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Fish Ecology Division

Northwest Fisheries Science Center

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Seattle, Washington

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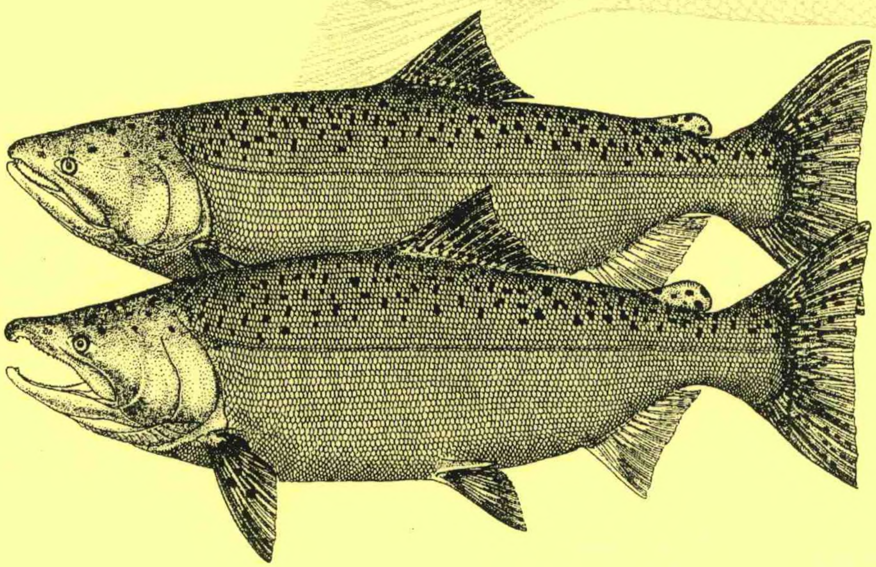
April 2008



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Report of research by

Fish Ecology Division
Northwest Fisheries Science Center
National Marine Fisheries Service
National Oceanic and Atmospheric Administration
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EXECUTIVE SUMMARY

In an effort to increase passage and survival for juvenile salmon, the U.S. Army Corps of Engineers, in conjunction with regional fishery managers, installed a removable spillway weir (RSW) at Ice Harbor Dam in spring 2005. During 2006, NOAA Fisheries Service continued the evaluation of the RSW at Ice Harbor Dam in order to optimize operations to increase fish passage efficiency (FPE) and survival.

In 2006, we evaluated passage behavior and estimated relative passage survival for radio-tagged, river-run subyearling Chinook salmon *Oncorhynchus tshawytscha* at Ice Harbor Dam on the Snake River. Fish were collected, surgically tagged with a radio transmitter, and PIT tagged at Lower Monumental Dam. Treatment groups were comprised of 1,107 fish released 4 km upstream of Ice Harbor Dam. Reference groups were comprised of 1,903 fish released into the tailrace of Ice Harbor Dam.

Releases occurred during both day and night operations for 8 days from 23 June to 1 July. The study was conducted during the period of time coinciding with the 84th to 98th percentile of the cumulative smolt passage index for subyearling Chinook salmon arrival at Lower Monumental Dam. For survival estimation, radio-telemetry detection arrays were installed at multiple locations between Ice Harbor Dam on the lower Snake River and the forebay of McNary Dam on the lower Columbia River. Fish that entered the study after 2 July were omitted from analysis due to an abrupt drop in detections at Ice Harbor Dam. We believe this drop resulted from behavioral changes rather than decreased survival.

Fish passage route distribution was 92, 4.3, and 1.8% for the spillway, juvenile bypass system, and turbines, respectively (Table 1). Median forebay residence time was 2 h. The RSW had the highest first approach at 55.2%, and of all fish that passed, 68% went through the RSW. For fish with a known passage route, fish guidance efficiency was 70.4%, fish passage efficiency was 98.2%, spill efficiency was 94%, and spill effectiveness was 2.00. RSW effectiveness was 4.59 and training spill effectiveness was 0.78. Median tailrace egress time was 10.7 minutes.

Relative dam survival was 95.2% (95% C.I., 93.8-96.7), relative concrete survival was 97.7% (95% C.I., 93.5-101.9), relative spillway survival was 98.8% (95% C.I., 95.0-102.5), and relative RSW survival for fish passing only through the RSW was 98.0% (95% C.I., 92.5-103.5)(Table 1).

Table 1. Passage conditions, passage behavior, and relative survival for radio-tagged subyearling Chinook salmon at Ice Harbor Dam, 2006 (95% CI in parentheses).

Passage conditions	Average project discharge (kcfs)	55.9
	Average spill discharge (kcfs)	30.0 (53.6%)
	Average RSW discharge (kcfs)	7.9 (14.1%)
	Average training flow discharge (kcfs)	22.1 (39.5%)
	Average tailwater elevation (ft msl)	342.2
	Average water temperature (°C)	19.1
Passage distribution (%)	Juvenile bypass	4.3
	Turbine 1	0.0
	Turbine 2	0.0
	Turbine 3	0.0
	Turbine 4	1.1
	Turbine 5	0.2
	Turbine 6	0.4
	Turbine passage	1.8
	Spillbay 1	0.0
	RSW	68.0
	Spillbay 3	5.3
	Spillbay 4	6.8
	Spillbay 5	0.7
	Spillbay 6	7.3
	Spillbay 7	3.3
	Spillbay 8	1.8
	Spillbay 9	0.9
	Spillbay 10	0.0
	Spillway passage	92.0
	Unknown route	0.2
Passage metric	Median forebay delay (h)	2.0
	Fish passage efficiency (FPE)	98.2%
	Spill efficiency	94.0%
	Spill effectiveness	2.00
	RSW effectiveness	4.59
	Training spill effectiveness	0.78
	Fish guidance efficiency (FGE)	70.4%
	Median tailrace egress (minutes)	10.7
Relative survival	Relative dam survival (forebay BRZ to tailrace)	95.2% (93.8-96.7)
	Relative concrete survival (all fish passing the dam)	97.7% (93.5-101.9)
	Relative spillway survival (fish passing only through the spillway)	98.8% (95.0-102.5)
	Relative RSW survival (fish passing only through the RSW)	98.0% (92.5-103.5)

CONTENTS

INTRODUCTION

Fall Chinook salmon *Oncorhynchus tshawytscha* in the Snake River Basin were listed under the U.S. Endangered Species Act (ESA) in 1992 (NMFS 1992). Survival studies of juvenile salmonid passage through various routes at dams on the lower Snake River have indicated that among the different passage routes, survival was highest through spillways, followed by bypass systems, then turbines (Muir et al. 2001).

In the Columbia and Snake River Basin, most juvenile salmon and steelhead *O. mykiss* tend to stay in the upper 3 to 6 m of the water column as they migrate downstream (Johnson et al. 2000, Beeman and Maule 2006). However, to enter juvenile fish passage routes at Columbia and Snake River dams operated by the U.S. Army Corp of Engineers (USACE), fish must dive to depths of 15 to 18 m. In recent years, surface collection and bypass systems have been identified as viable alternatives for increasing fish passage efficiency (FPE) and survival for migrating juvenile salmonids at hydroelectric dams on the Columbia and Snake Rivers. For example, a surface collector at Wells Dam on the Columbia River, where the spillway is located over the turbine units, passed 90% of the fish while spilling just 7% of the total discharge (Johnson et al. 1992).

Efforts to improve spillway passage have led to the development of a surface-oriented route through a removable spillway weir (RSW). The design of the RSW allows juvenile salmonids to pass the spillway near the water surface over a raised spillway crest, similar to a waterslide. This creates a surface passage route with lower accelerations and lower pressures, conditions that should increase passage efficiency and overall survival of juvenile salmonids, while reducing the amount of water spilled.

The USACE installed a prototype RSW at Lower Granite Dam on the Snake River in summer 2001 and evaluated its performance in spring 2002. Evaluation of the RSW was compared to the current management strategy of spilling water to the "gas cap," that is, to state and local limits based on resulting levels of dissolved gas. These evaluations indicated that the RSW was an effective and efficient passage structure (Angela 2003, Plumb et al. 2003). With the success of the prototype RSW at Lower Granite Dam, the USACE installed a RSW in spillbay 2 at Ice Harbor Dam in February 2005.

Passage survival studies had been conducted during several years preceding installation of the RSW at Ice Harbor Dam. In 2003, Absolon et al. (2005) evaluated survival using a 2-d block design wherein 2 d of no spill were alternated with 2 d of bulk spill,[1] which was concentrated into 2 to 4 spillbays. They reported relative spillway passage survival estimates of 96% for PIT-tagged fall Chinook salmon released during summer 2003 under bulk spill conditions. This estimate was significantly higher than previous estimates obtained by Eppard et al. (2002, 2004) in 2000 (88.5%, $t = 2.24$, $P = 0.036$) and 2002 (89.4%, $t = 2.72$, $P = 0.012$).

In 2004, a 4-d block study design was used to estimate relative spillway passage and dam survival for radio-tagged, river-run subyearling Chinook salmon volitionally passing Ice Harbor Dam. The bulk spill pattern was compared with a standard flat spill pattern. The bulk spill pattern used fewer bays, a minimum gate opening of 6 stops, and a spill volume equivalent to BIOP-recommended nighttime spill (up to 100% of river flow or to dissolved gas limits). The standard flat spill pattern used all bays, a maximum gate opening of 3 stops, and spill volumes equivalent to BIOP-recommended daytime spill (45,000 ft^3/s) (Ogden et al. 2005). Spillway passage survival for radio-tagged fish passing during bulk spill operations was estimated at 97.2% (95% CI, 90.3–104.5) compared to 93.3% (95% CI, 88.2-98.6) for flat spill operations. Estimated dam survival for all radio-tagged fish passing during bulk spill operations was 86.2% (95% CI, 69.2-107.5) compared to 84.6% (95% CI, 73.6-97.2) during flat spill operations (Ogden et al. 2005).

In 2005, a 2-day randomized block study design was used to estimate relative survival for radio-tagged, river-run subyearling Chinook salmon volitionally passing Ice Harbor Dam. A bulk spill pattern with the RSW closed was compared with a spill pattern with the RSW open. The bulk spill pattern used fewer bays, a minimum gate opening of 6 stops, and a spill volume equivalent to BIOP-recommended nighttime spill with the RSW closed (spillbay 2). The RSW spill pattern had the RSW open (spillbay 2) with training spill in adjacent bays. Training spill is spill used to draw flow toward the RSW and to encourage tailrace flow from the RSW to move downstream instead of eddying in the tailrace (Ogden et al. 2007).

Spillway passage survival for radio-tagged fish passing during bulk spill operation was estimated at 100% (95% CI, 98.0-102.0%) compared to 98.9% (95% CI, 94.5-104.0%) for RSW spill operations. Estimated dam survival for all radio-tagged fish passing during bulk spill operations was 96.0% (95% CI, 92.0-97.8%) compared to 95.1% (95% CI, 87.0-104.0%) during RSW spill operations. Estimated RSW survival (fish passing only through the RSW) was 99.7% (95% CI, 96.0-104.0%) (Ogden et al. 2007).

[1] Bulk spill was generally defined as spill volume as prescribed by the National Marine Fisheries Service (NMFS) Biological Opinion (BIOP), but distributed through fewer bays.

During 2006, NOAA Fisheries Service continued evaluation of the RSW at Ice Harbor Dam in order to optimize operations to increase FPE and survival. In 2006, the RSW study was to follow a 2-d randomized block interval design that alternated between 2 treatment operations utilizing the RSW. The first treatment was to be the NMFS 2000 BIOP recommended spill of 45,000 ft^3/s spill during the day with spill to the gas cap at night. The second treatment was to be 30% spill of the total river flow day and night.

Fish that entered the study area after 2 July were omitted from the analysis due to an abrupt drop in detections of study fish at Ice Harbor Dam. We believe this drop resulted from behavioral changes (from an ocean-type life history strategy to a reservoir or stream-type strategy) rather than decreased survival. In other words, fish tagged late in the study period were not migrating. However, because there were an insufficient number of days available for testing between the time that summer spill began and the time fish stopped migrating, analysis of the data by treatment block was not possible, so instead we analyzed temporal trends in survival related to spill level.

Fish passage behavior performance metrics, project survival, and route-specific survival as used in this report are defined as follows:

Spill Efficiency (SPE): Number of fish passing the dam through the spillway divided by the total number of fish passing the dam.

Spill Effectiveness (SPF): The proportion of fish passing the dam via the spillway divided by the proportion of water spilled.

RSW Effectiveness: The proportion fish passing the dam via the RSW divided by the proportion of water spilled.

