Passage Behavior and Survival of Radio-Tagged Yearling Chinook Salmon and Steelhead at Ice Harbor Dam, 2006

Gordon A. Axel, Eric E. Hockersmith, Darren A. Ogden, Brian J. Burke, Kinsey Frick,
Benjamin P. Sandford, and William D. Muir

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Fish Ecology Division
Northwest Fisheries Science Center
National Marine Fisheries Service
National Oceanic and Atmospheric Administration
2725 Montlake Boulevard East
Seattle, Washington 98112

to

Walla Walla District
U.S. Army Corps of Engineers
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EXECUTIVE SUMMARY

In 2006, we evaluated behavior, passage distributions, and survival of yearling Chinook salmon and steelhead at Ice Harbor Dam to determine effects of the recently installed removable spillway weir (RSW) in relation to two different spill treatments. Fish were collected, PIT tagged, and surgically tagged with a radio transmitter at Lower Monumental Dam. Treatment groups were comprised of 1,438 yearling Chinook salmon and 1,189 juvenile steelhead released 5 km above Lower Monumental Dam and 1,136 yearling Chinook salmon and 967 juvenile steelhead released into the tailrace of Lower Monumental Dam. Reference groups were comprised of 1,545 yearling Chinook salmon and 1,574 juvenile steelhead released into the tailrace of Ice Harbor Dam. Releases occurred during both day and night operations over 29 d, from 3 to 31 May. Project operations at Ice Harbor Dam consisted of 2-d random blocks alternating between BiOp spill (45 kcfs during the day and gas cap at night) and a reduced spill treatment of 30-40%, both with the RSW operating continuously. However, due to high river flows, the treatment schedule was altered.

Yearling Chinook salmon

Median forebay residence time for yearling Chinook salmon passing Ice Harbor Dam was slightly longer for fish approaching during the 30-40% spill operations (1.8 h) than it was for those approaching during BiOp spill (1.1 h). Overall passage distribution for yearling Chinook salmon during reduced spill treatments was 73.4% through the spillway, 19.1% through the juvenile bypass, and 7.5% through turbines at Ice Harbor Dam, with less than 0.9% of the fish having undetermined passage routes (Table 1). During BiOp spill, 80.0% passed via the spillway, 15.1% through the juvenile bypass, and 4.9% through the turbines, with less than 0.9% having undetermined passage routes. Fish passage efficiency (FPE) was 92.5% during 30-40% spill and 95.1% during BiOp spill. Fish guidance efficiency (FGE) was 71.8% during 30-40% spill and 75.4% during BiOp spill. Spill efficiency was 73.4% under 30-40% spill operations and 79.9% during BiOp spill. Spill efficiency for the RSW was 51.3% for the reduced spill treatment and 33.1% for the BiOp spill treatment. Mean spill effectiveness was 2.22:1 for 30-40% spill and 1.38:1 during BiOp spill. Mean RSW effectiveness was 7.77:1 for 30-40% spill and 6.02:1 for BiOp spill, with training spill effectiveness measuring less than 1:1 under both treatments.

Spillway passage survival was 0.96 (95% CI, 0.95-0.97) under 30-40% spill operations and 0.96 (95% CI, 0.96-0.98) during BiOp spill. RSW survival for the reduced spill treatment was 0.95 (95% CI, 0.92-0.97) with training spill survival

Table 1. Final study results of conditions, passage behavior, and relative survival for radio-tagged yearling Chinook salmon at Ice Harbor Dam under two operations, 2006 (95% CI in parentheses).

	30-40% Spill	**BiOp**
	Conditions	
Average project discharge (kcfs)	120.1	144.5
Average spill discharge (kcfs)	39.6 (33%)	83.5 (58%)
Average RSW discharge (kcfs)	7.9 (7%)	7.9 (6%)
Average training flow discharge (kcfs)	31.7 (26%)	75.6 (52%)
Average tailwater elevation (ft msl)	347.6	348.7
Average water temperature (°C)	12.5	12.8
Average Secchi depth (m)	1.9	2.1
	Passage distribution (%)	
Juvenile bypass	19.1	15.1
Turbine unit 1	0.0	0.1
Turbine unit 2	1.7	0.8
Turbine unit 3	1.8	0.9
Turbine unit 4	2.1	1.1
Turbine unit 5	1.7	1.2
Turbine unit 6	0.2	0.8
Turbine passage	7.5	4.9
Spill bay 1	0.0	0.7
Spill bay 3	5.4	3.6
Spill bay 4	1.4	9.4
Spill bay 5	9.1	4.0
Spill bay 6	1.0	9.1
Spill bay 7	2.4	7.5
Spill bay 8	0.8	5.6
Spill bay 9	1.0	5.2
Spill bay 10	1.0	1.7
Spillway passage	73.4	79.9
RSW	51.3	33.1
Training spill passage	22.1	46.9
Unknown route	<0.9	<0.9

Table 1. Continued.

	30-40% Spill	BiOp
Passage metric		
Median forebay delay (h)	1.8	1.1
FPE	92.5%	95.1%
Spill efficiency	73.4%	79.9%
Spill effectiveness	2.22	1.38
RSW effectiveness	7.77	6.02
Training spill effectiveness	0.85	0.90
FGE	71.8%	75.4%
Median tailrace egress (min)	8.6	8.5
Survival estimate		
Relative dam survival (forebay BRZ to tailrace)	91.2% (89.0-93.4)	91.6% (89.8-93.4)
Relative concrete survival (all fish passing the dam)	96.1% (94.3-97.9)	96.2% (94.8-97.6)
Relative spillway survival (fish passing through the spillway)	95.7% (93.7-97.7)	96.4% (94.8-98.0)
Relative RSW survival (fish passing only through the RSW)	94.7% (92.1-97.3)	95.5% (94.7-96.3)
Relative training spill survival (fish passing through the spillway without RSW)	98.0% (95.2-100.7)	96.9% (95.2-98.7)
Relative JBS survival (fish passing only through the JBS)	98.3% (95.5-101.1)	97.3% (94.4-100.2)

estimated at 0.98 (95% CI, 0.95-1.01). RSW survival for the BiOp spill treatment was 0.96 (95% CI, 0.95-0.96) with training spill survival estimated at 0.97 (95% CI, 0.95-0.99). Relative dam survival was 0.91 (95% CI, 0.89-0.93) during reduced spill and 0.92 (95% CI, 0.90-0.93) during BiOp operations. Bypass survival for reduced and BiOp spill treatments were 0.98 (95% CI, 0.96-1.01) and 0.97 (95% CI, 0.94-1.00), respectively. Insufficient numbers of radio-tagged fish passed through the powerhouse to estimate survival through turbines. Concrete survival, the survival estimate for all of the fish that passed the project disregarding forebay loss, during reduced and BiOp spill operations was 0.96 (95% CI, 0.94-0.98) and 0.96 (95% CI, 0.95-0.98), respectively.

Juvenile Steelhead

Median forebay residence time for juvenile steelhead passing Ice Harbor Dam was slightly longer for fish approaching during the 30-40% spill operations (1.9 h) than it was for those approaching during BiOp spill (1.1 h). Overall passage distribution for juvenile steelhead during reduced spill treatments was 61.3% through the spillway, 36.7% through the juvenile bypass, and 2.0% through turbines at Ice Harbor Dam, with less than 0.5% of the fish having undetermined passage routes (Table 2). During BiOp spill, 80.7% passed via the spillway, 17.9% through the juvenile bypass, and 1.4% through the turbines, with less than 0.5% having undetermined passage routes. Fish passage efficiency (FPE) was 98.0% during 30-40% spill and 98.6% during BiOp spill. Fish guidance efficiency (FGE) was 94.7% during 30-40% spill and 92.7% during BiOp spill. Spill efficiency was 61.3% under 30-40% spill operations and 80.7% during BiOp spill. Spill efficiency for the RSW was 37.5% for the reduced spill treatment and 30.9% for the BiOp spill treatment. Mean spill effectiveness was 1.86:1 for 30-40% spill and 1.39:1 during BiOp spill. Mean RSW effectiveness was 5.68:1 for 30-40% spill and 5.56:1 for BiOp spill with training spill effectiveness measuring less than 1:1 under both treatments.

Spillway passage survival was 1.02 (95% CI, 0.99-1.04) under 30-40% spill operations and 1.01 (95% CI, 0.99-1.03) during BiOp spill. RSW survival for the reduced spill treatment was 1.02 (95% CI, 0.99-1.05) with training spill survival estimated at 1.02 (95% CI, 0.99-1.05). RSW survival for the BiOp spill treatment was 0.98 (95% CI, 0.95-1.01) with training spill survival estimated at 1.02 (95% CI, 1.01-1.04). Relative dam survival during reduced spill was 0.90 (95% CI, 0.87-0.93) and 0.94 (95% CI, 0.92-0.96) during BiOp operations. Bypass survival for reduced and BiOp spill treatments were 1.00 (95% CI, 0.96-1.03) and 1.01 (95% CI, 0.98-1.04), respectively. Insufficient numbers of tagged fish passed through the powerhouse to estimate survival through turbines. Concrete survival during reduced and BiOp spill operations was 1.01 (95% CI, 0.98-1.03) and 1.01 (95% CI, 0.99-1.03), respectively.

Table 2. Final study results of conditions, passage behavior, and relative survival for radio-tagged juvenile steelhead at Ice Harbor Dam under two operations, 2006 (95% CI in parentheses).

	30-40% Spill	**BiOp**
	Conditions	
Average project discharge (kcfs)	120.1	144.5
Average spill discharge (kcfs)	39.6 (33%)	83.5 (58%)
Average RSW discharge (kcfs)	7.9 (7%)	7.9 (6%)
Average training flow discharge (kcfs)	31.7 (26%)	75.6 (52%)
Average tailwater elevation (ft msl)	347.6	348.7
Average water temperature (°C)	12.5	12.8
Average Secchi depth (m)	1.9	2.1
	Passage distribution	
Juvenile bypass	36.7	17.9
Turbine unit 1	0.0	0.1
Turbine unit 2	0.5	0.4
Turbine unit 3	0.2	0.1
Turbine unit 4	0.8	0.6
Turbine unit 5	0.5	0.1
Turbine unit 6	0.2	0.2
Turbine passage	2.0	1.4
Spill bay 1	0.0	0.8
Spill bay 3	5.8	4.3
Spill bay 4	0.5	9.7
Spill bay 5	9.2	5.6
Spill bay 6	0.6	9.7
Spill bay 7	2.2	6.4
Spill bay 8	0.9	4.6
Spill bay 9	1.9	5.2
Spill bay 10	2.7	3.6
Spillway passage	61.3	80.7
RSW passage	37.5	30.9
Training spill passage	23.9	50.0
Unknown route	<0.5	<0.5

Table 2. Continued.

	30-40% Spill	BiOp
Passage metrics		
Median forebay delay (h)	1.9	1.1
FPE	98.0%	98.6%
Spill efficiency	61.3%	80.7%
Spill effectiveness	1.86	1.39
RSW effectiveness	5.68	5.56
Training spill effectiveness	0.92	0.96
FGE	94.7%	92.7%
Median tailrace egress (min)	9.6	8.5
Survival estimates		
Relative dam survival (forebay BRZ to tailrace)	90.0% (86.8-93.2)	94.1% (91.9-96.3)
Relative concrete survival (all fish passing the dam)	100.7% (98.3-103.1)	100.9% (99.1-102.7)
Relative spillway survival (fish passing through the spillway)	101.7% (99.3-104.1)	100.9% (99.1-102.7)
Relative RSW survival (fish passing only through the RSW)	101.7% (98.9-104.5)	98.4 (95.4-101.4)
Relative training spill survival (fish passing through the spillway without RSW)	101.9% (98.9-104.9)	102.4% (100.6-104.2)
Relative JBS survival (fish passing only through the JBS)	99.7% (96.3-103.1)	101.0% (98.2-103.8)

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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). Anthropogenic factors 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.

At Columbia and Snake River dams, the spillway has long been considered the safest passage route for migrating juvenile salmonids. 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 spill bays 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 (BiOp; NMFS 2000), project operations at Lower Granite, Little Goose, and Lower Monumental Dams have relied on a combination of voluntary spill and collection of fish for transportation to improve hydrosystem passage survival for migrating juvenile salmonids, while efforts at Ice Harbor Dam have focused on increasing the proportion passing via voluntary spill.

Surface collection and bypass systems have been identified as a viable alternative for increasing survival and Fish Passage Efficiency (FPE) for migrating juvenile salmonids at hydroelectric dams on the Snake and Columbia Rivers. At Wells Dam on the Columbia River, the spillway (located over the turbine units) passes 90% of the juvenile fish while spilling just 7% of the total discharge (Whitney et al. 1997). Studies evaluating a removable spillway weir (RSW) installed at Lower Granite Dam in 2001 have shown the RSW is an effective and safe means of passing migrating juvenile salmonids (Anglea et al. 2003; Plumb et al. 2003, 2004). In 2002, the Lower Granite Dam RSW passed 56–62% of radio-tagged fish with only 8.5% of total discharge. In 2003, passage effectiveness ratios were 8.3-9.9:1 through the Lower Granite Dam RSW, with survival estimated at 98% (95% CI, ±2.3%).

Juvenile anadromous salmonids in the Columbia River Basin generally migrate in the upper 3 to 6 m of the water column (Johnson et al. 2000). However, at dams on the lower Columbia and Snake Rivers, fish are required to dive to a depth of 15 to 18 m to enter juvenile passage routes. Engineers and biologists from the USACE developed the RSW to provide a surface-oriented spillway passage route. The RSW is attached to the upstream face of a spill bay, and allows juvenile salmon and steelhead to pass near the surface under lower velocity and pressure, providing a more efficient and less stressful dam passage route. Existing spillbays have gates that open 50 ft below the water surface at the face of the dam, which causes high water pressure and velocity. In the lower Snake River, RSWs were installed at Lower Granite Dam in 2001 and Ice Harbor Dam in 2005. An RSW is scheduled for installation at Lower Monumental Dam prior to the 2008 spring juvenile migration.

Previous studies at Ice Harbor Dam have shown that the majority of spring migrants pass through the spillway (Eppard et al. 2000, 2005a,b; Axel et al. 2006). In 2004, we evaluated passage behavior and survival of yearling Chinook salmon and juvenile steelhead during two different spill conditions: a bulk spill, which used high spill bay openings limited by dissolved gas levels, and a flat spill, which utilized more spill bays with lower gate openings. Results indicated improved passage metrics and survival estimates for fish passing during the bulk spill treatments (Axel et al. 2006; Eppard et al. 2006). In the first year of RSW evaluation at Ice Harbor Dam in 2005, we found very high survival through the RSW, but there seemed to be an avoidance problem for yearling Chinook salmon, with a higher proportion of fish passing through spillbay 1 than through the RSW.

During 2006, we utilized radiotelemetry to determine variations in behavior, passage distribution, and survival of yearling Chinook salmon and juvenile steelhead during two different operational conditions: BiOp spill, which consists of 45 kcfs of water spilled during the day with spill limited only by dissolved gas levels at night, and a reduced level of 30-40% spill. Both spill conditions used the RSW operating continuously. Given the passage behavior results from 2005, regional managers agreed to close spillbay 1 in an attempt to draw spring migrants away from the powerhouse and pass them through the RSW and safer spillbays, where passage survival estimates have been higher.

METHODS

Study Area

The study area included a 119-km reach of the Snake and Columbia Rivers from Lower Monumental Dam at river kilometer (rkm) 589 on the lower Snake River to McNary Dam (rkm 470) on the lower Columbia River (Figure 1). The focal point of the study was Ice Harbor Dam (rkm 538) on the lower Snake River in southeast Washington State, the first dam upstream from its confluence with the Columbia River.

