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Basin-Wide Monitoring of Acoustically Tagged Salmon Smolts at Hydropower Dams in the Mid-Columbia River Basin, USA

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Introduction

To assess the passage behavior and survival of three species of juvenile salmonid smolts (Chinook salmon *Oncorhynchus tshawytscha*, sockeye salmon *O. nerka* and steelhead *O. mykiss*) during their downstream migration to the Pacific Ocean, acoustic tag studies were conducted in 2006 throughout the mid-Columbia River, USA. Salmonid runs on the Columbia River and its tributaries have been declining due to several factors. One contributing factor has been the operation of hydropower dams. Most downstream migrating salmonid smolts pass safely through a single dam; however, the cumulative mortality passing through several dams can be significant (Bell et al. 1967; Davidson 1965; Schweibert 1977).

Since the early 1980's, considerable effort has been devoted to restoring and enhancing mid-Columbia River salmon runs. For over 25 years the owners and operators if mid-Columbia River dams have been evaluating bypass methods to increase levels of smolt survival. Hydroacoustic techniques (Ransom and Steig 1994, Simmonds and MacLennan 2005) were employed from 1980 to 1999, and acoustic tag techniques applied beginning in 1998 (Steig 1999) at 11 major hydropower dams in the Columbia River Basin. The studies described in this paper are reported in detail by Skalski et al. (2006), Steig et al. (2007) and Timko et al. (2007).

A number of advances in three-dimensional (3D) acoustic tag tracking techniques have been made over the past few years, permitting fine-scale 3D tracking of fish movement with sub-meter position resolution, with positions calculated as frequently as 50 times per second. Improvements include the development of various fish density algorithms, stream trace modeling analyses, and advances in 3D animation techniques.

The passage effectiveness, survival estimates, and fine-scale behaviors of smolts obtained provided the dam operators and engineers with measures of the effectiveness of their dams that permitted improvements to be made to designs of safe fish bypass measures, while minimizing the impact on power production.

1. Study Objectives

The general objective of these studies was to monitor salmonid smolts passing four dams on the mid-Columbia River Basin. The results presented here were obtained from several studies conducted during the 2006 spring outmigration. The following objectives are addressed:

1) Evaluate the 3D swimming paths and behavior of acoustic tagged smolts approaching Rocky Reach and Priest Rapids dams;
2) Estimate the effectiveness of smolt bypass structures at four dams;
3) Estimate smolt migration rates throughout the study area; and
4) Estimate the survival rates of smolts passing Rocky Reach and Rock Island dams.

2. Site Description

The 2006 study area encompassed a 360 km (224 mile) long reach of the Columbia River, extending from Wells Dam at river kilometer (RKM) 830 (river mile (RM) 516) to McNary Dam at RKM 470 (RM 292). Acoustic tag receiver systems were deployed at four dams and nine open-river locations in the mid-Columbia River, located between these two dams (Figure 1 and Table 1).

Rocky Reach Dam is located at RKM 764 (RM 475). Its spillway is perpendicular and its powerhouse is parallel to river flow. The powerhouse is 332 m (1,088 ft) long and contains 11 vertical Kaplan turbines. Rock Island Dam is located at RKM 729 (RM 453). The dam has two separate powerhouses with a spillway between them. Powerhouse No. 1 (on the left/north shore) is 213 m (700 ft) long, and contains 10 vertical-axis Kaplan turbine units. Powerhouse No. 2 (on the right/south shore) is 152 m (500 ft) long, and contains eight horizontal-axis bulb turbine units.

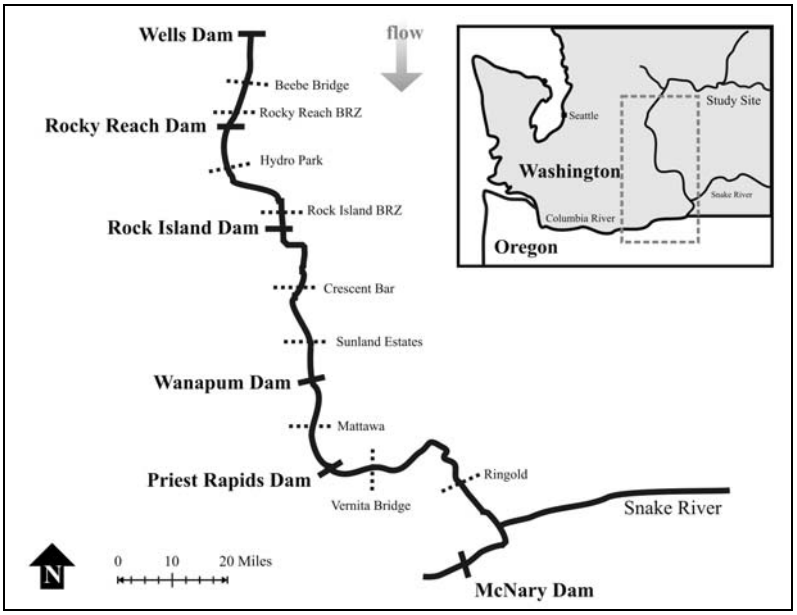

Figure 1. Mid-Columbia River in Washington State, USA, showing locations of hydropower dams and open-river acoustic receiver detection sites.

