetic system. Fish for treatment and reference release groups were randomly selected from the daily smolt-monitoring sample and transferred through a water-filled, 10.2-cm hose to a 935-L holding tank. Following collection and sorting, fish were maintained via flow-through river water and held for 24 h prior to radio tagging.

Fish were surgically tagged with a radio transmitter using techniques described by Adams et al. (1998a). A PIT tag was also inserted with the radio transmitter so that test fish would be separated by code in the fish collection system and returned to the river (Marsh et al. 1999). Surgical tagging was conducted simultaneously at four tagging stations. During a 4-h shift, approximately 238 fish were tagged.

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1 Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

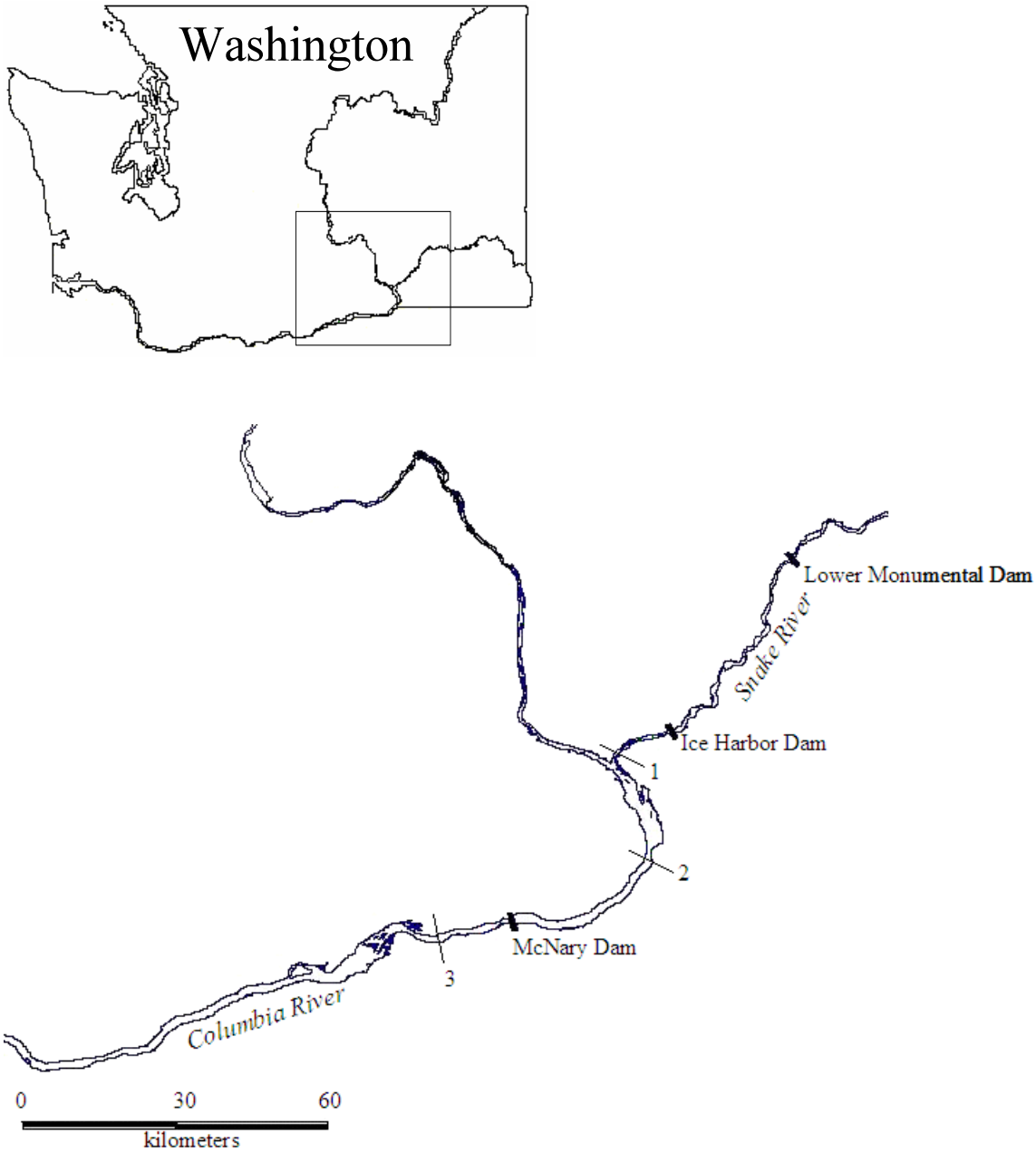

Figure 1. Detail of the study area showing locations of radiotelemetry transects used for estimating yearling Chinook salmon survival at Lower Monumental Dam in 2004. Transects included: 1 = mouth of the Snake River; 2 = Port Kelley and 3 = Irrigon; OR. The forebay, tailrace, and all routes of passage at Ice Harbor Dam and the forebay of McNary Dam were also monitored.

Immediately following tagging, fish were placed into 19-L, aerated recovery containers (two fish per container) and held a minimum of 18-h for recovery and determination of post-tagging mortality. Fish holding containers were perforated with 1.3-cm holes in the top 30.5 cm of the container to allow exchange of water during holding. Recovery containers were then closed and transferred to a 1,152-L holding tank designed to accommodate up to 28 containers. All holding tanks were supplied with flow-through water during tagging and holding and were aerated with oxygen during transport to release locations.

After the post-tagging recovery period, fish were moved in their recovery containers from the holding area to release areas (7 km upstream from Lower Monumental Dam or into the tailrace). To provide mixing of treatment and reference groups, treatment groups were released all at one time twice daily (daytime and nighttime periods), and reference release groups were released over a 4-h period twice daily (daytime and nighttime periods).

Treatment and reference groups were transferred water-to-water from holding tanks to a release tank mounted on an 8.5 × 2.4-m barge, transported either 7 km upstream or 1 km downstream from Lower Monumental Dam, and released mid-channel. The reference-group release location was determined from operations testing on a 1:55 scale model of Lower Monumental Dam at the USACE Engineer Research and Development Center in Vicksburg, MS. Specific operating conditions were not requested for release days, and project operations at Lower Monumental Dam included voluntary bulk spill from 29 April through 14 May and no spill from 14 through 26 May. (On 14 May, bulk spill operation was conducted from midnight to 0600 and no spill operation from 0600 to midnight.)

Project operation data were collected every 5 min by the USACE. Project operations assigned to treatment fish corresponded to conditions closest to time of passage. For treatment fish that passed the dam without a specific passage time, project operations were assigned based on conditions closest to the time of first detection recorded in the tailrace. For treatment fish that did not pass the dam, project operations corresponded to conditions closest to the time of forebay entry. Operational conditions assigned to reference fish corresponded to conditions closest to time of release.

Data Processing and Analysis

Telemetry data were retrieved through an automated process that downloaded networked telemetry receivers up to four times daily. Data processing and reduction are summarized in Appendix Figure C1. After downloading, individual data files were compressed by recording the first time a radio-tagged fish was detected and counting the number of detections where the time difference between adjacent detections was less than or equal to 1 min. When the difference between adjacent detections became greater than 1 min, a new line of data was created. All compressed data were combined and loaded into a database, where automated queries and algorithms were used to remove erroneous data. On the cleaned data set, detailed detection histories were created for each radio-tagged fish. These detection histories were used to calculate arrival time in the forebay, forebay approach pattern, passage route and timing, tailrace exit timing, and timing of downstream detections for individual radio-tagged fish.

Forebay Residence Time

Forebay arrival time was based on the first time a fish was detected on the forebay entry line at the upstream end of the boat restricted zone (BRZ) at Lower Monumental Dam. Forebay residence time was determined for fish that had been released upstream from Lower Monumental Dam, detected entering the forebay, detected in a passage route, and detected in the immediate tailrace on either the stilling-basin or tailrace-exit telemetry receivers (Figure 2). Forebay residence time for individual fish was measured as the time between the first detection on the forebay entrance line at the upstream end of the BRZ to the last detection in a passage route. Forebay residence data were partitioned by project operation based on operations at the time a fish passed the dam.

Hypothesis testing to compare specific cohorts was evaluated using permutation methods (Efron and Tibshirani 1993), with the null hypothesis that true median forebay residence time was not significantly different between a particular pair of cohorts. Data from the two cohorts were pooled, and a permutation of two samples (using the original sample sizes) was randomly generated without replacement. The medians of the two permuted samples were calculated as well as their difference. We repeated this process 1,000 times resulting in 1,000 permutation median difference estimates. We then calculated *P*-values as the proportion of times these differences were more extreme (usually larger) than the observed difference (doubled for a 2-tailed test).

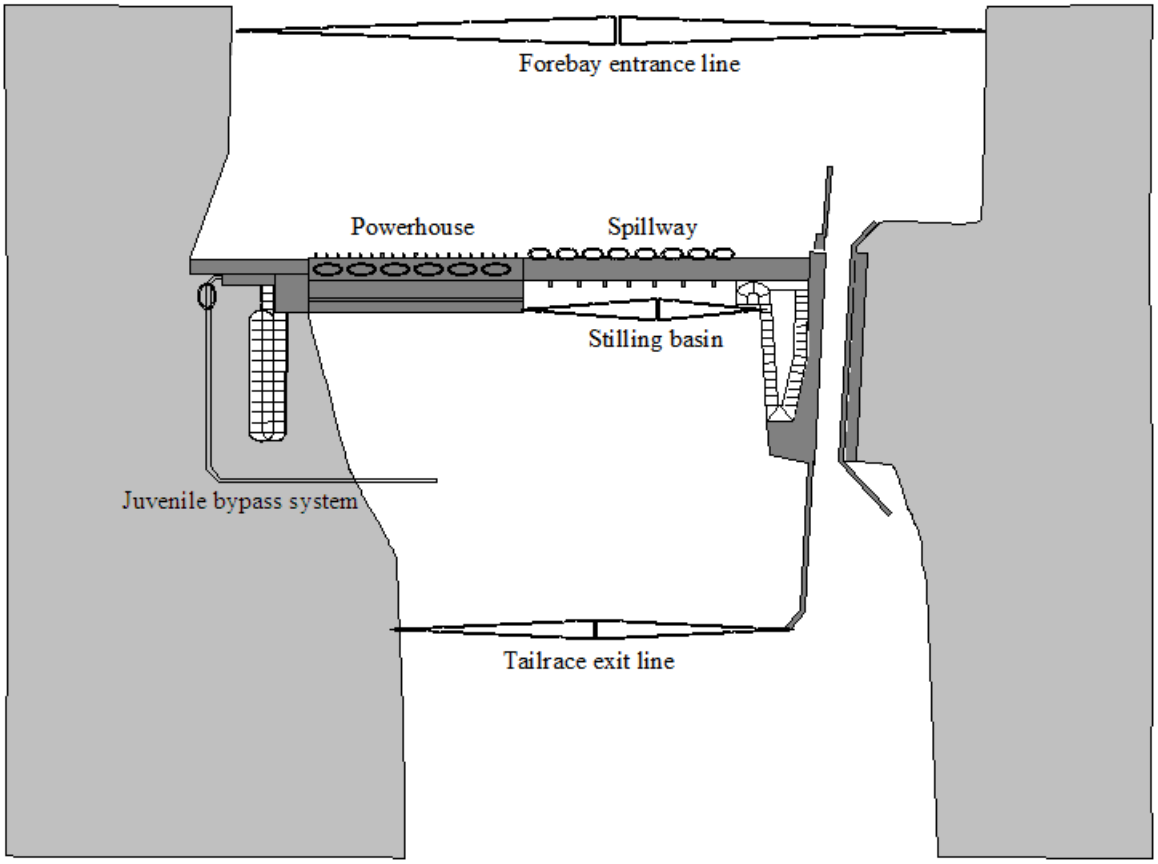

Figure 2. Plan view of Lower Monumental Dam showing approximate radiotelemetry detection zones in 2004 (Note: Dashed ovals represent underwater antennas. Dashed triangles represent aerial antennas).

Confidence intervals (95%) for individual medians and the differences in median forebay residence times were calculated using bootstrap methods (Efron and Tibshirani 1993). We generated 1,000 bootstrap medians for each group and the difference between the medians, then estimated 95% confidence intervals as the 2.5th and 97.5th percentiles of the ordered distribution of 1,000 medians or differences. When meaningful bias was detected, an adjustment was made to correct for it and bias-corrected, or BCA, intervals were used as detailed in Efron and Tibshirani (1993).

Approach and Passage Distribution

Approach patterns were established based on the first detection at either underwater dipole spillway antennas (Beeman et al. 2004) or on stripped coax underwater antennas (Knight et al. 1977) on the standard-length traveling screens.

Route of passage through the dam was based on the last time a fish was detected on a passage-route antenna and was assigned only to fish that were subsequently detected in the tailrace on either the stilling-basin or tailrace-exit telemetry receivers (Figure 2). Tailrace detections were needed to validate passage because it was possible for fish to be detected on a passage-route receiver while still in the forebay. Spillway passage was assigned to fish that were detected in the tailrace of the dam after last being detected in the forebay on 1 of the 8 antenna arrays deployed along each of the two pier noses on the sides of individual spillbays. Similarly, powerhouse passage was assigned to fish last detected in a turbine intake prior to detection in the tailrace of the dam.

Powerhouse passed fish were further partitioned into either turbine or the juvenile bypass system (JBS) passage based on the presence or absence of JBS detections (PIT-tag or telemetry detection). Fish that were assigned to powerhouse passage without detections in the JBS were assigned to turbine passage. Passage distribution included fish released upstream from Lower Monumental Dam, detected entering the forebay, detected in a passage route, and detected in the immediate tailrace on either the stilling-basin or tailrace-exit telemetry receivers.

The locations of fixed telemetry receiver sites at Lower Monumental Dam in 2004 are summarized in Table 1 and Figure 2. We did not have a double array on either the turbine or the spillbay passage routes; therefore, we could not determine detection probabilities for these routes or adjust the passage distribution for fish with undetermined passage routes during bulk spill. During periods of no spill, it was possible to determine the detection probability of fish passing through the JBS, which was monitored by both telemetry receivers and PIT-tag detectors.

Table 1. Fixed-site telemetry receivers for evaluating passage behavior and survival of radio-tagged yearling Chinook salmon at Lower Monumental Dam, 2004.