Three passage routes are available to fish passing Ice Harbor Dam: the spillway, the turbines, and a juvenile bypass system. The spillway is 179.8 m long and consists of 10 spill bays, numbered 1 to 10 from south to north. Spill bay flow is metered by operation of Tainter gates with the exception of the RSW bay (spill bay 2), where flow is regulated exclusively by forebay pool elevation. The spillway crest for the conventional bays is located at an elevation of 119.2 m, and for the RSW bay at 129.5 m. The powerhouse measures 204.5 m long, and each turbine unit intake is outfitted with submersible traveling screens, which divert downstream-migrating salmonids into the juvenile fish bypass system. Screens are deployed at an elevation of 106.7 m, and all fish that are not diverted pass through the turbine. Turbine units are numbered 1 to 6 from south to north, where the junction between the powerhouse and the spillway is located.

Fish Collection, Tagging, and Release

River-run yearling Chinook salmon and juvenile steelhead were collected at the Lower Monumental Dam smolt collection facility from 2 to 28 May. We chose fish that did not have any gross injury or deformity and that were at least 120 mm in length and 15 g in weight. Only fish that were not previously PIT tagged were used. Fish were anesthetized with tricaine methanesulfate 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 holding tank. Following collection and sorting, fish were maintained via flow-through river water and held for 20 h prior to radio transmitter implantation.

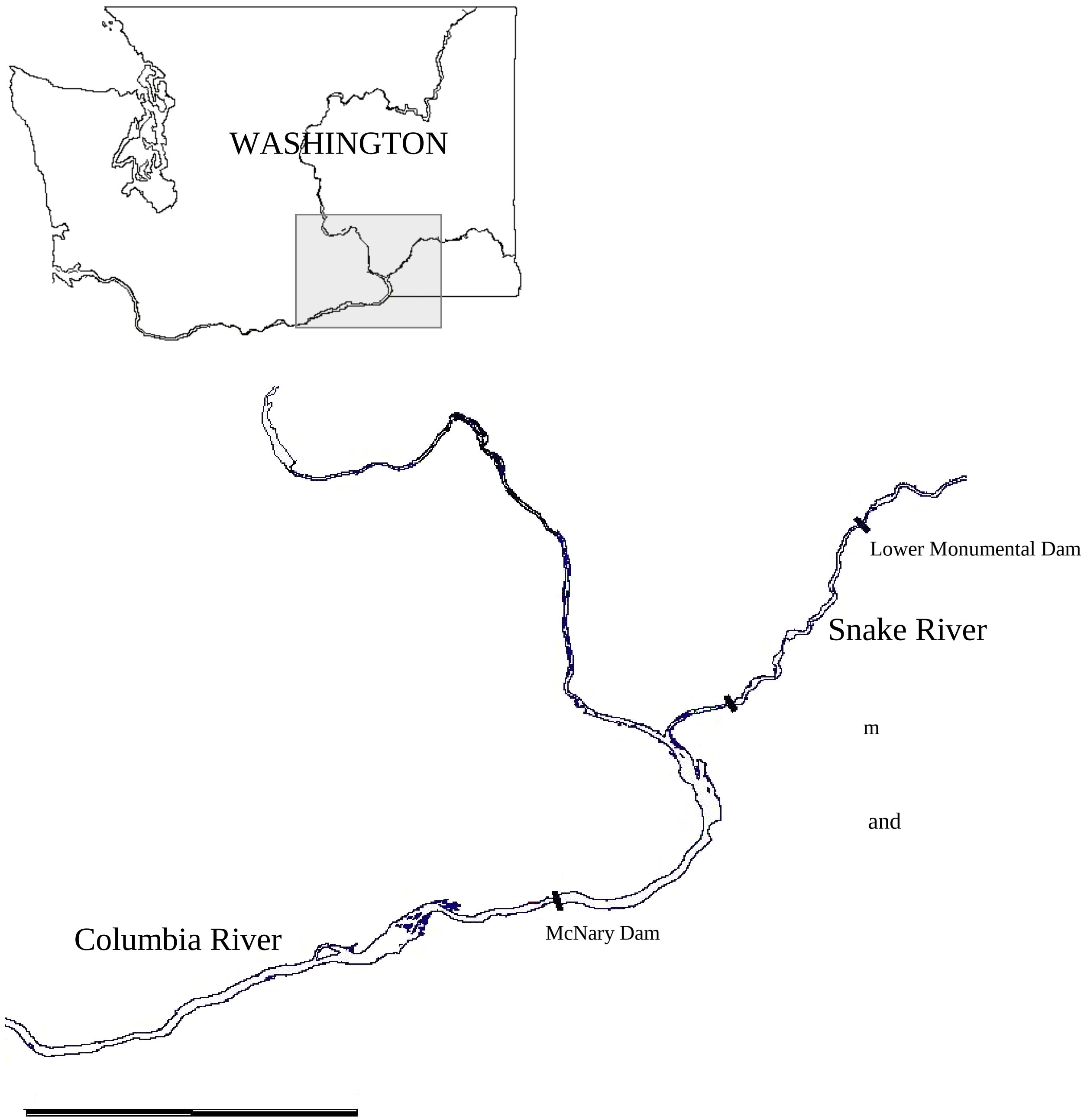

Figure 1. Study area showing location of radiotelemetry transects (numbered 1-4) used for partitioning reach and project survival for radio-tagged juvenile steelhead between Lower Monumental and McNary Dams, 2006. (Note: 1 = Ice Harbor Dam forebay; 2 = Sacajawea State Park; 3 = Burbank Railroad Bridge; and 4 = McNary Dam forebay).

Radio tags were purchased from Advanced Telemetry Systems Inc.,[1] had a user defined 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 by 6 mm in diameter and weighed 0.8 g in air.

Fish were surgically tagged with radio transmitters using techniques described by Adams et al. (1998a,b). Each fish also received a PIT tag before the incision was closed. The PIT tag detections were used to monitor radio-tag performance and also to ensure that study fish that passed via the juvenile fish bypass system were returned to the river in order to estimate survival through that passage route.

Immediately after 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 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 transportation 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. Pre- and post-tagging temperatures at Lower Monumental Dam ranged between 11.3 and 12.7°C.

After the post-tagging recovery period, radio-tagged fish were moved in their recovery containers from the holding area to release areas (Lower Monumental Dam and Ice Harbor Dam tailraces). 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.

Yearling Chinook Salmon

We released 25 groups of approximately 24 fish each into the tailrace about 1 km below Lower Monumental Dam during daytime between 1000 and 1500 PDT, and 25 groups of 24 fish each at night between 2200 and 0300. We also released fish 5 km above Lower Monumental Dam, with 25 releases of approximately 29 fish each during the daytime between 0900 and 1000 PDT, and 25 groups of 27 fish each between during nighttime between 2100 and 2200.

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

These fish were released to evaluate survival at Lower Monumental Dam, but were also used for passage and survival study at Ice Harbor Dam, since their tags had adequate battery life remaining to continue transmitting as fish passed through Ice Harbor Dam. Daytime releases at Ice Harbor Dam occurred between 0900 and 1530 PDT. Nighttime releases at Ice Harbor Dam were made between 2030 and 0500 PDT. We released 25 groups of approximately 31 fish each during both day and night into the tailrace of Ice Harbor Dam.

A total of 2,563 radio-tagged fish were released at Lower Monumental Dam. Release temperatures ranged between 11.5 and 13.0°C. A total of 1,549 radio-tagged fish were released into the tailrace of Ice Harbor Dam. Release temperatures in the tailrace of Ice Harbor ranged between 11.8 and 13.2°C.

Juvenile Steelhead

We released 25 groups of approximately 20 fish each into the tailrace of Lower Monumental Dam during both daytime (1000 to 1500 PDT) and nighttime hours (2200 to 0300 PDT). We made 25 releases of approximately 24 fish each 5 km above Lower Monumental Dam between 0900 and 1000 PDT during day releases, and 25 groups of 23 fish each between 2100 and 2200 during night releases. Daytime releases at Ice Harbor Dam occurred between 0900 and 1530, and nighttime releases between 2030 and 0500. We released 25 groups of approximately 31 fish each during both day and night into the tailrace of Ice Harbor Dam. A total of 2,156 radio-tagged fish were released at Lower Monumental Dam, and a total of 1,574 radio-tagged fish were released into the tailrace of Ice Harbor Dam.

Survival Estimates

Estimates of survival from the tailrace of Lower Monumental Dam to the forebay of Ice Harbor Dam were made using the single-release (SR) model (Cormack 1964; Jolly 1965; Seber 1965). The model uses recapture records (in this case, detections) to estimate survival for a single release group. These estimates consider the probability that a tagged fish may pass the downstream boundary of the area in question without being detected. Thus, in order to separate the probability of detection from that of survival, the model requires detections of at least some fish downstream from the area of interest.

To satisfy this requirement, we used detections at Goose Island, located 2 km below Ice Harbor Dam, for survival estimates through the pool. Previous studies indicated that dead, radio-tagged fish released at Ice Harbor Dam were not detected at the downstream survival transects (Axel et al. 2003); therefore, we could safely assume that fish detected at each transect did not die as a result of passage at Ice Harbor Dam and that dead fish were not used in our calculations of passage and survival. In order to make sure this was true, we released an additional number of dead, radio-tagged yearling Chinook salmon and juvenile steelhead into the tailrace of Ice Harbor Dam to see if varying operations contradicted this observation.

Additional estimates of survival provided for this evaluation were defined as follows:

Relative Dam Survival: Ratio of absolute survivals of groups passing through the effect zone between the forebay (approximately 500' upstream) and the tailrace (approximately 1000' downstream) of the dam.

Relative Spillway Survival: Ratio of absolute survivals of groups passing through the spillway versus the absolute survivals of groups released into the tailrace.

Relative RSW Survival: Ratio of absolute survivals of groups passing through the RSW versus the absolute survivals of groups released into the tailrace.

Relative Training Flow Survival: Ratio of absolute survivals of groups passing through the spillway (not including the RSW) versus the absolute survivals of groups released into the tailrace while the RSW was operating.

Relative Bypass Survival: Ratio of absolute survivals of groups passing through the bypass system versus the absolute survivals of groups released into the tailrace.

Relative Concrete Survival: Ratio of absolute survivals of groups passing through all routes of passage versus the absolute survivals of groups released into the tailrace (forebay loss was not included in the estimate).

For estimates of dam survival through Ice Harbor Dam, we created temporal release groups, that is, treatment replicate groups were composed of fish detected at the transect on the upstream edge of the Boat Restricted Zone during the same dam operation treatment block. These temporal release groups were then paired with reference groups released to the tailrace of Ice Harbor Dam during the same time period. Ratios of pooled survival estimates for treatment to reference fish provide the overall relative survival estimate for the dam.

Relative spillway survival estimates used fish with detections on a spillway receiver and at least one valid subsequent detection on a stilling basin or tailrace receiver. This validated the assumption that a fish last detected on a spillway receiver actually passed the dam via the spillway. Spillway fish were grouped by treatment (RSW or bulk spill), and paired with reference fish released during that particular treatment block. Subsequent downstream detections at Sacajawea State Park and below were used for both dam and spillway survival estimation (Figure 1). We used the same criteria for the remaining relative survival estimates.

Key assumptions underlying the SR model must be met in order to obtain unbiased estimates of survival through specific reaches or areas. One assumption was that radiotelemetry detection at a given site did not affect subsequent detection probabilities downstream from that site. Tests of model assumptions are presented in Appendix A. For a more detailed discussion of the SR model and its associated tests of assumption, see Iwamoto et al. (1994), Zabel et al. (2002), and Smith et al. (2003).

Passage Behavior and Timing

Travel, Arrival, and Passage Timing

Travel time was measured as the time from release to the first detection at the entrance line of the next dam downstream. The first detection on the entrance line at Ice Harbor Dam was also used to determine arrival times at the project. Passage timing was determined by using the last detection in a passage route, using only fish with a subsequent detection in the stilling basin or immediate tailrace.

Forebay Residence Time

Forebay residence time at Ice Harbor Dam was measured from the first detection on the forebay entrance line to either the last detection during spillway passage or the first detection moving past a fish guidance screen into a turbine unit or gatewell. We compared forebay residence and tailrace egress times between treatments using paired *t*-tests on the 50th and 90th passage percentiles of the temporal treatment replicate groups ($P < 0.05$).

Passage Route Distribution

To determine the route of passage individual fish used at Ice Harbor Dam, we monitored the spillway, STS, and the bypass system. The spillway was monitored using four underwater dipole antennas in each spill bay. In each spill bay, two antennas were installed along each of the two pier noses, with one at the 20-ft and one a the 40-ft depth. Pre-season range testing showed that this configuration effectively monitored the entire spill bay.

In addition, we mounted aerial loop 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 co-axial cable, stripped at the end, to detect radio-tagged fish passing through the turbine unit and bypass system. These antennas were attached on both ends of the downstream side of the STS support frame located within each slot of the turbine intake.

We also placed two loop antennas on the hand rail at the collection channel exit located upstream from the juvenile bypass pipe. Fish that were detected on STS telemetry antennas, but were not subsequently detected on the PIT-detection system or the telemetry monitor located 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 (FPE), and fish guidance efficiency (FGE) were also evaluated at Ice Harbor Dam using radiotelemetry detections in the locations used for passage route evaluation (described above). However, the method of calculating these metrics using radiotelemetry differs from those used in previous evaluations (e.g., FGE was formerly calculated based on the percentage of fish caught in gatewells and fyke nets). Fish-passage metrics used for this evaluation were defined as follows:

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

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

Fish passage efficiency: Number of fish passing the dam via non-turbine routes divided by total number passing the dam.

Fish guidance efficiency: Number of fish guided into the bypass system divided by total number passing via the powerhouse (i.e., the combined total for bypass system and turbine passage).

Tailrace Egress

Tailrace egress was measured from the last known detection through a passage route (spillway, turbine, or bypass system) to the last known detection at the telemetry transect located approximately 1 km downstream from Ice Harbor Dam. Hypothesis testing to compare specific cohorts was conducted using the same methodology as that described above for comparing forebay residence time.

Avian Predation

Predation from the Caspian tern *Caspia sterna* colony on Crescent Island, located 12.9 km downstream from the Snake River mouth (Figure 1), was measured by physical recovery of radio tags and electronic detection of PIT-tags deposited on the island. Radio tags and PIT tags were recovered on the tern colony during August 2006 after the birds had left Crescent Island. We physically recovered radio transmitters that were visible on the island and used radio-tag serial numbers to identify individual tagged fish. PIT-tag detections and physical recovery of radio transmitters at Crescent Island were provided by NMFS and Real Time Research, Inc. (B. Ryan, NMFS, personal communication; see also Ryan et al. 2001; A. Evans, Real Time Research, Inc., personal communication).

RESULTS

Fish Collection, Tagging, and Release

Unmarked yearling Chinook salmon and juvenile steelhead were collected, radio tagged, and PIT tagged at Lower Monumental over 27 d from 2 to 28 May. Tagging began after approximately 14% of the yearling Chinook salmon and 20% of the juvenile steelhead had passed Lower Monumental Dam. Tagging was completed when 97% of both species had passed (Figure 2). Overall mean fork length of tagged yearling Chinook and steelhead was 143 and 203 mm, respectively, similar to the mean length of run-at-large fish sampled at the smolt collection facility (139 and 197 mm). Overall handling (collection) and tagging mortality was 2.2%.