Fish Passage Efficiency (FPE): The number of fish passing the dam through non-turbine routes divided by number passing the dam.

Fish Guidance Efficiency (FGE): The number of fish passing the dam through the juvenile bypass system divided by the total number of fish passing the dam through the powerhouse.

Forebay residence: Elapsed time from arrival in the forebay of the dam until passage through the spillway, bypass, or turbines.

Tailrace egress: Elapsed time from dam passage to exit from the tailrace.

Dam survival: Relative survival from the upstream limit of the boat restricted zone a Ice Harbor Dam to the release location of reference groups downstream from the dam.

Concrete survival: Relative survival of all fish passing Ice Harbor Dam to the release location of reference groups downstream from the dam.

Route survival: Relative survival between detection within a passage route at Ice Harbor Dam to the release location of reference groups downstream from the dam.

Results of this study will be used to help make management decisions that will optimize survival for juvenile salmonids arriving at Ice Harbor Dam. This study addresses the reasonable and prudent alternatives listed in sections 9.6.1.4.5 and 9.6.1.4.6 of the NMFS 2000 Biological Opinion (NMFS 2000). This study also addresses questions 3 and 7 of the 10 key questions for salmon recovery in the Northwest Fisheries Science Center Salmon Research Plan (NWFSC 2002).

METHODS

Study Area

The study area included a 72-km reach of the Snake and Columbia Rivers from Ice Harbor Dam to the forebay of McNary Dam (Figure 1). Ice Harbor Dam, the first dam upstream from the mouth of the Snake River, is located 16 km upstream from the confluence of the Snake and Columbia Rivers. McNary Dam, the fourth dam on the Columbia River, is located 470 km upstream from the river mouth. Additional radio telemetry transects used for estimating survival at Ice Harbor Dam were located at the mouth of the Snake River at Sacajawea Park and the Burbank Railroad bridge downstream from the confluence of the Columbia and Snake Rivers (Figure 1).

Fish Collection, Tagging, and Release

River-run subyearling Chinook salmon were collected at the Lower Monumental Dam smolt collection facility. We chose fish that did not have any gross injury or deformity and were at least 105 mm in length and 10 g in weight. Only fish not previously tagged with a passive integrated transponder (PIT) were used. Fish were anesthetized with tricaine methane sulfonate (MS-222) and sorted in a recirculating anesthetic system. Fish for treatment and reference release groups were transferred through a water-filled, 10.2-cm hose to a 935-L tank. Following collection and sorting, fish were maintained via flow-through river water and held for 24 h prior to radio transmitter implantation.

Radio tags were purchased from Advanced Telemetry Systems Inc.,[2] had a predetermined tag life of 10 d, and were pulse-coded for unique identification of individual fish at 30 MHz. Each radio tag measured 13 mm in length and 6 mm in diameter, bringing the volume of the tag to 407 mm^3. The tags weighed 1.0 g in air.

Fish were surgically implanted with radio transmitters using techniques described by Adams et al. (1998a). Each fish also received a PIT tag before the incision was closed in order to monitor radio tag performance. Immediately following tagging, fish were placed into a 19-L recovery container (2 fish per container) with aeration until recovery from the anesthesia. Recovery containers were then closed and transferred to a 1,152-L

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

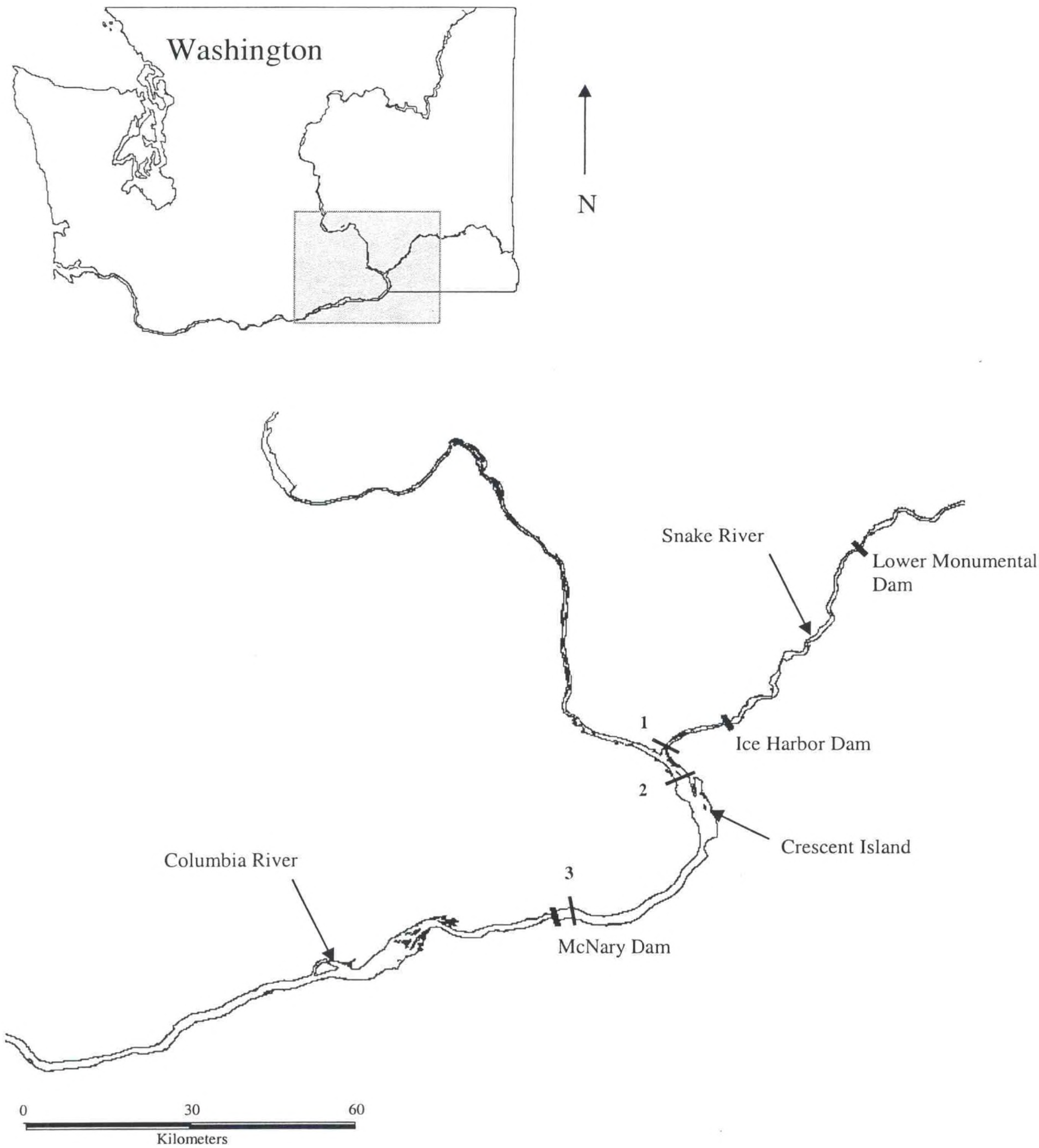

Figure 1. Study area showing location of radiotelemetry transects used for estimating survival at Ice Harbor Dam, 2006. (Note: 1 = Mouth of the Snake River at Sacajawea Park, WA; 2 = Railroad Bridge, WA; 3 = McNary Dam Forebay.)

holding tank designed to accommodate up to 28 containers. Fish holding containers were perforated with 1.3-cm holes in the top 30.5 cm of the container to allow an exchange of water during holding. All holding tanks were supplied with flow-through water during tagging and holding and were aerated with oxygen during transport to release locations. After tagging, fish were held a minimum of 24 h with flow-through water for recovery and determination of post-tagging mortality.

After the post-tagging recovery period, radio-tagged fish were moved in their recovery containers from the holding area to release areas (Ice Harbor Dam forebay and tailrace). Release groups were transferred from holding tanks to a release tank mounted on an 8.5 × 2.4-m barge, transported to the release location, and released mid-channel water-to-water. Two fish were released every 15 min in order to distribute releases over a period of 4-5 h.

Daytime releases occurred between 0800 and 1530 PDT. Nighttime releases occurred between 2000 and 0315 PDT. We released 78 groups of approximately 26-50 fish per group. A total of 1,107 radio-tagged fish were released 4 km upstream of Ice Harbor Dam during both daytime and nighttime project operations. A total of 1,903 radio-tagged fish were released 2 km downstream from Ice Harbor Dam at river kilometer 535.7 during both daytime and nighttime operations (Figure 2).

Monitoring and Data Analysis

Radio telemetry receivers and multiple-element aerial antennas were used to establish detection transects between the forebay of Ice Harbor Dam and the forebay of McNary Dam (Figure 1). Receivers using underwater dipole or multiple-element aerial antennas were used to monitor entrance into the forebay and approach to and exit from Ice Harbor Dam (Figure 2). Underwater antennas were used to monitor passage routes (Figure 3). Monitored passage routes included the juvenile fish bypass system, individual spillbays, and all turbine unit gate slots (gatewells).

Telemetry data were retrieved through an automated process that downloaded data from network telemetry receivers up to four times daily and placed them on an FTP server once daily for downloading into the database. All compressed data were combined and loaded to a database where automated queries and algorithms were used to remove erroneous data, thus creating a detailed detection history for each radio-tagged fish (Appendix B).

Using detailed detection histories, we determined forebay arrival time, dam approach pattern, passage distribution and timing, exit from the tailrace, and timing of downstream detection for individual radio-tagged fish. Forebay arrival time was based on the first time a fish was detected in the forebay of the dam. 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 receiver prior to detection in the tailrace. Routes were assigned only to fish detected in the tailrace of the dam, meaning at least one detection on the stilling basin, tailrace exit transect, or at Goose Island (Figures 2 and 3). Spillway passage was assigned to fish last detected in the forebay on one of the 10 antenna arrays deployed in the spillway. Similarly, turbine passage was assigned to fish last detected in a turbine intake and not detected in the juvenile bypass system (JBS) prior to detection in the tailrace. Passage through the JBS was assigned to fish detected in the collection channel prior to detection in the tailrace.

Project Operations

From 24 June to 15 July 2006, the voluntary spill program followed a 2-d randomized block interval design that alternated between 2 treatment operations that utilized the RSW. The first treatment operation used spill at 45,000 ft^3/s during the day and to the dissolved gas limit at night, as recommended by the NMFS 2000 BIOP. The second treatment was spill at 30% of total river flow during both day and night.

Fish that entered the study area after 2 July were omitted from analysis because their migration behavior differed markedly from that of fish that entered earlier (i.e., they were not migrating). However, this resulted in an insufficient number of days available for testing between the time that tagging began and the time fish stopped migrating. Therefore, analysis of the data by treatment blocks was not possible, so instead we analyzed temporal trends in survival related to spill level.