Site description	Type of monitoring	Antenna type
Forebay north shore	Entrance line and residence time	3-element Yagi
Forebay mid channel	Entrance line and residence time	3-element Yagi
Forebay south shore	Entrance line and residence time	3-element Yagi
Turbine unit 1	Approach and passage	Striped coax
Turbine unit 2	Approach and passage	Striped coax
Turbine unit 3	Approach and passage	Striped coax
Turbine unit 4	Approach and passage	Striped coax
Turbine unit 5	Approach and passage	Striped coax
Turbine unit 6	Approach and passage	Striped coax
Spillbay 8	Approach and passage	Underwater dipole
Spillbay 7	Approach and passage	Underwater dipole
Spillbay 6	Approach and passage	Underwater dipole
Spillbay 5	Approach and passage	Underwater dipole
Spillbay 4	Approach and passage	Underwater dipole
Spillbay 3	Approach and passage	Underwater dipole
Spillbay 2	Approach and passage	Underwater dipole
Spillbay 1	Approach and passage	Underwater dipole
Stilling basin south shore	Project passage	2-element Yagi
Stilling basin north shore	Project passage	2-element Yagi
Juvenile bypass system	Bypass passage	Tuned loop
Tailrace exit north shore	Project passage and tailrace egress	3-element Yagi
Tailrace exit south shore	Project passage and tailrace egress	3-element Yagi

Probability estimates were derived from radiotelemetry and PIT-tag detections in the JBS, and these detection methods were assumed to be independent. Fish with undetermined routes of passage during no spill were assigned to passage routes by applying the JBS detection probability.

Fish Passage Performance Metrics

Fish passage performance metrics included spill efficiency, spill effectiveness, fish passage efficiency (FPE), and fish guidance efficiency (FGE). These metrics were estimated as follows:

Spill efficiency: Number of fish passing the dam via the spillway divided by the total number of fish passing the dam.

Spill effectiveness: Proportion of fish passing the dam via the spillway divided by the proportion of water spilled.

FPE: Number of fish passing the dam through non-turbine routes divided by total number of fish passing the dam.

FGE: Number of fish passing the dam through the JBS divided by the total number of fish passing the dam through the powerhouse (turbines and JBS).

Tailrace Egress

Analysis of tailrace egress included fish that were released upstream from Lower Monumental Dam, detected entering the forebay, detected in a passage route, and detected in the immediate tailrace. Tailrace egress time was defined as the time between last detection in a passage route and last detection on the tailrace exit array. Tailrace egress data were partitioned by project operation based on operations at the time fish passed the dam. Hypothesis testing to compare specific cohorts was evaluated using the permutation methods described above for forebay residence data (Efron and Tibshirani 1993). Confidence intervals were constructed using bootstrap methods as described previously for forebay residence times.

Survival Estimates

Estimates of survival were based on detection histories using a single-release model (Cormack 1964, Jolly 1965, Seber 1965) as implemented in SURPH (Smith 1994). Survival estimates were based on detections of individual fish at telemetry transects on

the Snake River at Ice Harbor Dam and the Snake River mouth and on the Columbia River at Port Kelley, McNary Dam, and Irrigon (Figure 1). Capture histories of treatment and reference groups were partitioned into two periods for survival estimation: detection at Ice Harbor Dam and detection downstream from Ice Harbor Dam. Relative survival estimates were the ratios of pooled survival estimates, where groups of tagged fish were released upstream (treatment/numerator) and downstream (reference/denominator) from Lower Monumental Dam.

Since project operations during the first half of the study used a bulk-spill pattern, whereas during the second half of the study there was no spill, results comparing the two operations may have been affected by changes over time in conditions that affect survival. Factors potentially affecting survival (e.g., fish stock and condition, river flow and temperature) were not expected to be experimentally averaged, considering the original randomized block study design. Therefore, these results are most accurately assessed as an empirical measure of differences at two points (early and late). Our analyses reflects this, as we used pooled estimates across individual release days for comparisons between the two treatments/time periods. We analyzed and examined daily estimated survival and found very little difference between the pooled analysis and daily point estimates or their associated standard errors.

Treatment "release groups" for estimates of dam survival were created from detections on the forebay entrance line. Treatment groups for estimates of route-specific survival were comprised of fish detected on a passage route and subsequently detected in the immediate tailrace of the dam (either on the stilling basin or tailrace exit telemetry receivers). The reference groups of fish for estimates of dam survival and route specific survival were based on release date. Comparisons of survival estimates were evaluated using a *z*-test (<0.05). An approximate *z*-test was generated based on the estimated treatment difference divided by the binomially-based estimated standard error of the difference and relying on the asymptotic normality of maximum likelihood estimators and the assumption of independence between treatments. Critical study assumptions and methods used to evaluate them are detailed in Appendix A.

Treatment fish that were not detected on the forebay entry line were excluded from analysis. Fish that passed Lower Monumental Dam after 26 May were also excluded from analysis, since there were no tailrace reference groups released for comparison after that date. Travel time for tailrace reference fish to Ice Harbor Dam was 3 d or less; therefore, treatment fish that were above Lower Monumental Dam with less than 3 d of tag life remaining were also excluded from analysis. In addition, we excluded from analysis any treatment fish that passed Lower Monumental Dam via the juvenile bypass system and was collected in the smolt monitoring sample, transported, or returned

to the river without being detected on a river-return monitor (i.e., without verification of the fish's destiny).

To provide continuity between analysis and interpretation of survival and passage behavior, we excluded the same fish from investigations of both passage and survival. These exclusions did not bias any of the estimated parameters, but decreased the precision of estimates, since the effect was to decrease the sample size. At present, no formal analysis of adult returns of PIT-tagged fish used in this study is anticipated.

RESULTS

Fish Collection, Tagging, and Releases

Yearling Chinook salmon were collected, radio tagged, and PIT tagged at Lower Monumental Dam on 25 d from 29 April to 25 May. During 2004, the Chinook salmon smolt passage distribution at Lower Monumental Dam was skewed toward earlier timing because operations of the lower Snake River hydropower system included periods of transportation with voluntary spill and periods of full transportation (Figure 3). Tagging comprised the period between the 30th and 96th percentile of the 9-year average Chinook salmon smolt index at Lower Monumental Dam. Handling and tagging mortality was 1.8% overall.

We released 1,916 radio-tagged fish 7 km upstream and 2,019 fish into the tailrace of Lower Monumental Dam. Overall mean fork length was 149.2 mm (SD = 11.3) and 149.8 mm (SD = 11.7) for fish released above and below Lower Monumental Dam, respectively (Table 2). Overall mean weight was 27.6 g (SD = 8.2) and 28.0 g (SD = 8.7) for fish released above and below Lower Monumental Dam, respectively (Table 3). Treatment fish were released between 0900 and 1105 and between 1800 and 1930 PDT. Reference fish were released between 1000 and 1615 and between 1905 and 0345 PDT.

Project Operations

During our evaluation of passage and survival at Lower Monumental Dam the project discharge averaged 75 kcfs or 66% of the 10-year average of 114 kcfs (Figure 4). Project operations at Lower Monumental Dam included voluntary bulk spill from 29 April through 0600 on 14 May and no spill from 0600 on 14 May through 26 May. The percent time individual spillbays were open during the bulk spill operation are presented in Figure 5. Lower Monumental Dam daily project operations during bulk spill averaged 72.2 kcfs total project discharge, 44.5 kcfs powerhouse discharge, 27.7 kcfs total spill volume (38.4% of total project discharge), spillway gate openings of 6 stops, and tailwater elevation of 439.5 ft msl (Table 4 and Figure 6). Daily project operations during no spill averaged 78.1 kcfs total project discharge and tailwater elevation of 440.6 ft msl (Table 4 and Figure 6).

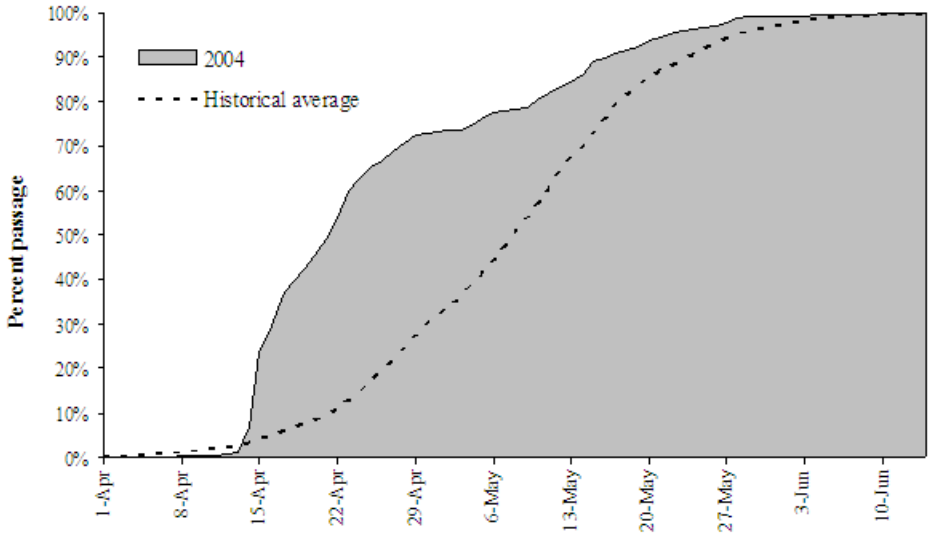

Figure 3. Cumulative passage distribution of hatchery yearling Chinook salmon at Lower Monumental Dam during 2004 and historical average (1994-2003). Note due to irregular smolt-monitoring protocols in 2002, that year was excluded from the historical average.

Table 2. Sample size, mean fork length, standard deviation (SD), and range of fork lengths for radio-tagged, yearling Chinook salmon released at Lower Monumental Dam to evaluate passage behavior and survival, 2004.

	Forebay treatment groups				Tailrace reference groups			
Date	N	Mean length (mm)	SD	Range (mm)	N	Mean length (mm)	SD	Range (mm)
30 Apr	59	140.7	9.0	122-163	72	144.7	10.6	130-179
01 May	77	156.4	17.5	125-200	84	160.7	19.7	124-209
02 May	78	152.9	15.3	128-184	80	152.1	14.5	130-194
03 May	67	152.3	17.9	124-197	52	151.5	14.8	134-193
05 May	76	155.3	14.8	131-199	67	152.4	14.0	128-189
07 May	72	151.7	16.7	130-195	82	144.8	13.6	126-205
08 May	80	147.6	12.2	128-187	84	144.8	12.0	122-181
09 May	70	149.3	12.6	129-184	66	153.7	15.1	129-214
10 May	79	150.5	11.9	132-199	86	150.1	10.6	131-188
11 May	79	148.7	13.4	128-195	86	147.8	10.7	130-182
12 May	80	144.4	9.7	128-178	83	145.0	10.6	127-181
13 May	79	146.3	10.3	132-200	87	150.2	14.2	133-204
14 May	79	147.2	8.9	135-182	88	150.6	12.1	130-195
15 May	74	148.3	12.4	132-187	76	145.8	11.2	130-189
16 May	73	143.5	9.3	127-181	72	145.2	11.4	129-196
17 May	78	148.0	12.1	132-192	84	151.8	13.6	129-203
18 May	79	144.8	6.9	130-167	88	150.1	9.9	135-193
19 May	79	148.6	8.0	133-169	86	147.5	8.9	132-178
20 May	77	144.4	6.9	132-171	85	147.2	9.8	133-190
21 May	91	146.4	8.7	132-172	87	147.7	9.0	135-178
22 May	80	148.0	7.7	135-172	85	147.6	6.9	132-166
23 May	75	153.8	8.7	137-176	86	151.4	8.4	138-178
24 May	84	154.7	9.3	136-181	86	156.5	13.0	135-207
25 May	72	154.4	11.9	137-204	80	155.3	8.6	138-182
26 May	79	150.9	8.8	130-181	87	151.1	9.6	136-182
Overall	1,916	149.2	11.3	122-204	2,019	149.8	11.7	122-214

Table 3. Sample size, mean weight, standard deviation (SD), and range of weights for radio-tagged, yearling Chinook salmon released at Lower Monumental Dam to evaluate passage behavior and survival, 2004.

	Forebay treatment groups				Tailrace reference groups			
Date	N	Mean weight (g)	SD	Range (g)	N	Mean weight (g)	SD	Range (g)
30 Apr	59	24.5	7.8	15.0-67.7	72	26.6	7.6	17.7-51.9
01 May	77	34.4	12.4	16.6-62.9	84	38.6	14.8	15.7-84.0
02 May	78	32.0	10.3	18.3-57.7	80	31.2	9.7	19.1-65.3
03 May	67	31.5	11.0	20.0-63.0	52	30.9	9.5	20.1-58.3
05 May	76	34.7	10.8	18.2-66.0	67	32.6	10.2	21.1-64.0
07 May	72	30.8	11.3	18.1-58.9	82	26.7	8.8	18.5-67.2
08 May	80	28.2	8.2	18.0-54.6	84	26.7	8.0	17.9-59.1
09 May	70	28.2	8.7	18.6-54.2	66	31.8	12.0	19.0-93.3
10 May	79	27.6	7.9	18.2-64.1	86	27.1	7.5	18.7-59.2
11 May	79	27.9	8.8	18.1-62.0	86	26.9	7.2	19.0-53.9
12 May	80	25.6	6.4	17.8-53.0	83	25.7	6.2	18.7-51.0
13 May	79	26.3	6.7	19.5-62.4	87	29.1	10.9	18.8-77.0
14 May	79	26.5	6.5	19.2-58.9	88	29.2	8.9	19.0-74.7
15 May	74	27.4	7.4	18.9-56.3	76	26.0	7.5	17.9-60.1
16 May	73	24.2	5.3	18.6-50.7	72	26.0	7.3	18.6-63.8
17 May	78	26.0	8.6	17.3-59.3	84	28.0	10.7	17.8-81.2
18 May	79	23.9	3.3	18.3-33.0	88	25.8	6.5	17.7-68.9
19 May	79	26.5	4.6	18.8-40.5	86	25.7	5.9	17.5-57.3
20 May	77	24.3	3.4	18.8-38.6	85	26.4	6.0	19.9-54.0
21 May	91	25.7	5.5	19.2-43.2	87	27.7	7.6	19.1-53.7
22 May	80	26.7	5.5	18.5-45.9	85	26.2	4.3	19.9-42.2
23 May	75	25.3	5.1	19.1-42.5	86	25.2	4.5	18.3-47.9
24 May	84	27.5	6.0	19.2-46.0	86	27.5	6.4	19.8-56.1
25 May	72	26.8	7.0	19.5-59.8	80	26.5	4.5	19.1-37.1
26 May	79	27.6	6.7	18.5-58.3	87	27.7	6.0	19.6-49.0
Overall	1,916	27.6	8.2	15.0-67.7	2,019	28.0	8.7	15.7-93.3

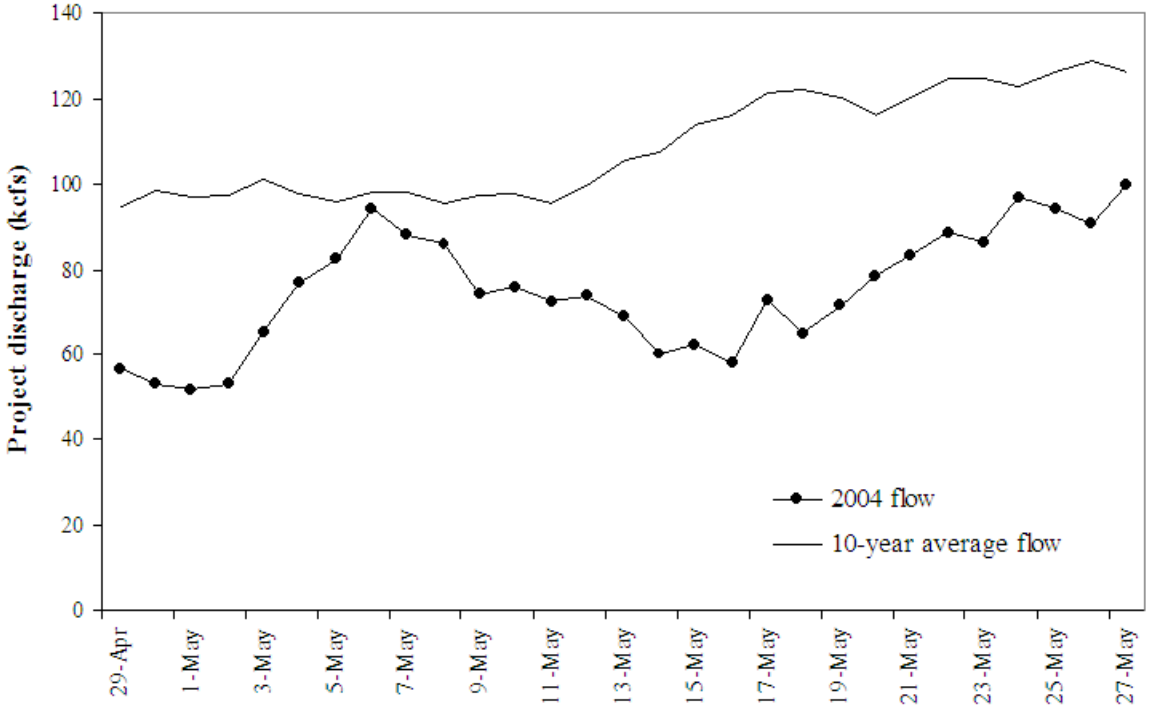

Figure 4. Daily and 10-year average (1994-2003) project discharge during releases of radio-tagged, hatchery yearling Chinook salmon at Lower Monumental Dam, 2004.