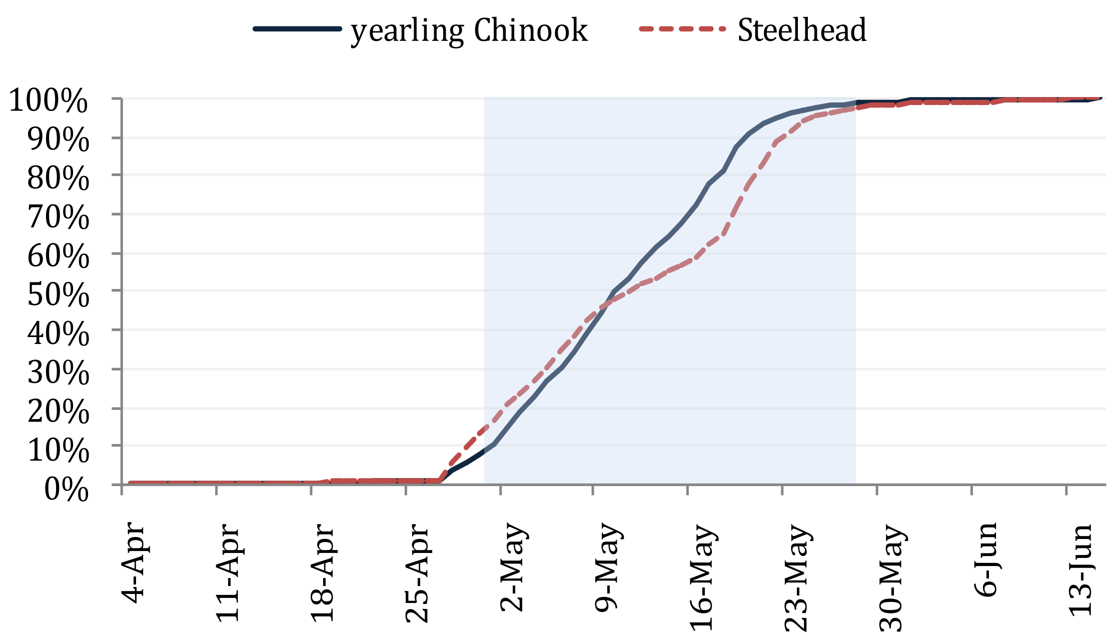

Figure 2. Passage index of juvenile steelhead and yearling Chinook salmon estimated at Lower Monumental Dam during 2006. The shaded area depicts the tagging period and portion of the run targeted for tagging.

Dam Operations

The 2006 voluntary spill program followed a 2-d random block design with a higher spill discharge during BiOp spill operation (45 kcfs during the day and spill limited only by dissolved gas levels at night) and a decreased volume of spill during 30-40% spill operation, with both treatments utilizing the RSW. The spill pattern attempted to utilize spillway gates for each bay that were open at least 5 stops where feasible.

Median spill during BiOp treatments was 83.5 kcfs, while median spill volume during the 30-40% spill treatment was 39.6 kcfs. Mean flow through turbines and spill bays for each treatment are shown in Figure 3. Mean daily total discharge was 144.5 kcfs during BiOp spill treatments (range 55.0-222.9 kcfs) and 120.1 kcfs during 30-40% spill treatments (range 60.0-153.0 kcfs).

Mean daily river flow and percentage of spill during the spring evaluation, with treatment blocks identified, are shown in Figure 4 with mean hourly percent spill by treatment shown in Figure 5. Mean flow (kcfs) for each turbine unit and spill bay, and mean gate openings (stops) by spill bay during treatment blocks are shown in Tables 3 and 4, respectively. The operating pool level in the forebay of Ice Harbor Dam was reduced by 1 ft in 2006, which effectively reduced the amount of water flowing over the RSW from 8.9 kcfs in 2005 to 7.9 kcfs in 2006.

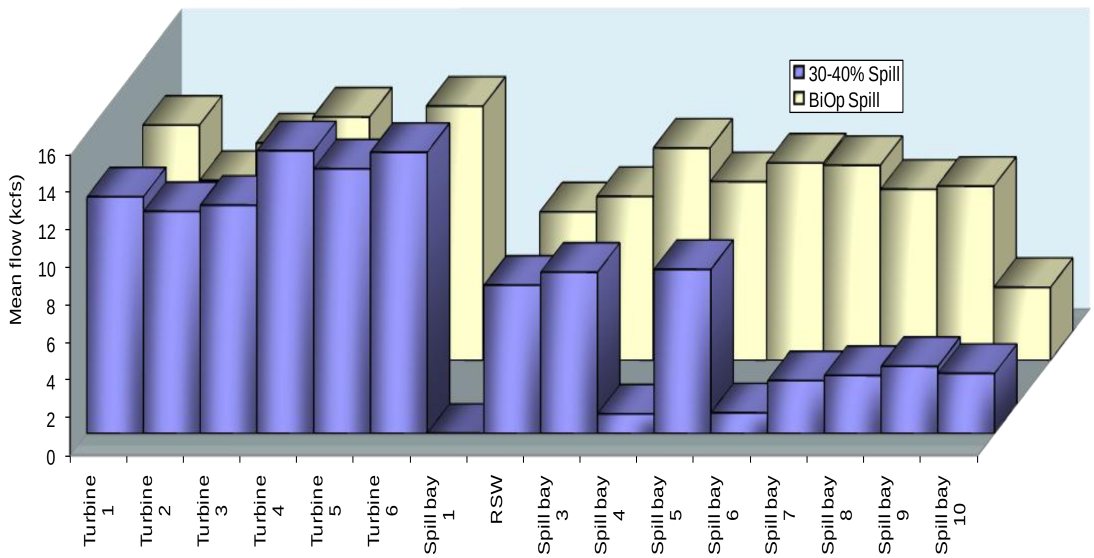

Figure 3. Mean flow (kcfs) for each treatment block for radio-tagged yearling Chinook salmon and juvenile steelhead arriving at Ice Harbor Dam, 2006.

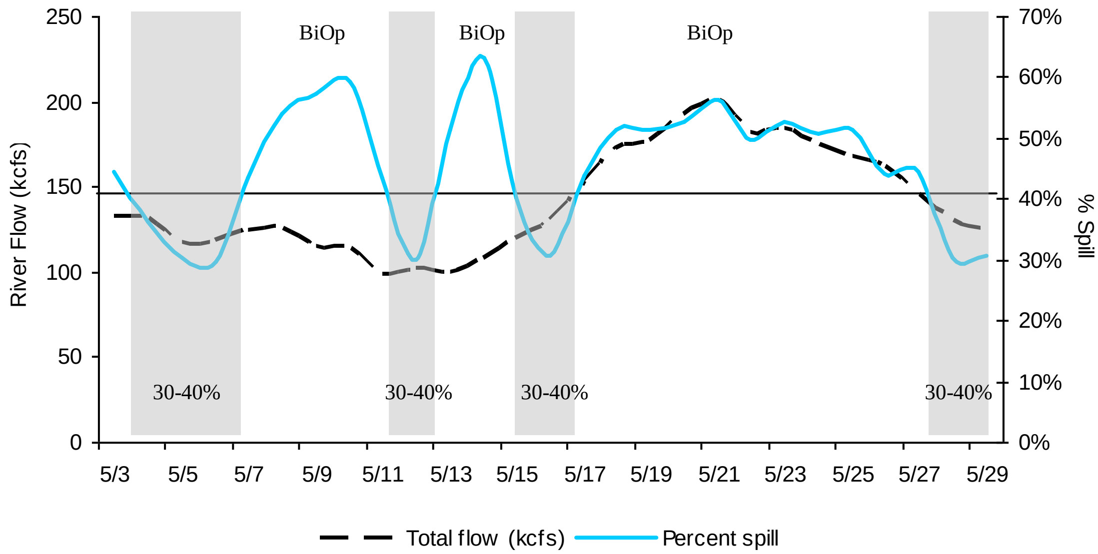

Figure 4. Mean daily river flow (kcfs) and spill percentage with treatment blocks for radio-tagged yearling Chinook salmon and juvenile steelhead arriving at Ice Harbor Dam, 2006.

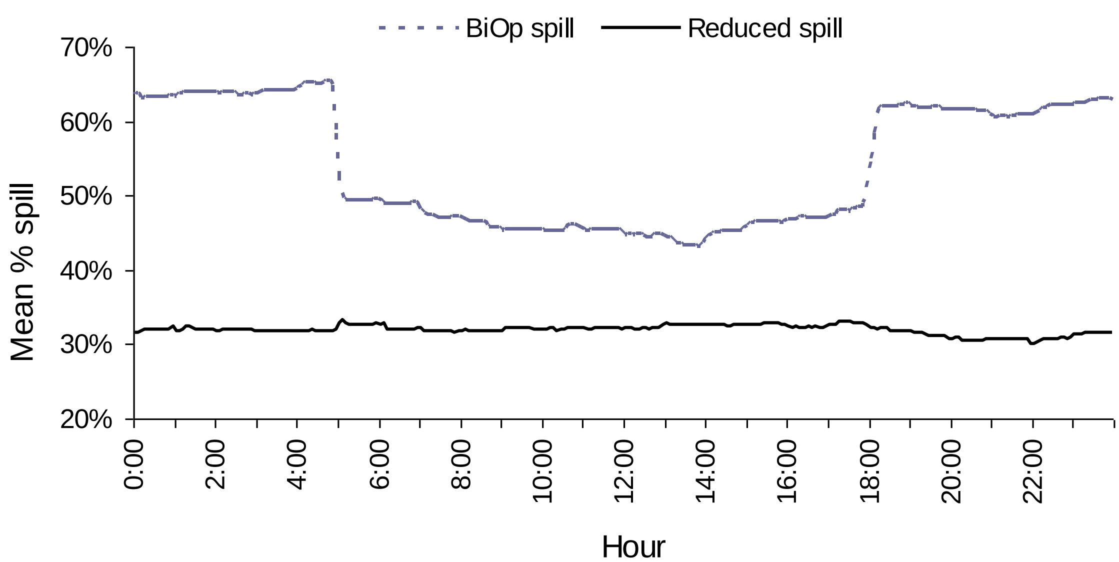

Figure 5. Mean hourly percent spill by treatment for radio-tagged yearling Chinook salmon and juvenile steelhead arriving at Ice Harbor Dam, 2006.

Table 3. Average flow (kcfs) by turbine unit and spill bay at Ice Harbor Dam during 30-40% spill and BiOp spill operation blocks, 2006.

		Turbine unit						Spill bay									
Date	Test block	1	2	3	4	5	6	1	RSW	3	4	5	6	7	8	9	10
		30-40% spill															
May 3-7	1	12.5	12.4	12.5	15.1	13.8	15.0	0.0	7.9	8.3	1.3	7.8	1.2	3.8	3.2	3.7	3.4
May 11-13	2	11.3	7.9	9.1	14.0	13.0	13.8	0.0	7.9	8.4	0.0	8.5	0.0	0.0	1.3	1.6	2.1
May 15-17	3	13.3	13.3	13.4	16.3	15.7	16.2	0.0	7.9	7.7	1.9	9.5	2.4	3.2	3.4	4.2	3.5
May 27-31	4	12.9	12.2	12.7	14.8	13.9	14.7	0.0	7.9	9.6	0.7	9.4	0.7	3.0	3.7	4.1	3.4
		BiOp spill															
May 7-11	1	11.6	5.3	9.4	6.8	5.6	9.0	0.0	7.9	6.7	11.0	6.2	10.3	10.1	7.5	7.4	3.3
May 13-15	2	11.3	3.9	6.9	5.9	2.9	7.1	0.0	7.9	5.7	10.9	5.1	9.7	9.6	6.9	6.9	3.4
May 17-27	3	13.1	12.8	13.0	16.0	14.3	16.1	1.2	7.9	11.1	11.8	11.6	11.2	11.0	10.9	10.7	4.4
May 31-June 2	4	11.5	3.7	8.8	7.3	0.0	8.7	0.0	7.9	2.3	9.9	4.4	8.6	8.3	5.6	5.6	3.3

Table 4. Average gate openings (stops) by spill bay at Ice Harbor Dam during 30-40% and BiOp spill operation blocks, 2006.

		Spillbay									
Date	Test block	1	RSW	3	4	5	6	7	8	9	10
		30-40% spill									
May 3-7	1	0.0	4.7	4.9	0.8	4.6	0.7	2.2	1.9	2.2	2.0
May 11-13	2	0.0	4.7	5.0	0.0	5.0	0.0	0.0	0.8	0.9	1.3
May 15-17	3	0.0	4.7	4.6	1.1	5.7	1.4	1.9	2.0	2.5	2.1
May 27-31	4	0.0	4.7	5.7	0.4	5.6	0.4	1.8	2.2	2.4	2.0
		BiOp spill									
May 7-11	1	0.0	4.7	4.0	6.6	3.7	6.2	6.1	4.5	4.4	2.0
May 13-15	2	0.0	4.7	3.4	6.5	3.1	5.8	5.7	4.1	4.1	2.0
May 17-27	3	0.7	4.7	6.7	7.1	7.0	6.7	6.6	6.5	6.5	2.6
May 31-June 2	4	0.0	4.7	1.3	5.9	2.6	5.1	5.0	3.3	3.3	2.0

Survival Estimates

Yearling Chinook Salmon

Spillway passage survival was 0.96 (95% CI, 0.94-0.98) under 30-40% spill operations and 0.96 (95% CI, 0.95-0.98) during BiOp spill (Table 1). RSW survival for the reduced spill treatment was 0.95 (95% CI, 0.92-0.97), with training spill survival estimated at 0.98 (95% CI, 0.95-1.00). RSW survival for the BiOp spill treatment was 0.96 (95% CI, 0.95-0.96), with training spill survival estimated at 0.97 (95% CI, 0.95-0.99). Relative dam survival during reduced spill was 0.91 (95% CI, 0.89-0.93) and 0.92 (95% CI, 0.90-0.93) during BiOp operations. Bypass survival for reduced and BiOp spill treatments were 0.98 (95% CI, 0.96-1.01) and 0.97 (95% CI, 0.95-1.00), respectively. Insufficient numbers of tagged fish passed through the powerhouse to estimate survival through turbines. Concrete survival, the survival estimate for all of the fish that passed the project, during both 30-40% and BiOp spill operations was 0.96 (95% CI, 0.94-0.98) and 0.96 (95% CI, 0.95-0.98), respectively. None of these comparisons were significantly different.

We estimated pool survival (i.e., between the tailrace of Lower Monumental Dam and the forebay of Ice Harbor Dam) to be 0.99 (95% CI, 0.98–0.99).

Juvenile Steelhead

Spillway passage survival was 1.02 (95% CI, 0.99-1.04) under 30-40% spill operations and 1.01 (95% CI, 0.99-1.03) during BiOp spill (Table 2). RSW survival for the reduced spill treatment was 1.02 (95% CI, 0.99-1.05), with training spill survival estimated at 1.02 (95% CI, 0.99-1.05). RSW survival for the BiOp spill treatment was 0.98 (95% CI, 0.95-1.01), with training spill survival estimated at 1.02 (95% CI, 1.01-1.04). Relative dam survival during reduced spill was 0.90 (95% CI, 0.87-0.93), and 0.94 (95% CI, 0.92-0.96) during BiOp operations. Bypass survival for reduced and BiOp spill treatments were 1.00 (95% CI, 0.96-1.03) and 1.01 (95% CI, 0.98-1.04), respectively. Insufficient numbers of tagged fish passed through the powerhouse to estimate survival through turbines. Concrete survival, the survival estimate for all of the fish that passed the project, during 30-40% and BiOp spill operations was 1.01 (95% CI, 0.98-1.03) and 1.01 (95% CI, 0.99-1.03), respectively. None of these comparisons were significantly different.

We estimated pool survival (i.e., between the tailrace of Lower Monumental Dam and the forebay of Ice Harbor Dam) to be 0.95 (95% CI, 0.94–0.95).

Passage Behavior and Timing

Travel, Arrival, and Passage Timing

We detected 2,066 radio-tagged yearling Chinook salmon and 1,619 juvenile steelhead released at Lower Monumental Dam that were subsequently detected at the forebay entrance line of Ice Harbor Dam. Travel times were calculated for each species from their respective release sites in the forebay or tailrace of Lower Monumental Dam (Tables 5 and 6).

Table 5. Travel time for radio-tagged yearling Chinook released in the forebay and tailrace of Lower Monumental Dam and detected at the forebay entrance of Ice Harbor Dam, 2006.