Table 1. Dam owner/operators on the mid-Columbia River within the 360 km reach of acoustic tag studies of salmonids smolts conducted in 2006.

Douglas County Public Utility District No. 1:	Wells Dam (RKM 830), in service 1961, 1213 MW
Chelan County Public Utility District No. 1:	Rocky Reach Dam (RKM 764), in service 1961, 1213 MW
	Rock Island Dam (RKM 729), in service 1933, 623 MW
Grant County Public Utility District No. 2:	Wanapum Dam (RKM 669), in service 1963; 900 MW
	Priest Rapids Dam (RKM 639), in service 1959; 855 MW
US Army Corps of Engineers:	McNary Dam (RKM 470), in service 1953, 980 MW

Wanapum Dam is located at RKM 669 (RM 416). It has a 469 m (1,540 ft) long powerhouse, oriented parallel to river flow, and a 254 m (832 ft) long spillway at approximately a 45° angle to flow. The powerhouse has 10 Kaplan turbine units. Priest Rapids Dam is located at RKM 639 (RM 397), 113 km (70 miles) upstream from the confluence of the Snake and Columbia rivers. The dam has a 213 m (1,025 ft) long powerhouse with 10 Kaplan turbine units, and a 351 m (1,152 ft) long spillway. Weekly median river flows during the study ranged from approximately 4 to 7 m^3/sec (140 to 250 ft^3/sec).

3. Methods

3.1 Acoustic Tag Systems

Acoustic tags have been used to monitor fish movement for over 30 years, and have been used to study smolts at Columbia River dams since 1998 (Steig et al. 2006a). Most commercially available acoustic tags operate at frequencies between 50 and 100 kHz. An investigation in 1997 at Rocky Reach Dam determined the optimum frequency for acoustic tags in the forebay was approximately 300 kHz, due to high background noise levels at lower frequencies, and high signal attenuation at higher frequencies (Hydroacoustic Technology, Inc. 1997). All mid-Columbia River acoustic tag studies since 1997 have used 307 kHz acoustic tags and hydrophones.

To address the objectives listed above, four dams and nine open-river locations were instrumented in 2006 with HTI *Model 290 Acoustic Tag Tracking Systems* (Figure 2). Hydrophones are the listening devices which "hear" the signals emitted from acoustic tags in fish swimming in and around a hydrophone array. Two types of hydrophone arrays were deployed. Open-river arrays were deployed as presence or absence line arrays to detect whether or not a tag was passing an instrumented site. Detection arrays at each open-river monitoring site consisted of a line of hydrophones anchored to the bottom of the river and connected to an acoustic tag receiver

located on shore. Detection ranges for the acoustic tags were estimated to be 400-600 m (1312-1968 ft) near the hydropower dams, and up to 1 km (0.6 miles) in the open river.

At two dams, 3D hydrophone arrays were deployed in order to not only detect the presence or absence of a particular tagged fish, but to also provide fine-scale tracks of each fish's behavior. For 3D acoustic tag tracking at Rocky Reach and Priest Rapids dams, hydrophones were deployed in cells in the forebay with approximately half located near the surface, and half near the bottom (Figures 3 and 4). Due to background noise levels near hydropower dams, the maximum dimensions of a four-hydrophone sample cell are typically 100 m x 100 m x 100 m. Additional adjacent sample cells can be added by mounting two more hydrophones at the appropriate corners of the new cell, keeping in mind that an acoustic tag passing through any of the sample cells must fall within the range of four hydrophones that do not lie in one plane. Once the precise location of each hydrophone was known, 3D tag locations were determined by arrival time triangulation between four or more fixed hydrophones. The position of each monitored acoustic tag within the array could be typically estimated within +/- 0.5 m for each tag pulse (every 1-8 sec), following Ehrenberg and Steig (2002, 2003). Fish were tracked as they approached and passed into the dams' turbine intakes, spillways, and surface bypass entrances.

