Basin-wide monitoring of salmon smolts at US dams

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Studies have been conducted in the mid-Columbia river basin in the USA , based on acoustic tagging of salmon smolts, to assess behaviour patterns and survival rates of fish in the vicinity of major hydropower dams; the aim is to check the effectiveness of existing bypass structures, and ultimately to restore and enhance salmon runs in the river.

To assess the passage behaviour 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 as a result of 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[1]; Davidson 1965[2]; Schweibert 1977[3]].

Since the early 1980s, considerable effort has been devoted to restoring and enhancing the mid-Columbia river salmon runs. For more than 25 years, the owners and operators of mid-Columbia river dams have been evaluating bypass methods to increase levels of smolt survival. Hydroacoustic techniques [Ransom and Steig, 1994[4], Simmonds and MacLennan, 2005[5]] were used from 1980 to 1999, and acoustic tag techniques were applied beginning in 1998 [Steig, 1999[6]] 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[7]], Steig *et al*. [2007[8]] and Timko *et al*. [2007[9]].

Fig. 1. The course of the Mid-Columbia river in Washington State, USA, showing the locations of hydropower dams and open-river acoustic receiver detection sites.

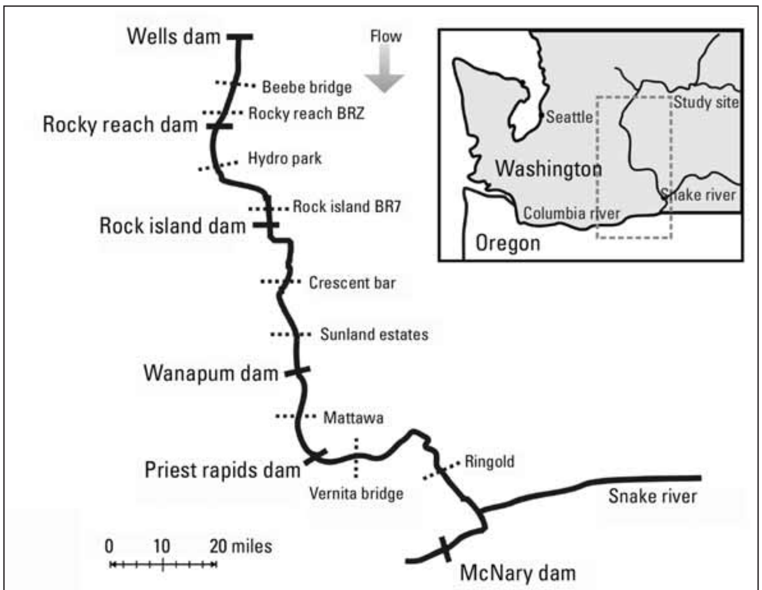

Table 1: Dam owner/operators on the mid-Columbia river within the 360 km reach of acoustic tag studies of salmonid smolts conducted in 2006

Owner/operator	Dam name	Location (RKM)	In service (year)	Installed capacity (MW)
Douglas County PUD No. 1	Wells	830	1961	1213
Chelan County PUD No. 1	Rocky Reach	764	1961	1213
	Rock Island	729	1933	623
Grant County PUD No. 2	Wanapum	669	1963	900
	Priest Rapids	639	1959	855
US Army Corps of Engineers	McNary	470	1953	980

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 modelling analyses, and advances in 3D animation techniques.

The passage effectiveness, survival estimates, and fine-scale behaviour of smolts obtained provided the dam operators and engineers with measures of the effectiveness of their dams which 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 in the mid-Columbia river basin. The results presented here were obtained from several studies conducted during the 2006 spring outmigration. The following objectives were addressed:

- evaluate the 3D swimming paths and behaviour of acoustic tagged smolts approaching the Rocky Reach and Priest Rapids dams;
- estimate the effectiveness of smolt bypass structures at four dams;
- estimate smolt migration rates throughout the study area; and,
- estimate the survival rates of smolts passing the Rocky Reach and Rock Island dams.

2. Site description

The 2006 study area encompassed a 360 km-long reach of the Columbia river, extending from Wells dam at river kilometre (RKM) 830 to McNary dam at RKM 470. Acoustic tag receiver systems were deployed at four dams and nine open-river locations in the mid-Columbia river, located between these two dams (see Fig. 1 and Table 1).

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

Wanapum dam is located at RKM 669. It has a 469 m-long powerhouse, oriented parallel to river flow, and a 254 m-long spillway at an angle of approximately 45° to the flow. The powerhouse is equipped with 10 Kaplan turbine units. Priest Rapids dam is located at RKM 639, 113 km upstream of the confluence of the Snake and Columbia rivers. The dam has a 213 m-long powerhouse with 10 Kaplan turbine units, and a 351 m-long spillway. Weekly median river flows during the study ranged from approximately 4 to 7 m^3/s.