			Travel time (d) by passage percentile											
Release site	N	Min	10	20	30	40	50	60	70	80	90	Max	Mean	>6 d
$LMN_{Forebay}$	1,074	0.6	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.5	3.0	7.9	1.9	5 (0.5%)
$LMN_{Tailrace}$	992	0.5	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.5	1.7	4.8	1.2	0 (0.0%)

Table 6. Travel time for radio-tagged juvenile steelhead released in the forebay and tailrace of Lower Monumental Dam and detected at the forebay entrance of Ice Harbor Dam, 2006.

			Travel time (d) by passage percentile											
Release site	N	Min	10	20	30	40	50	60	70	80	90	Max	Mean	>6 d
$LMN_{Forebay}$	839	0.5	1.1	1.3	1.5	1.7	1.9	2.2	2.4	2.7	3.5	7.1	2.2	7 (0.8%)
$LMN_{Tailrace}$	780	0.5	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.5	1.9	6.0	1.2	0 (0.0%)

First approach for both species under a BiOp treatment was primarily at the spillway, with very few fish being directed towards the powerhouse (Figures 6 and 7). During 30-40% spill treatments, the amount of flow through the spillway was reduced and shifted to the powerhouse, which resulted in higher percentages of fish approaching the powerhouse.

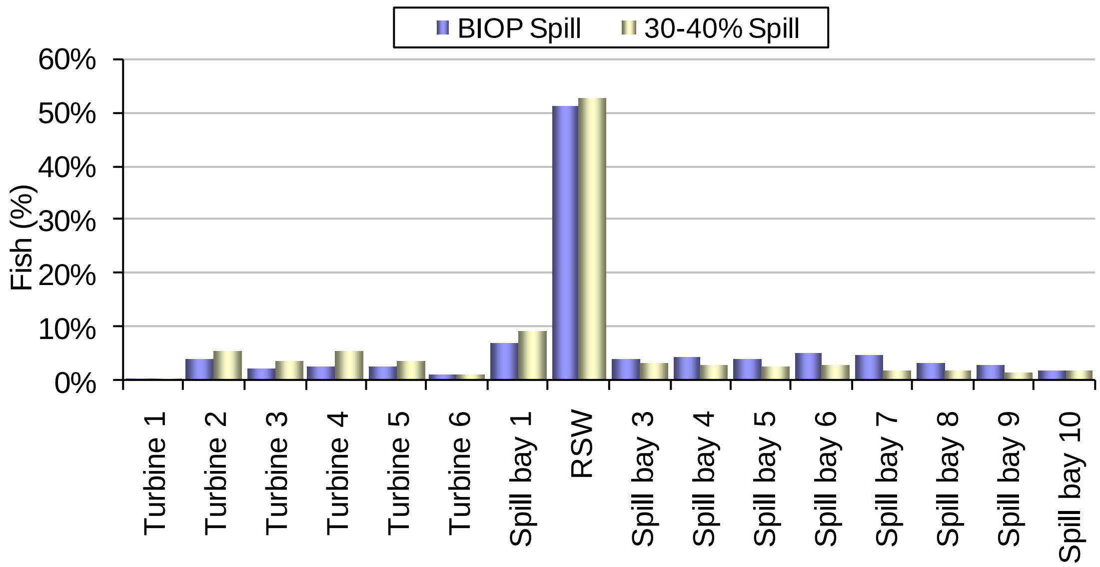

Figure 6. First approach location (percent) of radio-tagged yearling Chinook salmon at Ice Harbor Dam during two spill treatments, 2006.

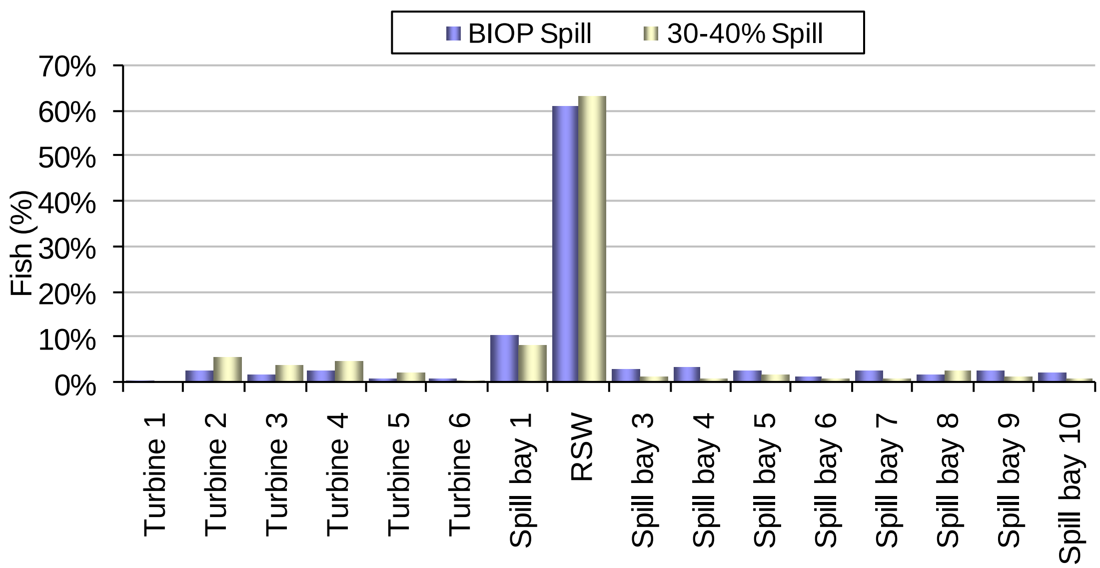

Figure 7. First approach location (percent) of radio-tagged juvenile steelhead at Ice Harbor Dam during two spill treatments, 2006.

Hours of arrival and passage at Ice Harbor Dam were fairly consistent throughout both treatments of the study with anywhere from 3 to 6% of both species arriving at all hours of the day (Figures 8-11). We observed a slight peak in passage for both species during early morning hours of the 30-40% spill treatments, while during BiOp spill treatments, fish passage was relatively constant throughout all hours. Both species displayed similar results under both treatments, with approach and passage trends suggesting relatively little delay in the forebay.

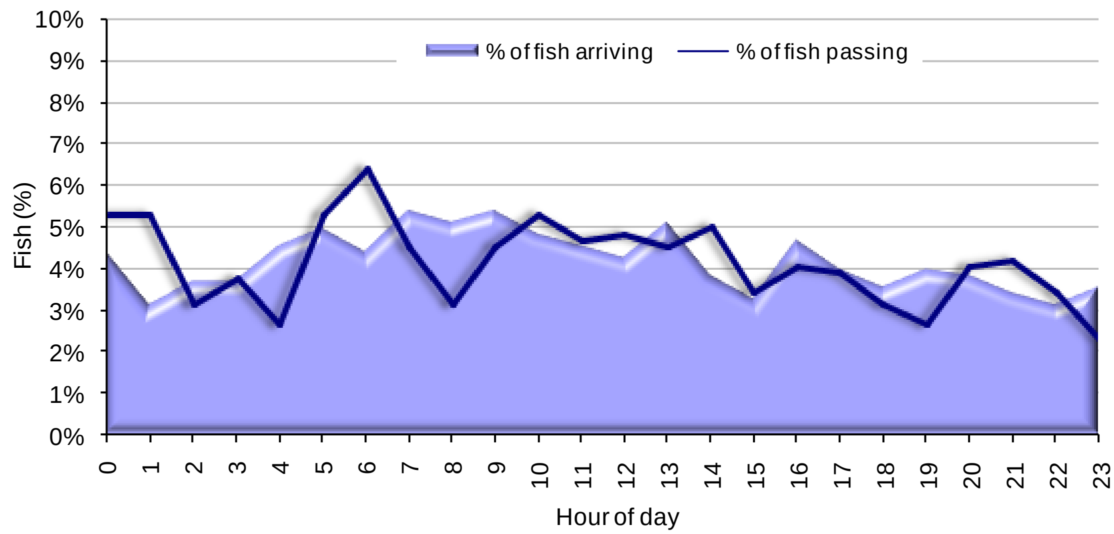

Figure 8. Percent of radio-tagged juvenile steelhead arriving and passing Ice Harbor Dam during 30-40% spill treatments, 2006.

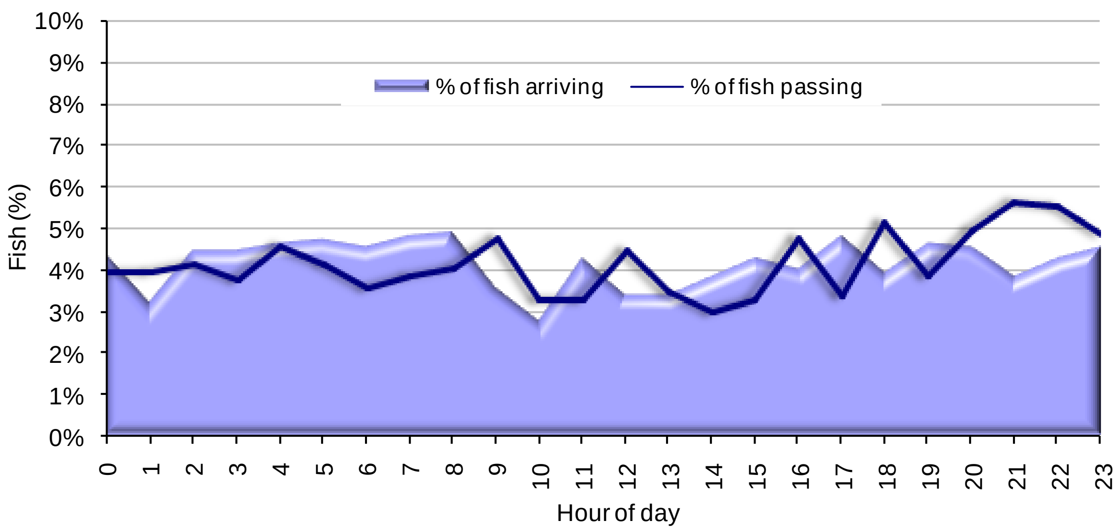

Figure 9. Percent of radio-tagged juvenile steelhead arriving and passing Ice Harbor Dam during BiOp spill treatments, 2006.

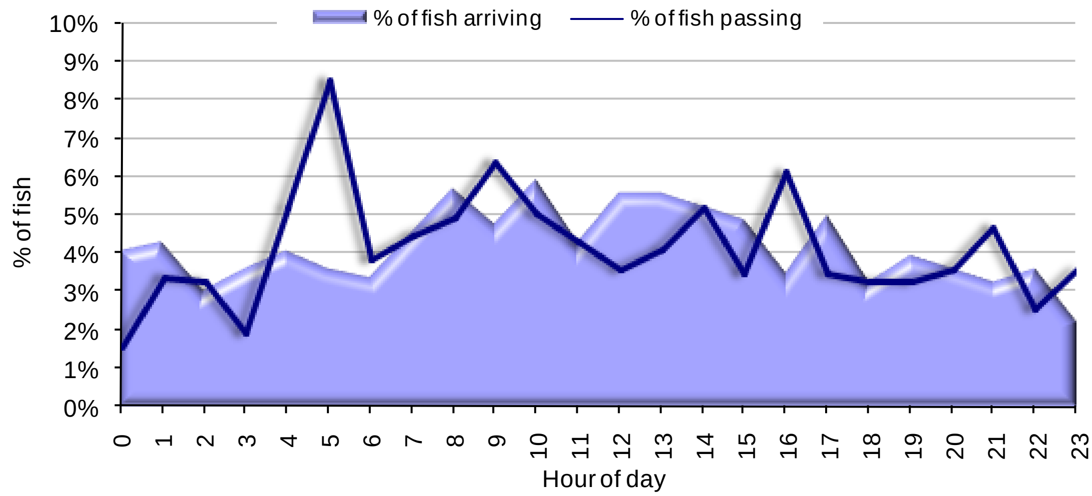

Figure 10. Percent of radio-tagged yearling Chinook salmon arriving and passing Ice Harbor Dam during 30-40% spill treatments, 2006.

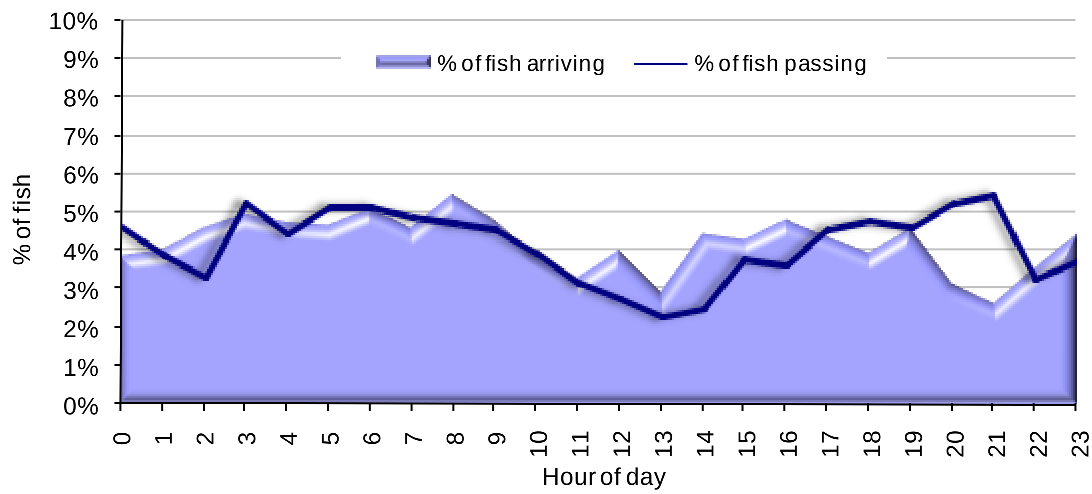

Figure 11. Percent of radio-tagged yearling Chinook salmon arriving and passing Ice Harbor Dam during BiOp spill treatments, 2006.

Forebay Residence Time

Yearling Chinook salmon median forebay residence times of the 50th percentiles of replicate treatment groups was significantly longer (P = 0.007) for those that passed during 30-40% spill operations (1.8 h) than for those that passed during BiOp spill (1.1 h, Figure 12 and 13). The two treatments continued to display statistically significant results for the 90th percentiles of forebay residence times (P = 0.003, Figure 14).

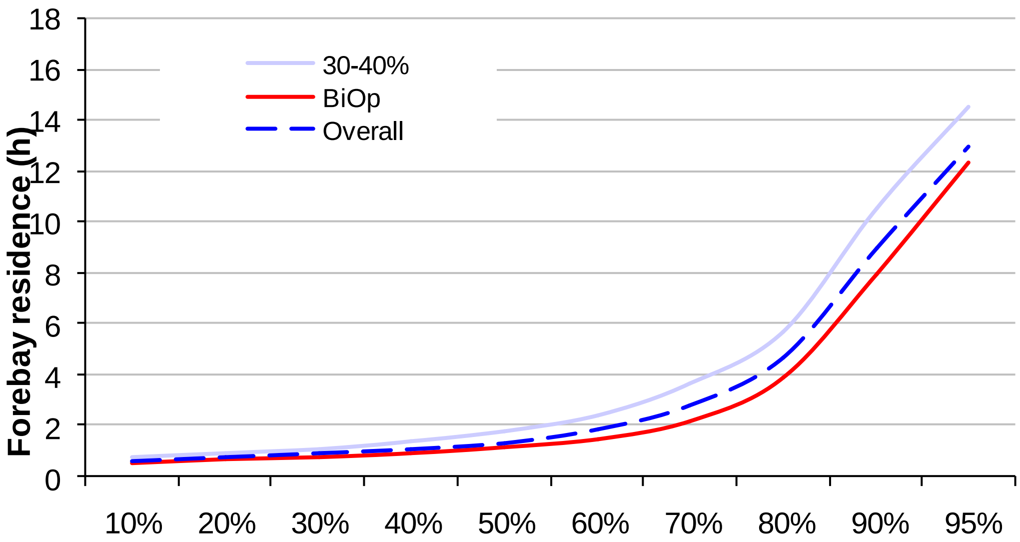

Figure 12. Forebay residence time versus the cumulative percent of radio-tagged yearling Chinook salmon passing Ice Harbor Dam under two different spill treatments, 2006.