Two models of acoustic tags were used. For Chinook smolts and steelhead, HTI *Model 795E Acoustic Tags* were 6.8 mm in diameter by 18 mm long, averaged 1.5 g in air, and their average operating life was approximately 25 days. For the smaller sockeye smolts, HTI *Model 795m Acoustic Tags* were 6.8 mm in diameter by 16.5 mm long, averaged 0.75 g in air, and had an average operating life of approximately 14 days. The transmission rates (i.e., ping rates) were user-selected at one ping every 1-8 sec, with a transmit pulse width of 1.0 msec. All acoustic tags were surgically implanted. The minimum length of steelhead and Chinook tagged was 104 mm, and for sockeye was 100 mm. All fish were typically held for 48 hours before release, to allow for recovery from the tagging procedure. Fish were released at five different locations (Table 2).

Data collection was conducted 24 h/d, 7 d/wk from mid-April to early July, with data from each sample site periodically queried remotely from a central station using satellite communication systems.

3.2 Objective 1: Evaluate the 3D Behavior of Smolts Approaching Rocky Reach and Priest Rapids Dams

The fine scale behavior of sockeye smolts approaching Rocky Reach Dam and Chinook and steelhead smolts approaching Priest Rapids Dam was tracked in 3D. To illustrate the distribution of smolts in the Rocky Reach and Priest Rapids dams' forebays, density plots of fish concentrations were produced. The monitored forebay was subdivided into individual cells each measuring 15.2 x 15.2 x 15.2 m (50 ft x 50 ft x 50 ft), and each cell was assigned a value based on the total number of fish that entered each cell, regardless of how long each fish remained in a particular cell. Data were interpolated by kriging between cells (Davis 1986). The resulting binary density plots removed the masking effect of milling and presented a more representative indication of the overall spatial distribution of smolts in the forebay.

Figure 2. HTI *Model 290 Acoustic Tag Tracking Receiver*, *Model 590 Hydrophone*, and *Model 795 Acoustic Tags* (not to scale).

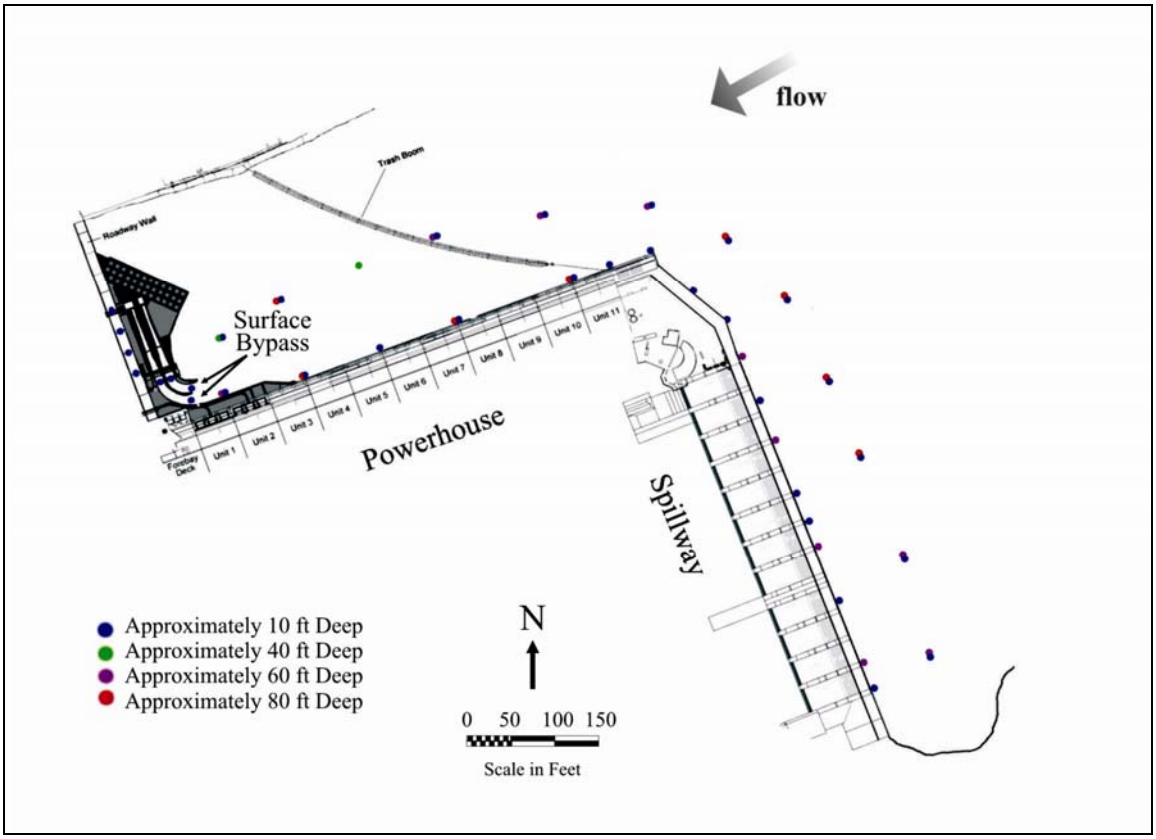

Figure 3. Plan view of Rocky Reach Dam and hydrophone deployments in the forebay for monitoring acoustically tagged fish during 2006.