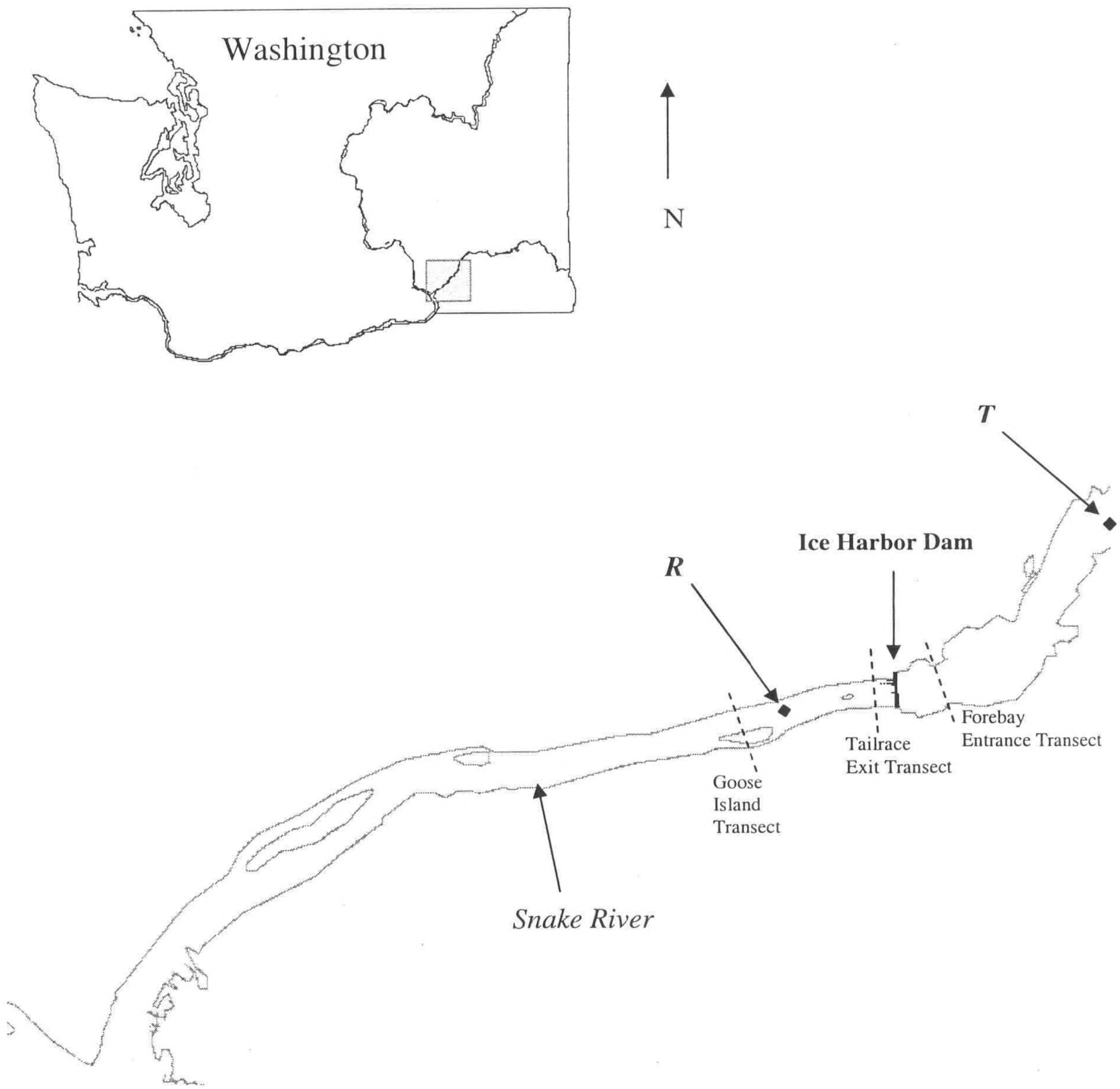

Figure 2. The Lower Snake River and Ice Harbor Dam showing the release locations for treatment (***T***) and reference (***R***) groups of radio-tagged subyearling Chinook salmon, 2006. Also shown are radiotelemetry transects used to detect fish entering the immediate forebay (rkm 538.5) and subsequently exiting the tailrace (rkm 537.7), 2006.

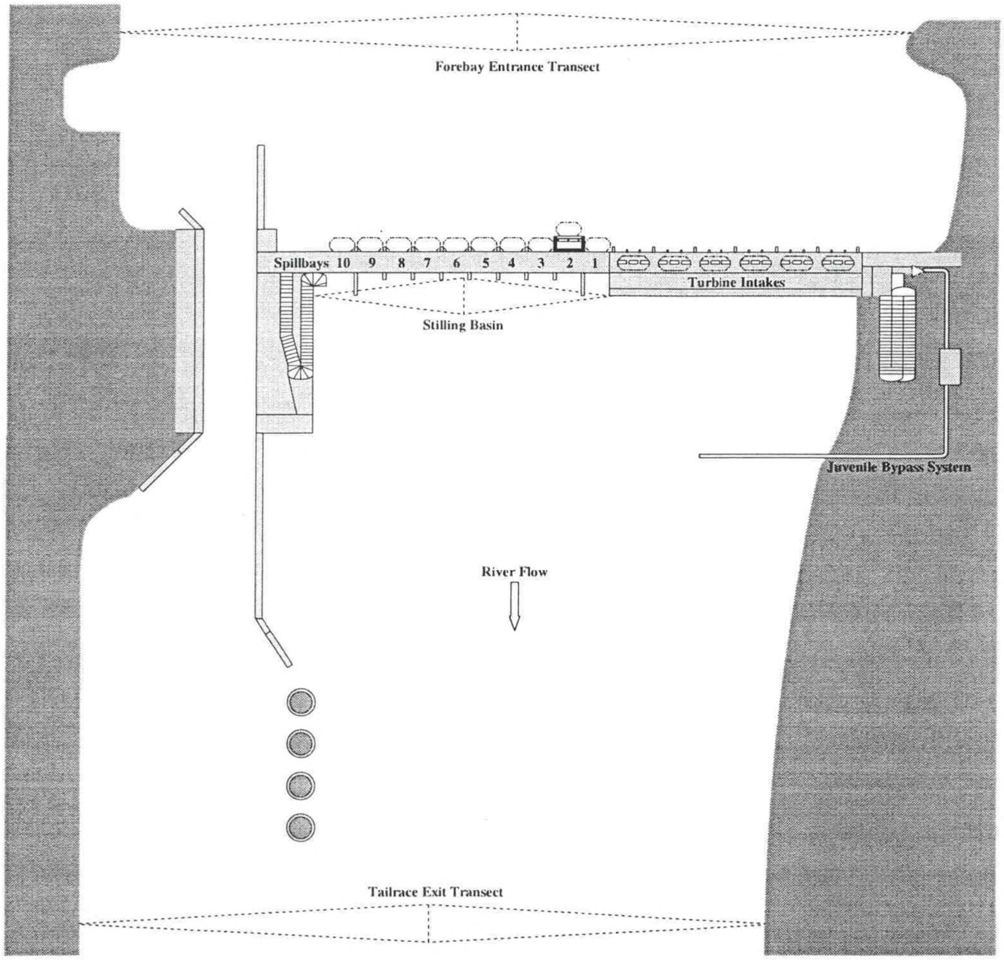

Figure 3. Plan view of Ice Harbor Dam showing approximate radiotelemetry detection zones in 2006 (Note: Dashed ovals represent underwater antennas. Dashed triangles represent aerial antennas).

Survival Estimates

A paired-release study design was used for estimating relative survival where groups of radio-tagged fish were released at one of two sites; upstream (treatment) and downstream (reference) from Ice Harbor Dam (Figure 2). Treatment groups were formed by grouping daily detections of radio-tagged fish as they entered the forebay of Ice Harbor Dam. Reference groups were released directly into the tailrace of Ice Harbor Dam (Figure 2) and the release dates were used to pair them with the treatment fish that entered the forebay on the same date.

The Cormack-Jolly-Seber (CJS) single-release model (Cormack 1964; Jolly 1965; Seber 1965) was used to estimate probability of detection and survival from release to the mouth of the Snake River at Sacajawea Park for both treatment and reference groups. This model provided unbiased estimates if certain assumptions were met (Zabel et al. 2002; Smith et al. 2003), in particular that detection and survival probabilities downstream from detection sites were not conditional on radio telemetry detection at upstream sites. Testing of model assumptions is addressed in Appendix A.

Relative spillway passage survival was then expressed as the ratio of CJS survival estimates for treatment fish to reference fish. Average relative survival was calculated using geometric means. The weights were the inverses of the respective sample variances (Burnham et al. 1987; Muir et al. 2003). A primary assumption made when using a paired-release study design is that treatment and reference groups have similar survival probabilities in the reach that is common to both groups; that is, groups are mixed temporally upon detection at the primary detection array. This assumption is addressed in Appendix A.

Passage Behavior and Timing

Forebay residence was defined as elapsed time from detection on the forebay entrance transect to last detection on a passage-route receiver; tailrace egress was defined as the time from last detection on a passage route to first detection on the tailrace exit transect. We used paired *t*-tests to compare median forebay residence and tailrace-egress time between temporally paired replicate groups ($\alpha = 0.05$). On 24 June, 19 study fish were used to estimate forebay residence and tailrace egress times. These fish were not used for relative survival estimates because there was no temporal reference group with which to pair them.

Passage Route Distribution

To determine the route of passage used by individual fish at Ice Harbor Dam, we monitored the spillway, standard-length submersible traveling screens (fish guidance screens), and JBS. The spillway was monitored by four underwater dipole antennas in each spillbay; two antennas were installed along each of the two pier noses of each spillbay at depths of 6 and 12 m. Pre-season range testing showed that this configuration monitored the entire spillbay. In addition, we mounted aerial antennas to the handrail of the RSW and the downstream pier noses in the tailrace in order to ensure that we detected all fish that passed over the RSW. We used armored coaxial cable, stripped at the end, to detect fish passage in the turbine units. Antennas in turbine units were attached on both ends of the downstream side of the fish screen support frame located within each slot of the turbine intake. For the JBS, two loop antennas were placed on the handrail at the collection channel exit located upstream from the juvenile bypass pipe. Fish that were detected on fish guidance screen telemetry antennas, but not subsequently detected on the PIT-detection system or telemetry monitor in the collection channel, were designated turbine-passed fish.

Fish Passage Metrics

The standard fish-passage metrics of spill efficiency, spill effectiveness, fish passage efficiency, and fish guidance efficiency were also evaluated at Ice Harbor Dam using radio telemetry detections in the locations used for passage route evaluation (described above).

Avian Predation

Predation from the Caspian Tern *Hydroprogne caspia* colony on Crescent Island, located 12.9 km downstream from the Snake River mouth (Figure 1), was evaluated by physical recovery of radio transmitters that were visible on the island and by PIT tag detection. Radio tags and PIT tags were recovered on the tern colony at Crescent Island during fall 2006 after the birds left the island. Radio-tag serial numbers were used to identify individual tagged fish. PIT tag detections and recovery of radio transmitters at Crescent Island were provided by NMFS (Scott Sebring, NMFS, personal communication; see also Ryan et al. 2001) and Real Time Research, Inc. (A. Evans, Real Time Research, Inc., personal communication). There is an ongoing monitoring effort to recover PIT tags from active Caspian Tern colonies in the region conducted by NOAA Fisheries and by the Columbia Bird Research group.

RESULTS

Fish Collection, Tagging, and Release

River-run, subyearling Chinook salmon were collected and tagged at Lower Monumental Dam for 8 d from 23 June to 1 July. Tagging began after 84% of the juvenile subyearling Chinook salmon had passed Lower Monumental Dam and was completed when 98% of these fish had passed (Figure 4). Mean fork length was 118.6 mm for treatment fish and 119.4 mm for reference fish (Table 2). Mean weight was 15.8 g for treatment fish and 16.2 g for reference fish (Table 3). For fish from the run at large sampled at the dam during this same period, mean length was 111.9 mm and mean weight was 16.2 g (Tables 4 and 5). As mentioned above, fish that entered the study after 2 July were omitted from analysis due to non-migratory behavior. During the study period, handling and tagging mortality for subyearling Chinook salmon held for a minimum of 24 h after tagging was 0.7%.

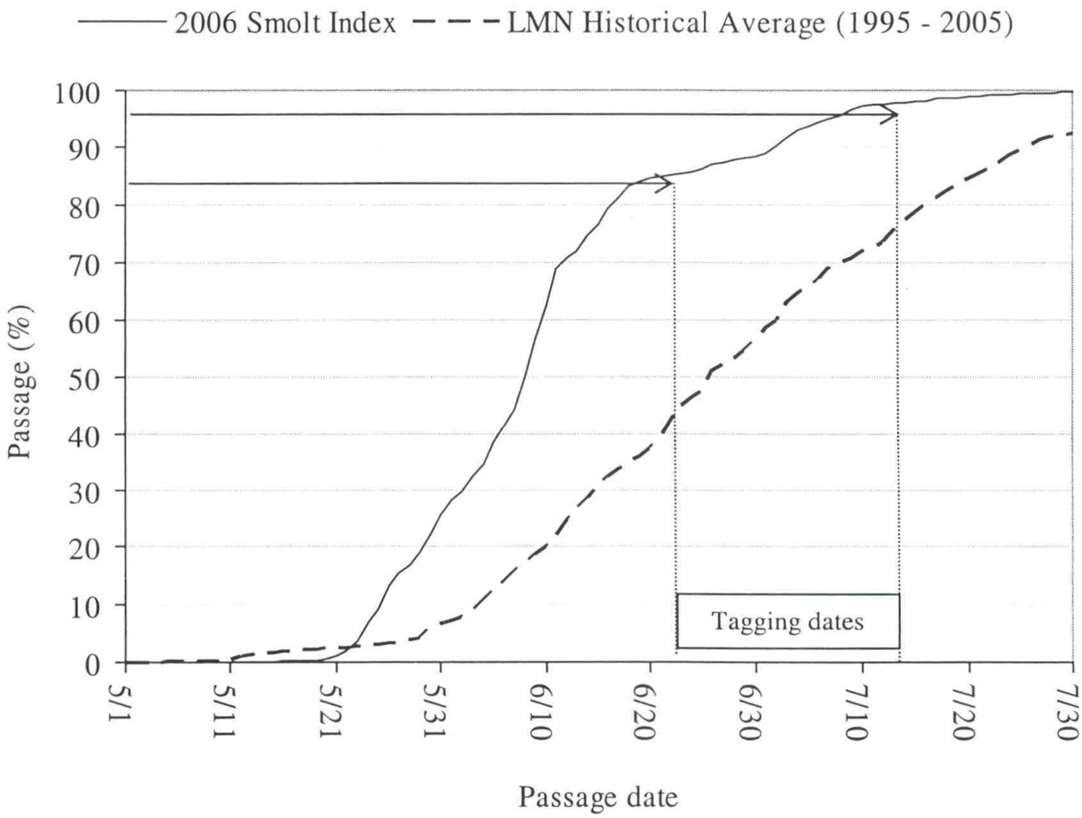

Figure 4. The 2006 cumulative passage distribution compared to the historical average (1995-2005) for subyearling Chinook salmon passing Lower Monumental Dam.