3. Methods

3.1 Acoustic tag systems

Acoustic tags have been used to monitor fish movement for more than 30 years, and have been used to study smolts at Columbia river dams since 1998 [Steig *et al*., 2007[8]]. Most commercially available acoustic tags operate at frequencies of 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, because of the high background noise levels at lower frequencies, and high signal attenuation at higher frequencies [Hydroacoustic Technology, Inc, 1997[10]]. 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 (Fig. 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 used. 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 near the hydropower dams, and up to 1 km in the open river.

At two dams, 3D hydrophone arrays were deployed so it would be possible not only to detect the presence or absence of a particular tagged fish, but also to provide fine-scale tracks of each fish's behaviour. For 3D acoustic tag tracking at the 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 (Figs. 3 and 4). Because of the background noise levels near hydropower dams, the maximum dimensions of a four-hydrophone sample cell are typically 100 × 100 × 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 which 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 typically be estimated within ± 0.5 m for each tag pulse (every 1 to 8 sec), following Ehrenberg and Steig [2002[11], 2003[12]]. Fish were tracked as they approached and passed into the 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 ('ping' rates) were user-selected at one ping every 1 to 8 s, with a transmit pulse width of 1.0 µs. All acoustic tags were surgically implanted. The minimum length of the 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 (see Table 2).

Data collection was conducted 24 h/day, 7 days a week 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 Objectives

3.2.1 Objective 1: Evaluate the 3D behaviour of smolts approaching Rocky Reach and Priest Rapids dams

The fine scale behaviour 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 forebays of both dams, density plots of fish concentrations were produced. The monitored forebay was subdivided into individual cells each measuring 15.2 × 15.2 × 15.2, 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[13]]. 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.

3.2.2 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),

Fig. 2. HTI Model 290 acoustic tag tracking receiver, Model 590 hydrophone, and Model 795 acoustic tags (not to scale).

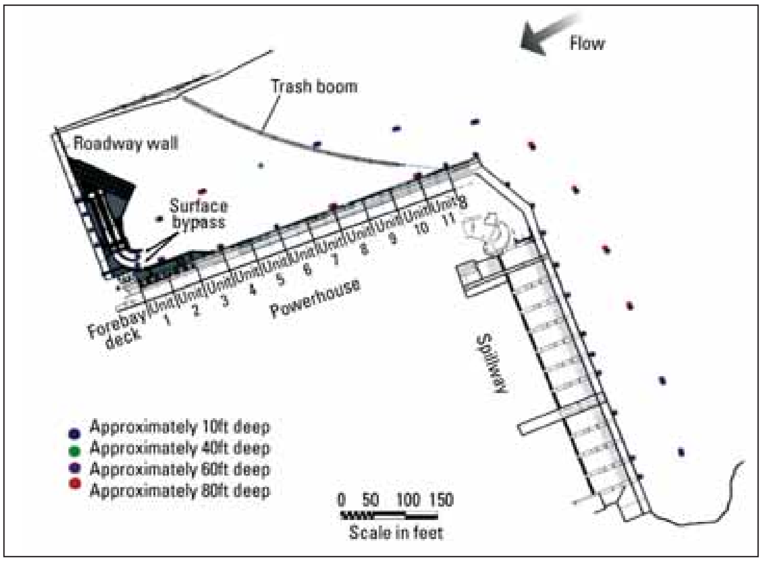

Fig. 3. Plan view of the Rocky Reach dam and hydrophone deployments in the forebay for monitoring acoustically tagged fish during 2006.

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.

3.2.3 Objective 3: Estimate smolt migration rates

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

3.2.4 Objective 4: Estimate the survival of smolts passing Rocky Reach and Rock Island dams

For Rocky Reach and Rock Island dams, smolt survival (both at the dam and reservoir) was estimated using the paired release-recapture method of Burnham *et al*. [1987[14]], following the implementation of Skalski *et al*. [2004[15]] and Steig *et al*. [2005[16]]. 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.