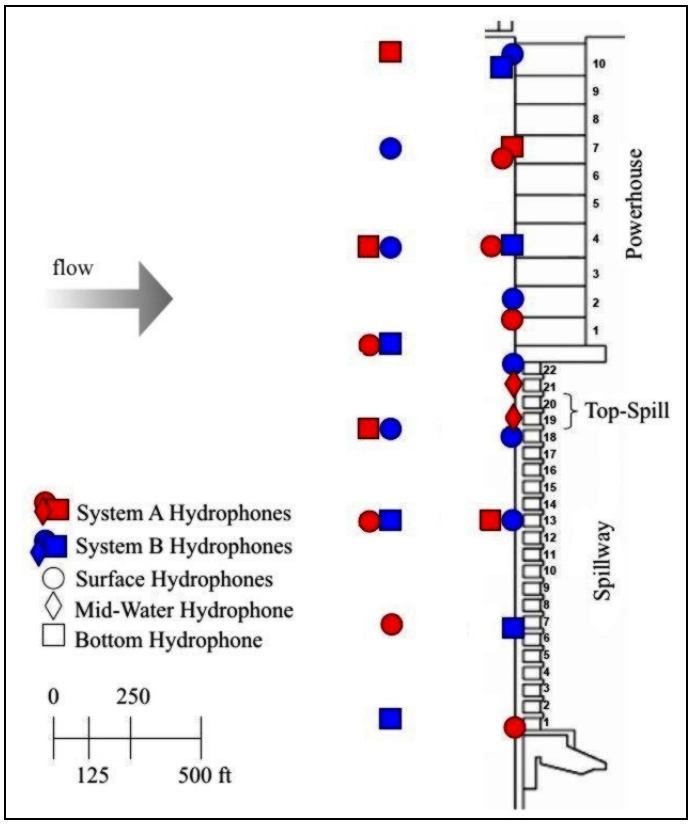

Figure 4. Plan view of Priest Rapids Dam and hydrophone deployments, 2006.

Table 2. Acoustic tagged smolt release locations, species, and approximate numbers of smolts released in the mid-Columbia River in 2006.

Release Location	Species	Number of Acoustically Tagged Fish
Wells Dam	Steelhead	500
Wells Dam	Sockeye	1500
Rocky Reach Dam	Steelhead	500
Rocky Reach Dam	Sockeye	1500
Rock Island Dam	Steelhead	500
Rock Island Dam	Sockeye	500
Wanapum Dam	Steelhead	1000
Wanapum Dam	Chinook	1000
Priest Rapids Dam	Steelhead	500
Priest Rapids Dam	Chinook	500
	Totals	8000

3.3 Objective 2: Estimate the Effectiveness of Smolt Bypass Structures at the Dams

The collection efficiency of fish bypass structures at Rocky Reach (surface bypass and collection screens), Rock Island (spillway), Wanapum (top spill and sluiceway), and Priest Rapids (top spill and sluiceway) dams was estimated. Fish passage efficiency (FPE) of these bypass routes was defined as the proportion of tagged fish passing through non-turbine routes relative to total project tagged fish passage via all available routes.

3.4 Objective 3: Estimate Smolt Migration Rates

Smolt migration rates were estimated between all monitored acoustic array sites (i.e., between all four dams and nine open-river detection sites).

3.5 Objective 4: Estimate the Survival of Smolts Passing Rocky Reach and Rock Island Dams

For Rocky Reach and Rock Island dams, smolt survival (both dam and reservoir) was estimated using the paired release-recapture method of Burnham et al. (1987), following the implementation of Skalski et al. (2004) and Steig et al. (2005). A test group of tagged fish was released at the head of the reservoir of each dam, and a control group immediately downstream of each dam. For each release location and species, approximately 500 tagged fish were released in 19-24 replicates at each site, with 19-34 fish per replicate.