Table 2. Mean length of radio-tagged subyearling Chinook salmon (sample size, mean, standard deviation, and range) releases at Ice Harbor Dam used to evaluate passage behavior and relative survival, 2006.

		Mean length of radio-tagged fish (mm)							
		Treatment				Reference			
Tag day	Release date	N	Mean	SD	Range	N	Mean	SD	Range
23-Jun	24-Jun	55	114.1	5.9	102-132	84	117.2	6.2	102-136
24-Jun	25-Jun	54	117.2	6.0	108-134	93	117.2	6.6	103-136
25-Jun	26-Jun	57	115.8	6.7	105-132	97	117.5	7.4	104-134
26-Jun	27-Jun	59	118.2	7.8	105-147	96	117.6	6.6	105-136
27-Jun	28-Jun	60	118.0	7.2	104-136	99	119.4	6.0	108-134
28-Jun	29-Jun	60	119.1	6.2	108-137	97	122.6	6.9	107-139
29-Jun	30-Jun	59	120.8	6.5	108-137	97	123.0	6.6	110-141
30-Jun	1-Jul	59	122.1	7.0	109-138	98	120.8	7.2	105-146
1-Jul	2-Jul	59	122.2	6.4	108-143	84	117.2	6.2	102-136
Total		522	118.6	6.6	102-147	761	119.4	6.7	102-146

Table 3. Mean weight of radio-tagged subyearling Chinook salmon (sample size, mean, standard deviation, and range) releases at Ice Harbor Dam used to evaluate passage behavior and relative survival, 2006.

		Mean weight of radio-tagged fish (g)							
		Treatment				Reference			
Tag day	Release date	N	Mean	SD	Range	N	Mean	SD	Range
23-Jun	24-Jun	55	14.5	2.5	11.8-23.3	84	15.5	2.7	12.1-23.9
24-Jun	25-Jun	54	15.6	2.6	12-22.1	93	15.4	2.6	12.2-23.1
25-Jun	26-Jun	57	15.2	2.7	12.1-21.7	97	15.8	2.9	12.2-27.1
26-Jun	27-Jun	59	15.9	3.5	12.3-33.2	96	15.6	2.5	12.1-24.6
27-Jun	28-Jun	60	15.8	2.7	12.2-23.6	99	15.9	2.6	12.3-23.8
28-Jun	29-Jun	60	15.6	2.7	12.4-26.2	97	17.2	3.0	12.1-26.5
29-Jun	30-Jun	59	16.1	2.4	12.1-21.5	97	17.4	2.9	12.5-26.1
30-Jun	1-Jul	59	16.9	3.4	12.2-26.5	98	17.0	3.3	12.3-31.0
1-Jul	2-Jul	59	16.8	2.9	12.5-30.3	84	15.5	2.7	12.1-23.9
Total		522	15.8	2.8	11.8-33.2	761	16.2	2.8	12.1-31.0

Table 4. Sample size, mean, range, and standard deviation (SD) of length (mm) by tagging date for river-run, subyearling Chinook salmon from the smolt monitoring sample at Lower Monumental Dam, 2006.

	Mean length (mm) smolt monitoring sample			
Date	N	Mean	Range	SD
23-Jun	200	107.9	65-130	8.51
24-Jun	147	109.6	90-130	8.07
25-Jun	193	108.8	75-130	8.67
26-Jun	182	111.5	95-130	7.94
27-Jun	183	113.1	60-140	9.95
28-Jun	163	116.6	75-135	8.83
29-Jun	143	115.3	85-135	7.22
30-Jun	200	113.1	65-140	10.40
1-Jul	200	112.3	90-140	6.96
Total	1,611	111.9	60-140	9.01

Table 5. Sample size, mean, range, and standard deviation (SD) of weight (g) by tagging date for river-run, subyearling Chinook salmon from the smolt monitoring sample at Lower Monumental Dam, 2006.

	Mean weight (g) smolt monitoring sample			
Date	N	Mean	Range	SD
23-Jun	200	14.1	6.4-25.4	3.20
24-Jun	147	15.0	8.6-24.0	3.12
25-Jun	193	15.3	6.8-28.6	3.58
26-Jun	182	16.3	10.0-24.5	3.25
27-Jun	183	17.1	3.2-33.6	4.35
28-Jun	163	17.4	3.6-27.2	3.80
29-Jun	143	17.7	10.0-29.0	3.06
30-Jun	200	17.1	3.6-34.5	4.05
1-Jul	200	16.2	9.1-30.8	3.22
Total	1,611	16.2	3.2-34.5	3.73

Project Operations

From 24 June to 2 July 2006, total project discharge at Ice Harbor Dam was regulated by the Bonneville Power Administration and the USACE to meet changing regional power needs while staying within the planned research operations. Discharge varied greatly on many days during the study period (Figure 5 and Table 6). Spill levels were also quite variable during the study (Table 6).

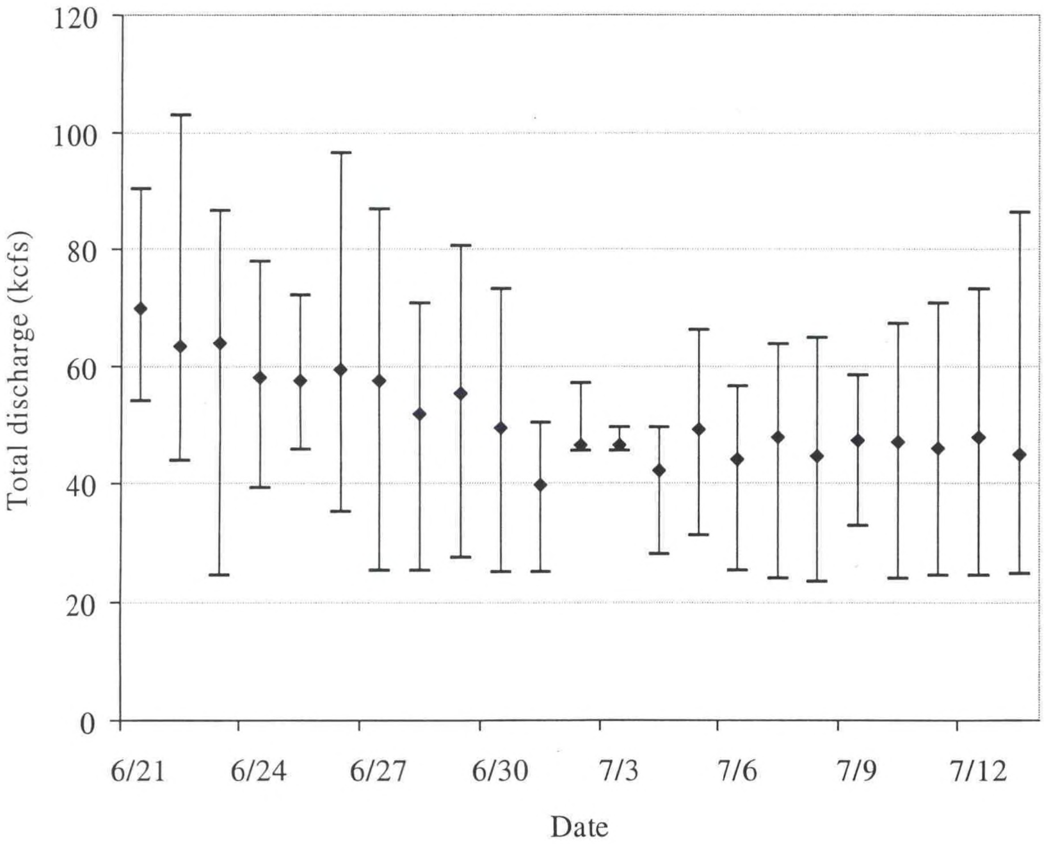

Figure 5. Average daily total project discharges at Ice Harbor Dam during the 2006 passage survival study (whisker bars represent the range of project discharge for each day).

Table 6. Median, mean, range, and standard deviation (SD) of operations and/or conditions by test date at Ice Harbor Dam, 2006.

Test	Total discharge (1,000 ft^3/s)				Total spill (1,000 ft^3/s)				Total turbine (1,000 ft^3/s)				Spill proportion				Tailwater elevation (ft)			
date	Median	Mean	Range	SD	Median	Mean	Range	SD	Median	Mean	Range	SD	Median	Mean	Range	SD	Median	Mean	Range	SD
6/24	67.1	64.8	53.3-77.8	7.5	19.8	19.7	15.3-23.1	2.2	47.1	45.1	36.9-54.8	5.4	0.3	0.3	0.3-0.3	0.0	343.2	342.8	341.8-343.8	0.6
6/25	54.2	57.5	45.5-71.9	9.7	18.0	17.7	15.2-21.1	2.6	36.6	39.8	30.4-50.9	7.1	0.3	0.3	0.3-0.3	0.0	342.5	342.6	341.3-344.0	0.8
6/26	54.2	59.3	35.1-96.3	19.9	44.8	44.3	15.2-80.1	20.6	10.4	15.1	9.0-42.5	8.7	0.8	0.7	0.4-0.9	0.2	342.2	342.5	340.5-344.7	1.3
6/27	55.4	57.5	25.1-86.8	21.4	44.9	37.8	15.3-54.9	12.2	10.5	19.6	9.8-41.8	13.0	0.6	0.7	0.5-0.8	0.1	341.8	342.1	339.6-344.9	1.7
6/28	62.0	51.9	25.2-70.6	17.2	19.8	17.8	14.9-19.9	2.2	42.3	34.1	9.9-50.8	15.3	0.3	0.4	0.3-0.6	0.1	342.9	342.1	339.3-343.7	1.5
6/29	58.7	55.2	27.4-80.6	20.4	17.6	18.8	14.3-23.9	3.6	40.9	36.3	12.2-56.7	17.1	0.3	0.4	0.3-0.6	0.1	342.7	342.3	339.7-344.8	1.7
6/30	59.5	49.4	24.9-72.9	17.9	18.1	17.6	14.7-22.8	2.6	41.4	31.8	9.8-50.2	15.5	0.3	0.4	0.3-0.6	0.1	342.5	341.6	339.2-343.9	1.7
7/1	47.4	39.6	24.9-50.1	10.3	15.1	15.1	15.1-15.2	0.0	32.3	24.5	9.9-34.9	10.3	0.3	0.4	0.3-0.6	0.1	341.6	340.9	339.2-342.3	1.1
7/2	45.8	46.5	45.4-56.8	1.6	36.1	31.8	15.1-36.2	8.5	9.6	14.7	9.3-34.7	9.9	0.8	0.7	0.3-0.8	0.2	341.5	341.6	341.3-342.3	0.2
Total	49.6	53.0	24.9-96.3	17.1	19.0	24.8	14.3-80.1	13.5	32.5	28.2	9.0-56.7	15.8	0.4	0.5	0.3-0.9	0.2	341.9	342.0	339.2-344.9	1.4

Migration Behavior and Passage Distribution

Forebay Behavior and Timing

Of the 493 radio-tagged treatment fish released above Ice Harbor Dam, 452 (91.7%) were detected entering the forebay and of these 452 fish, 446 (98.7%) were detected approaching the dam. Of the 446 fish detected approaching the dam, 32 (7.2%) were first detected approaching in front of the powerhouse, 168 (37.7%) were first detected approaching in front of the spillway, and 246 (55.2%) were first detected approaching in front of the RSW (Figure 6).