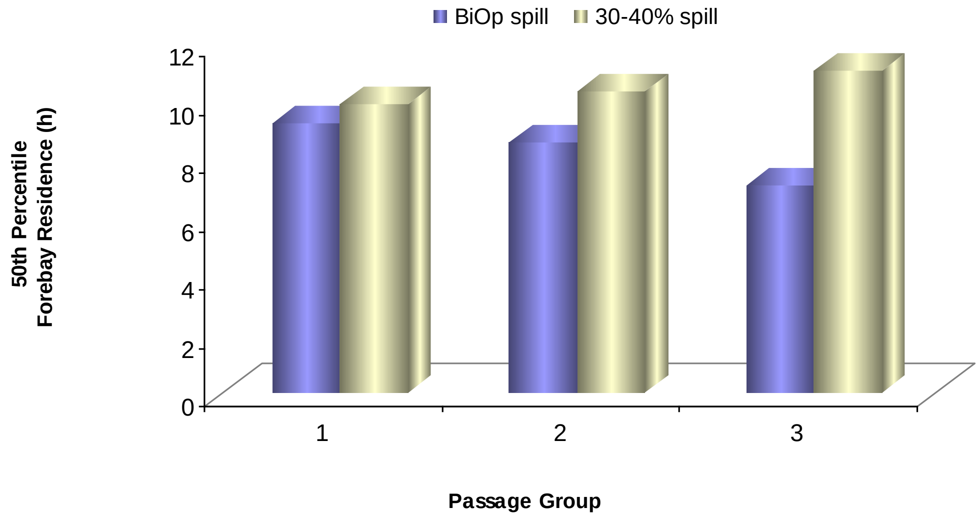

Figure 13. Paired 50th percentiles of forebay residence time (in hours) of radio-tagged yearling Chinook salmon passing Ice Harbor Dam under two different spill treatments, 2006.

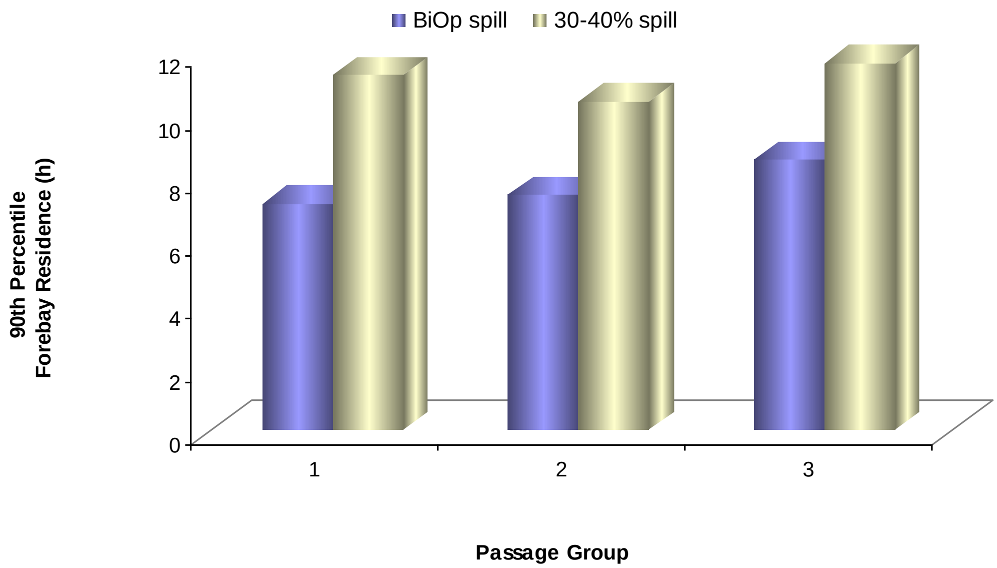

Figure 14. Paired 90th percentiles of forebay residence time (in hours) for radio-tagged yearling Chinook salmon passing Ice Harbor Dam under two different spill treatments, 2006.

Median forebay residence time was significantly longer (P = 0.012) for juvenile steelhead passing during 30-40% spill operations (1.9 h) than for those passing during BiOp spill (1.1 h, Figure 15) in comparisons between spill conditions on the 50th percentiles of the temporal replicate treatment groups (Figure 16), but differences were not significant for the 90th percentiles (P = 0.118, Figure 17).

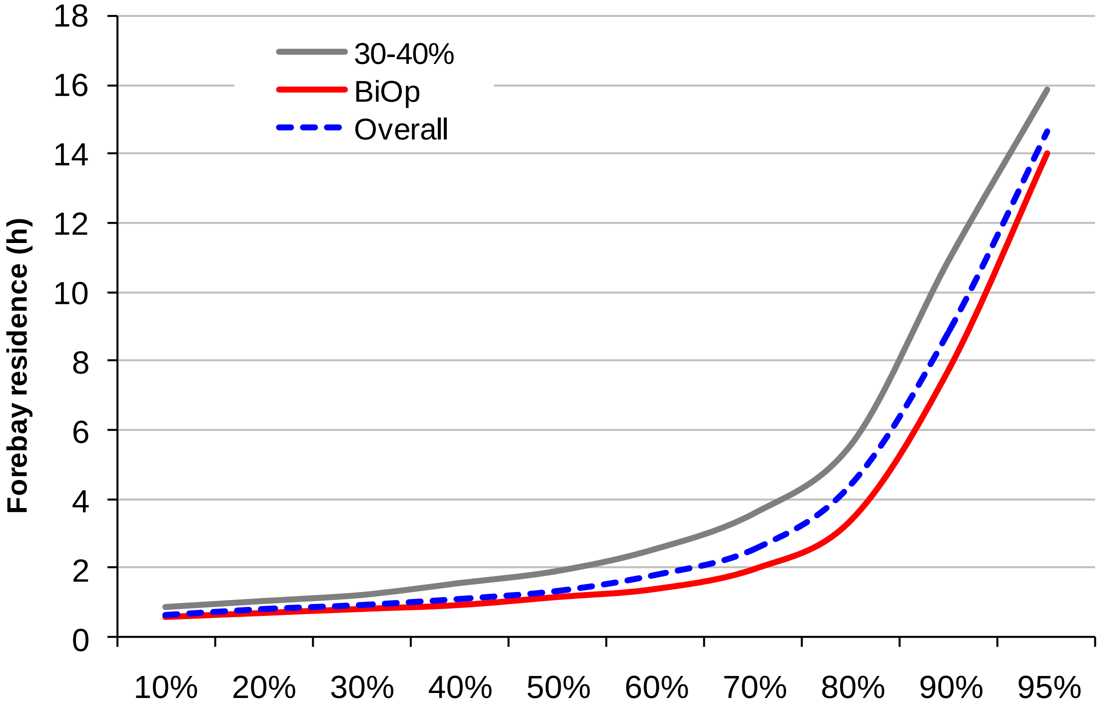

Figure 15. Forebay residence time versus the cumulative percent of radio-tagged juvenile steelhead passing Ice Harbor Dam under two different spill treatments, 2006.

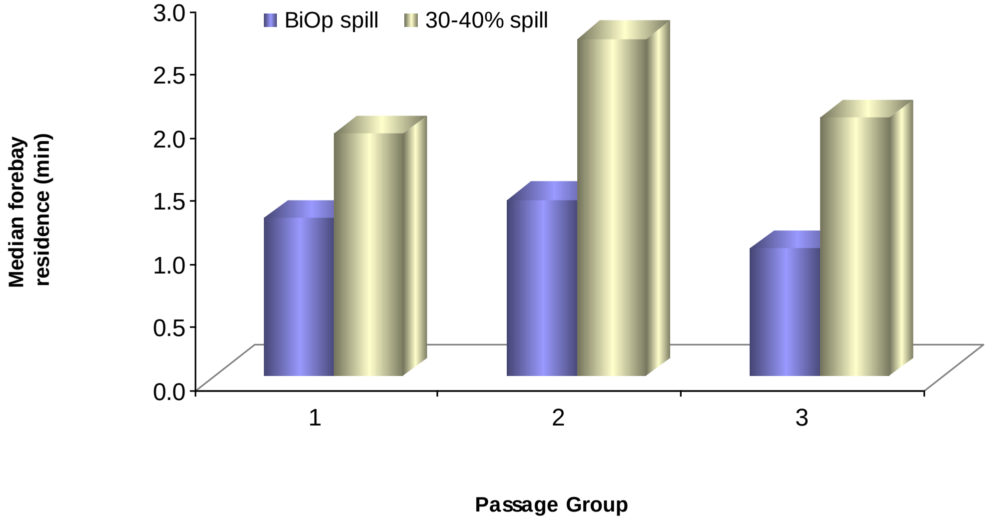

Figure 16. Paired 50th percentiles of forebay residence time (in minutes) of radio-tagged juvenile steelhead passing Ice Harbor Dam under two different spill treatments, 2006.

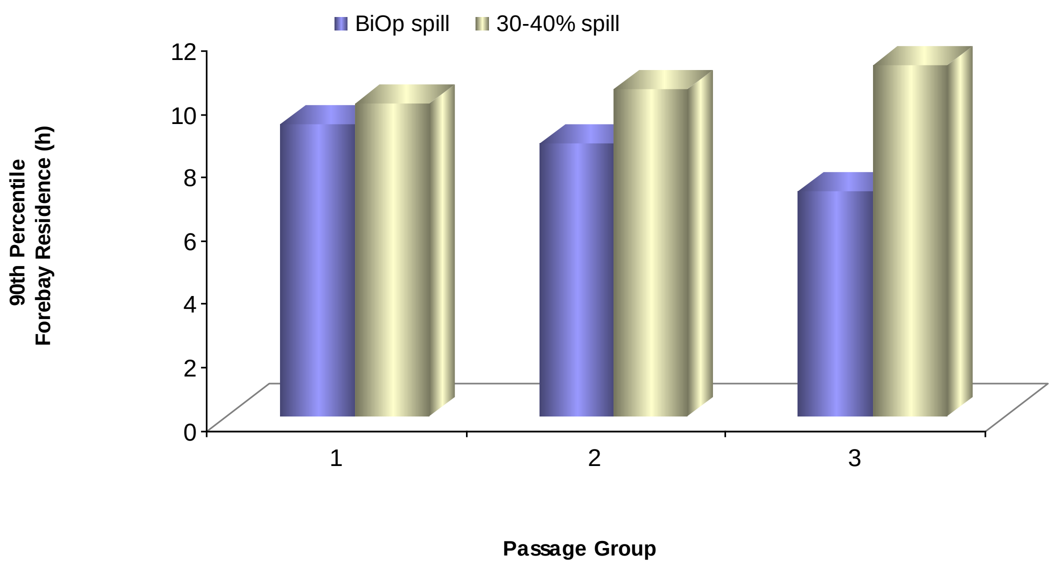

Figure 17. Paired 90th percentiles of forebay residence time (in hours) for radio-tagged juvenile steelhead passing Ice Harbor Dam under two different spill treatments, 2006.

Passage Route Distribution

Overall passage distribution for radio-tagged Snake River yearling Chinook salmon through spillway, bypass, and turbine routes during 30-40% spill treatments was 73.4 (51.3% of which passed through the RSW bay), 19.1, and 7.5%, respectively (Table 1). Less than 0.9% (14) of the fish passed the project by an unknown route, and an additional 105 fish entered the forebay, but did not pass the project. During BiOp spill, passage distribution through spillway, bypass, and turbine routes was 80.0 (33.1% of which passed through the RSW bay), 15.1, and 4.9%, respectively. Less than 0.9% (14) of the fish passed the project by an unknown route. Horizontal passage distribution during both spill treatments is shown in Figure 18.

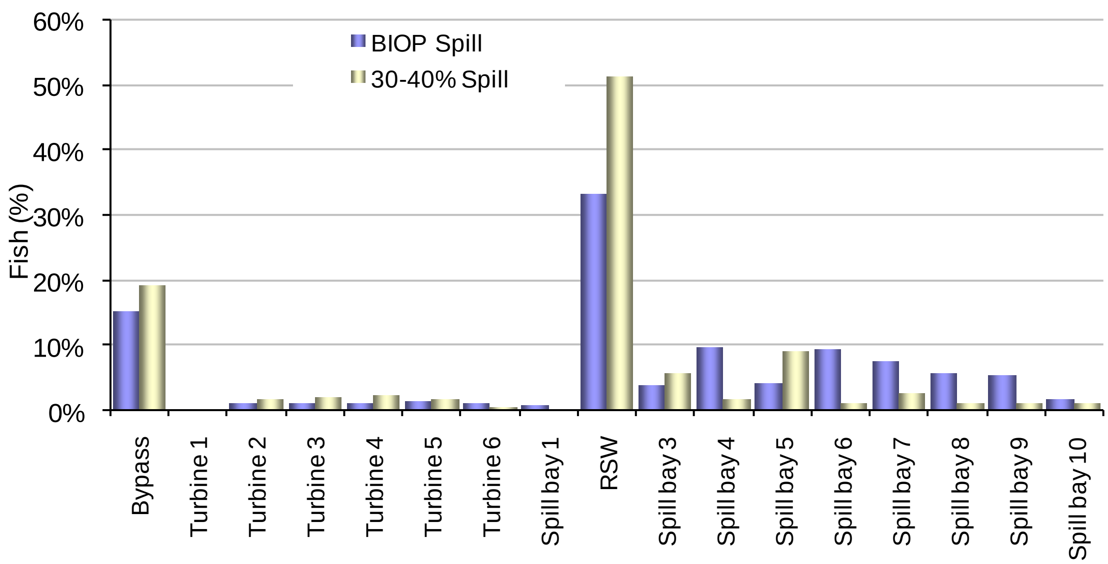

Figure 18. Horizontal passage distribution of radio-tagged juvenile yearling Chinook salmon during two spill treatments at Ice Harbor Dam, 2006.

Overall passage distribution for radio-tagged Snake River juvenile steelhead through spillway, bypass, and turbine routes during 30-40% spill treatments was 61.3 (37.5% of which passed through the RSW bay), 36.7, and 2.0%, respectively (Table 2). Less than 0.5% (4) of the fish passed the project by an unknown route, and an additional 142 fish entered the forebay, but did not pass the project. During BiOp spill, passage distribution through spillway, bypass, and turbine routes was 80.7 (30.9% of which passed through the RSW bay), 17.9, and 1.4%, respectively. Less than 0.5% (5) of the fish passed the project by an unknown route. Horizontal distribution during both spill treatments is shown in Figure 19.

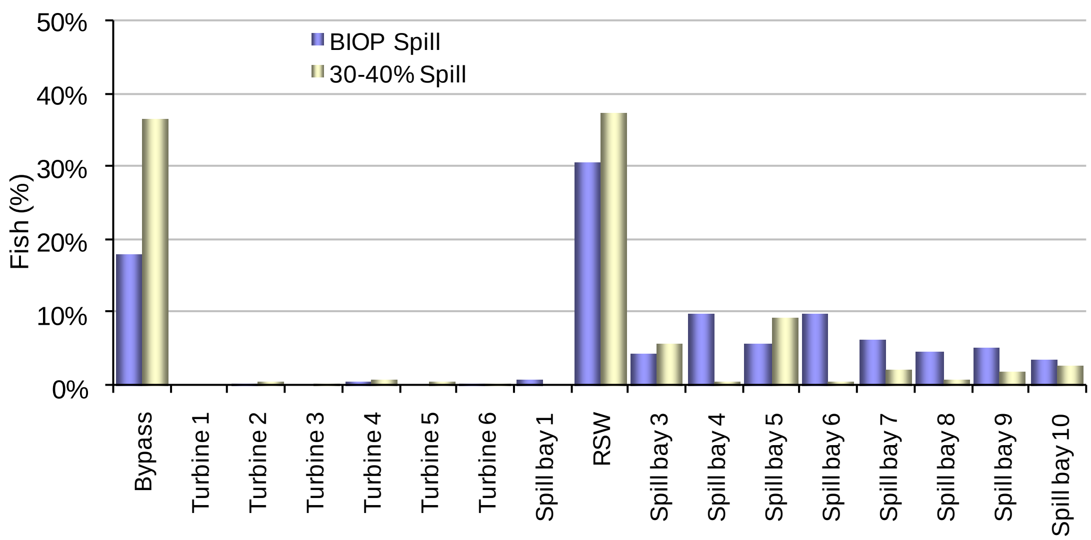

Figure 19. Horizontal passage distribution of radio-tagged juvenile steelhead during two spill treatments at Ice Harbor Dam, 2006.