4. Results

During April and May 2006, approximately 8,000 salmonid smolts were surgically implanted with acoustic tags and released into the mid-Columbia River (Table 2). At each acoustic detection site (four dams and nine open-river hydrophone arrays), a minimum of 95% of the smolts were detected. Nearly 200 million acoustic tag detections were recorded across all hydrophone arrays.

4.1 Objective 1: Evaluate the 3D Behavior of Smolts Approaching Rocky Reach and Priest Rapids Dams

4.1.1 Rocky Reach

Approximately 400,000 individual 3D sockeye positions were calculated in the forebay of Rocky Reach Dam. Sockeye density distributions were produced based on the 3D swimming path information from tagged fish approaching the dam (Figure 5). In general, the majority of sockeye passing through the surface collector were shallow and located above the floor of the surface collector, with the highest fish densities occurring near the surface collector entrance (Figure 6). Sockeye entering the surface collector appeared to be distributed in the upper 12.2 m (40 ft) of the water column and did not demonstrate large-scale vertical movement.

The mean depth of the 3D pathway of sockeye approaching the dam was calculated for each passage route (surface collector, bypass screens, Units 1-2, Units 3-11, and spillway). Sockeye that passed into the surface collector were the most surface-oriented compared to other passage routes, followed by the bypass screen and then Units 1-2 passage. Sockeye passing through Units 3-11 were deeper than in all other passage routes.

Stream traces developed from the movement of all 3D tracked sockeye smolts illustrated a movement predominantly toward the surface collector (Figure 7).

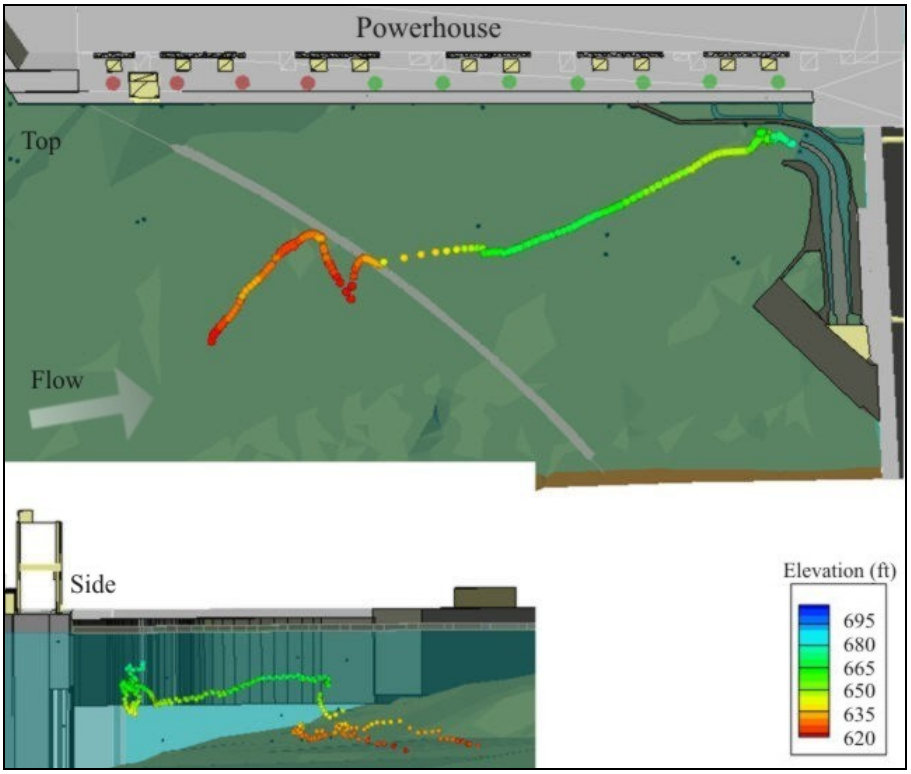

Figure 5. Example of a 3D track of a sockeye smolt passing into the surface collector at Rocky Reach Dam in 2006, in plan view (top) and side view looking downstream toward the surface collector (bottom). Color indicates relative elevation.