Table 4. Average daily conditions by project operation during releases and passage of radio-tagged hatchery yearling Chinook salmon at Lower Monumental Dam, 2004. Conditions on 14 May were from midnight to 0600 for bulk spill and from 0600 to midnight for no spill operations.

Release date	Spill (kcfs)	Powerhouse (kcfs)	Total discharge (kcfs)	Tailwater elevation (ft msl)	Water temperature (°C)	Secchi depth (m)
			Bulk spill			
30 Apr	25.4	27.2	53.4	438.7	11.4	1.4
01 May	24.8	26.2	51.9	438.6	11.5	1.4
02 May	25.5	26.9	53.3	438.7	11.7	1.5
03 May	30.9	33.6	65.4	439.2	12.2	1.5
04 May	27.4	49.1	76.6	439.8	12.3	1.6
05 May	25.7	55.8	82.3	439.8	12.5	1.6
06 May	30.4	63.8	94.2	440.4	13.0	1.1
07 May	30.7	56.8	88.3	440.1	12.9	1.1
08 May	29.3	55.8	85.9	440.1	12.8	1.0
09 May	28.7	44.6	74.1	439.6	12.9	1.1
10 May	29.0	46.0	75.9	439.7	13.1	1.0
11 May	26.7	44.9	72.4	439.7	13.2	1.0
12 May	26.7	46.1	73.7	439.6	12.9	0.6
13 May	27.7	40.5	69.1	439.4	12.9	1.3
14 May	23.5	25.4	48.9	438.7	12.9	1.3
Average	27.7	44.5	72.2	439.5	12.5	1.2
			No spill			
14 May		63.7	63.7	439.8	12.9	1.3
15 May		61.4	62.3	439.8	12.7	1.3
16 May		57.4	58.2	439.7	12.7	1.1
17 May		71.9	72.8	440.5	12.7	1.4
18 May		64.2	65.1	439.9	12.5	1.5
19 May		70.7	71.7	440.4	12.5	1.5
20 May		77.7	78.6	440.6	12.1	1.5
21 May		82.2	83.1	440.8	12.0	1.3
22 May		87.9	88.7	441.0	12.4	0.8
23 May		85.7	86.4	440.8	12.7	0.6
24 May		96.2	97.0	441.4	12.9	0.5
25 May		93.1	94.0	441.2	13.2	0.6
26 May		89.7	90.6	441.1	13.4	0.8
Average		78.1	78.1	440.6	12.7	1.1

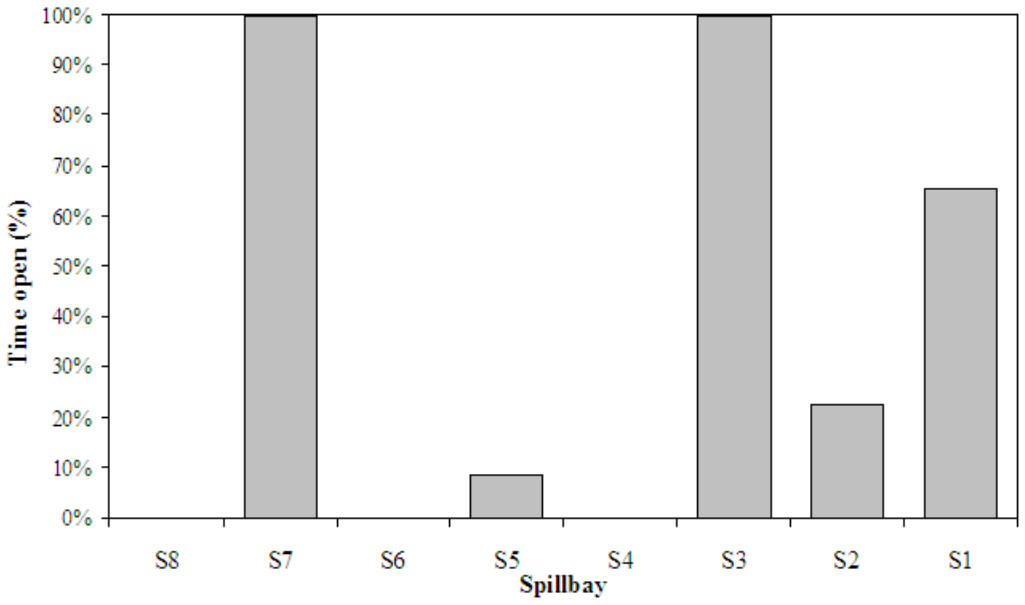

Figure 5. Percent of the time individual spillbays were open during the bulk spill operation at Lower Monumental Dam, 2004.

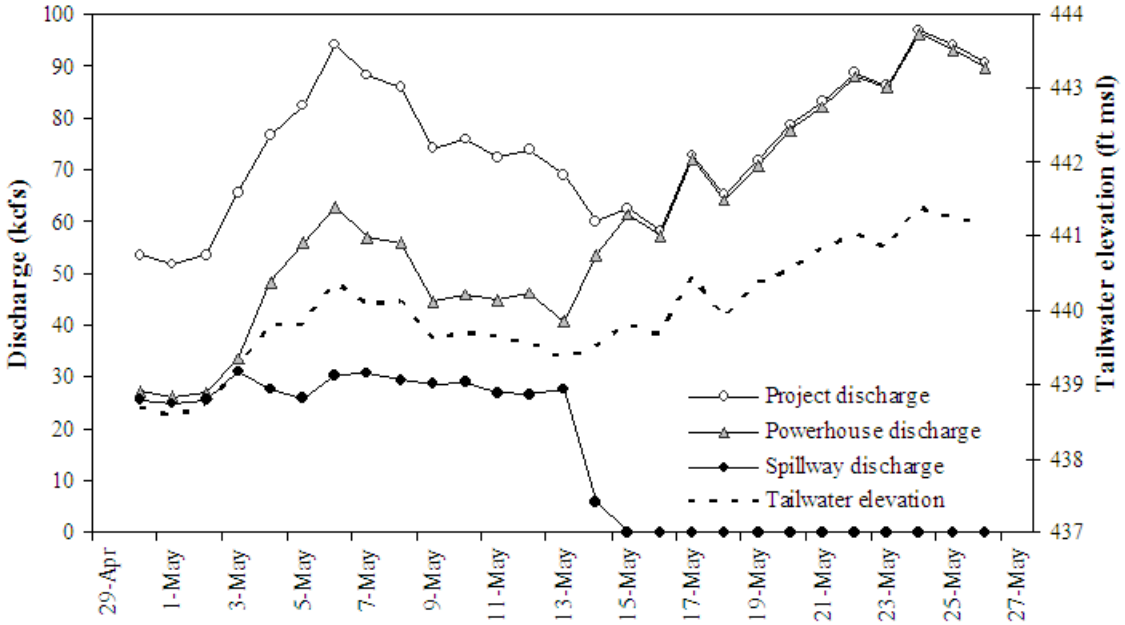

Figure 6. Average daily project discharge, powerhouse discharge, spillway discharge, and tailwater elevation during releases of radio-tagged, hatchery yearling Chinook salmon at Lower Monumental Dam, 2004.

Water temperature during tagging averaged 12.6°C and ranged from 11.2 to 14.2°C. During the post-tagging holding period, water temperature averaged 12.5°C and ranged from 11.2 to 14.2°C. Average daily water temperature during releases was 12.6°C and ranged from 11.4 to 13.4°C. Secchi disk measurements in the forebay of Lower Monumental Dam during releases averaged 1.2 m and ranged from 0.5 to 1.6 m. The visible depth in the forebay of Lower Monumental Dam during 2004 was twice the 10-year average (Figure 7).

Twenty-two treatment fish (9 during bulk spill and 13 during no spill operations) that passed Lower Monumental Dam via the JBS were not used in analysis because they were either sampled, transported, or their return to the river could not be verified from the last PIT-tag detection location at the dam. In addition, we excluded from survival estimates 103 treatment fish that were still above Lower Monumental Dam with less than 3 d of tag life remaining and 160 treatment fish that passed Lower Monumental Dam after the last reference release on 26 May.

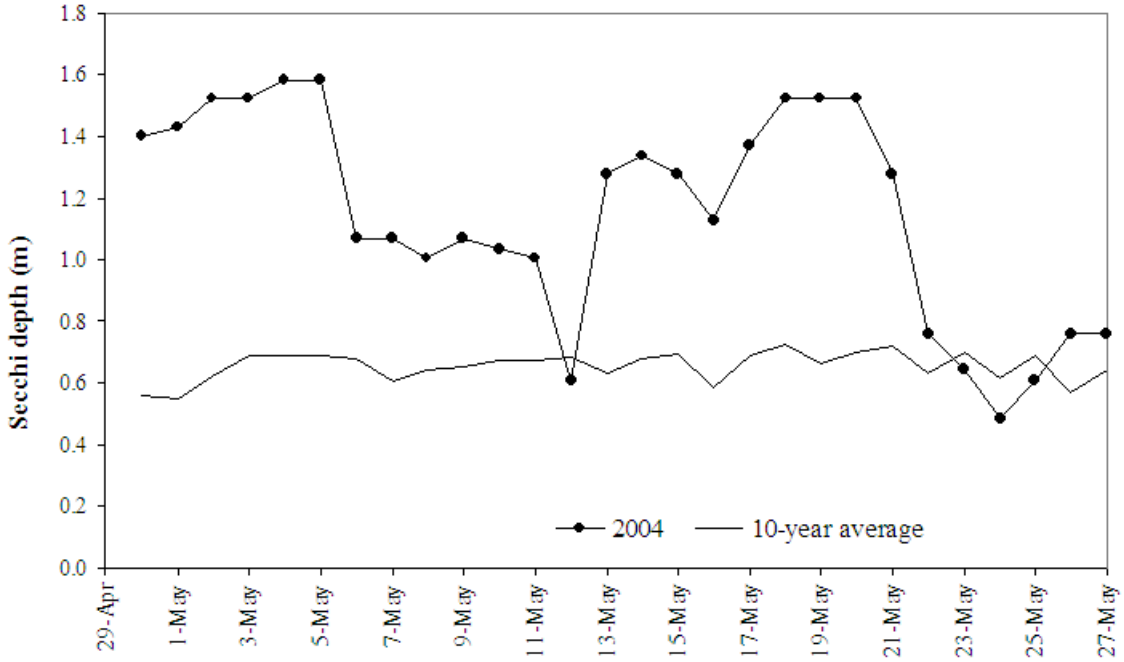

Figure 7. Daily and 10-year average (1994-2003) turbidity in the forebay of Lower Monumental Dam during releases of radio-tagged, hatchery yearling Chinook salmon, 2004. Turbidity was measured by the visible depth of a Secchi disk below the surface.

Forebay Residence Time

Of the 1,916 radio-tagged yearling Chinook salmon released above Lower Monumental Dam, 1,739 (91%) were detected on the forebay entrance line at the upstream end of the BRZ. Fish entering the forebay of Lower Monumental Dam had a bimodal distribution during both bulk spill and no spill operations, with peak numbers at approximately 0700 and 1500 (Figure 8). Median forebay residence time during bulk spill was 0.09 d (95% CI, 0.08-0.10) and ranged from 0.01 to 4.78 d (Table 5). Median forebay residence time during no spill was 1.10 d (95% CI, 0.98-1.31) and ranged from 0.02 to 6.61 d (Table 5). Median forebay residence time was significantly longer (1.01 d; 95% CI, 0.88-1.21) during no spill (permutation P <0.001).

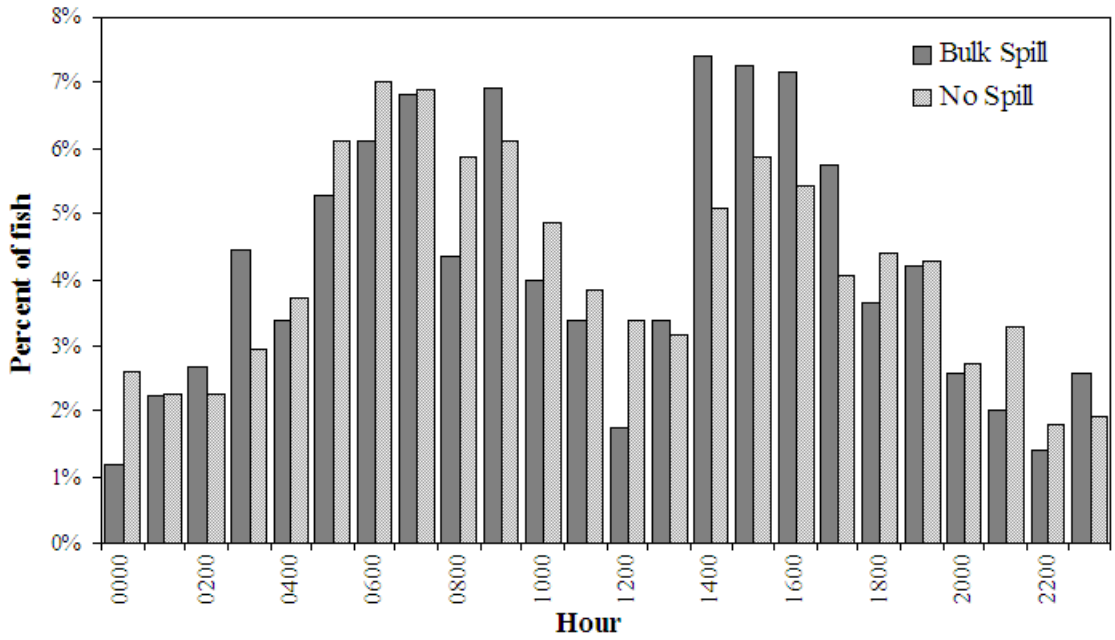

Figure 8. Hour of first detection for radio-tagged yearling Chinook salmon released upstream from Lower Monumental Dam and detected in the forebay of Lower Monumental Dam , 2004.