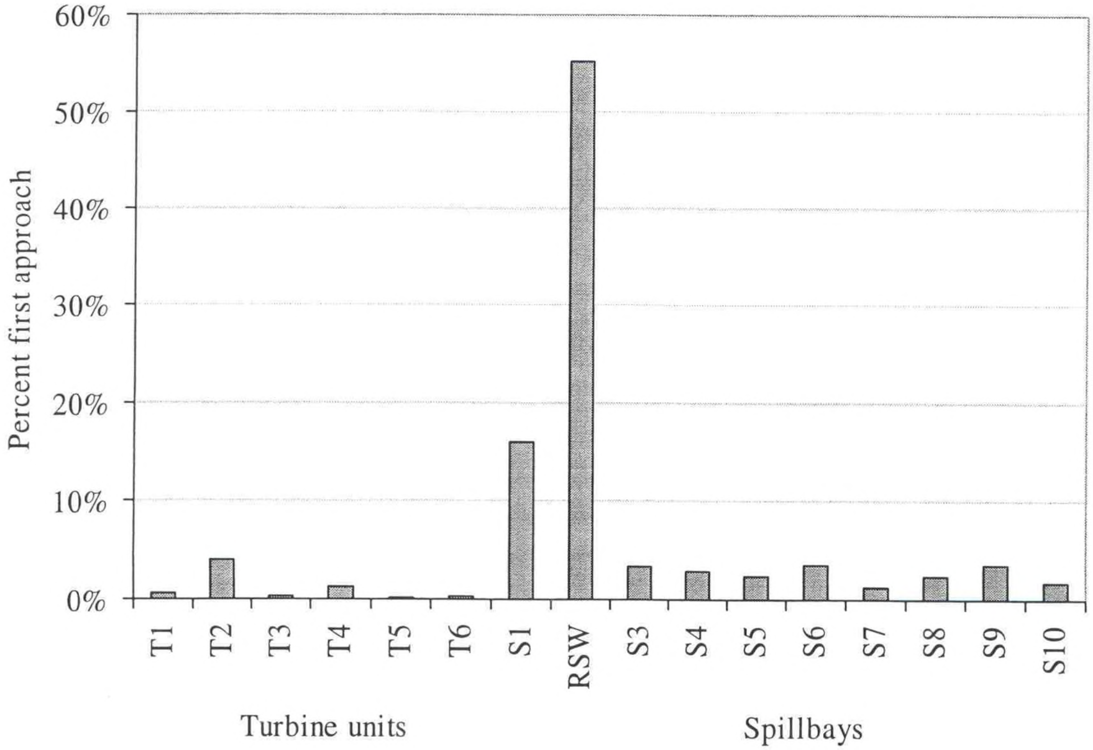

Figure 6. Approach patterns for radio-tagged, river-run subyearling Chinook salmon in the forebay of Ice Harbor Dam, 2006.

Forebay residence times were calculated for 399 fish, each with detections on both the forebay entrance transect and a passage-route receiver (Table 7). Overall median forebay residence time for these fish was 2.0 h during the study period. Median forebay residence time was compared by test day to the median amount of water being spilled (% spill) for that day (Table 8). No apparent correlation was observed between median proportion of spill and forebay residence time for any passage route ($P = 0.422$) or for the RSW ($P = 0.987$).

Table 7. Forebay residence time in hours by passage route for radio-tagged, river-run subyearling Chinook salmon during project operations at Ice Harbor Dam, 2006.

		Forebay residence time (h) by percentile		
Passage route	N	10th	50th	90th
Turbine	4	1.1	1.6	4.5
Bypass	17	0.9	5.3	10.8
Training spill	103	0.5	1.4	12.1
RSW	275	0.6	2.0	9.0
Overall	399	0.6	2.0	10.1

Table 8. Forebay residence time in hours by test date for radio-tagged, river-run subyearling Chinook salmon during project operations at Ice Harbor Dam, 2006.

	All routes		RSW		% Spill	
Test date	N	Median	N	Median	Median	Mean
6/24	16	0.09	14	0.09	0.30	0.30
6/25	41	0.12	29	0.08	0.31	0.31
6/26	52	0.10	25	0.10	0.79	0.72
6/27	56	0.10	32	0.12	0.65	0.67
6/28	47	0.09	42	0.09	0.30	0.38
6/29	53	0.12	36	0.12	0.31	0.38
6/30	47	0.06	40	0.06	0.31	0.40
7/1	42	0.06	39	0.06	0.32	0.41
7/2	45	0.03	18	0.05	0.79	0.69

Passage Distribution and Metrics

Of the 452 radio-tagged treatment fish detected entering the forebay of Ice Harbor Dam, 12 (2.7%) were not recorded as passing the dam, and 446 (98.7%) were detected at or below the dam. Of these 446 fish, 412 (92.4%) passed the dam through the spillway, 19 (4.3%) through the JBS, 8 (1.8%) through turbines, and 1(0.2%) passed the dam through an undetermined route (Figure 7). Of the 412 fish that passed through the spillway, 302 (67.7%) passed through the RSW. Distribution through individual spillbays is presented in Figure 8.

Overall FPE at Ice Harbor Dam was 0.982 (SE = 0.013, 95% CI 0.969-0.995), spill efficiency (SPE) was 0.940 (SE = 0.023, 95% CI 0.917-0.963), spill effectiveness (SPF) was 2.00:1 (SE = 0.033, 95% CI 1.967-2.033), RSW effectiveness was 4.59:1(SE = 0.059, 95% CI 4.531-4.649), training spill effectiveness was 0.78:1 (SE = 0.040, 95% CI 0.740-0.820), and FGE was 0.704 (SE = 0.176, 95% CI 0.528-0.880) (Table 9).

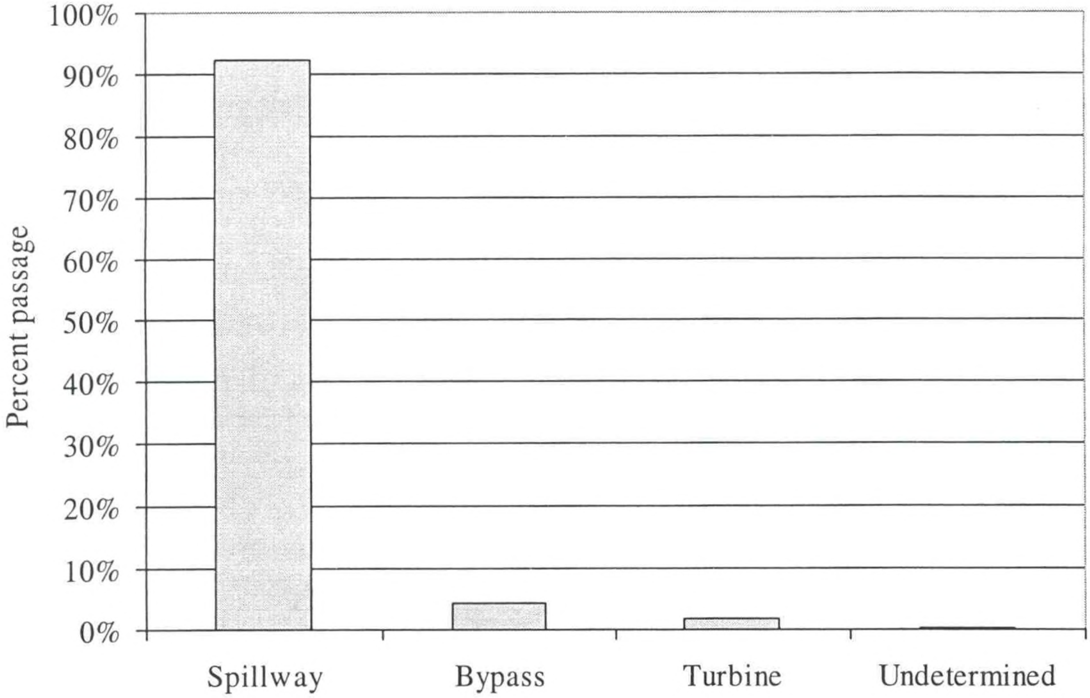

Figure 7. Passage distribution of radio-tagged, subyearling Chinook salmon at Ice Harbor Dam, 2006.

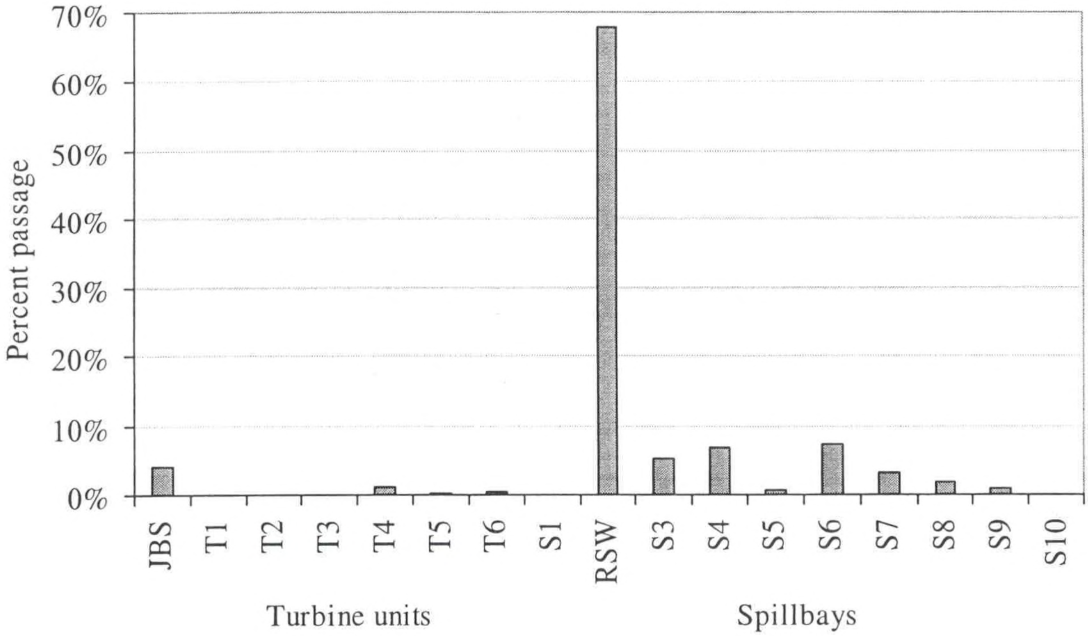

Figure 8. Individual passage route distribution for radio-tagged, river-run subyearling Chinook salmon during spill testing at Ice Harbor Dam, 2006. JBS-juvenile bypass system, RSW-removable spillway weir.

Table 9. Estimates of fish passage efficiency, spill efficiency, spill effectiveness, RSW effectiveness, training spill effectiveness, and fish guidance efficiency for radio-tagged, river-run subyearling Chinook salmon passing Ice Harbor Dam, 2006.

Passage metric	Estimate	SE
Fish passage efficiency	0.982	0.013
Spill efficiency	0.940	0.023
Spill effectiveness	2.00	0.033
RSW effectiveness	4.59	0.059
Training spill effectiveness	0.78	0.040
Fish guidance efficiency	0.704	0.176

Tailrace Behavior and Timing

Tailrace egress times by passage route were calculated for 404 radio-tagged, river-run subyearling Chinook salmon and overall median tailrace egress time was 10.7 min during the study period (Table 10). Median tailrace egress time (Table 11) was compared by test day to the median amount of water being spilled (% spill) for that day. No apparent correlations were observed between median % spill and tailrace egress times for all routes ($P = 0.114$) or the RSW ($P = 0.987$).

Table 10. Tailrace egress time in minutes by passage route for radio-tagged, river-run subyearling Chinook salmon during project operations at Ice Harbor Dam, 2006.

	Tailrace egress time (min)			
		Percentiles		
Passage route	N	10th	50th	90th
Turbine	4	8.7	11.0	18.5
Bypass	17	9.5	14.3	59.8
Training spill	108	5.8	10.5	20.1
RSW	275	5.9	10.7	38.0
Overall	404	5.9	10.7	34.1

Table 11. Tailrace egress time in minutes by test date for radio-tagged, river-run subyearling Chinook salmon during project operations at Ice Harbor Dam, 2006.

	Tailrace egress time (min)					
	All routes		RSW		% Spill	
Test date	N	Median	N	Median	Median	Mean
6/24	15	10.23	13	10.23	0.30	0.30
6/25	37	10.70	29	11.03	0.31	0.31
6/26	47	11.12	19	16.60	0.79	0.72
6/27	52	9.72	29	10.55	0.65	0.67
6/28	53	9.32	45	8.77	0.30	0.38
6/29	57	10.40	40	9.44	0.31	0.38
6/30	49	12.65	41	11.77	0.31	0.40
7/1	45	10.90	42	10.88	0.32	0.41
7/2	49	10.98	21	10.58	0.79	0.69

Detection Probability and Estimated Survival

Detection probabilities at Sacajawea Park were similar for both treatment and reference groups at 0.983 (SE = 0.012) and 0.989 (SE = 0.003), respectively. The overall estimated relative dam survival at Ice Harbor Dam was 0.952 (SE = 0.018, 95% CI 0.938-0.967). Survival estimates by test date ranged from 0.867 (SE = 0.045) to 1.019 (SE = 0.053) (Table 12). Overall estimated relative spillway survival at Ice Harbor Dam was 0.988 (SE = 0.016, 95% CI 0.950-1.025). Survival estimates by test date ranged from 0.925 (SE = 0.051) to 1.067 (SE = 0.048) (Table 13). Overall estimated relative concrete survival at Ice Harbor Dam was 0.977 (SE = 0.018, 95% CI 0.935-1.019). Survival estimates by test date ranged from 0.916 (SE = 0.053) to 1.048 (SE = 0.050) (Table 14). Overall estimated relative RSW survival at Ice Harbor was 0.980 (SE = 0.023, 95% CI 0.925-1.035). Survival estimates by test date ranged from 0.896 (SE = 0.082) to 1.064 (SE = 0.049) (Table 15).