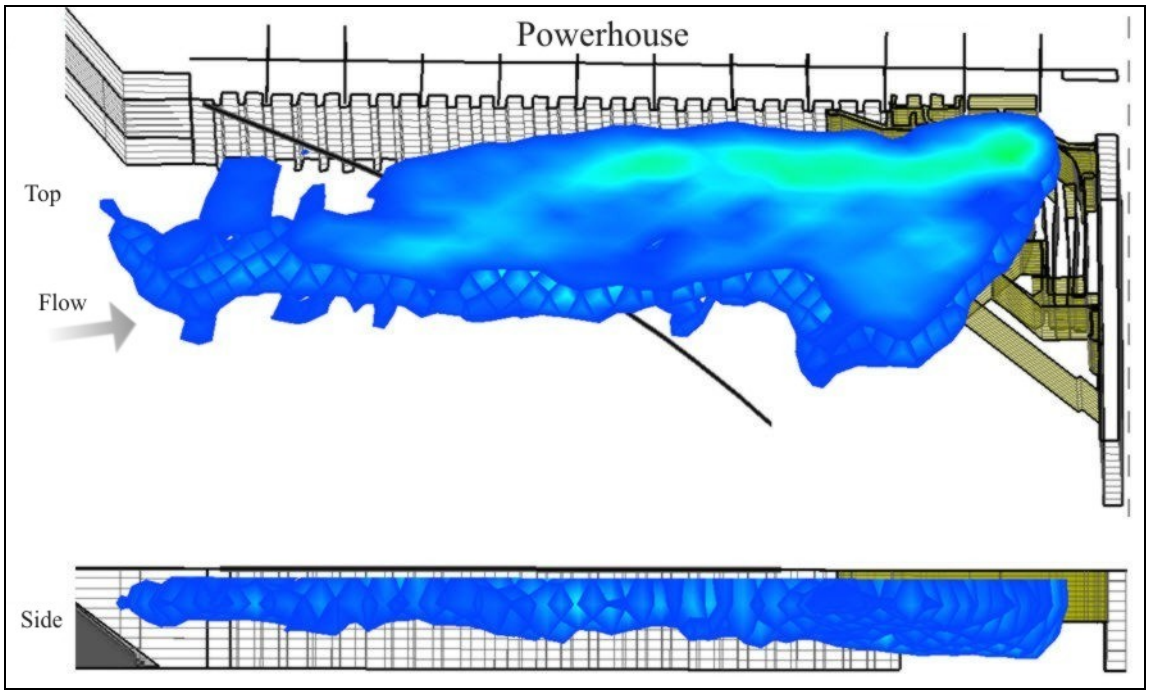

Figure 6. Binary density plot for sockeye smolts passing into the surface collector at Rocky Reach Dam in 2006, in plan view (top) and side view looking downstream toward the powerhouse (bottom). Blue indicates lower densities, green higher densities.

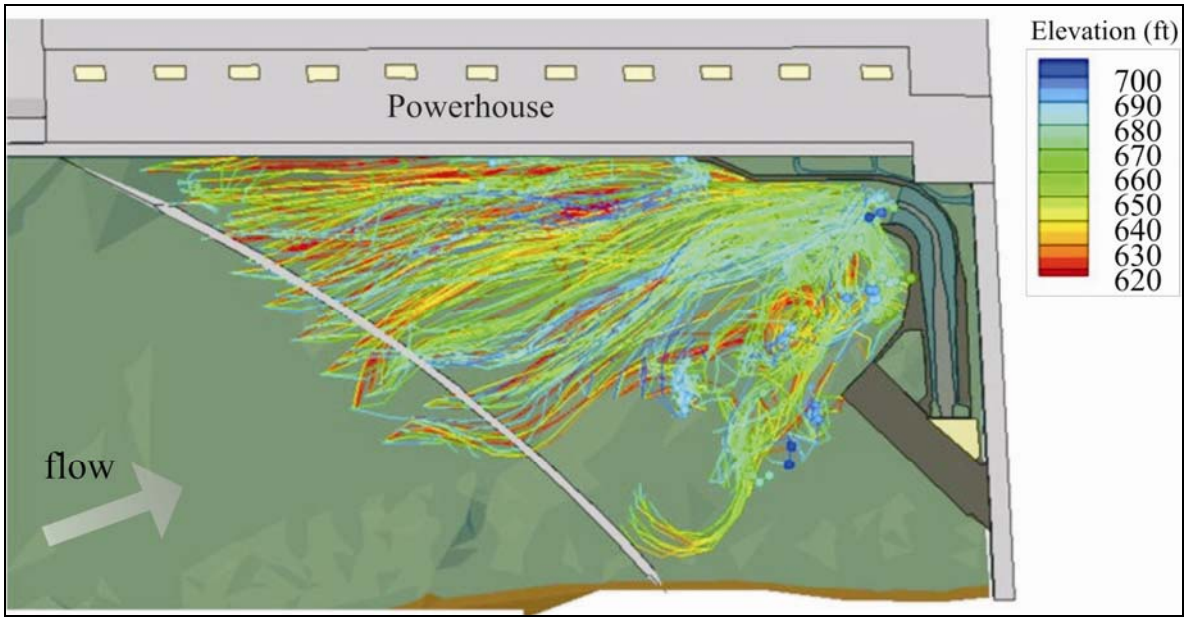

Figure 7. Stream traces of sockeye movement at Rocky Reach Dam, projected from empirical sockeye 3D tracks collected in 2006.