Table 5. Forebay residence time (elapsed time in days from first detection on the forebay entry line to time of passage) by project operation for radio-tagged hatchery yearling Chinook salmon at Lower Monumental Dam, 2004.

	Forebay residence time (d)	
Percentile	Bulk spill operation	No spill operation
n	702	507
minimum	0.01	0.02
10	0.03	0.20
20	0.04	0.42
30	0.05	0.62
40	0.06	0.80
50	0.09	1.10
60	0.13	1.49
70	0.19	1.84
80	0.28	2.46
90	0.52	3.29
maximum	4.78	6.61

Approach and Passage Distribution

During bulk spill, 856 fish entered the forebay of Lower Monumental Dam and 830 (97%) subsequently passed the dam. Ninety-two percent of the fish first approached the spillway portion of Lower Monumental Dam, with the majority of these (44%) approaching at spillbays 7 and 8 (Figure 9). Passage route distribution during bulk spill was 87, 7, 2, and 4% through the spillway, JBS, turbines, and undetermined routes, respectively. The majority (62%) passed through either spillbay 3 or 7, with the highest passage rate at spillbay 7 (40%) (Figure 10).

Some of the underwater antennas on the standard length traveling screens became damaged and deteriorated over time; therefore, the detection efficiency of the powerhouse array was reduced. In addition, the relatively small size of the detection field and the speed at which fish pass through these fields in the spillway and powerhouse can result in fish passing the dam through either the turbines or spillway undetetected. We could not determine the location of entry into the powerhouse for 8 fish that passed through the JBS during the bulk spill operation. In addition, 27 (4%) fish passed the dam during bulk spill through an undetermined route (either through the spillway or the turbines).

During no spill, 886 fish entered the forebay of Lower Monumental Dam, and 710 of these fish (80%) subsequently passed the dam. Fish approached the spillway and powerhouse in similar proportions (55% to the spillway and 45% to the powerhouse) during no spill (Figure 11). The majority (35%) of the fish first approached spillbays 7 and 8 during no spill. Observed passage-route distribution during no spill was 72, 6, and 22% through the JBS, turbines, and undetermined routes, respectively.

Detection probability in the JBS (combined PIT-tag detection and telemetry) was estimated at 0.999 (Table 6). Since the detection probability of fish passing through the JBS was nearly 100%, the 124 fish with an undetermined passage route during no spill were all assumed to have passed through the turbines. Therefore, the adjusted passage-route distribution during no spill was 72% through the JBS and 28% through the turbines. The majority (43%) of fish that entered the powerhouse during no spill did so at turbine intake 1 or 4 (Figure 12).

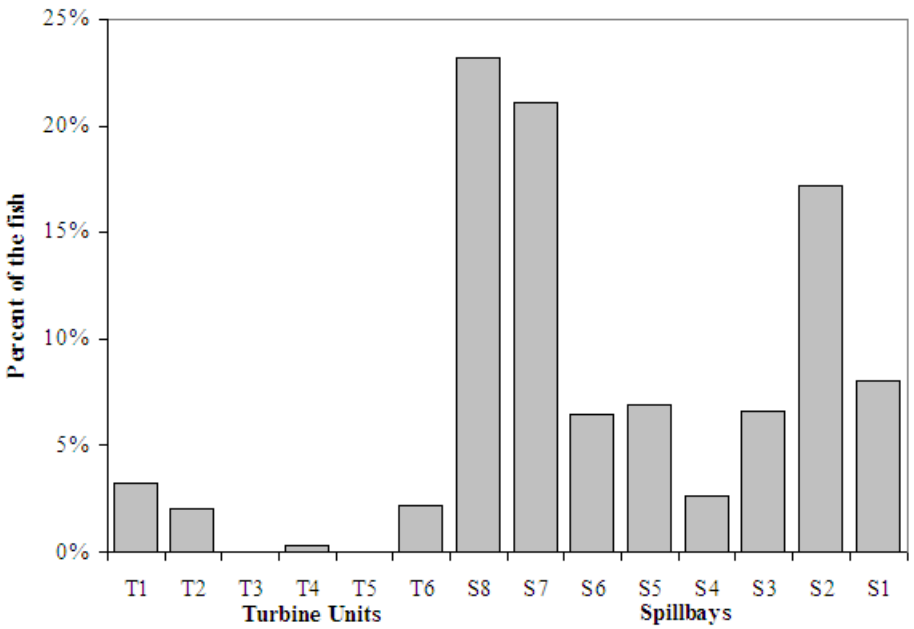

Figure 9. Horizontal approach distribution for radio-tagged yearling Chinook salmon released upstream from Lower Monumental Dam based on first detections at either individual turbine intakes or spillbays during bulk spill, 2004. Approach patterns were temporally consistent across release groups.

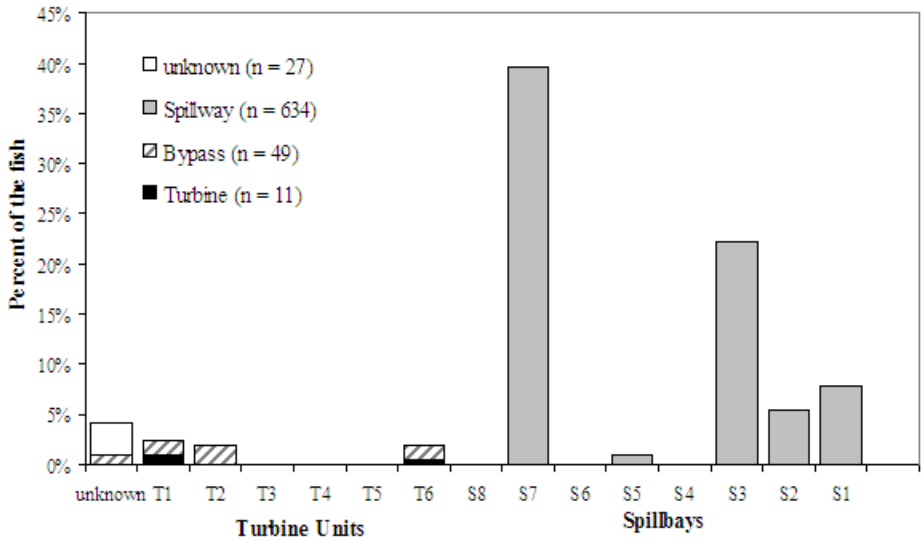

Figure 10. Passage route distribution for radio-tagged yearling Chinook salmon released upstream from Lower Monumental Dam during bulk spill, 2004. Passage patterns were temporally consistent across release groups.

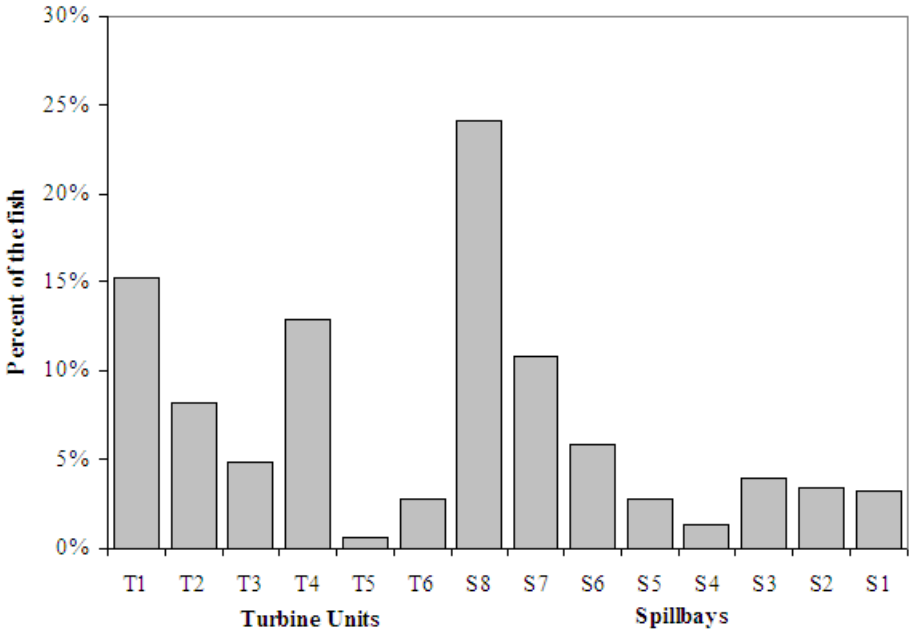

Figure 11. Horizontal approach distribution for radio-tagged yearling Chinook salmon released upstream from Lower Monumental Dam based on first detections at either individual turbine intakes or spillbays during no spill, 2004. Approach patterns were temporally consistent across release groups.

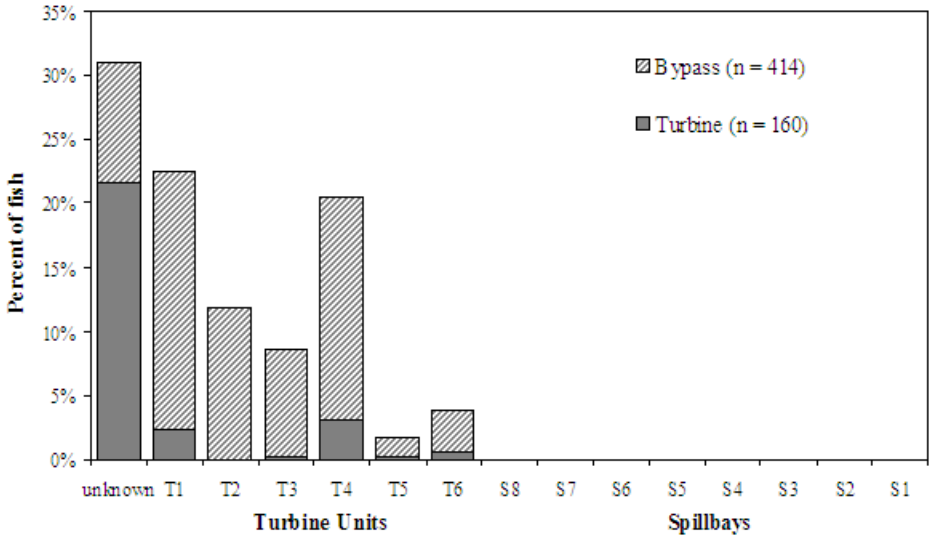

Figure 12. Passage route distribution for radio-tagged yearling Chinook salmon released upstream from Lower Monumental Dam during no spill, 2004. Passage patterns were temporally consistent across release groups.

Table 6. Detection probability for double tagged (radio-tagged and PIT-tagged) yearling Chinook salmon passing through the juvenile bypass system (PIT-tag and telemetry detection) during evaluations of passage behavior and survival at Lower Monumental Dam, 2004.

	PIT-tag detection	Telemetry detection	Detected on both	PIT-tag detection efficiency	Telemetry detection efficiency	Overall detection efficiency
01 May	1	1	1	1.000	1.000	1.000
02 May	2	2	2	1.000	0.667	1.000
03 May	4	4	4	1.000	1.000	1.000
04 May	3	3	3	1.000	1.000	1.000
05 May	4	5	4	0.800	1.000	1.000
06 May	8	8	8	1.000	1.000	1.000
07 May	1	2	1	0.500	1.000	1.000
08 May	1	2	1	0.500	1.000	1.000
09 May	4	5	4	0.800	1.000	1.000
10 May	1	2	1	0.500	1.000	1.000
11 May	6	6	5	0.833	0.833	0.972
12 May	4	4	4	1.000	1.000	1.000
13 May	8	9	8	0.889	1.000	1.000
14 May	7	7	7	1.000	0.875	1.000
15 May	20	18	18	1.000	0.909	1.000
16 May	13	14	13	0.929	1.000	1.000
17 May	10	10	10	1.000	1.000	1.000
18 May	23	30	23	0.767	1.000	1.000
19 May	33	36	32	0.889	0.971	0.997
20 May	33	33	32	0.970	0.971	0.999
21 May	34	34	33	0.971	0.946	0.999
22 May	32	38	32	0.842	1.000	1.000
23 May	50	57	50	0.877	1.000	1.000
24 May	53	57	53	0.930	1.000	1.000
25 May	46	47	46	0.979	1.000	1.000
26 May	27	27	26	0.963	0.935	0.999
Overall	428	461	421	0.913	0.984	0.999

Fish Passage Performance Metrics

For fish with a known passage route, FGE was 81.7%, FPE was 98.4%, spill efficiency was 89.3% with an average of 38% spill, and spill effectiveness was 2.33 to 1 during bulk spill. During the no spill operations, FGE and FPE were 72.1%.

Tailrace Egress

Median tailrace egress during bulk spill was 9.6 min (95% CI, 8.9-10.2) and ranged from 1 to 7,009 min (Table 7). Median tailrace egress during no spill was 7.9 min (95% CI, 7.5-8.5) and ranged from 1 to 7,525 min (Table 7). The median tailrace egress during bulk spill was significantly longer (1.8 min; 95% CI, 1.0-2.6; permutation $P < 0.001$) than during no spill. However, this short difference in timing was not likely to have had any meaningful biological consequence. Tailrace egress times for fish passing through the JBS during bulk spill (median 28.0 min; 95% CI, 21.5-39.4) were significantly longer than during no spill (7.5 min; 95% CI, 7.2-7.8; permutation $P < 0.001$). This was probably related to the proximity of the JBS outfall and a strong clockwise eddy which forms in the tailrace near the outfall during bulk spill.

Table 7. Tailrace egress (elapsed time in minutes from last detection in a passage route to last detection in the tailrace) by project operation for radio-tagged hatchery yearling Chinook salmon at Lower Monumental Dam, 2004.