Fish Passage Metrics

Fish passage efficiency (FPE) for yearling Chinook salmon was 93% (95% CI, 91-94%) during 30-40% spill and 95% (95% CI, 94-96%) during BiOp spill (Table 7). Fish guidance efficiency (FGE) was 72% (95% CI, 66-78%) during 30-40% spill and 75% (95% CI, 70-81%) during BiOp spill. Spill efficiency was 73% (95% CI, 70-77%) under 30-40% spill and 80% (95% CI, 78-82%) during BiOp spill. Mean spill effectiveness during 30-40% spill treatments was 2.2:1 (95% CI, 2.1-2.3) for the spillway and 7.8:1 (95% CI, 7.3-8.2) for the RSW (Table 1). Mean spill effectiveness during BiOp spill treatments was 1.4:1 (95% CI, 1.4-1.4) for the spillway and 6.0:1 (95% CI, 5.7-6.4) for the RSW.

Table 7. Passage distribution and fish passage metrics for radio-tagged yearling Chinook salmon passing Ice Harbor Dam during 30-40% and BiOp spill treatments, 2006.

Date	Treatment block	Mean spill (kcfs)	Passage route (n) Spill-way	RSW	Bypass	Turbine	Total	Fish passage metrics (%) Spill efficiency	FPE	FGE
			30-40% spill							
May 3-7	1	40.4	48	109	67	18	242	65	93	79
May 11-13	2	29.9	33	103	21	12	169	81	93	64
May 15-17	3	43.8	56	154	34	20	264	8	92	63
May 27-31	4	42.4	46	59	36	12	153	69	92	75
Totals			*183*	*425*	*158*	*62*	*828*	*73*	*93*	*72*
			BiOp spill							
May 7-11	1	70.3	177	90	36	9	312	86	97	80
May 13-15	2	66.0	94	55	9	1	159	94	99	90
May 17-27	3	91.9	344	289	154	55	842	75	94	74
May 31-June 2	4	55.8	1	1	0	0	2	100	100	
Totals			*616*	*435*	*199*	*65*	*1315*	*80*	*95*	*75*

Fish passage efficiency (FPE) for juvenile steelhead was 98% (95% CI, 97-99%) during 30-40% spill and 99% (95% CI, 98-99%) during BiOp spill (Table 8). Fish guidance efficiency (FGE) was 95% (95% CI, 92-98%) during 30-40% spill and 93% (95% CI, 89-96%) during BiOp spill. Spill efficiency was 61% (95% CI, 57-65%) under 30-40% spill and 81% (95% CI, 78-83%) during BiOp spill.

Mean spill effectiveness during 30-40% spill treatments was 1.9:1 (95% CI, 1.7-2.0) for the spillway and 5.7:1 (95% CI, 5.1-6.2) for the RSW (Table 2). Mean spill effectiveness during BiOp spill treatments was 1.4:1 (95% CI, 1.4-1.4) for the spillway and 5.6:1 (95% CI, 5.2-6.0) for the RSW.

Table 8. Passage distribution and fish passage metrics for radio-tagged juvenile steelhead passing Ice Harbor Dam during 30-40% and BiOp spill treatments, 2006.

			Passage route (n)					Fish passage metrics (%)		
Date	Spill treatment	Mean spill (kcfs)	Spill-way	RSW	Bypass	Turbine	Total	Spill efficiency	FPE	FGE
			30-40% spill							
May 3-7	1	40.4	39	68	80	5	192	56	97	94
May 11-13	2	29.9	23	52	50	2	127	59	98	96
May 15-17	3	43.8	46	81	57	2	186	68	99	97
May 27-31	4	42.4	44	38	47	4	133	62	97	92
Totals			*152*	*239*	*234*	*13*	*638*	*61*	*98*	*95*
			BiOp spill							
May 7-11	1	70.3	132	64	34	4	234	84	98	90
May 13-15	2	66.0	58	52	10	1	121	91	99	91
May 17-27	3	91.9	340	212	146	10	708	78	99	94
May 31-June 2	4	55.8	1	0	0	0	1	100	100	NA
Totals			*531*	*328*	*190*	*15*	*1064*	*81*	*99*	*93*

Tailrace Egress

Median tailrace egress for juvenile yearling Chinook salmon was similar during 30-40% spill operations (8.6 min) versus those that passed during BiOp spill (8.5 min; Figure 20). No significant differences were found in comparisons of egress time between spill treatments for the 50th percentiles (*P* = 0.300; Figure 21) or the 90th percentiles (*P* = 0.458; Figure 22) of temporal replicate treatment groups.

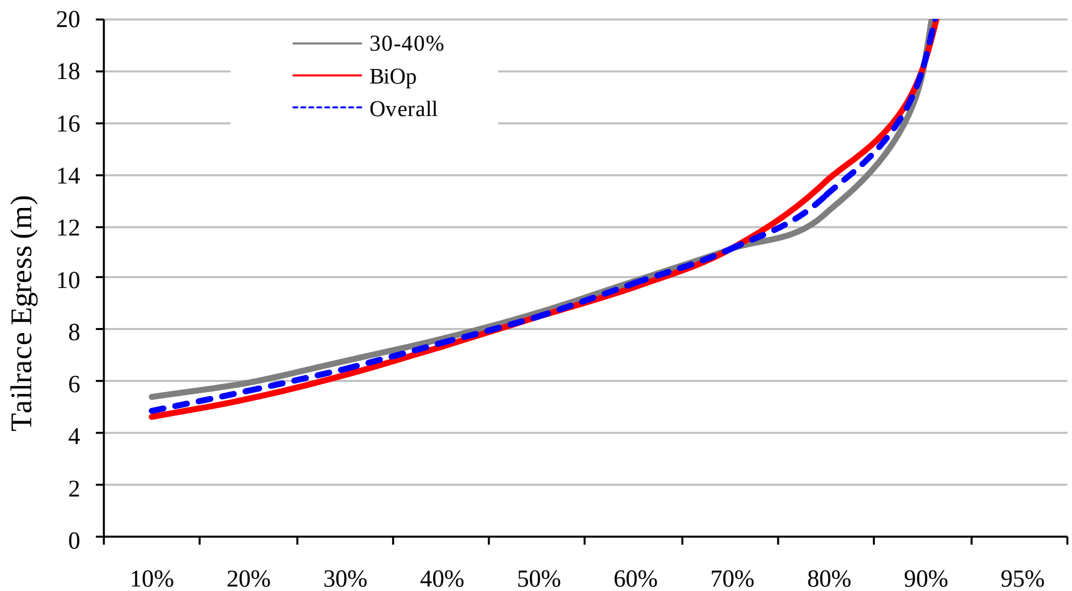

Figure 20. Tailrace egress of radio-tagged yearling Chinook salmon during two different spill treatments at Ice Harbor Dam, 2006.

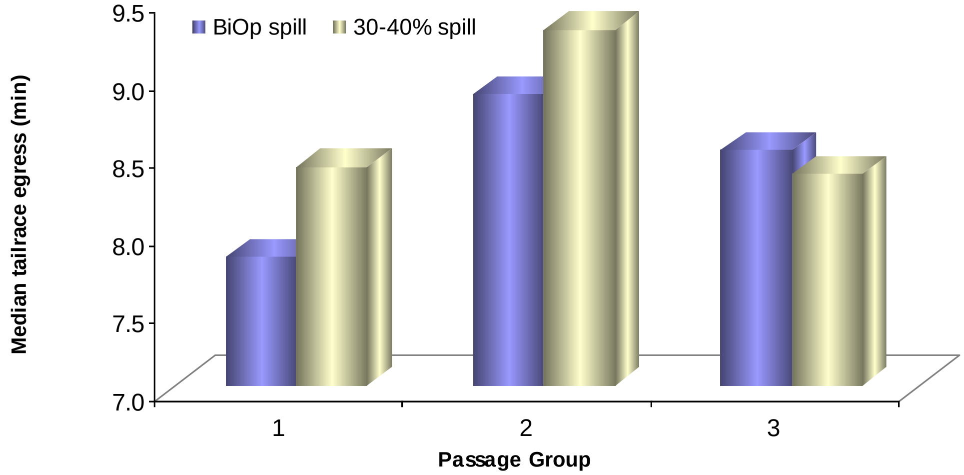

Figure 21. Paired 50th percentile of tailrace egress of radio-tagged yearling Chinook salmon at Ice Harbor Dam under two different spill treatments, 2006.

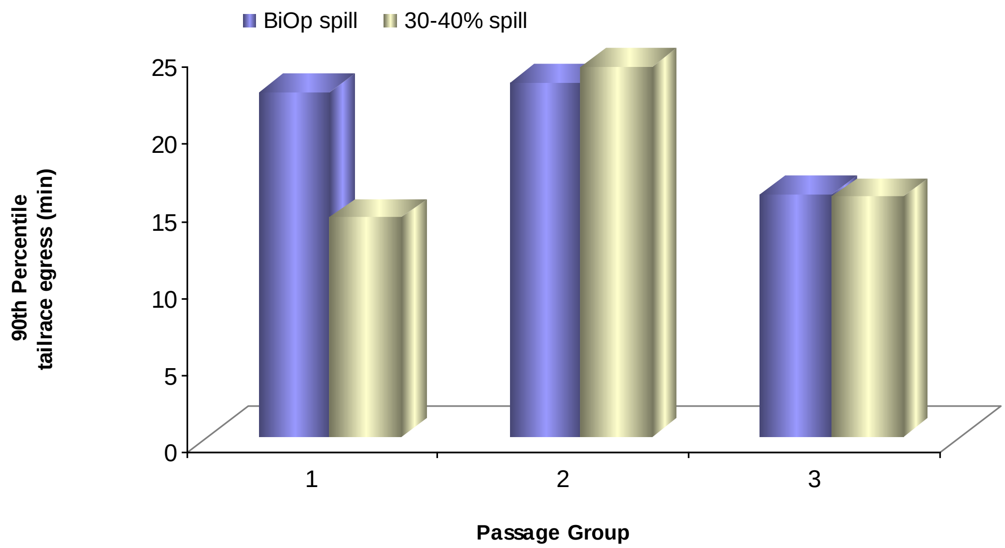

Figure 22. Paired 90th percentile of tailrace egress of radio-tagged yearling Chinook salmon at Ice Harbor Dam under two different spill treatments, 2006.

Median tailrace egress was longer for juvenile steelhead passing during 30-40% spill operations (9.6 min) than for those passing during BiOp spill (8.5 min; Figure 23). These differences were marginally significant ($P = 0.045$) in comparisons of egress time between spill treatments on the 50th percentiles of temporal replicate treatment groups (Figure 24), but non-significant as tailrace egress times approached the 90th percentile ($P = 0.620$; Figure 25).

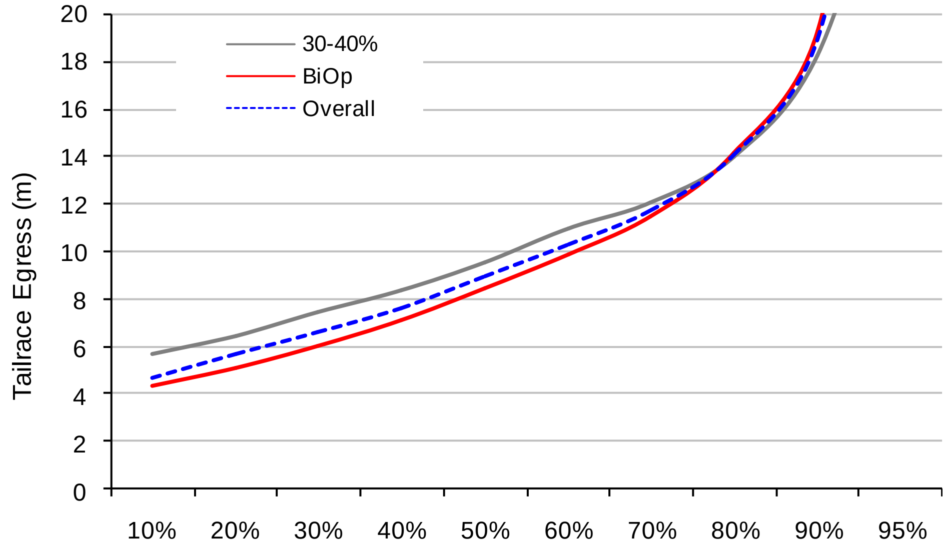

Figure 23. Tailrace egress of radio-tagged juvenile steelhead during two different spill treatments at Ice Harbor Dam, 2006.

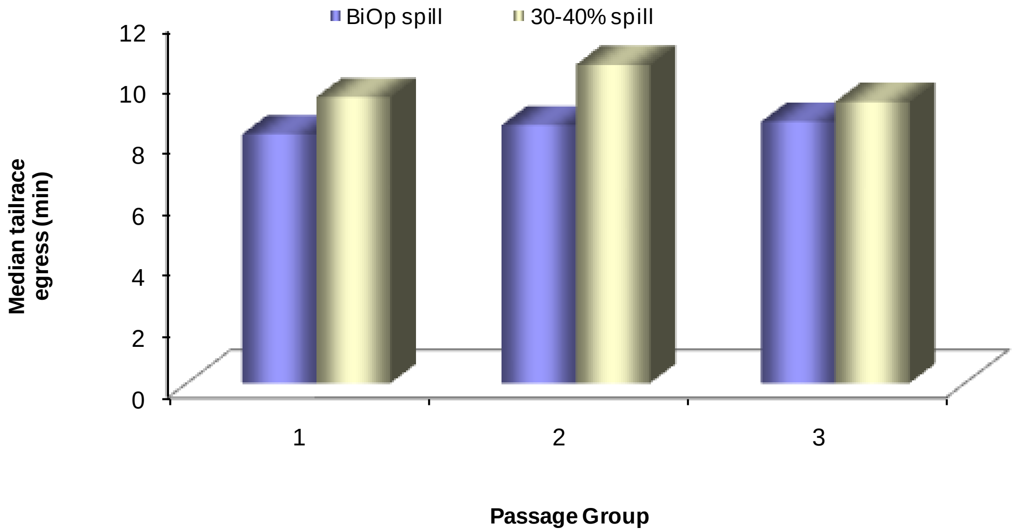

Figure 24. Paired 50th percentiles of tailrace egress time (in minutes) of radio-tagged juvenile steelhead at Ice Harbor Dam under two different spill treatments, 2006.

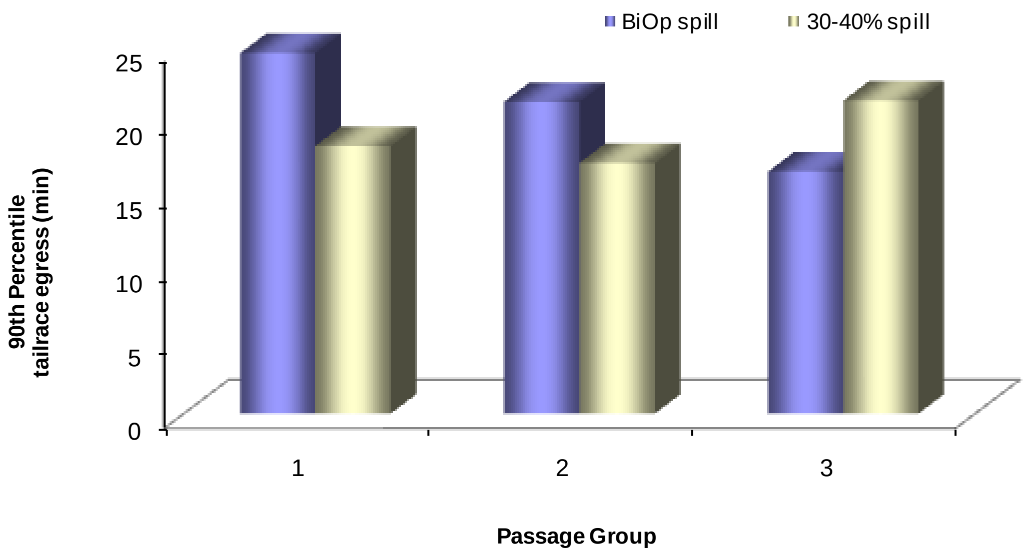

Figure 25. Paired 90th percentiles of tailrace egress times (in minutes) for radio-tagged juvenile steelhead at Ice Harbor Dam under two different spill treatments, 2006.