Table 12. Estimated survival (CJS and relative dam survival) for radio-tagged, subyearling Chinook salmon passing Ice Harbor Dam, 2006. Standard errors are in parenthesis; overall relative survival estimates are geometric means.

	Treatment		Reference		Relative dam
Test date	n	CJS survival	n	CJS survival	survival
24-Jun	19	---	---	---	---
25-Jun	42	0.934 (0.032)	60	0.917 (0.036)	1.019 (0.053)
26-Jun	59	0.881 (0.042)	90	0.956 (0.022)	0.922 (0.049)
27-Jun	59	0.949 (0.029)	91	0.958 (0.022)	0.991 (0.037)
28-Jun	49	0.959 (0.028)	95	0.971 (0.018)	0.988 (0.034)
29-Jun	63	0.858 (0.044)	97	0.990 (0.010)	0.867 (0.045)
30-Jun	54	0.889 (0.043)	97	0.951 (0.023)	0.935 (0.050)
1-Jul	50	0.882 (0.046)	97	0.898 (0.031)	0.982 (0.061)
2-Jul	56	0.875 (0.044)	93	0.947 (0.023)	0.924 (0.052)
Overall	451	0.904 (0.013)	720	0.948 (0.010)	0.952 (0.018)

Table 13. Estimated survival (CJS and relative spillway survival) for radio-tagged, subyearling Chinook salmon passing through the spillway at Ice Harbor Dam, 2006. Standard errors are in parenthesis; overall relative survival estimates are geometric means.

	Treatment		Reference		Relative spillway survival
Test date	n	CJS survival	n	CJS survival	
24-Jun	15	---	---	---	---
25-Jun	31	0.978 (0.022)	60	0.917 (0.036)	1.067 (0.048)
26-Jun	52	0.885 (0.044)	90	0.956 (0.022)	0.925 (0.051)
27-Jun	52	0.962 (0.027)	91	0.958 (0.022)	1.004 (0.036)
28-Jun	46	0.957 (0.030)	95	0.971 (0.018)	0.986 (0.036)
29-Jun	53	0.943 (0.032)	97	0.990 (0.010)	0.953 (0.034)
30-Jun	49	0.918 (0.039)	97	0.951 (0.023)	0.966 (0.047)
1-Jul	51	0.924 (0.038)	97	0.898 (0.031)	1.029 (0.055)
2-Jul	55	0.927 (0.035)	93	0.947 (0.023)	0.979 (0.044)
Overall	404	0.937 (0.010)	720	0.948 (0.010)	0.988 (0.016)

Table 14. Estimated survival (CJS and relative concrete survival) for radio-tagged, subyearling Chinook salmon passing Ice Harbor Dam, 2006. Standard errors are in parenthesis; overall relative survival estimates are geometric means.

	Treatment		Reference		Relative concrete survival
Test date	n	CJS survival	n	CJS survival	
24-Jun	16	---	---	---	---
25-Jun	35	0.961 (0.027)	60	0.917 (0.036)	1.048 (0.050)
26-Jun	53	0.887 (0.044)	90	0.956 (0.022)	0.928 (0.050)
27-Jun	52	0.962 (0.027)	91	0.958 (0.022)	1.004 (0.036)
28-Jun	51	0.961 (0.027)	95	0.971 (0.018)	0.990 (0.034)
29-Jun	61	0.918 (0.035)	97	0.990 (0.010)	0.928 (0.037)
30-Jun	54	0.870 (0.046)	97	0.951 (0.023)	0.916 (0.053)
1-Jul	53	0.927 (0.037)	97	0.898 (0.031)	1.032 (0.054)
2-Jul	56	0.929 (0.034)	93	0.947 (0.023)	0.980 (0.044)
Overall	431	0.927 (0.012)	720	0.948 (0.010)	0.977 (0.018)

Table 15. Estimated survival (CJS and relative survival) for radio-tagged, subyearling Chinook salmon passing through the RSW at Ice Harbor Dam, 2006. Standard errors are in parenthesis; overall relative survival estimates are geometric means.

	Treatment		Reference		Relative RSW
Test date	n	CJS survival	n	CJS survival	survival
24-Jun	14	---	---	---	---
25-Jun	26	0.975 (0.025)	60	0.917 (0.036)	1.064 (0.049)
26-Jun	21	0.857 (0.076)	90	0.956 (0.022)	0.896 (0.082)
27-Jun	28	1.000 (0.000)	91	0.958 (0.022)	1.044 (0.024)
28-Jun	44	0.955 (0.031)	95	0.971 (0.018)	0.984 (0.037)
29-Jun	41	0.951 (0.034)	97	0.990 (0.010)	0.961 (0.035)
30-Jun	45	0.911 (0.042)	97	0.951 (0.023)	0.959 (0.050)
1-Jul	50	0.943 (0.034)	97	0.898 (0.031)	1.050 (0.052)
2-Jul	27	0.852 (0.068)	93	0.947 (0.023)	0.899 (0.076)
Overall	296	0.930 (0.019)	720	0.948 (0.010)	0.980 (0.023)

Avian Predation

When the Crescent Island Caspian Tern colony had left the island for the season, we initiated a recovery effort for radio tags deposited on the island. There were 24 total radio tags found on the tern colony, representing approximately 1.9% of the fish we released into the Snake River. Known tern predation accounted for 1.9% of the fish we released into the forebay of Ice Harbor Dam as treatment fish, and 1.8% of the fish released into the tailrace of Ice Harbor Dam as reference fish.

DISCUSSION

During 2006, we began tagging after the 84th percentile of the juvenile subyearling Chinook salmon population had passed Lower Monumental Dam and finished when the 98th percentile had passed. We had intended to conduct tagging operations during the 30th to 70th percentile passage period for this population, as predicted based on the 10-year average passage distribution observed at Lower Monumental Dam. The shift upward out of the target passage range occurred because we were waiting for weight of the fish sampled at the Lower Monumental Dam smolt monitoring facility to reach a size that would accommodate radio tags. Therefore, because the migration was earlier than normal, most of the population had passed by the time tagging commenced.

The initial study design called for Ice Harbor Dam to operate under two different spill conditions for 2006. Due to the late start of tagging and to the non-migratory behavior of fish that entered the study area after 2 July (omitted from the analysis), analysis of the data by treatment blocks was inappropriate (too few days). Instead, we analyzed temporal trends in survival, ignoring differences between spill treatments. It is likely that during the study period, we encountered fall Chinook salmon that exhibited two different life history strategies. As the study progressed into July, there were sharp declines in the proportion of study fish reaching the forebay of Ice Harbor Dam (Figure 9).

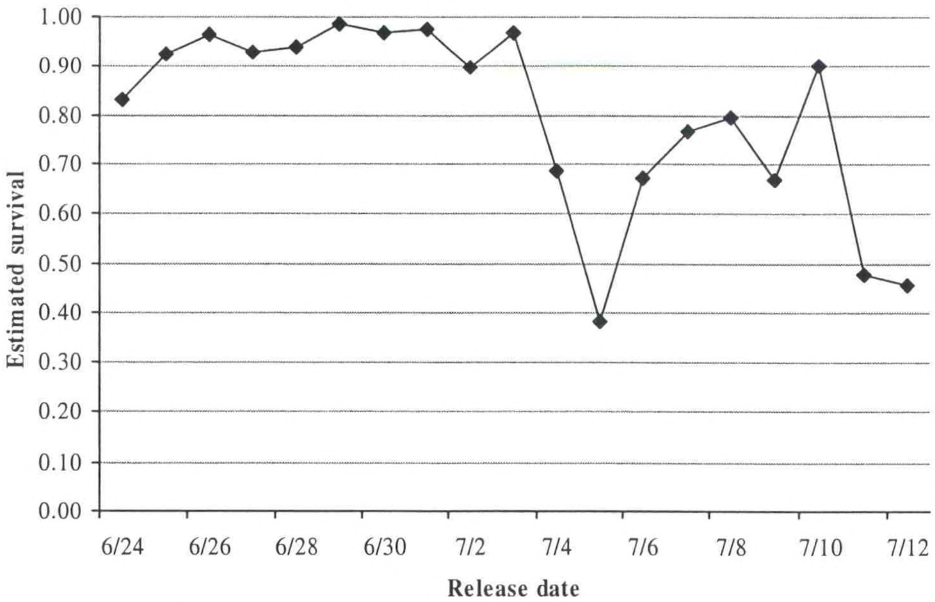

Figure 9. Estimated survival of river-run subyearling Chinook salmon treatment fish from release to the forebay entry line of Ice Harbor Dam, 2006.

Fall Chinook that arrived at Lower Monumental Dam early in the study were likely exhibiting the ocean-type life strategy, but those that arrived during the last half of the study in July were likely exhibiting the reservoir-type juvenile life history described by Conner et al. (2005). This behavioral trend was also encountered during the 2004 season (Ogden et al. 2005).

Operations at Ice Harbor Dam during 2006 continued to be effective at passing migrating juvenile fall Chinook salmon quickly, while efficiently guiding fish away from turbines. During the study, radio-tagged fish entered the forebay and passed the project quickly with little delay. Overall median forebay residence time for these fish was 2.0 h during the study period, with no apparent correlations observed between median percent spill and residence time for all routes, or for the RSW.

Previous studies at Ice Harbor Dam have shown the majority of yearling Chinook salmon typically pass through the spillway, with relatively few entering either turbine or JBS routes (Eppard et al. 2000). During 2006, nearly 92% of radio-tagged river-run subyearling Chinook salmon passed via the spillway, with 68% passing exclusively through the RSW. Fewer than 6% of radio-tagged subyearling Chinook salmon passed through either powerhouse route.

Spill efficiency, spill effectiveness, FPE, and FGE improved slightly from 2005 to 2006 during periods of RSW operation. Spill efficiency was 95.1% in 2005 compared to 98.2% in 2006; spill effectiveness was 1.9:1 in 2005 compared to 2.0:1 in 2006. From 2005 to 2006, fish passage efficiency increased from 95.1 to 98.2% and FGE increased 8.9%, from 61.5 to 70.4% (Ogden et al. 2007).

Overall, for all passage routes, 90% of all radio-tagged fish passing Ice Harbor Dam exited the tailrace in less than 34 min, with no apparent correlations observed between median percent spill and tailrace egress time for all routes or the RSW. Median tailrace egress time for the RSW increased from 4.2 min in 2005 to 10.7 min in 2006 (Ogden et al. 2007). However, based on both survival estimates and timing through the tailrace, predation on fish in the tailrace appeared to be minimal.

Survival estimates between years at Ice Harbor Dam are not directly comparable due to differences among years in tagging methodologies used and spill patterns evaluated, as well as river flow and other environmental conditions. However, estimates of subyearling Chinook salmon survival through the spillway have increased over the past few years. Eppard et al. (2002) reported spillway survival at 88.5% (PIT tag) for subyearling Chinook salmon in 2000. Since then, improved spill patterns and the installment of the RSW have increased survival estimates to 98–100% (radio tag) for subyearling salmon in 2005.

Survival estimates in 2006 were consistent with those in 2005 while the RSW was operating (Ogden et al. 2007). From 2005 to 2006, relative dam survival increased slightly from 95.1 to 95.2%, relative spillway survival changed only 0.1%, from 98.9 to 98.8%, and relative concrete survival decreased slightly from 98.6 to 97.7%. For fish passing exclusively through the RSW, survival decreased slightly from 99.7% in 2005 to 98.0% in 2006. Overall, the RSW is extremely effective in passing more fish with less water and high survival.

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REFERENCES

Absolon, R. F., B. P. Sandford, M. B. Eppard, D. A. Brege, K. W. McIntyre, E. E. Hockersmith, and G. M. Matthews. 2005. Survival of juvenile Chinook salmon through Ice Harbor Dam, 2003. Annual report to the U.S. Army Corps of Engineers, Contract W68SBV92844866, Walla Walla, Washington.