4.1.2 Priest Rapids

Nearly 600,000 individual 3D smolt positions were calculated in the forebay of Priest Rapids Dam. Data illustrated a strong movement pattern in the direction of the powerhouse regardless of where the fish entered the hydrophone array. Fish collection efficiency of the top-spill bulkhead was measured at 97% for all three species of fish that entered a radial zone extending 15.2 m (50 ft) from the center of the top-spill. Collection efficiency dropped as the distance from the top-spill increased. Fish collection efficiency at 31, 70 and 91 m (100, 200 and 300 ft) was measured at 84%, 52% and 38%, respectively. Vector (streamtrace) analysis illustrated that many of the fish that did not pass through the top-spill did not encounter the hydrodynamic fields established by the operating top-spill. All species had a strong propensity to travel across the mouth of the operating top-spill and exit the dam through the powerhouse. Chinook and steelhead that approached upstream of the spillway also displayed trends of movement toward the left shore prior to dam passage through the spillway.

Kernel density analyses also illustrated a strong movement pattern in the direction of the powerhouse (Figure 8). This powerhouse affinity was evident regardless of where fish first entered the forebay hydrophone array. Fish that entered the array immediately upstream of the powerhouse tended to move directly into the powerhouse. Fish that entered the array upstream of the top-spill and spillway also displayed directed movement toward the powerhouse, crossing upstream of the top-spill entrance.

There were two important trends which were observed in fish that did not select the top-spill bulkhead for passage at Priest Rapids Dam. First, many of these fish did not exhibit true rejection behavior. Most of these fish did not directly approach the top-spill and sequentially turn away from the opening and retreat. Second, most of the fish which rejected the top-spill did not appear to detect the existence of the top-spill, and likely did not encounter the hydrodynamic zone upstream of the top-spill

It appears that most of the “rejection” behavior was composed of fish swimming across edges of the 91 m (300 foot radial zone, in route to the powerhouse. In fact, when a perpendicular boundary line is extended from the center of the top-spill, out into the forebay, 83% of these fish “rejected” on the powerhouse side of this boundary line. Of the limited number of fish that “rejected” the top-spill after passing within 15 m (50 ft) and 30 m (100 ft) of the top spill, the greatest proportion of these were approximately 9-15 m (30-50 ft) below the surface. Of all fish within 15 m (50 ft) of the top-spill, where fish were assumed to have detected the flow net from the top-spill, 97% of the fish accept this passage route.

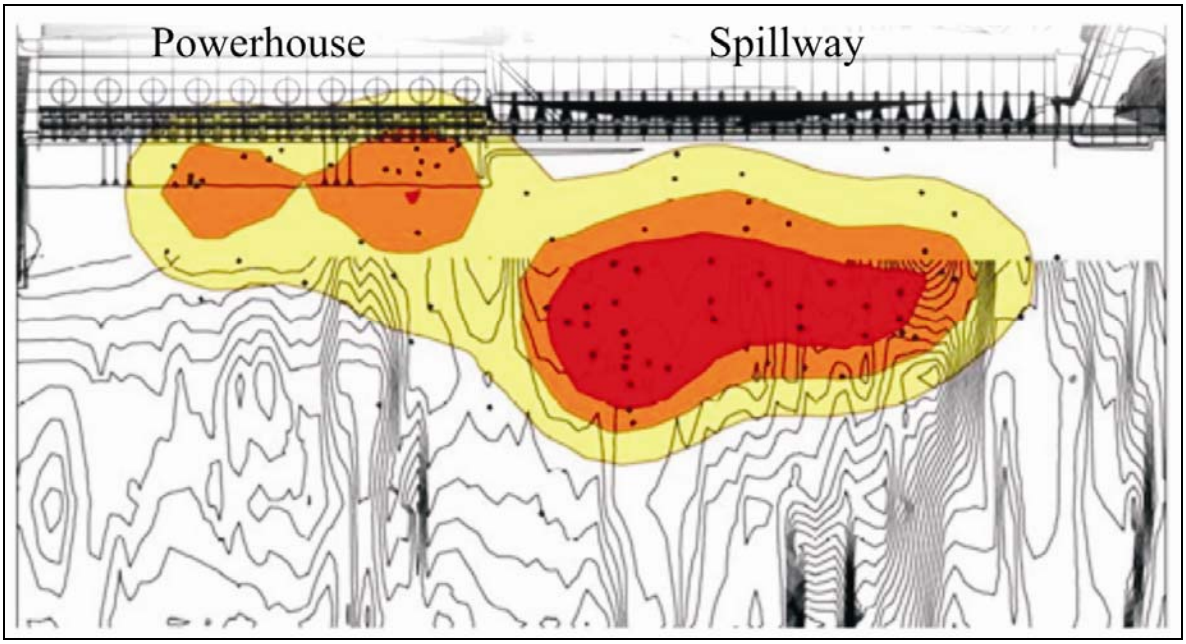

Figure 8. Kernel density volume contour lines for Chinook smolts that passed Priest Rapids Dam via the top-spill bulkhead during 2006.