	Egress time (min)						
	Bypass passage		Turbine passage		Spillway passage	Overall	
Percentile	Bulk spill	No spill	Bulk spill	No spill	Bulk spill	Bulk spill	No spill
n	53	406	11	36	623	688	442
minimum	11	1	7	10	1	1	1
10	13	5	9	11	4	4	5
20	15	6	11	12	5	5	6
30	19	6	11	13	6	6	6
40	23	7	12	14	8	8	7
50	28	8	14	15	9	10	8
60	34	8	14	22	10	11	9
70	53	10	15	48	13	15	12
80	112	15	15	274	25	30	16
90	515	131	19	624	102	113	270
maximum	4,285	7,525	4,810	4,514	7,009	7,009	7,525

Survival Estimates

Dam Survival

The pooled estimate of relative dam survival during bulk spill was 0.919 (SE = 0.019; 95% CI, 0.882-0.956; Table 14). Relative dam survival during no spill was 0.750 (SE = 0.026; 95% CI, 0.699-0.802). Relative dam passage survival was significantly higher during bulk spill than during no spill ($z = 5.20$; $P < 0.001$).

Route-Specific Survival

The pooled estimate of spillway survival for radio-tagged yearling Chinook salmon at Lower Monumental Dam during bulk spill relative to those released in the tailrace was 0.961 (SE = 0.019; 95% CI, 0.924-0.999; Table 14). Spillway survival in 2004 during bulk spill was significantly higher than spillway survival in 2003 during a flat spill pattern (0.961 vs. 0.834) under similar project discharge levels ($z = 3.92$, $P < 0.001$).

During no spill, pooled relative survival for radio-tagged yearling Chinook salmon was estimated at 0.922 (SE 0.031; 95% CI, 0.862-0.983) for fish passing through the JBS, 0.881 (SE 0.047; 95% CI, 0.789-0.973) for fish passing via turbines, and 0.911 (SE 0.028; 95% CI, 0.857-0.965) for fish passing through the powerhouse (JBS and turbines combined) at Lower Monumental Dam (Table 14). During no spill, relative project passage survival (0.760) was significantly lower ($z = 4.21$, $P < 0.001$) than survival through the powerhouse (0.908).

Avian Predation

A total of 15 tags from fish released during bulk spill (3 treatment and 12 reference fish) were recovered from the Caspian Tern *Sterna caspia* colony on Crescent Island in the McNary Dam pool of the Columbia River (Table15). A total of 78 tags from fish released during no spill (28 treatment fish and 50 reference fish) were recovered from Crescent Island. The majority of these fish were last detected in the McNary Dam pool (below our primary survival line at Ice Harbor Dam) prior to being recovered from Crescent Island.

Table 14. Sample sizes and pooled estimates of survival for radio-tagged, hatchery yearling Chinook salmon passing (treatment) Lower Monumental Dam relative to fish released into the tailrace (reference) during bulk spill and no spill, 2004. Standard errors in parenthesis.

	Treatment		Reference		Relative survival
	n	Survival	n	Survival	
		Bulk Spill			
Dam survival	748	0.816 (0.014)	929	0.888 (0.010)	0.919 (0.019)
Spillway survival	634	0.853 (0.014)	929	0.888 (0.010)	0.961 (0.019)
		No Spill			
Dam survival	700	0.598 (0.019)	1,090	0.797 (0.012)	0.750 (0.026)
JBS survival	415	0.735 (0.022)	1,090	0.797 (0.012)	0.922 (0.031)
Turbine survival	161	0.702 (0.036)	1,090	0.797 (0.012)	0.881 (0.047)
Powerhouse survival	576	0.726 (0.019)	1,090	0.797 (0.012)	0.911 (0.028)

Table 15. Numbers of radio-tagged hatchery yearling Chinook salmon released to evaluate passage behavior and survival at Lower Monumental Dam and subsequently recovered from the Caspian Tern colony on Crescent Island in the McNary Dam pool of the Columbia River. Project operations during releases of these fish are also shown.

	Treatment fish		Reference fish	
Last telemetry detection	Bulk spill	No spill	Bulk spill	No spill
Lower Monumental Dam tailrace	0	7	0	8
Ice Harbor Dam forebay	0	9	1	7
Ice Harbor Dam tailrace	0	1	6	4
McNary Dam pool	3	11	5	29
John Day Dam pool	0	0	0	2
Total	3	28	12	50

DISCUSSION

The majority of our radio-tagged yearling Chinook salmon approached and passed Lower Monumental Dam at the thalweg of the river in the vicinity of spillbays 7 and 8 during both bulk spill and no spill conditions. Johnson et al. (1998) observed similar horizontal distribution patterns where smolts approach Lower Monumental at the midpoint of the thalweg. This behavior has also been observed at Lower Granite Dam in studies using hydroacoustics and radiotelemetry (Johnson and Dauble 1995; Adams et. al. 1998b).

A modified spill pattern could take advantage of the horizontal distribution to enhance spill effectiveness and decrease forebay delay. The 2.3:1 spill effectiveness we observed was similar to the 1.9:1 reported by Johnson et al. (1998), and higher than the 1:1 ratio of spilled fish to spilled water expected by the regional spill program. Our observation of 89% spill efficiency was higher than the 69% estimated by Johnson et al. (1998) from a hydroacoustic evaluation at Lower Monumental Dam.

Snake River flows in the spring of 2004 at Lower Monumental Dam averaged 66% of the 10-year average. Because of these low flows, transportation was maximized at Lower Granite and Little Goose Dams, and spill was minimized during most of the spring migration. With little or no spill, an estimated 91% of non-tagged yearling Chinook salmon arriving at Lower Granite Dam were subsequently transported, from either Lower Granite, Little Goose, or Lower Monumental Dam (Steve Smith, NMFS, personal communication). The high percentage of fish transported in 2004 reduced the overall abundance of Snake River juvenile salmonids arriving at and passing Lower Monumental Dam compared to previous years. This may have influenced predator/prey dynamics for our radio-tagged fish and had a large impact on their survival.

Another factor potentially affecting predator/prey dynamics in 2004 was the above-average water clarity, which made salmonid smolts more susceptible to visual predators (Gregory and Levings 1998). Zabel et al (2002) reported that the combination of decreased spill and operations associated with full transportation at Snake River dams during a low flow year (2001) resulted in substantially decreased in-river survival for yearling Chinook salmon.

The low flow and spill conditions that prevailed during the 2004 spring migration led to lower-than-normal survival for fish migrating through the lower Snake River (Steve Smith, NMFS, personal communication). Under moderate to high flow and spill levels, our survival estimates would likely have been higher. The low flows in 2004 also

increased travel and forebay residence times substantially, especially during periods of no spill. We observed significantly higher dam survival during bulk spill (0.919) than during no spill conditions (0.750) at Lower Monumental Dam in 2004. Forebay residence times were also shorter during bulk spill and longer during no spill operations. The extended forebay residence times during no spill may have contributed to poor survival by lengthening exposure time to predators (Vigg and Burley 1991). During periods of no spill, we observed significantly lower dam survival than powerhouse survival, indicating that the majority of mortalities had occurred in the forebay rather than within passage routes.

Potential positive effects of spill likely go beyond those directly measured as dam survival. Smith et al. (2002) found a strong inverse relationship between travel time and spill exposure in the Snake River for yearling Chinook salmon. Positive effects of spill on a season-wide basis have also been demonstrated (Zabel et al. 2002). Analysis based on early data (1973-1979) suggested that increases in spill had a direct impact on increasing survival (Sims and Ossiander 1981). Zabel et al (2002) reported lower survival through the hydropower system in 1993 and 1994, when spill occurred only in excess of powerhouse capacity, than after spill was prescribed at all dams in the 1995 Biological Opinion (NMFS 1995).

In general, among the various passage routes (spillway, bypass, or turbine) at lower Snake River dams, spillway passage is considered to provide the highest survival for juvenile salmonids (Muir et al. 2001). Higher survival for spillway passage is attributed to reductions in passage time and exposure to predators in the forebay and tailrace (Beamesderfer et al. 1990; Vigg et al. 1991). However, recent spillway survival studies at Lower Monumental Dam (Muir et al. 2001; Hockersmith et al. 2004), Ice Harbor Dam (Eppard et al. 2002, 2005a,b), The Dalles Dam (Absolon et al. 2002; Dawley et al. 1998, 2000a,b) and Bonneville Dam (Normandeau et al. 2003), have found that spillway survival for juvenile fish can be inconsistent across years. A reanalysis of juvenile salmonid survival studies by Bickford and Skalski (2000) also found high variability among spillway survival estimates. This is not surprising, since the hydraulic conditions in the stilling basin and immediate tailrace can be highly variable across a range of project operations and total river flow.

Previous evaluations of spillway survival at Lower Monumental Dam have seen considerable variation across species, runs, and years; this variation may have been species- or run-specific, or it may be related to differences in project operations. Long and Ossiander (1974) reported spillway passage survival of 97 to 110% for coho salmon released into spillbays with flow deflectors. Estimated survival of steelhead was 98% for releases into a spillbay with a flow deflector and 76% for releases into a spillbay without

a flow deflector (Long et al. 1974). For subyearling Chinook salmon released into a spillbay with a flow deflector, survival estimates were 83 to 84% (Long et al 1972). For yearling Chinook salmon, Muir et al. (1995a) estimated survival at 93% for releases into a spillbay with a flow deflector (spillbay 7) and 98% for releases into a spillbay without a flow deflector (spillbay 8) at Lower Monumental Dam.

Relationships between juvenile salmonid spillway survival and project operations (project and powerhouse discharge, spill volume, spill pattern, spillbay gate opening, and tailwater elevation) in the lower Snake and Columbia River Basins are not well understood. In addition, the indirect effects of spill operations on predation of smolts passing hydroelectric dams (i.e., increased vulnerability of smolts due to delay, structures, back-eddies, or disorientation) remain critical uncertainties. Few spillway survival studies have identified relationships between survival and project operations because the range of project operations available to evaluate are often limited by river flow, lack of a power supply, regulations governing dam operations, or timing of the juvenile migration.

Hockersmith et al. (2004) observed significantly higher spillway survival (0.987 vs. 0.834) for fish released during periods of higher total river flow, powerhouse discharge, and tailwater elevation at Lower Monumental Dam in 2003. However, because these variables were highly correlated among themselves, their relative importance with regard to spillway survival could not be determined.

During the late 1960s and early 1970s, high levels of involuntary spill at hydroelectric projects on the Snake and Columbia Rivers resulted in severe dissolved gas supersaturation problems and high mortalities of fish from gas bubble disease (Weitkamp and Katz 1980). To reduce plunging and associated air entrainment of spilled water, flow deflectors were installed on the spillway ogees at lower Snake and Columbia River dams (Smith 1974). Because flow deflectors are at a fixed elevation, spillway passed fish may come in contact with the flow deflector and become injured at lower tailwaters. The flow deflectors at Lower Monumental Dam for spillbays 2 through 7 are at elevation 434 ft msl and the end bays are at elevation 432 ft msl.

Muir et al (2001) did not find statistically significant differences in spillway survival when comparing releases of juvenile salmonids into spillbays with and without flow deflectors at Little Goose or Lower Monumental Dams. However, point estimates of survival were higher for releases into spillbays without a flow deflector than with a flow deflector (100 vs. 97% at Little Goose Dam and 98 vs. 93% at Lower Monumental Dam, respectively).

Survival evaluations at Ice Harbor Dam in 2000 (Eppard et al. 2002) and at Lower Monumental Dam in 2004 (Hockersmith et al. 2004) indicate that under higher flow conditions and BiOp operations (NMFS 2000), spillway survival through spillbays with flow deflectors is high (97 to 100%), whereas survival is less than 90% under BiOp operations during lower flows such as those that occur in early spring and summer. Hockersmith et al. (2004) reported that spillway survival at Lower Monumental Dam appears to be related to the tailrace conditions such as the depth of submergence of the flow deflectors or the hydraulic conditions near the deflector since survival was significantly higher during periods of higher total river flow and tailwater elevation.

Due to relatively low spillway passage survival when project discharges are low, a new spill pattern was developed in 2004 for Lower Monumental Dam. The new spill pattern, bulk spill, does not change the volume spilled; however it decreases the number of spillbays open and increases the volume per bay spilled by increasing the gate opening. Larger spillbay gate openings may create tailrace conditions at the deflector similar to those under higher project discharges by increasing the submergence of the flow deflector because the volume and depth of water over the deflector is increased. We observed significantly higher spillway survival in 2004 (96%) with a bulk spill pattern than we did in 2003 (83%) with a flat spill pattern. Tailrace conditions during 2003 and 2004 at Lower Monumental Dam during each evaluation were similar (average project discharge 81 vs. 72 kcfs, tailwater elevation 440 vs. 440 ft msl, and average volume spilled 30 vs. 28 kcfs, respectively). However, the average gate openings for individual spillbays during 2004 was 6 stops whereas in 2003 it was 3 stops.

In 2004, our estimate of bypass survival was slightly lower than those previously reported for Lower Monumental Dam (92% vs. 96 and 95%) (Hockersmith et al. 2000; Muir el al. 2001). However, in these studies, fish were released directly into either the bypass flume or collection channel; therefore, the resulting survival estimates could not include potential mortality associated with submersible traveling screens, gatewells, or orifice passage. We observed a similar estimates of turbine survival to that reported by Muir et al. (2001) (88 vs.87%) for Lower Monumental Dam.

The results of our study indicated that survival through spillbays equipped with flow deflectors is higher for bulk spill than flat spill patterns when project discharges are low. Our study also indicated that dam survival at Lower Monumental Dam for yearling Chinook salmon was significantly higher with voluntary bulk spill than without spill during low flow conditions, possibly because delays in the forebay and exposure time to predators are reduced.

RECOMMENDATIONS

1. The bulk spill pattern used in 2004 should be examined by model testing at the USACE Waterways Experiment Station, in Vicksburg, MS to determine whether it could be modified to use spillbays 7 and 8 instead of spillbays 3 and 7. This would make better use of the horizontal distribution pattern of yearling Chinook salmon to further enhance spill effectiveness and decrease forebay delay.
2. Lower Monumental Dam passage behavior and survival under bulk spill operations should be evaluated for a second year to validate 2004 study findings.
3. Balloon-tag, spillway survival studies should be conducted to determine direct impacts of spillway passage at Lower Monumental Dam under low, medium, and high flow conditions.
4. Spillway survival at Lower Monumental Dam should also be evaluated with juvenile steelhead and subyearling Chinook salmon.

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APPENDIX A: Evaluation of Study Assumptions

We used a single-release model (Cormack 1964; Jolly 1965; Seber 1965) to estimate survival of radio-tagged juvenile Chinook salmon released above and below Lower Monumental Dam. Ratios of these survival estimates (treatment survival divided by reference survival) were calculated to determine relative survival. Evaluation of critical model and biological assumptions of the study are detailed below.

A1. All tagged fish have similar probabilities of detection at a detection location.

Of the 1,916 radio-tagged yearling Chinook salmon released above Lower Monumental Dam, 1,167 (60.9% of those released) were detected either at or below Ice Harbor Dam. Of the 2,019 radio-tagged yearling Chinook salmon released into the tailrace of Lower Monumental Dam, 1,689 (83.7% of those released) were detected either at or below Ice Harbor Dam. The detection probability for fish used in survival analysis at Ice Harbor Dam was 0.992 overall (Appendix Table A1).