Avian Predation

Recovery efforts on the Crescent Island tern colony found 228 juvenile steelhead radio tags, representing approximately 6.1% of the steelhead we released into the Snake River. We recovered 55 yearling Chinook salmon radio tags, representing approximately 1.3% of the yearling Chinook salmon we released.

We plotted the last known detection transect where the fish was observed in order to determine where the largest "kill zone" might be located. Both juvenile steelhead and yearling Chinook salmon were most vulnerable when they entered the confluence area of the Snake and Columbia Rivers (Figures 26 and 27). Physical locations of tag recovery sites are displayed in Figure 28.

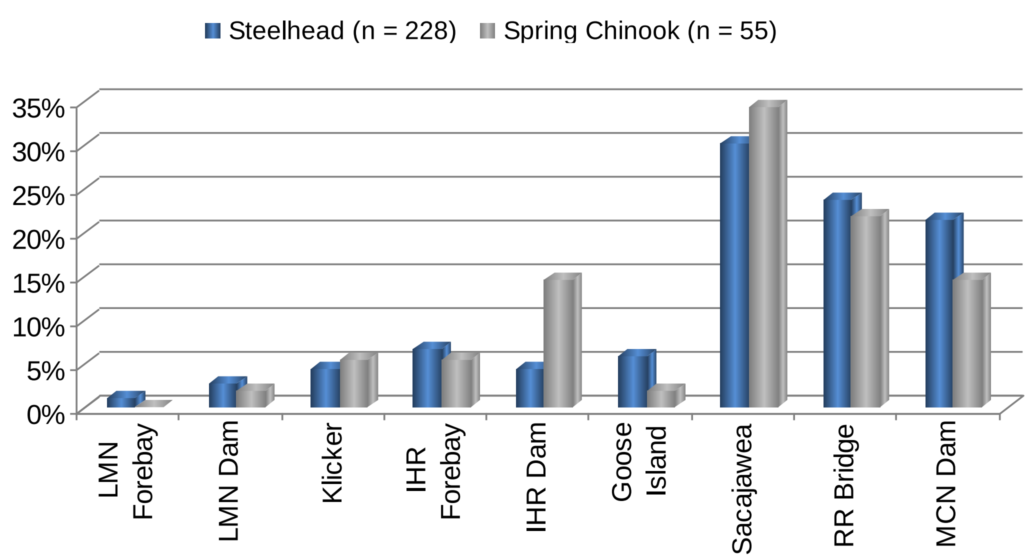

Figure 26. Percentage of radio-tagged yearling Chinook salmon and juvenile steelhead migrants with their last known telemetry detection site before predation event by Caspian terns, 2006.

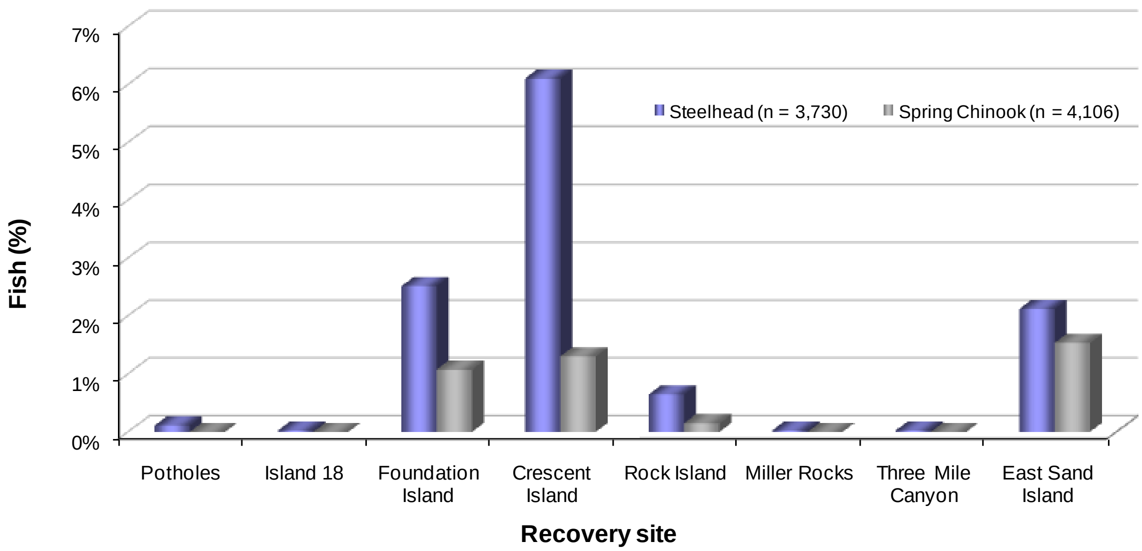

Figure 27. Percentage of radio-tagged juvenile spring and summer migrants recovered near known colonies of avian predators (numbers in parentheses represent total number tagged and released), 2006.

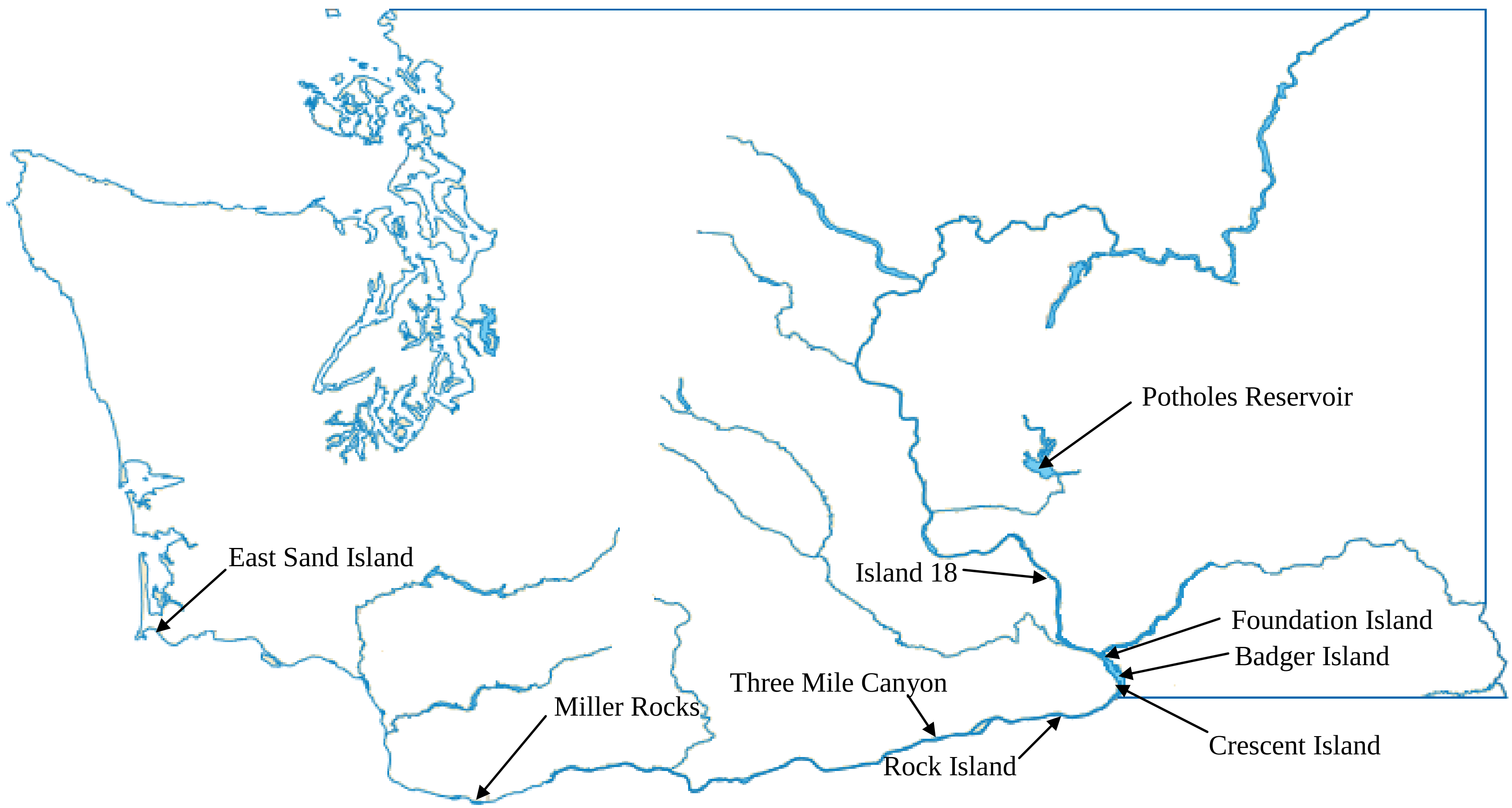

Figure 28. Locations of radio-tagged juvenile spring and summer migrants recovered near known colonies of avian predators, 2006.

DISCUSSION

Overall, it appears that the RSW was extremely effective in passing more fish over Ice Harbor Dam with less water. Survival estimates were high and not significantly different between spill treatments.

The hour of arrival and passage at Ice Harbor Dam was comparatively consistent during the study for both yearling Chinook salmon and juvenile steelhead. Both species displayed similar patterns under both treatments, with approach and passage trends suggesting relatively little delay in the forebay. Median forebay delay was reduced by nearly 0.5 h for both species under each spill treatment when compared to delays observed in 2005 (Axel et al. 2006). Both species exhibited slightly longer forebay delay under the reduced spill treatments, and this delay may have been due to increased flow through the powerhouse; the additional flow likely resulted in a wandering behavior while fish were deciding which flow queue to follow.

Our 2006 results suggest the changes made to project operations (i.e. spill patterns, spill bay 1 closure, etc.) increased juvenile salmonid passage through the RSW and the central spill bays at Ice Harbor Dam. During 2005, we observed higher than expected passage through spill bay 1, particularly by yearling Chinook salmon. After closing spill bay 1, yearling Chinook salmon distribution shifted to the north resulting in increased effectiveness ratios at both the RSW and the spillway as a whole. Greater than 50% of the yearling Chinook salmon and 60% of the juvenile steelhead had first approach detections in the vicinity of the RSW.

Horizontal passage distribution for both yearling Chinook salmon and juvenile steelhead indicated the RSW directed a large proportion of the radio tagged fish past the project, especially under the reduced spill treatment. To some extent, additional spill under BiOp project conditions tended to direct more fish into the conventional bays rather than over the RSW; however, the distribution still favored the RSW. Steelhead passage through the juvenile bypass system increased considerably under the reduced spill treatment. This behavior was most likely attributable to increased flow through the powerhouse. With fish guidance efficiencies as high as they were, few fish of either species passed through the turbine intakes under increased loading conditions.

Tailrace egress was longer this year for both species than what was observed in previous years (Axel et al. 2003, 2006). This may have been a result of a large eddy that develops in the tailrace with a larger proportion of the river being spilled and fewer turbine units being operated. However, there were no significant differences between treatments for yearling Chinook salmon and only marginally significant differences for juvenile steelhead at the 50^{th} percentile of temporal replicate groups. The mean differences were less than 2 min and were probably not biologically significant given the high survival estimates.

Survival estimates indicate that a large portion of the mortality associated with migrating juvenile steelhead appears to occur prior to passage at Ice Harbor Dam and at the mouth of the Snake River. We can effectively attribute 6.1% of our juvenile steelhead and 1.3% of our yearling Chinook salmon mortality to the Caspian tern colony on Crescent Island, although this is a minimum estimate, since the tags of fish consumed by birds are also deposited elsewhere. Steelhead are particularly susceptible to predation by birds; Collis et al. (2001) found that greater than 15% of the PIT-tagged steelhead entering the Columbia River estuary in 1998 were later found on Rice Island, which at the time was the home of the largest Caspian tern colony in western North America. Crescent Island harbors the second largest Caspian tern colony in western North America and large populations of gulls, while nearby islands support burgeoning populations of double-breasted cormorant *Phalacrocorax auritas* and pelicans *Pelecanus erythrorhynchos*. The last detection of radio-tagged fish subsequently found on Crescent Island indicated that, at a minimum, terns foraged from the forebay of Lower Monumental Dam to the forebay of McNary Dam, a distance of nearly 120 km.

RECOMMENDATIONS

We recommend a sustained reduction in spill through spill bay 1 at Ice Harbor dam to allow more yearling Chinook salmon to be directed through the RSW. With high survival estimates achieved for RSW and spillway passage, we should continue to improve spill efficiency and FPE by further decreasing turbine passage even as spill levels are decreased. We also suggest a continued effort to evaluate juvenile steelhead survival in the lower Snake River in order to identify critical areas of avian predation for potential mitigation. It has become apparent that the Crescent Island Caspian tern colony is targeting Snake River juvenile steelhead at a much higher rate than other salmonids, including Mid-Columbia juvenile steelhead. We need to continue monitoring tern (and double-breasted cormorant) predation and consider alternatives to improve steelhead migration through the McNary pool. Further investigation into the possibility of latent mortality associated with RSW passage at Ice Harbor Dam should continue in order to determine if there is a need to redesign the ogee and/or spill deflector.

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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 Ice Harbor 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 2,256 radio-tagged yearling Chinook salmon detected at Ice Harbor Dam, 2,042 (90.5% of those observed) were detected either at or below the Sacajawea survival transect. Of the 1,545 radio-tagged yearling Chinook salmon released into the tailrace of Ice Harbor Dam, 1,526 (98.8% of those released) were detected either at or below Sacajawea. The detection probability for fish used in survival analysis at Ice Harbor Dam was 0.971 overall (Appendix Table A1a). With detection probabilities at or near 97% for all fish, there was likely no disparity between detection probabilities of treatment and reference groups.

Of the 1,814 radio-tagged juvenile steelhead detected at Ice Harbor Dam, 1,625 (89.6% of those observed) were detected either at or below the Sacajawea survival transect. Of the 1,574 radio-tagged juvenile steelhead released into the tailrace of Ice Harbor Dam, 1,500 (95.3% of those released) were detected either at or below Sacajawea. The detection probability for fish used in survival analysis at Ice Harbor Dam was 0.918 overall (Appendix Table A1b). With detection probabilities at or near 92% for all fish, there was likely no disparity between detection probabilities of treatment and reference groups.

Appendix Table A1a. Detections at and below Ice Harbor Dam and detection probabilities at Ice Harbor Dam for evaluating survival of hatchery yearling Chinook salmon passing through Ice Harbor Dam, 2006.

Release group	Release location	Detection at Sacajawea	Detection at or below Sacajawea	Detection probability
Treatment	Above IHR Dam	1,985	2,042	0.972
Reference	IHR Dam Tailrace	1,479	1,526	0.969
Totals		3,464	3,568	0.971

Appendix Table A1b. Detections at and below Ice Harbor Dam and detection probabilities at Ice Harbor Dam for evaluating survival of juvenile steelhead passing through Ice Harbor Dam, 2006.