Adams, N. S., D. W. Rondorf, S. D. Evans, and J. E. Kelly. 1998a. Effects of surgically and gastrically implanted radio transmitters on swimming performance and predator avoidance of juvenile Chinook salmon (*Oncorhynchus tshawytscha*). Canadian Journal of Fisheries and Aquatic Science 55:781-787.

Adams, N. S., D. W. Rondorf, S. D. Evans, and J. E. Kelly. 1998b. Effects of surgically and gastrically implanted radio transmitters on growth and feeding behavior of juvenile Chinook salmon. Transactions of the American Fisheries Society 127:128-136.

Angela, S. M., K. D. Ham, G. E. Johnson, M. A. Simmons, C. S. Simmons, E. Kudera, and J. Skalski. 2003. Hydroacoustic evaluation of the removable spillway weir at Lower Granite Dam in 2002. Annual report to the U.S. Army Corps of Engineers, Contract DACW68-02-D-0001, Walla Walla, Washington.

Beeman, J. W., C. Grant, and P. V. Haner. 2004. Comparison of three underwater antennas for use in radiotelemetry. North American Journal of Fisheries Management 24:275-281.

Beeman, J. W., and A. G. Maule. 2006. Migration depths of juvenile Chinook salmon and steelhead relative to total dissolved gas supersaturation in a Columbia River reservoir. Transactions of the American Fisheries Society 135:584-594.

Burnham, K. P., D. R. Anderson, G. C. White, C. Brownie, and K. H. Pollock. 1987. Design and analysis methods for fish survival experiments based on release-recapture. American Fisheries Society Monograph 5:1-437.

Connor, W. P., J. G. Sneva, K. F. Tiffan, R. K. Steinhorst, and D. Ross. 2005. Two alternative juvenile life history types for fall Chinook salmon in the Snake River Basin. Transactions of the American Fisheries Society 134:291-304.

Cormack, R. M. 1964. Estimates of survival from the sightings of marked animals. Biometrika 51:429-438.

Eppard, M. B., G. A. Axel, B. P. Sandford, and D. B. Dey. 2000. Effects of spill on the passage of hatchery yearling Chinook salmon at Ice Harbor Dam, 1999. Report of the National Marine Fisheries Service to the U.S. Army Corps of Engineers, Walla Walla District, Contract W66QKZ91521282.

Eppard, M. B., E. E. Hockersmith, G. A. Axel, and B. P. Sandford. 2002. Spillway survival for hatchery yearling and subyearling Chinook salmon passing Ice Harbor Dam, 2000. Report of the National Marine Fisheries Service to the U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington.

Eppard, M. B., E. E. Hockersmith, G. A. Axel, and B. P. Sandford. 2004. Spillway survival for hatchery yearling and subyearling Chinook salmon passing Ice Harbor Dam, 2002. Report of the National Marine Fisheries Service to the U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington.

Hockersmith, E. E., W. D. Muir, S. G. Smith, B. P. Sandford, R. W. Perry, N. S. Adams, and D. W. Rondorf. 2003. Comparison of migration rate and survival between radio-tagged and PIT-tagged migrant yearling Chinook salmon in the Snake and Columbia Rivers. North American Journal of Fisheries Management 23:404-413.

Johnson, G. E., N. S. Adams, R. L. Johnson, D. W. Rondorf, D. D. Dauble, and T. Y. Barila. 2000. Evaluation of the prototype surface bypass for salmonid smolts ins spring 1996 and 1997 at Lower Granite Dam on the Snake River, Washington. Trans. Am. Fish. Soc. 129:381-397.

Johnson, G. E., C. M. Sullivan, and M. W. Echo. 1992. Hydroacoustic studies for developing a smolt bypass system at Wells Dam. Fisheries research 14:221-237.

Jolly, G. M. 1965. Explicit estimates from capture-recapture data with both death and immigration—stochastic model. Biometrika 52:225-247.

Knight, A .E., G. Marancik, and J. B. Layzer. 1977. Monitoring movements of juvenile anadromous fish by radiotelemetry. Progressive Fish-Culturist 39:148-150.

Muir, W. D., S. G. Smith, J. G. Williams, and B. P. Sandford. 2001. Survival of juvenile salmonids passing through bypass systems, turbines, and spillways with and without flow deflectors at Snake River dams. North American Journal of Fisheries Management 21:135-146.

Muir, W. D., S. G. Smith, R. W. Zabel, D. M. Marsh, and J. G. Williams. 2003. Survival estimates for the passage of spring-migrating juvenile salmonids through Snake and Columbia River dams and reservoirs, 2002. Report of the National Marine Fisheries Service to the Bonneville Power Administration, Project 1993-02900.

NMFS (National Marine Fisheries Service). 1992. Threatened status for Snake River spring-summer Chinook salmon, threatened status for Snake River fall Chinook salmon. Federal Register 57:78 (22 April 1992):14653-14663.

NMFS (National Marine Fisheries Service). 2000. Federal Columbia River Power System Biological Opinion issued 21 December 2000.

NWFSC (Northwest Fisheries Science Center). 2002. National Marine Fisheries Service Salmon Research Plan Vol. I & II. Northwest Fisheries Science Center, Seattle, WA. Available online at research.nwfsc.noaa.gov/.

Ogden, D. A., E. E. Hockersmith, M. B. Eppard, G. A. Axel, and B. P. Sandford. 2005. Passage behavior and survival for river-run subyearling Chinook salmon at Ice Harbor Dam, 2004. Report of the National Marine Fisheries Service to the U.S. Army Corps of Engineers, Walla Walla District, Contract W68SBV92844866.

Ogden, D. A., E. E. Hockersmith, G. A. Axel, B. J. Burke, K. E. Frick, and B. P. Sandford. 2007. Passage behavior and survival for river-run subyearling Chinook salmon at Ice Harbor Dam, 2005. Report of the National Marine Fisheries Service to the U.S. Army Corps of Engineers, Walla Walla District, Contract W68SBV92844866.

Plumb, J. M., A. C. Braatz, J. N. Lucchesi, S. D. Fielding, J. M. Sprando, G. T. George, N. S. Adams, and D. W. Rondorf. 2003. Behavior of radio-tagged juvenile Chinook salmon and steelhead and performance of a removable spillway weir at Lower Granite Dam, Washington, 2002. Annual report to the U.S. Army Corps of Engineers, Contract W68SBV00104592, Walla Walla, Washington.

Ryan, B. A., J. W. Ferguson, R. D. Ledgerwood, and E. P. Nunnallee. 2001. Methods to detect passive integrated transponder tags on piscivorous bird colonies in the Columbia River Basin. North American Journal of Fisheries Management 21:971-975.

Seber, G. A. F. 1965. A note on the multiple recapture census. Biometrika 52:249-259.

Smith, S. G., W. D. Muir, R. W. Zabel, D. M. Marsh, R. A. McNatt, J. G. Williams, and J. R. Skalski. 2003. Survival estimates for the passage of spring-migrating juvenile salmonids through Snake and Columbia River dams and reservoirs, 2003. Report of the National Marine Fisheries Service to the Bonneville Power Administration, Portland, Oregon.

Zabel, R. W. , S. G. Smith, W. D. Muir, D. M. Marsh, J. G. Williams, and J. R. Skalski. 2002. Survival estimates for the passage of spring-migrating juvenile salmonids through Snake and Columbia River dams and reservoirs, 2001. Report of the National Marine Fisheries Service to the Bonneville Power Administration, Portland, Oregon.

APPENDIX A

Evaluations of Model Assumptions

We used the CJS single-release model (Cormack 1964; Jolly 1965; Seber 1965) to estimate survival and probability of detection for both treatment and reference groups from detection in the forebay of Ice Harbor Dam (treatment groups) or release into the tailrace (reference groups) to the mouth of the Snake River at Sacajawea Park. The ratios of these survival estimates (dam or spillway survival divided by tailrace survival) were calculated to determine relative dam or spillway survival. Critical assumptions associated with the survival estimates that were evaluated using statistical tests include:

A1. All tagged fish have the same probability of being detected at a detection location.

Radio-tag detection probabilities at the Sacajawea Park array in the mouth of the Snake River were close to 100% for both treatment (98.3%) and reference groups (98.9%) (Appendix Table A1). With detection probabilities at or near 100% for all fish, there was no disparity between detection of treatment and reference groups. Detection histories for Dam, Concrete, Spillway, and RSW survival are shown in Appendix Tables A2 to A5, respectively.

Appendix Table A1. Detection probabilities at Ice Harbor Dam for evaluating survival of river-run, subyearling Chinook salmon passing, 2006.

	Treatment group		Reference group	
Test date	$\hat{p}$	SE	$\hat{p}$	SE
6/25	1.000		1.000	
6/26	1.000		0.990	
6/27	1.000		0.980	
6/28	1.000		0.980	
6/29	1.000		1.000	
6/30	1.000		0.980	
7/1	0.950		0.990	
7/2	0.910		0.990	
Mean	0.983	0.012	0.989	0.003

Appendix Table A2. Detection histories of radio-tagged subyearling Chinook salmon released above (Treatment group) and below (Reference group) Ice Harbor Dam to evaluate Dam passage survival in 2006. The primary survival array was 14 km downstream of Ice Harbor Dam and detections downstream of the primary array are shown in Figure 1. Detection histories recorded as: 1 – detected; 0 – not detected.

	Detection history		
	Primary survival array	Post survival array	n
Treatment group (451)			
	0	0	44
	1	0	26
	0	1	7
	1	1	374
Reference group (720)			
	0	0	37
	1	0	59
	0	1	9
	1	1	615

Appendix Table A3. Detection histories of radio-tagged subyearling Chinook salmon released above (Treatment group) and below (Reference group) Ice Harbor Dam to evaluate Concrete passage survival in 2006. The primary survival array was 14 km downstream of Ice Harbor Dam and detections downstream of the primary array are shown in Figure 1. Detection histories recorded as: 1 – detected; 0 – not detected.

	Detection history		
	Primary survival array	Post survival array	n
Treatment group (431)			
	0	0	32
	1	0	7
	0	1	26
	1	1	366
Reference group (720)			
	0	0	37
	1	0	59
	0	1	9
	1	1	615

Appendix Table A4. Detection histories of radio-tagged subyearling Chinook salmon released above (Treatment group) and below (Reference group) Ice Harbor Dam to evaluate Spillway passage survival in 2006. The primary survival array was 14 km downstream of Ice Harbor Dam and detections downstream of the primary array are shown in Figure 1. Detection histories recorded as: 1 – detected; 0 – not detected.

	Detection history		
	Primary survival array	Post survival array	n
Treatment group (404)			
	0	0	26
	1	0	25
	0	1	7
	1	1	346
Reference group (720)			
	0	0	37
	1	0	59
	0	1	9
	1	1	615

Appendix Table A5. Detection histories of radio-tagged subyearling Chinook salmon released above (Treatment group) and below (Reference group) Ice Harbor Dam to evaluate RSW passage survival in 2006. The primary survival array was 14 km downstream of Ice Harbor Dam and detections downstream of the primary array are shown in Figure 1. Detection histories recorded as: 1 – detected; 0 – not detected.

	Detection history		
	Primary survival array	Post survival array	n
Treatment group (296)			
	0	0	19
	1	0	6
	0	1	21
	1	1	250
Reference group (720)			
	0	0	37
	1	0	59
	0	1	9
	1	1	615

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 the Sacajawea survival transect. An assumption of the CJS model is that fish in all groups have equal probabilities of survival and detection downstream from the point of release (i.e., the tailrace of Ice Harbor Dam). This assumption is reasonable if the release groups have similar passage distributions at downstream detection sites at Sacajawea survival transect. To evaluate this assumption, we compared passage date percentiles at this site (10th, 20th,...,80th, 90th) for treatment fish versus reference fish. Treatment fish grouped at the forebay entry transect by day were paired with tailrace fish grouped by release day with the same pairings used in the survival analysis. Confidence intervals (95%) and t-tests were constructed for statistical comparison. However, the reasonableness of the assumption was evaluated based on the biological size of these differences.

Tests of homogeneity in median passage timing to Sacajawea survival transect were statistically significantly different between treatment and reference groups used to calculate relative survival estimates (Appendix Tables A6). However, the differences between median passage times at both sites were only a few hours (4 for Sacajawea). Therefore, it is reasonable to conclude that the survival estimates were not significantly biased by this statistical violation of the assumption regarding mixing through the common reach.