4.2 Objective 2: Estimate the Effectiveness of Smolt Bypass Structures at the Dams

At Rocky Reach Dam, a higher proportion of tagged steelhead were passed by the surface collector (64%), than were sockeye (39%) in 2006. For steelhead, 73% passed the dam via the surface collector, bypass screens, and spillway. For sockeye, 45% passed via those routes.

FPE at Rock Island Dam was greater for sockeye (32%), than for steelhead (28%), indicating higher rates of bypass via the spillway for the former species. At Rock Island Dam, 32% of steelhead passed via the spillway, and 14% via Powerhouse 1, and 53% via Powerhouse 2. For sockeye, 28% passed through the spillway, 7% through Powerhouse 1, and 65% through Powerhouse 2.

At Wanapum Dam, roughly 55% of all sockeye and steelhead passed the dam through the powerhouse, 30% through the top-spill and sluiceway, and 15% through the spillway. At Priest Rapids Dam, 71-73% of all species passed at the powerhouse. Of the remaining fish, approximately half exited through the top-spill bulkhead and the other half exited through the bottom-spill tainter gates.

4.3 Objective 3: Estimate Smolt Migration Rates

Mean travel speeds for tagged sockeye through the 360 KM study area varied by reach from 0.2 to 1.7 m/sec (Figure 9).

4.4 Objective 4: Estimate the Survival of Smolts Passing Rocky Reach and Rock Island Dams

Estimated survivals for smolts passing through the reservoirs and dams of Rocky Reach and Rock Island dams were 94% to 96%, with low standard errors of approximately 1% (Table 3).

5. Acknowledgements

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Table 3. Survival proportion estimates for smolts passing through the reservoirs and dams of Rocky Reach and Rock Island dams (adapted from Skalski et al. 2006).

Dam	Fish	Survival Estimate	Standard Error
Rocky Reach	Steelhead	0.9598	0.0100
Rock Island	Steelhead	0.9396	0.0132
	Sockeye	0.9600	0.0108

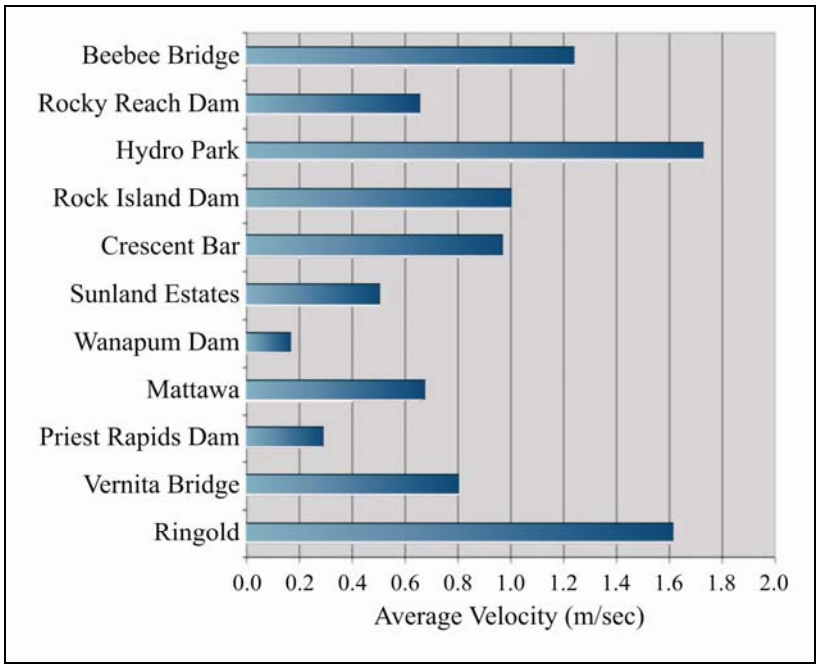

Figure 9. Mean travel speeds for tagged sockeye passing through the 360 KM study area in the mid-Columbia River Basin in 2006.

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