Thus radiotelemetry detection probability at Ice Harbor Dam was almost 100%, with only seventeen fish (0.6%) detected downstream that were not detected at Ice Harbor Dam. With detection probabilities at or near 100% for all fish, there was no disparity between detection probabilities of treatment and reference groups.

Appendix Table A1. Detections at and below Ice Harbor Dam and detection probabilities at Ice Harbor Dam for evaluating survival of hatchery yearling Chinook salmon passing Lower Monumental Dam, 2004.

Release group	Lower Monumental Dam operation	Detection at Ice Harbor Dam	Detection at or below Ice Harbor Dam	Detection probability
Treatment	Bulk spill	615	619	0.994
Treatment	No spill	430	439	0.980
Reference	Bulk spill	798	798	1.000
Reference	No spill	825	829	0.995
Totals		2,668	2,685	0.994

A2. Treatment and corresponding reference groups are evenly mixed and travel together through downstream reaches.

To test that treatment and reference fish mixed evenly and traveled together downstream, we evaluated mixing of release groups at Ice Harbor Dam by using contingency tables (chi-square goodness-of-fit) to test for differences in arrival distributions. The passage date of treatment fish at Lower Monumental Dam was paired with the release date of reference fish. Ice Harbor observations were grouped by date, since nearly all fish were detected in less than 3 d. *P*-values were calculated using the Monte Carlo approximation of the exact method described in the StatXact software user manual (Mehta and Patel 1992; <0.05).

Test of homogeneity of arrival distributions at Ice Harbor Dam were similar for treatment and reference groups in 8 of the 11 paired releases for each relative survival estimate (Appendix Tables A2-A6; Appendix Figures B1 and B15). Therefore, we concluded that treatment and corresponding reference groups were evenly mixed and traveled together through downstream reaches for 8 of 11 groups in each operation evaluated.

There were more significant tests than expected if all groups were generally mixed (for = 0.05 level we would expect 1 out of 20 tests not to be mixed). However, in general the differences between arrival times at Ice Harbor Dam were less than 1 day. In some tests, treatment fish arrived somewhat earlier, while in others reference fish arrived earlier. Since our survival estimates were pooled over the treatment period, and the bulk of distributions generally occurred over a 2-3 day period, it is reasonable to conclude that the survival estimates were not significantly biased by violation of the assumption regarding mixing through the common reach.

Appendix Table A2. Test of homogeneity of arrival timing at Ice Harbor Dam for treatment and reference groups of radio-tagged hatchery yearling Chinook salmon used for estimating dam survival during bulk spill at Lower Monumental Dam. The passage date of treatment fish at Lower Monumental Dam was paired with the release date of reference fish. Ice Harbor observations were grouped by date since nearly all fish were detected in less than 3 d. Shaded cells indicate significant differences in passage timing among tests ($\alpha = 0.05$).

Passage/release date	χ^2	Degrees of freedom	*P*
30 April-1 May	11.37	4	0.022
02 May	8.41	4	0.061
03 May	5.83	6	0.468
04-05 May	18.72	5	0.001
06-07 May	20.29	6	<0.001
08 May	3.42	4	0.538
09 May	2.90	4	0.958
10 May	1.24	2	0.573
11 May	5.09	5	0.424
12 May	2.91	4	0.669
13-14 May	7.82	5	0.127

Appendix Table A3. Test of homogeneity of arrival timing at Ice Harbor Dam for treatment and reference groups of radio-tagged hatchery yearling Chinook salmon used for estimating spillway survival during bulk spill at Lower Monumental Dam. The passage date of treatment fish at Lower Monumental Dam was paired with the release date of reference fish. Ice Harbor observations were grouped by date since nearly all fish were detected in less than 3 d. Shaded cells indicate significant differences in passage timing among tests ($\alpha = 0.05$).

Passage/Release date	χ^2	Degrees of freedom	*P*
30 April-1 May	11.22	4	0.024
02 May	8.77	4	0.051
03 May	6.07	6	0.432
04-05 May	20.43	4	<0.001
06-07 May	15.86	6	0.005
08 May	3.93	4	0.444
09 May	2.86	4	0.920
10 May	1.30	2	0.536
11 May	4.66	5	0.474
12 May	3.17	4	0.575
13-14 May	7.26	5	0.164

Appendix Table A4. Test of homogeneity of arrival timing at Ice Harbor Dam for treatment and reference groups of radio-tagged hatchery yearling Chinook salmon used for estimating dam survival and powerhouse survival during no spill at Lower Monumental Dam. The passage date of treatment fish at Lower Monumental Dam was paired with the release date of reference fish. Ice Harbor observations were grouped by date since nearly all fish were detected in less than 3 d. Shaded cells indicate significant differences in passage timing among tests ($\alpha = 0.05$).

Passage/Release date	χ^2	Degrees of freedom	*P*
14-15 May	6.28	4	0.178
16-17 May	9.14	5	0.073
18 May	22.32	4	<0.001
19 May	2.75	4	0.655
20 May	4.31	4	0.376
21 May	5.02	3	0.139
22 May	4.37	4	0.371
23 May	9.30	5	0.048
24 May	4.00	4	0.428
25 May	11.06	2	0.003
26 May	4.54	3	0.256

Appendix Table A5. Test of homogeneity of arrival timing at Ice Harbor Dam for treatment and reference groups of radio-tagged hatchery yearling Chinook salmon used for estimating bypass survival during no spill at Lower Monumental Dam. The passage date of treatment fish at Lower Monumental Dam was paired with the release date of reference fish. Ice Harbor observations were grouped by date since nearly all fish were detected in less than 3 d. Shaded cells indicate significant differences in passage timing among tests ($\alpha = 0.05$).

Passage/Release date	χ^2	Degrees of freedom	*P*
14-15 May	5.19	4	0.260
16-17 May	6.99	5	0.223
18 May	24.29	4	<0.001
19 May	4.05	4	0.394
20 May	6.22	4	0.179
21 May	4.62	3	0.196
22 May	5.32	3	0.133
23 May	9.11	4	0.028
24 May	3.84	4	0.453
25 May	8.04	2	0.010
26 May	2.33	2	0.283

Appendix Table A6. Test of homogeneity of arrival timing at Ice Harbor Dam for treatment and reference groups of radio-tagged, hatchery yearling Chinook salmon used for estimating turbine survival during no spill at Lower Monumental Dam. The passage date of treatment fish at Lower Monumental Dam was paired with the release date of reference fish. Ice Harbor observations were grouped by date since nearly all fish were detected in less than 3 d. Shaded cells indicate significant differences in passage timing among tests ($\alpha = 0.05$).

Passage/Release date	χ^2	Degrees of freedom	*P*
14-15 May	4.05	4	0.305
16-17 May	7.64	4	0.176
18 May	4.35	3	0.197
19 May	4.35	3	0.198
20 May	2.65	4	0.470
21 May	1.36	2	0.631
22 May	10.87	3	0.018
23 May	8.35	4	0.119
24 May	0.33	4	0.999
25 May	18.00	2	0.004
26 May	15.40	3	0.046

A3. Individuals tagged for the study are a representative sample of the population of interest.

River-run, hatchery yearling Chinook salmon were collected at the Lower Monumental Dam smolt collection facility from 29 April to 25 May. Only hatchery-origin yearling Chinook salmon not previously PIT tagged, without any visual signs of disease or injuries, and 15 g or larger were used. During 2004, the Chinook salmon smolt index at Lower Monumental Dam was skewed early because operations of the lower Snake River hydropower system included periods of transportation with voluntary spill and periods of full transportation (Figure 3). Tagging comprised the period between the 30th and 96th percentile of the 9-year average Chinook salmon smolt index at Lower Monumental Dam. Overall mean fork lengths was 149.2 mm (SD = 11.3) and 149.8 mm (SD = 11.7) for fish released above and below Lower Monumental Dam, respectively (Table 1). Overall mean weight was 27.6 g (SD = 8.2) and 28.0 g (SD = 8.7) for fish released above and below Lower Monumental Dam, respectively (Table 2).

A4. The tag and/or tagging method does not significantly affect the subsequent behavior or survival of the marked individual.

Assumption A4 was not tested for validation in this study. However, the effects of radio tagging on survival, predation, growth, and swimming performance of juvenile salmonids have previously been evaluated by Adams et al. (1998a) and Hockersmith et al. (2003). From their conclusions, we assumed that behavior and survival were not significantly affected over the length of our study area.

A5. Fish that die as a result of passing through a passage route are not subsequently detected at a downstream array that is used to estimate survival for that passage route.

Assumption A5 was not tested for validation in this study. However, the distance between release at Lower Monumental Dam and the first downstream telemetry array used to estimate survival (Ice Harbor Dam) was 51 km. Axel et al. (2003) found that dead, radio-tagged fish released into the bypass systems at Ice Harbor and McNary Dams were not subsequently detected at telemetry transects, which were more than 3.2 km downstream.

A6. The radio transmitters functioned properly and for the predetermined period of time.

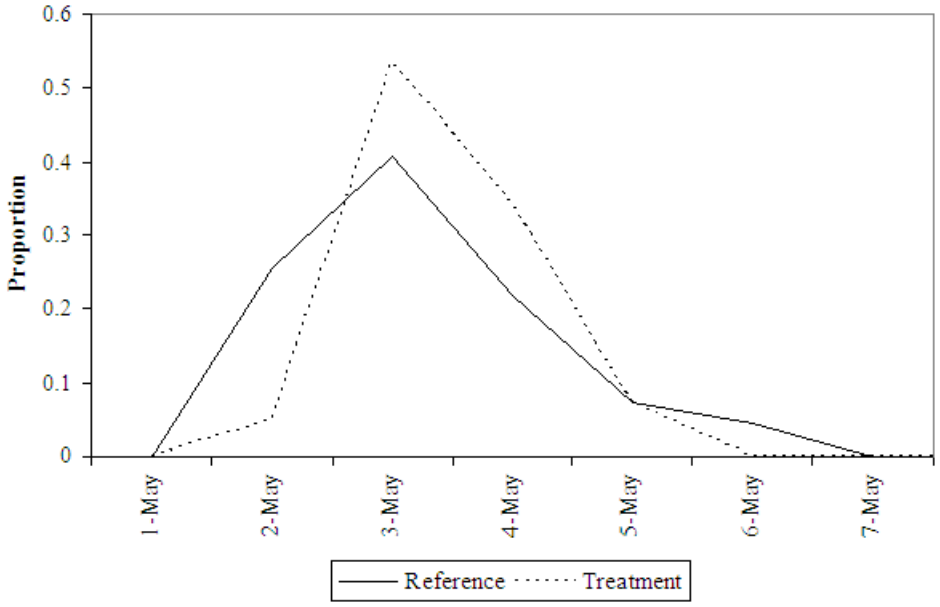
All transmitters were checked upon receipt from the manufacturer, prior to implantation into a fish and prior to release, to ensure that the transmitter was functioning properly. Tags not functioning properly were not used in the study. In addition, radio transmitters from tagging mortalities throughout the study were tested for tag life by allowing them to run in river water and checking them daily to determine if they functioned for the predetermined period of time. None of the tags tested for tag life failed prior to the preprogrammed shut-down after 10 d.

A7. Treatment fish that pass through a specific route are appropriately assigned to that route.

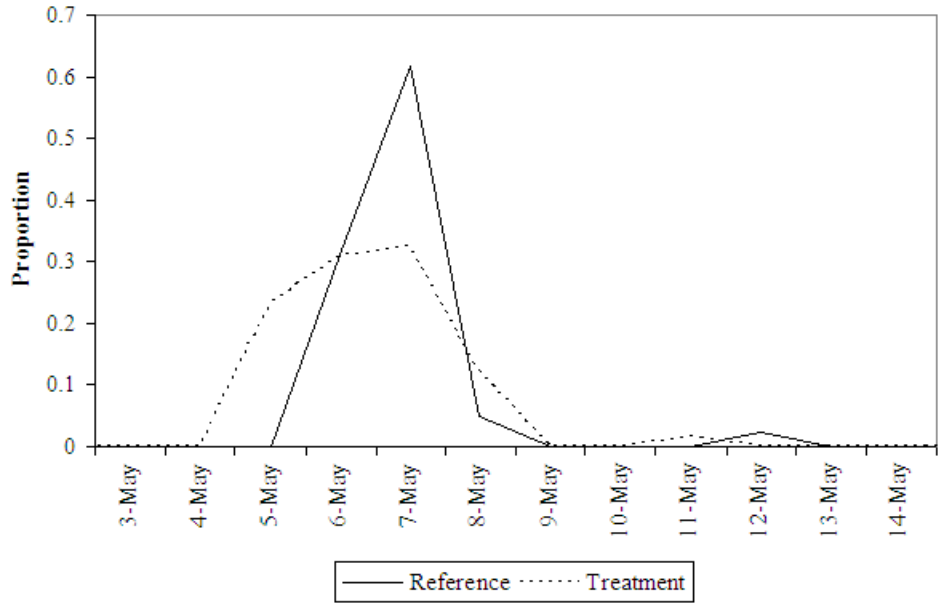
The route of passage for individual fish was determined from telemetry receivers and antenna arrays which monitored individual turbine intakes, individual spillbays, and the JBS. Passage routes were assigned to individual fish based on the last detection within a passage route and subsequent detection in the immediate tailrace. Tailrace detections were used to validate passage because it was possible for fish to be detected on a passage array while still in the forebay.