Appendix Table A6. Test of homogeneity of arrival timing at the Sacajawea survival transect for treatment (forebay) and reference groups (tailrace) of radio-tagged, river-run subyearling Chinook salmon used for estimating survival at Ice Harbor Dam, 2006. The treatment fish at Ice Harbor Dam were grouped at the forebay entry transect by day and paired with tailrace fish group by release day with the same pairings used in the survival analysis.

	Treatment - reference passage date difference (h)								
Date	10th	20th	30th	40th	50th	60th	70th	80th	90th
6/24	--	--	--	--	--	--	--	--	--
6/25	-20.1	-13.3	-4.5	-2.3	-5.8	-11.4	-10.5	-7.5	-0.9
6/26	-3.1	-1.6	-0.7	-0.3	-0.1	-9.0	-9.0	0.8	3.4
6/27	-0.3	-0.4	-0.5	-1.3	-2.1	-14.3	-10.4	-3.3	1.7
6/28	-3.1	-1.9	-2.2	-1.7	-5.8	-12.3	-12.6	-10.0	-0.7
6/29	-0.7	0.4	0.9	1.9	1.2	-6.8	-7.8	-3.6	0.0
6/30	-2.4	-0.9	-0.7	-1.8	-11.6	-13.6	-14.3	-14.1	-2.4
7/1	0.5	0.4	-0.3	-0.4	-8.0	-8.7	-9.1	-9.4	-9.7
7/2	-0.6	-0.5	-0.8	-0.8	-0.2	0.0	-0.7	-7.4	-6.0
Mean	-3.7	-2.2	-1.1	-0.8	-4.0	-9.5	-9.3	-6.8	-1.8
SE	2.4	1.6	0.6	0.5	1.6	1.6	1.4	1.6	1.5
95 % Lo CI	-9.4	-6.0	-2.4	-1.9	-7.8	-13.4	-12.7	-10.7	-5.4
95% Hi CI	1.9	1.6	0.3	0.3	-0.3	-5.6	-5.9	-2.9	1.7
t	-1.6	-1.4	-1.9	-1.8	-2.5	-5.8	-6.5	-4.2	-1.2
df	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
p-value	0.2	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.3

Evaluation of Biological Assumptions

In addition to model assumptions this study also had several biological assumptions which included:

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

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

Assumption A3 was not tested for validation in this study; fish were size-selected for radio tagging. Assumption A4 has been evaluated previously by Adams et al. (1998a,b) and Hockersmith et al. (2003), who reported the effects of radio tagging on survival, predation, growth, and swimming performance of juvenile salmonids.

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

The distance between our releases in the Ice Harbor Dam tailrace and our first downstream array used to estimate survival (Sacajawea Park) was approximately 14 km. Dead radio-tagged fish released concurrently with live fish into the tailrace of the dam during our study were not detected on the Sacajawea Park detection array.

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. A total of 1,242 tags were implanted in river-run subyearling Chinook salmon of which all were working 24 h after tagging. Tags that were not functioning properly were not used in the study.

In addition, a total of 100 radio transmitters distributed throughout the study were tested for tag life by allowing them to run in river water and checking them 2 times daily to determine if they functioned for the predetermined period of time. Thirty-six tags (36%) failed prior to the preprogrammed shut-down after 10 d (Appendix Table A6). Of these only 2 (2.0%) failed within 5 d of activation. Median travel time from release to the primary survival line at Sacajawea Park was 0.3 d overall with less than 0.4% of the fish taking 5 d or more to reach the primary survival line (Appendix Table A7). Although we documented transmitters failing during our study, the short travel times to our survival line, and the low tag failure rate were such that they would not have significantly changed our findings.

Appendix Table A7. Number of days tags lasted in tag life testing, 2006.

Tags (n)	Tag life (d)	Tags (%)
0	1	0.0
0	2	0.0
0	3	0.0
0	4	0.0
2	5	2.0
0	6	0.0
0	7	0.0
2	8	2.0
32	9	32.0
62	10	62.0
2	11	2.0

Appendix Table A8. Travel time from release to detection at the primary survival line at Sacajawea Park for river-run subyearling Chinook salmon released into the forebay and tailrace of Ice Harbor Dam, 2006.

	Travel time (d) to primary survival line at Sacajawea Park		
Percentile	Forebay	Tailrace	Overall
Min	0.2	0.0	0.0
10	0.3	0.1	0.2
20	0.4	0.2	0.2
30	0.5	0.2	0.2
40	0.6	0.2	0.3
50	0.7	0.2	0.3
60	0.8	0.3	0.4
70	0.9	0.3	0.5
80	1.0	0.3	0.7
90	1.4	0.4	1.0
Max	7.1	5.8	7.1
n	402	682	1,084
Travel time > 5d	2 (0.5%)	2 (0.3%)	4 (0.4%)

APPENDIX B: Telemetry Data Processing and Reduction

Overview

The database stores the data collected for the Juvenile Salmon Radio Telemetry project in the Fish Ecology Division at NOAA Fisheries' Northwest Fisheries Science Center. This project tracks the migration routes and passage of juvenile salmon and steelhead past dams within the Columbia and Snake Rivers using a network of radio receivers to record signals emitted from radio transmitters ("tags") surgically implanted into the fish. Special emphasis is placed on the routes of passage, and survival for individual routes at the various hydroelectric dams on the lower Columbia and Snake Rivers. The data stored in the database include observations of tagged fish and the locations and configurations of radio receivers and antennas.

Database Inputs

The majority of data supplied to the database are observations of tagged fish recorded at the various radio receivers, which the receivers store in hexadecimal-formal files ("hex" files). The files are saved to a central computer four times daily, and placed on an FTP server automatically once daily for downloading into the database.

In addition, data arrives in the form of a daily updated tag file, which contains the attributes of each fish tagged, along with the channel and code of the transmitter used and the date, time, and location or release after tagging.

Database Outputs

Data are consolidated into a summary form that lists each fish and receiver on which it was detected, and includes the specifics of the first and last hits and the total number of detections for each series where there was no more than a 5-minute gap between detections. This summarized data is immediately available for preliminary data analyses.

Processes

The processes in this database fall into three main categories or stages in the flow of data from input to output: loading, validation, and summarization.

A. Data Loading The loading process consists of copying data files from their initial locations to the database server, converting the files from their original format into a format readable by SQL, and having SQL read the files and store the data in preliminary tables.

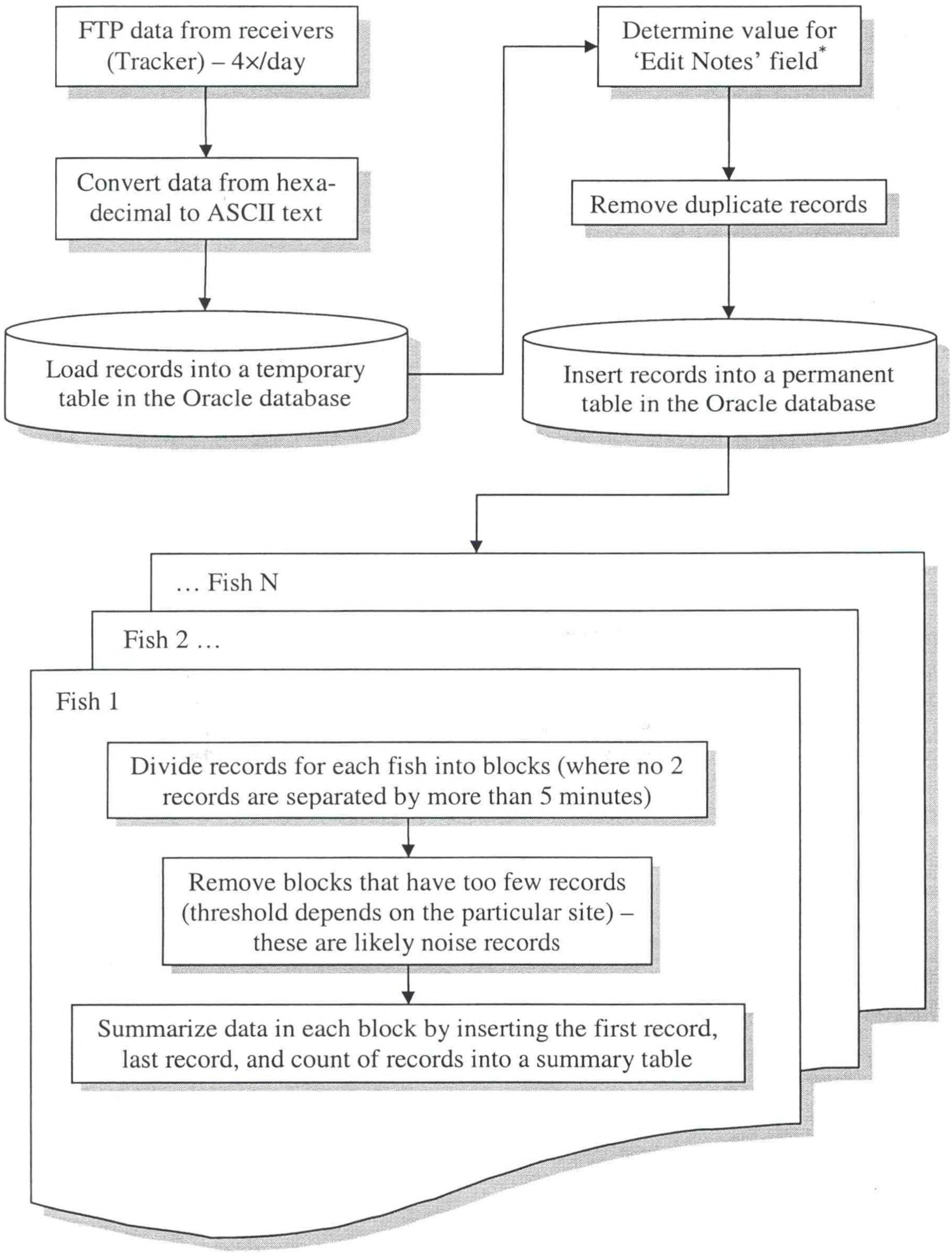
B. Data Validation During the validation process, the records stored in the preliminary tables are analyzed. We determine which study year, site identifier, antenna identifier, and tag identifier they belong to, flagging them as invalid if one or more of these relationships cannot be determined. Records are flagged by storing brief comments in the edit notes field. Values of edit notes are as follows:

- Null: denotes a valid observation of a tag
- Not tagged: Denotes an observation of a channel-code combination that was not in use at the time. Such values are likely due to radio-frequency noise being picked up at an antenna.
- Noise record: Denotes an observation where the code equal to 995, 997, or 999. These are not valid records, and relate to radio-frequency noise being picked up at the antenna.
- Beacon record: Hits recorded on channel = 5, code=575, which is being used to ensure proper functioning of the receivers. This combination does not indicate the presence of a tagged fish.
- Invalid record date: Denotes an observation whose date/time is invalid (occurring before we started the database; prior to Jan. 1, 2004, or some time in the future). Due to improvements in the data loading process, such records are unlikely to arise.
- Invalid site: Denotes an observation attributed to an invalid (non-existent) site: These are typically caused by typographical errors in naming hex files at the receiver end. They should not be present in the database, since they should be filtered out during the data loading process.
- Invalid antenna: Denotes an observation attributed to an invalid (non-existent) antenna. These are most likely due to electronic noise within the receiver.
- Lt start time: Assigned to records occurring prior to the time a tag was activated (its start time). Note: These records represent noise.
- Gt end time: Assigned to records occurring after the end time on a tag (they run for 10 days once activated). Note: These records represent noise.
- Gt 40 records: Denotes tags that registered more than 40 records per minute on an individual receiver. This is not possible as the tags emit a signal every 2 seconds (30/minute). Note: these patterns represent noise.

In addition, duplicate records (records for which the channel, code, site, antenna, date and time are the same as those of another record) are removed. Finally, the records are copied from the preliminary tables into the appropriate storage table based on study year. The database can accommodate multiple years with differing site and antenna configuration. Once a record's study year has been determined, its study year, site, and antenna are used to match it to a record in the site table.

C. Generation of the Summary Tables The summary table summarizes the first detection, last detection, and count of detections for blocks of records within a site for a single fish where no two consecutive records are separated by more than a specified number of minutes (currently using 5 min).

Flow Chart



FTP data from receivers (Tracker) – 4×/day
Convert data from hexa-decimal to ASCII text
Load records into a temporary table in the Oracle database
Determine value for 'Edit Notes' field*
Remove duplicate records
Insert records into a permanent table in the Oracle database
… Fish N
Fish 2 …
Fish 1
Divide records for each fish into blocks (where no 2 records are separated by more than 5 minutes)
Remove blocks that have too few records (threshold depends on the particular site) – these are likely noise records
Summarize data in each block by inserting the first record, last record, and count of records into a summary table