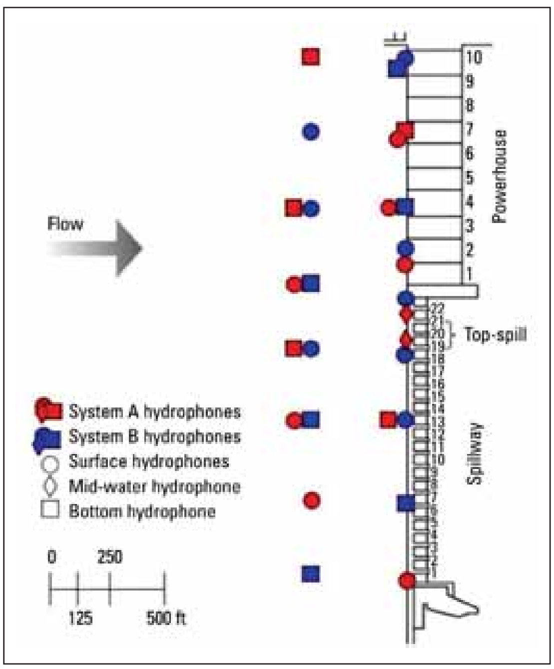

Fig. 4. Plan view of the Priest Rapids dam and hydrophone deployments in 2006.

Table 2: Details of acoustic tagged smolt released in 2006 in the mid-Columbia river

Release location (dam name)	Species	Number of acoustically tagged fish
Wells	Steelhead	500
Wells	Sockeye	1500
Rocky Reach	Steelhead	500
Rocky Reach	Sockeye	1500
Rock Island	Steelhead	500
Rock Island	Sockeye	500
Wanapum	Steelhead	1000
Wanapum	Chinook	1000
Priest Rapids	Steelhead	500
Priest Rapids	Chinook	500
Total		8000

4. Results

During April and May 2006, approximately 8000 salmonid smolts were surgically implanted with acoustic tags and released into the mid-Columbia river (see Table 2). At each acoustic detection site (four dams and nine open-river hydrophone arrays), a minimum of 95 per cent of the smolts were detected. Nearly 200 million acoustic tag detections were recorded across all the hydrophone arrays.

4.1 Objective 1: Evaluate 3D behaviour 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 (Fig. 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 (Fig. 6). Sockeye entering the surface collector appeared to be

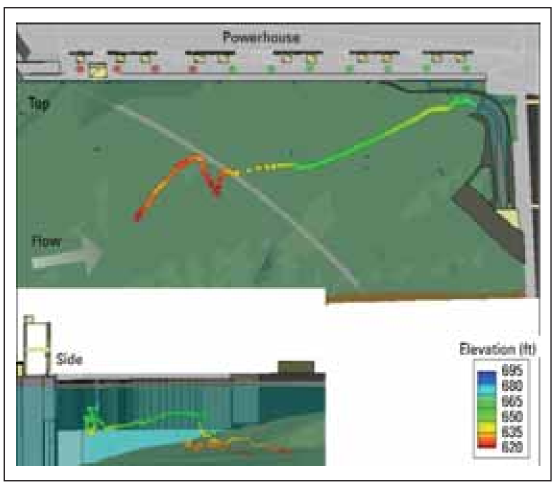

Fig. 5. Example of a 3D track of a sockeye smolt passing into the surface collector at Rocky Reach dam in 2006, in plan view (top) and side view looking downstream toward the surface collector (bottom). The colour indicates the relative elevation.

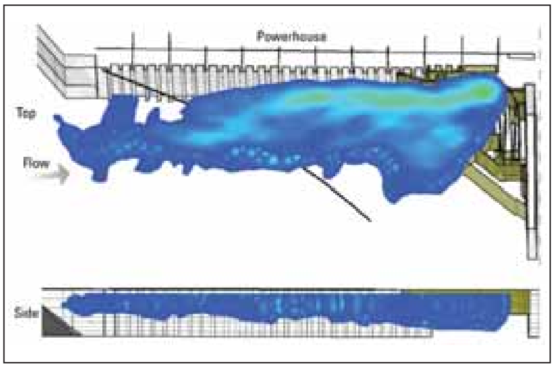

Fig. 6. Binary density plot for sockeye smolts passing into the surface collector at Rocky Reach dam in 2006, in plan view (top) and side view looking downstream towards the powerhouse (bottom). Blue indicates lower densities, and green higher densities.

distributed in the upper 12.2 m 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 which passed into the surface collector were the most surface-oriented compared with 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 towards the surface collector (see Fig. 7).

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 per cent for all three species of fish which entered a radial zone extending 15.2 m from the centre of the top-spill. Collection efficiency dropped as the distance from the top-spill increased. Fish collection efficiency at 31, 70 and 91 was measured at 84 per cent, 52 per cent and 38 per cent, respectively. Vector (streamtrace) analysis illustrated that many of the fish which 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 towards the left shore prior to dam passage through the spillway.