APPENDIX B:

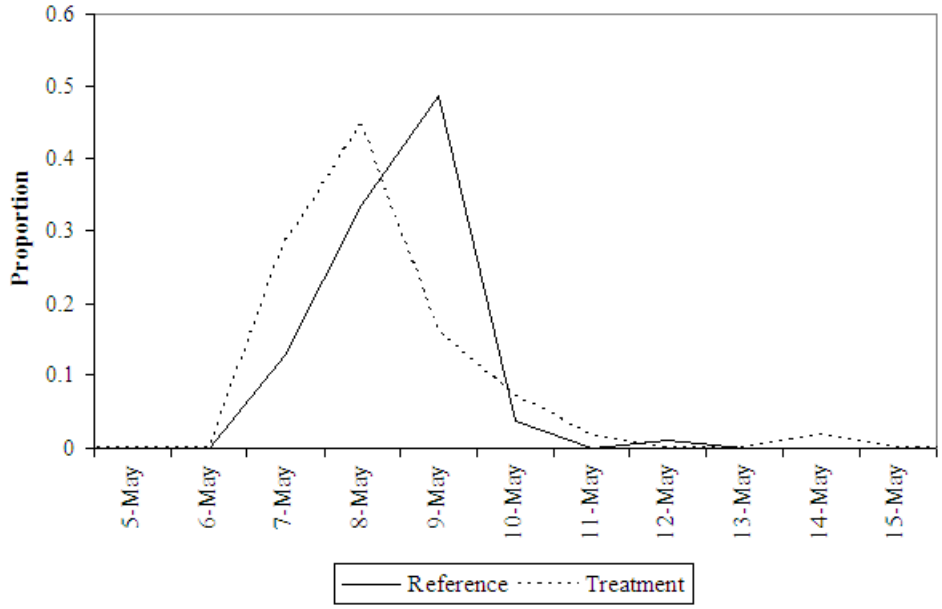
Ice Harbor Dam Arrival Distributions for Treatment and Reference Release Groups with Significantly Different Travel Timing



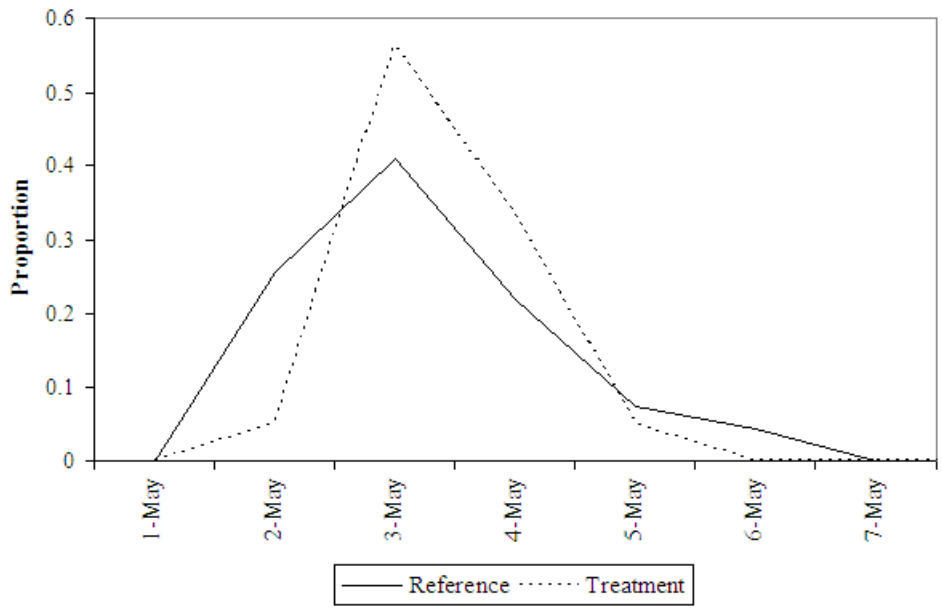
Appendix Figure B1. Arrival distribution at Ice Harbor Dam for treatment fish passing and reference fish released into the tailrace of Lower Monumental Dam from 30 April to 1 May 2004 which were used to estimate dam survival during periods of bulk spill.



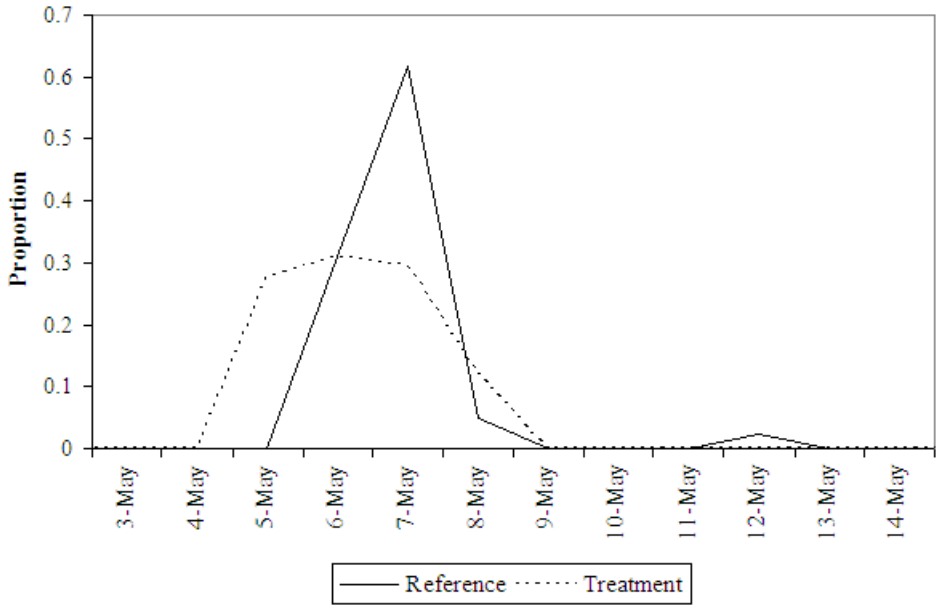
Appendix Figure B2. Arrival distribution at Ice Harbor Dam for treatment fish passing and reference fish released into the tailrace of Lower Monumental Dam from 4 to 5 May 2004 which were used to estimate dam survival during periods of bulk spill.



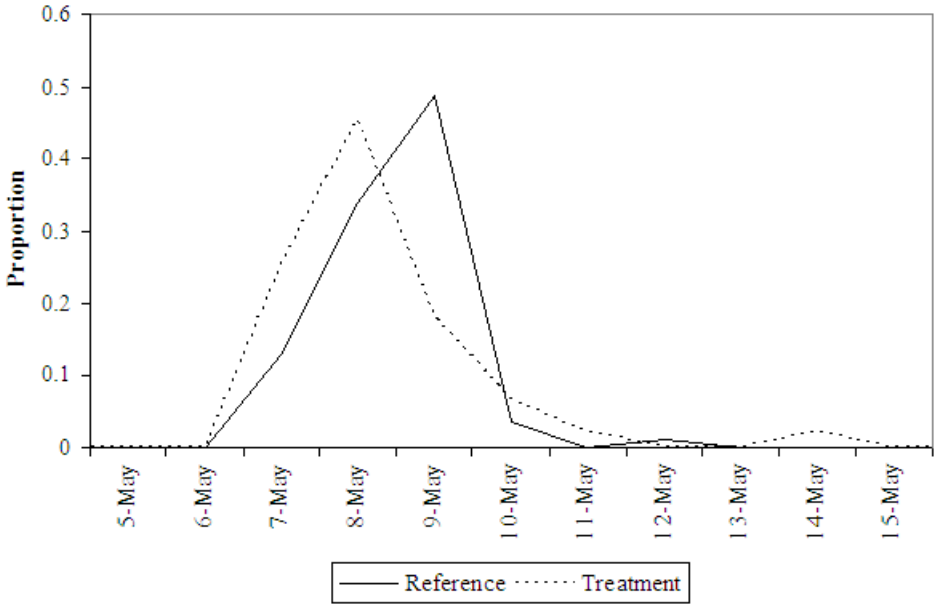
Appendix Figure B3. Arrival distribution at Ice Harbor Dam for treatment fish passing and reference fish released into the tailrace of Lower Monumental Dam from 6 to 7 May 2004 which were used to estimate dam survival during periods of bulk spill.



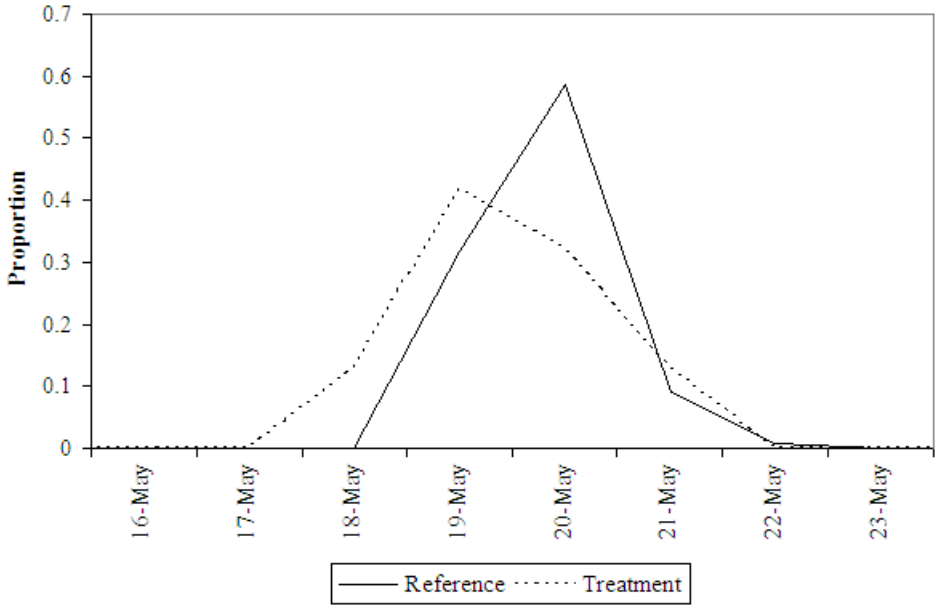
Appendix Figure B4. Arrival distribution at Ice Harbor Dam for treatment fish passing and reference fish released into the tailrace of Lower Monumental Dam from 30 April to 1 May 2004 which were used to estimate spillway survival.



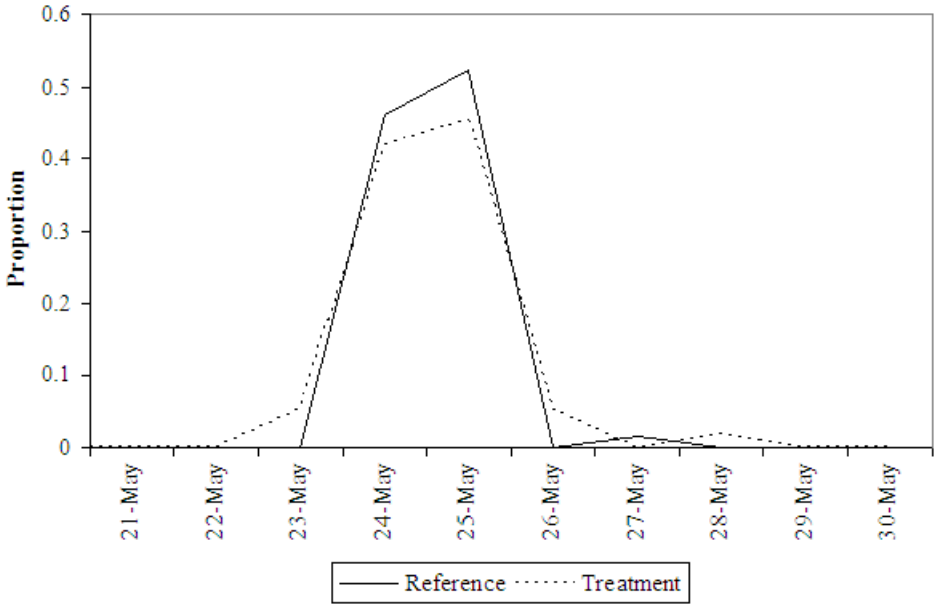
Appendix Figure B5. Arrival distribution at Ice Harbor Dam for treatment fish passing and reference fish released into the tailrace of Lower Monumental Dam from 4 to 5 May 2004 which were used to estimate spillway survival.



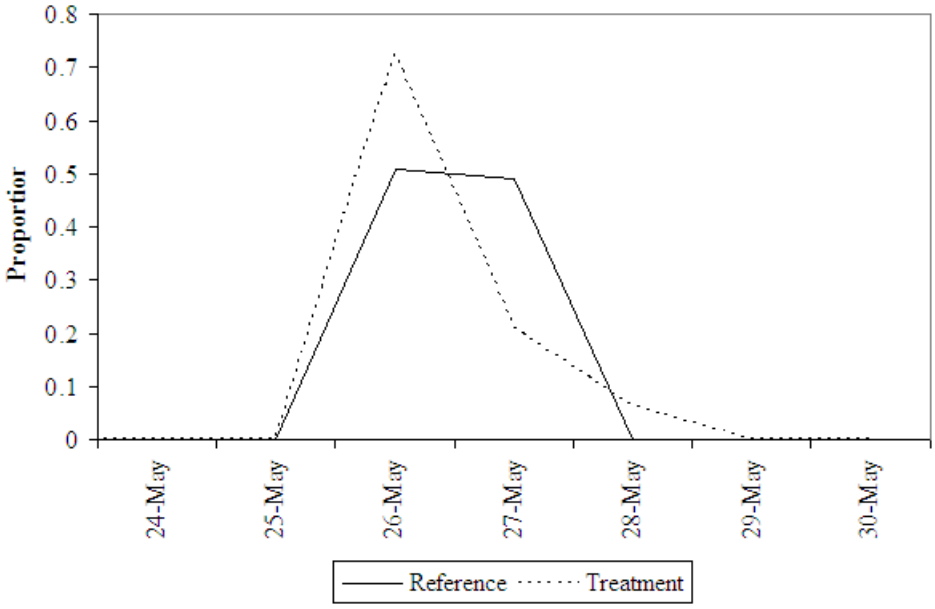
Appendix Figure B6. Arrival distribution at Ice Harbor Dam for treatment fish passing and reference fish released into the tailrace of Lower Monumental Dam from 6 to 7 May 2004 which were used to estimate spillway survival.



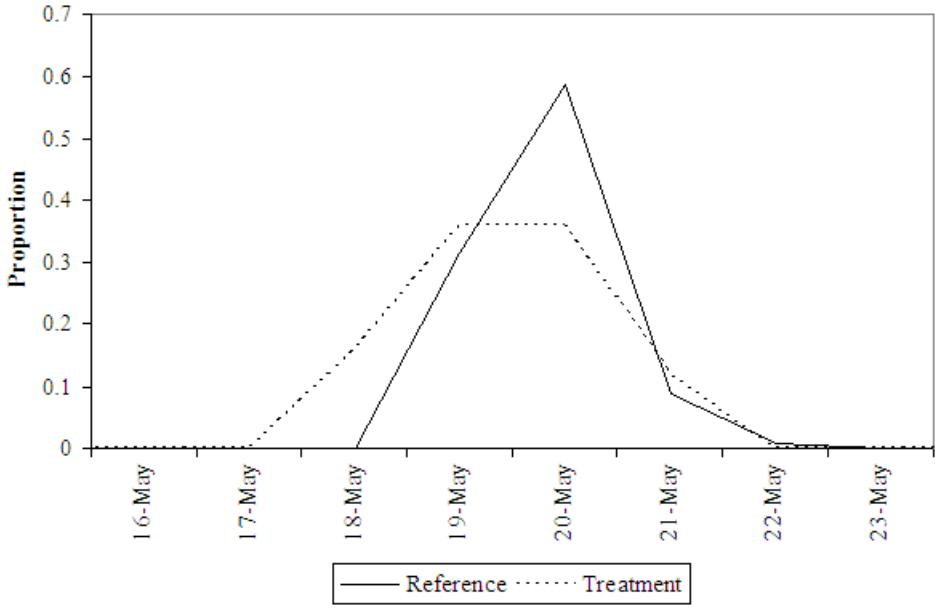
Appendix Figure B7. Arrival distribution at Ice Harbor Dam for treatment fish passing and reference fish released into the tailrace of Lower Monumental Dam 18 May 2004 which were used to estimate dam and powerhouse survival during periods of no spill.