Release group	Release location	Detection at Sacajawea	Detection at or below Sacajawea	Detection probability
Treatment	Above IHR Dam	1,456	1,625	0.896
Reference	IHR Dam Tailrace	1,413	1,500	0.942
Totals		2,869	3,125	0.918

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 by using contingency tables (chi-square goodness-of-fit) to test for differences in arrival distributions. The treatment fish at Ice Harbor Dam were paired with the release reference fish by the project operations at the time of treatment fish passage. *P*-values were calculated using the Monte Carlo approximation of the exact method described in the StatXact software user manual (Mehta and Patel 1992; $\alpha < 0.05$).

Test of homogeneity of arrival distributions at Ice Harbor Dam were similar for treatment and reference groups in 6 of the 7 paired treatment groups for yearling Chinook salmon (Appendix Tables A2a) and 5 of the 7 paired treatment groups for juvenile steelhead (Appendix Tables A2b). There were more significant tests than expected if all groups were generally mixed (for $\alpha = 0.05$ level we would expect 1 out of 20 tests not to be mixed). However, in general the differences between arrival times at Sacajawea were less than 1 day. 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. The arrival distributions for those releases which were not mixed are plotted in Appendix Figures B1 through B6.

Appendix Table A2a. Test of homogeneity of arrival timing at the Sacajawea survival transect for treatment (regrouped at Ice Harbor Dam forebay) and reference groups (tailrace) of radio-tagged hatchery yearling Chinook salmon used for estimating survival at Ice Harbor Dam. The treatment fish at Ice Harbor Dam were paired with the reference fish according to project operations at the time of passage. Shaded cells indicate significant differences in passage timing among tests (α = 0.05).

Treatment group	χ^2	Degrees of freedom	*P*
30% 1	3.58	5	0.646
30% 2	5.86	4	0.166
30% 3	3.43	5	0.772
30% 4	19.67	5	0.000
B1	1.80	5	0.935
B2	4.24	2	0.123
B3	15.49	12	0.205

Appendix Table A2b. Test of homogeneity of arrival timing at the Sacajawea survival transect for treatment (regrouped at Ice Harbor Dam forebay) and reference groups (tailrace) of radio-tagged juvenile steelhead used for estimating survival at Ice Harbor Dam. The treatment fish at Ice Harbor Dam were paired with the reference fish according to project operations at the time of passage. Shaded cells indicate significant differences in passage timing among tests (α = 0.05).

Treatment group	χ^2	Degrees of freedom	*P*
30% 1	9.94	5	0.060
30% 2	1.30	3	0.865
30% 3	6.55	7	0.477
30% 4	10.73	5	0.035
B2	2.25	6	0.935
B3	6.88	5	0.199
B4	10.17	11	0.519

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

Unmarked yearling Chinook salmon and juvenile steelhead were collected at Lower Monumental for 27 d from 1 May to 27 May. Tagging began after approximately 14% of the yearling Chinook salmon and 20% of the juvenile steelhead had passed Lower Monumental Dam and was completed when 97% of these fish had passed (Figure 2). Overall mean fork length for yearling Chinook and steelhead was 146 mm (SD = 11.0) and 219 mm (SD = 22.0), respectively. This compared closely with the mean length of the clipped yearling Chinook and steelhead run-at-large sampled at the smolt collection facility (140 mm and 213 mm, respectively).

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, b) 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.

We released 2 dead radio-tagged hatchery yearling Chinook salmon and 4 juvenile steelhead into the tailrace of Ice Harbor Dam to test Assumption A5 (Appendix Table A3). The low numbers were indicative of extremely low tagging mortality. The distance between release at Ice Harbor Dam and the first downstream telemetry array used to estimate survival (Ice Harbor Dam) was 16 km. Similar to the findings of Axel et al. (2003, 2006), none of our dead, radio-tagged fish were subsequently detected at telemetry transects which were used for estimating survival.

Appendix Table A3. Numbers of dead fish released and subsequently detected at and below the survival transect at Sacajawea for testing assumption A5.

	Yearling Chinook	Steelhead
Number of dead fish released	2	4
Proportion of dead fish released (%)	0.1	0.3
Number detected at Sacajawea	0	0
Number detected below Sacajawea	0	0

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 8,220 tags were implanted in hatchery yearling Chinook salmon and steelhead of which 78 (0.9%) were not working 24 h after tagging. All fish with tags that were not functioning properly were excluded from the study.

In addition, a total of 108 radio transmitters 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. Twenty tags (19%) failed prior to the preprogrammed shut-down after 10 d (Appendix Table A4). Of these, only 2 failed in less than 8 d. Median travel time from release to Ice Harbor Dam was 1.4 d overall with less than 1% of the fish taking 5 d or more to reach Ice Harbor Dam (Appendix Table A5). Although we documented transmitter failures during our study, the short travel times to our survival line and the relatively low failure rate were such that they would not have significantly changed our findings.

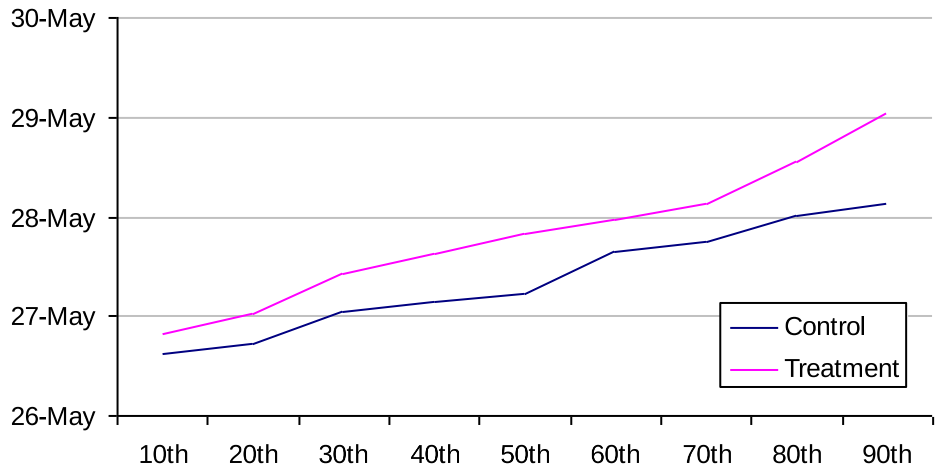
Appendix Table A4. Frequency of days tags lasted in tag-life testing.

N	Tags (%)	Tag life (d)
0	0	1
0	0	2
0	0	3
0	0	4
0	0	5
0	0	6
2	2	7
4	4	8
14	13	9
88	82	10

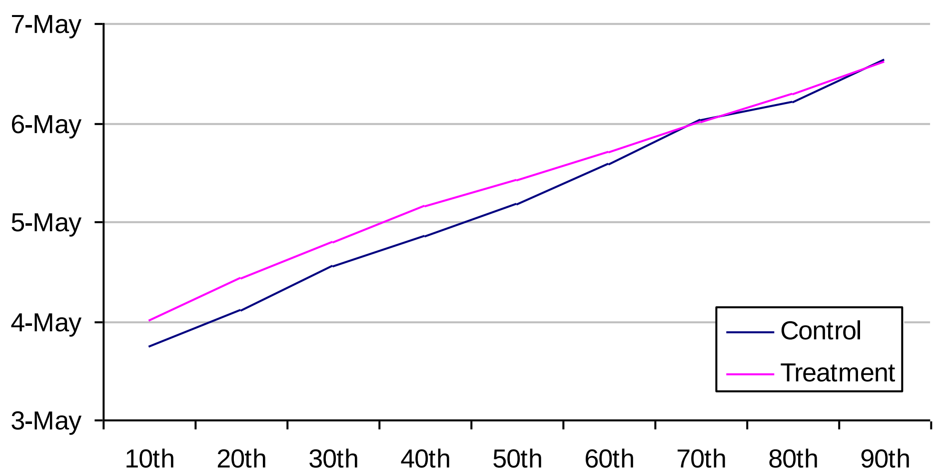
Appendix Table A5. Travel time (d) from release to detection at 1st survival array below Ice Harbor Dam for radio-tagged, hatchery yearling Chinook salmon released into the forebay and tailrace and steelhead released into the tailrace of Lower Monumental Dam, 2006.

	Yearling Chinook		Steelhead	
Percentile	Forebay	Tailrace	Forebay	Tailrace
N	1,074	992	839	780
Min	0.6	0.5	0.5	0.5
10	1.0	0.7	1.1	0.7
20	1.2	0.8	1.3	0.8
30	1.4	0.9	1.5	0.9
40	1.6	1.0	1.7	1.0
50	1.8	1.1	1.9	1.1
60	2.0	1.2	2.2	1.2
70	2.2	1.3	2.4	1.3
80	2.5	1.5	2.7	1.5
90	3.0	1.7	3.5	1.9
Max	7.9	4.8	7.1	6.0
Travel time > 6 d	5 (0.5%)	0 (0.0%)	7 (0.8%)	0 (0.0%)

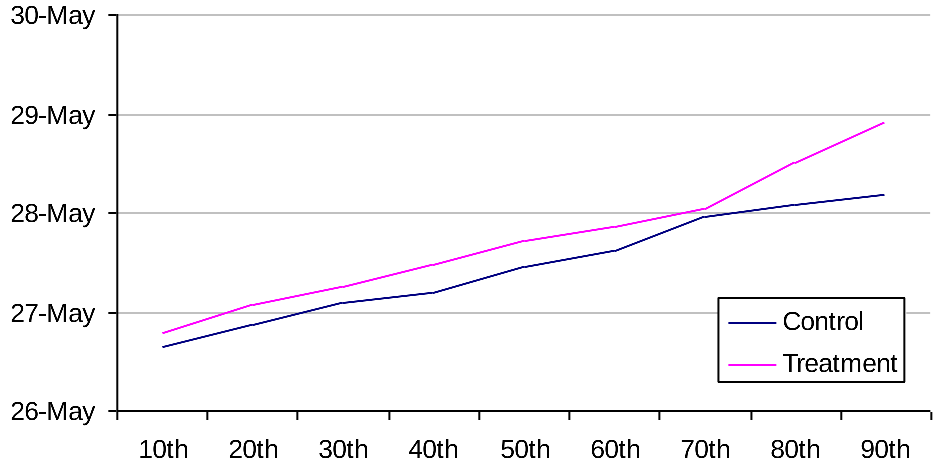
APPENDIX B: Passage Distributions of Groups with Differing Travel Time



Appendix Figure B1. Arrival distribution at Sacajawea for treatment yearling Chinook salmon passing Ice Harbor Dam and reference fish released into the tailrace during the 4th 30% spill treatment operation, 2006.



Appendix Figure B2. Arrival distribution at Sacajawea for treatment juvenile steelhead passing Ice Harbor Dam and reference fish released into the tailrace during the 1st 30% spill treatment operation, 2006.



Appendix Figure B3. Arrival distribution at Sacajawea for treatment juvenile steelhead passing Ice Harbor Dam and reference fish released into the tailrace during the 4th 30% spill treatment operation, 2006.

APPENDIX C: 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 (http://rtagweb.nwfsc.noaa.gov/home/index.cfm). This project tracks the passage and migration routes of juvenile salmon and steelhead passing dams on the Columbia and Snake River. A network of radio receivers is used to record signals emitted from radio transmitter tags that are implanted into the fish. Special emphasis is placed on route of dam passage and survival through individual routes at each dam. 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 per day for downloading into the database.

In addition, data in the form of a daily updated tag files, which contain the attributes of each fish tagged, along with the channel and code of the transmitter used and the date, time, and location of 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 transmittal recorded for each fish, 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 used for 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.

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.

Data Validation

During the validation process, the records stored in the preliminary tables are analyzed. We determine which study year, site identifier, ant 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 associated with each record 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 is 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 chan = 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.

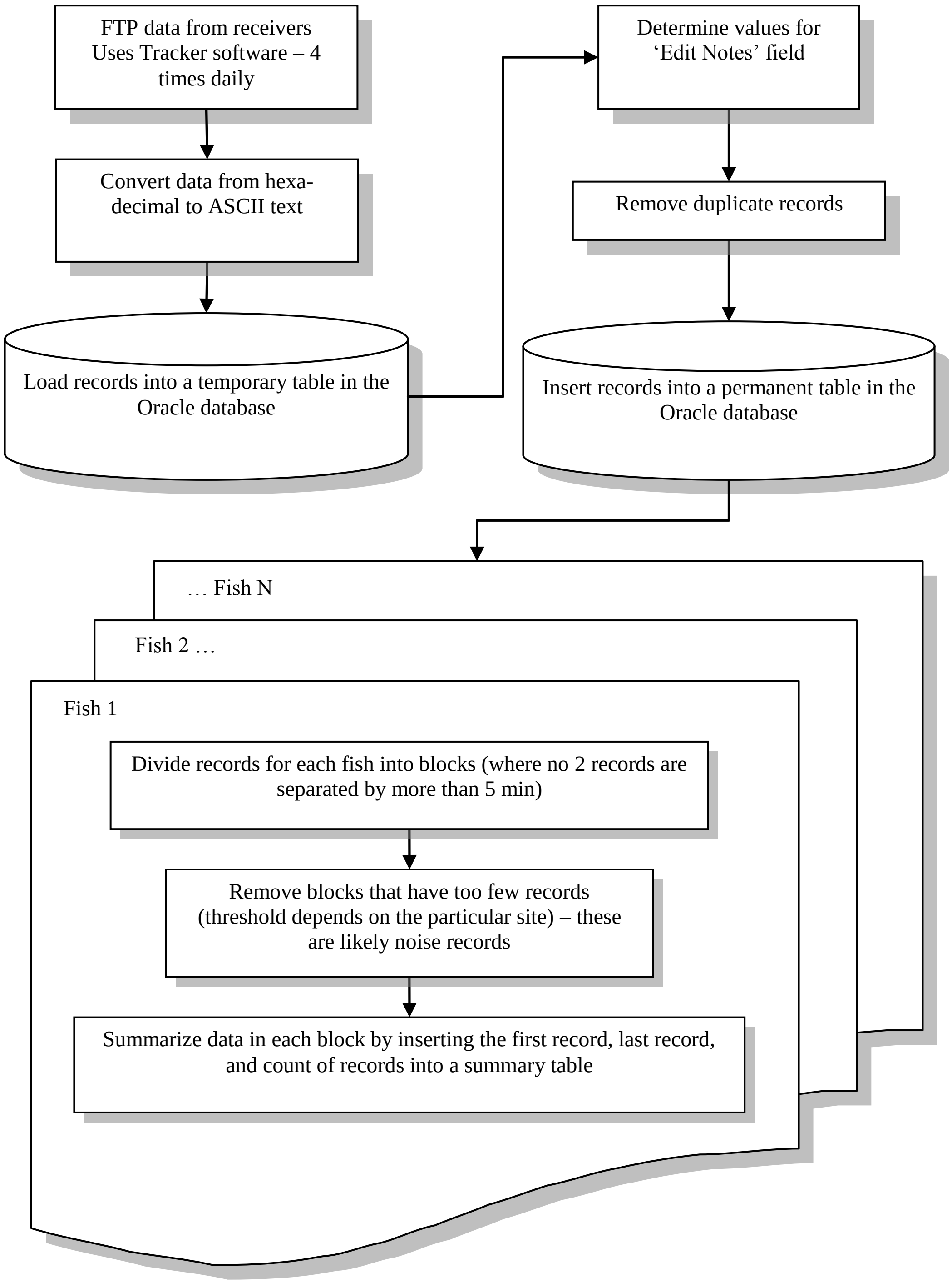
- Lt start time: Assigned to records occurring prior to the time a tag was activated (its start time).
- Gt end_time: Assigned to records occurring after the end time on a tag (they run for 10 d once activated).
- Gt 40 recs: Denotes tags that registered more than 40 records per minute on an individual receiver. This is not possible as the tags emit a signal every 2 seconds (30/minute). Such patterns indicate noise.

In addition, duplicate records (records for which the channel, code, site, antenna, date and time are the same as those of another record). 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 sites table.

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



Appendix Figure C1. Flowchart of telemetry data processing and reduction used in evaluating behavior and survival at Ice Harbor Dam for yearling Chinook salmon and steelhead, 2006.