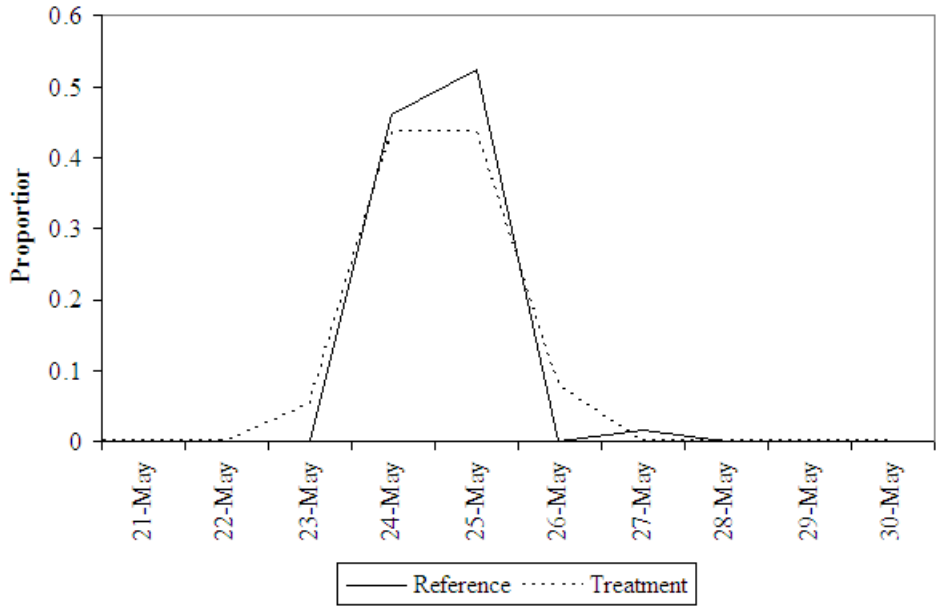
Appendix Figure B8. Arrival distribution at Ice Harbor Dam for treatment fish passing and reference fish released into the tailrace of Lower Monumental Dam 23 May 2004 which were used to estimate dam and powerhouse survival during periods of no spill.



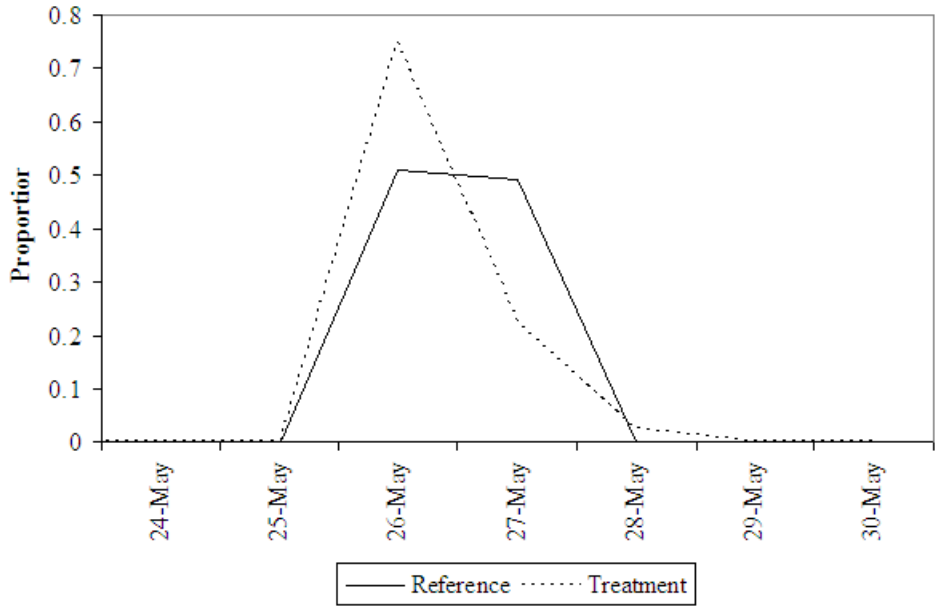
Appendix Figure B9. Arrival distribution at Ice Harbor Dam for treatment fish passing and reference fish released into the tailrace of Lower Monumental Dam 25 May 2004 which were used to estimate dam and powerhouse survival during periods of no spill.



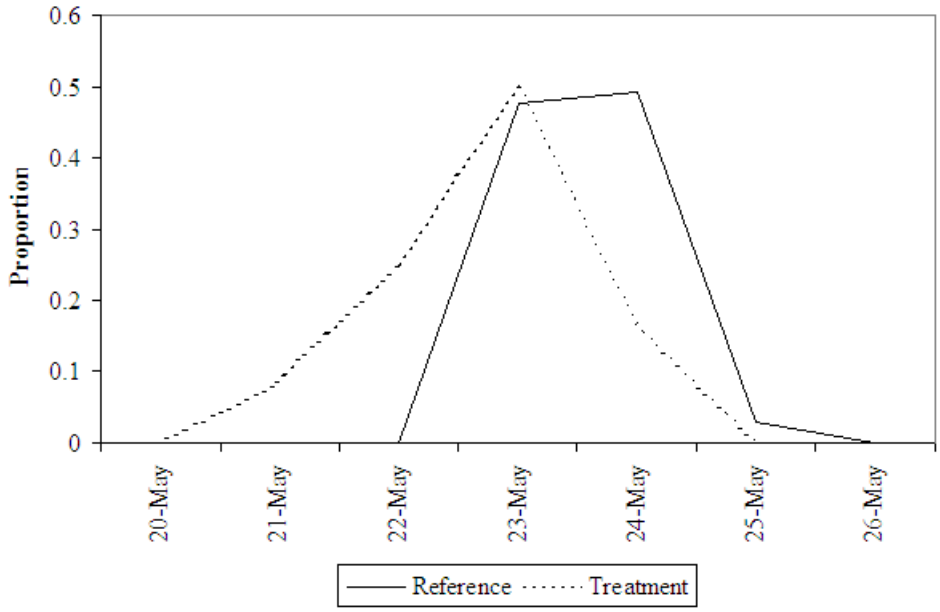
Appendix Figure B10. Arrival distribution at Ice Harbor Dam for treatment fish passing and reference fish released into the tailrace of Lower Monumental Dam 18 May 2004 which were used to estimate bypass survival during periods of no spill.



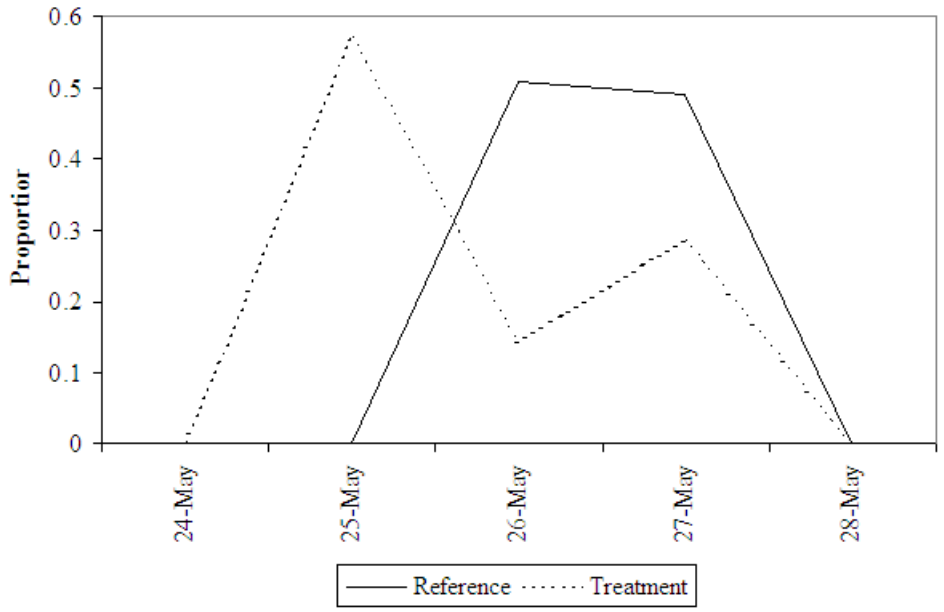
Appendix Figure B11. Arrival distribution at Ice Harbor Dam for treatment fish passing and reference fish released into the tailrace of Lower Monumental Dam 23 May 2004 which were used to estimate bypass survival during periods of no spill.



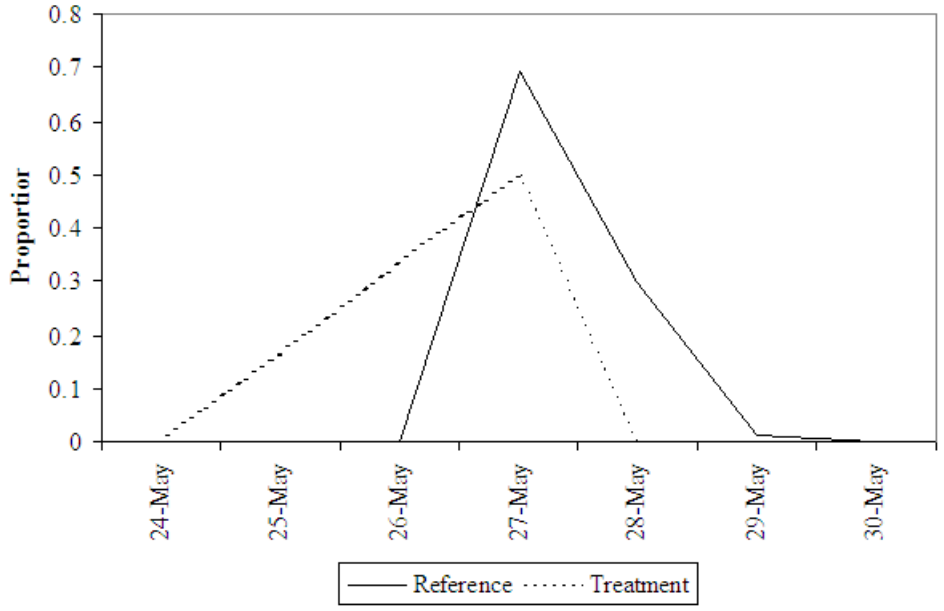
Appendix Figure B12. Arrival distribution at Ice Harbor Dam for treatment fish passing and reference fish released into the tailrace of Lower Monumental Dam 25 May 2004 which were used to estimate bypass survival during periods of no spill.



Appendix Figure B13. Arrival distribution at Ice Harbor Dam for treatment fish passing and reference fish released into the tailrace of Lower Monumental Dam 22 May 2004 which were used to estimate turbine survival during periods of no spill.

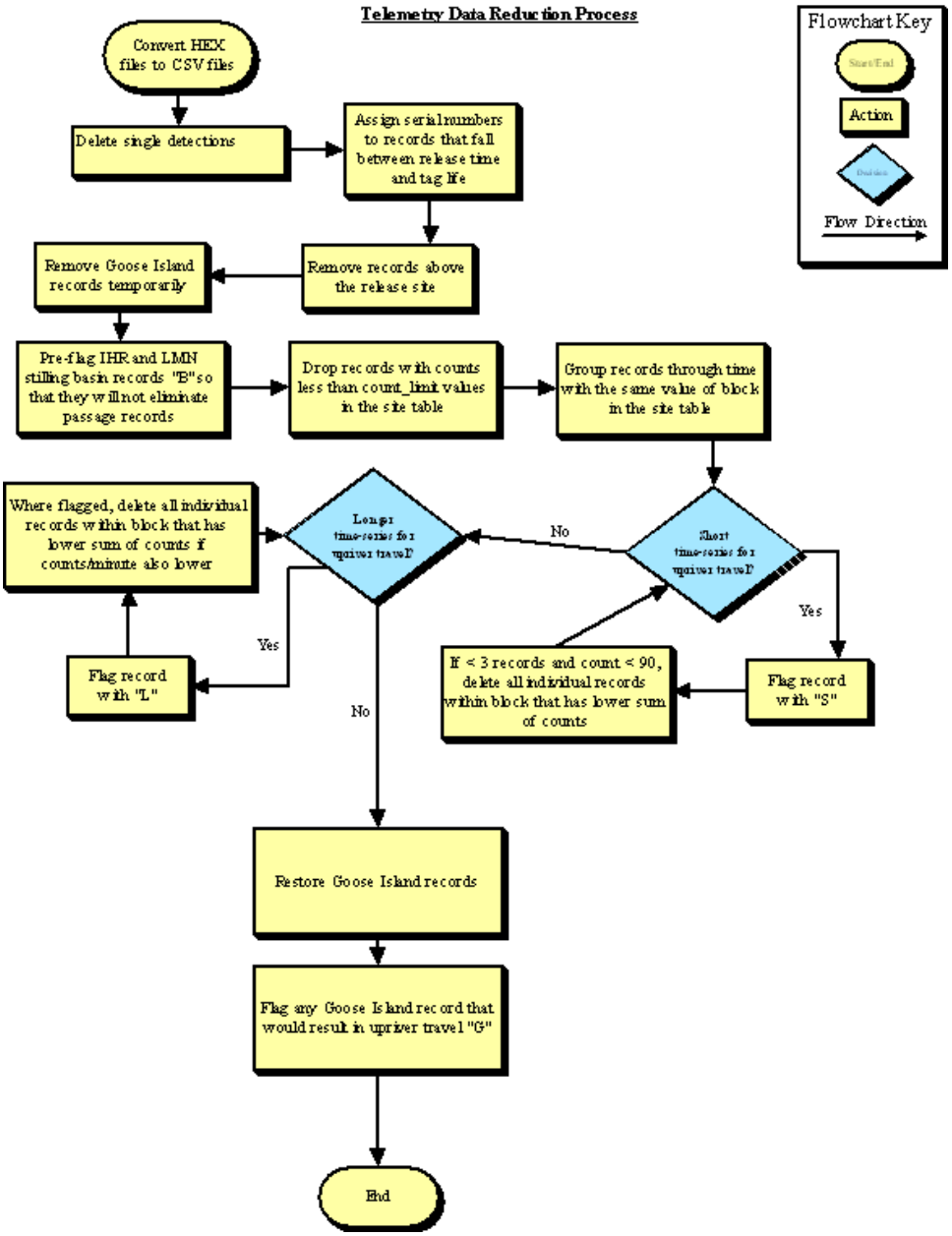


Appendix Figure B14. Arrival distribution at Ice Harbor Dam for treatment fish passing and reference fish released into the tailrace of Lower Monumental Dam 25 May 2004 which were used to estimate turbine survival during periods of no spill.



Appendix Figure B15. Arrival distribution at Ice Harbor Dam for treatment fish passing and reference fish released into the tailrace of Lower Monumental Dam 26 May 2004 which were used to estimate turbine survival during periods of no spill.

APPENDIX C: Telemetry Data processing and Reduction Flowchart



Appendix Figure C1. Flowchart of telemetry data processing and reduction used in evaluating behavior and survival at Lower Monumental Dam for yearling Chinook salmon, 2004.