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

Table 3: Survival proportion estimates for smolts passing through two of the reservoirs* [Skalski *et al* 2006[7]]

Dam	Fish species	Survival estimate	Standard error
Rocky Reach	Steelhead	0.9598	0.0100
Rock Island	Steelhead	0.9396	0.0132
	Sockeye	0.9600	0.0108

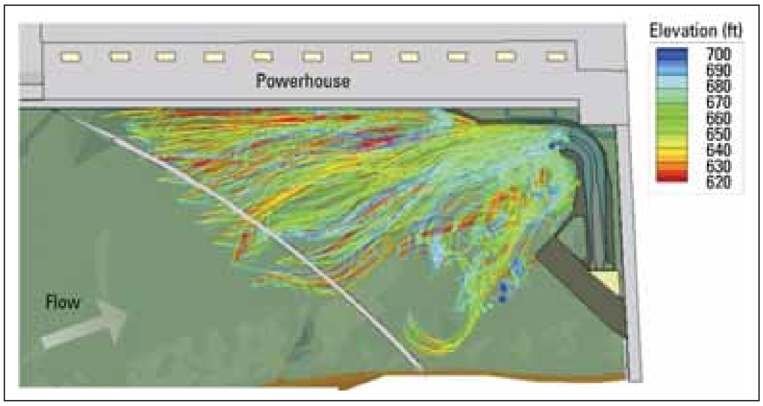

Fig. 7. Stream traces of sockeye movement at Rocky Reach dam, projected from empirical sockeye 3D tracks collected in 2006.

Two important trends were observed in fish which did not select the top-spill bulkhead for passage at Priest Rapids dam. First, many of these fish did not exhibit true rejection behaviour. Most of them did not directly approach the top-spill and sequentially turned 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 probably did not encounter the hydrodynamic zone upstream of the top-spill

It appears that most of the 'rejection' behaviour was composed of fish swimming across edges of the 91 m radial zone, en route to the powerhouse. In fact, when a perpendicular boundary line is extended from the centre of the top-spill, out into the forebay, 83 per cent 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 and 30 m of the top spill, the greatest proportion of these were approximately 9-15 m below the surface. Of all fish within 15 m of the top-spill, where fish were assumed to have detected the flow net from the top-spill, 97 per cent of the fish accepted this passage route.

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 per cent), than were sockeye (39 per cent) in 2006. For steelhead, 73 per cent passed the dam through the surface collector, bypass screens, and spillway. For sockeye, 45 per cent passed via those routes.

FPE at Rock Island dam was greater for sockeye (32 per cent), than for steelhead (28 per cent), indicating higher rates of bypass through the spillway for the for-

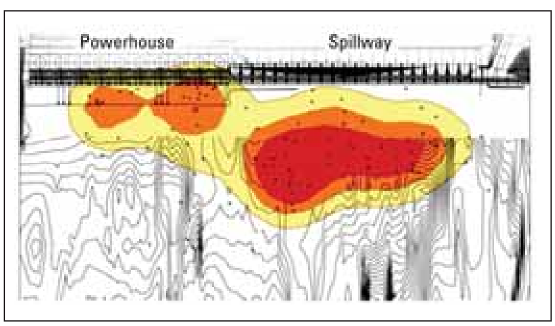

Fig. 8. Kernel density volume contour lines for Chinook smolts which passed the Priest Rapids dam via the top-spill bulkhead during 2006.

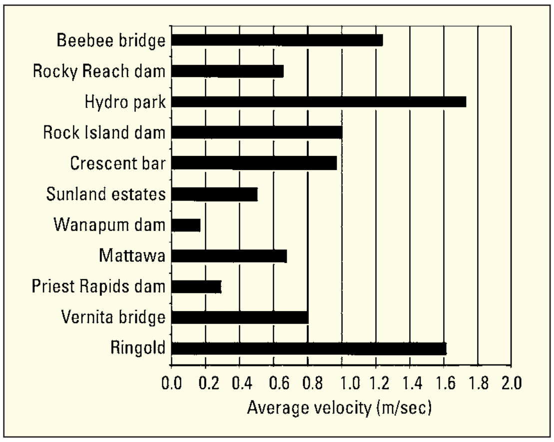

Fig. 9. Mean travel speeds for tagged sockeye passing through the 360 km study area in the mid-Columbia river basin in 2006.

mer species. At Rock Island dam, 32 per cent of steelhead passed via the spillway, and 14 per cent via Powerhouse 1, and 53 per cent via Powerhouse 2. For sockeye, 28 per cent passed through the spillway, 7 per cent through Powerhouse 1, and 65 per cent through Powerhouse 2.

At Wanapum dam, roughly 55 per cent of all sockeye and steelhead passed the dam through the powerhouse, 30 per cent through the top-spill and sluiceway, and 15 per cent through the spillway. At Priest Rapids dam, 71-73 per cent of all species passed at the powerhouse. Of the remaining fish, approximately half exited through the top-spill bulkhead and the other half 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/s (see Fig. 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 the Rocky Reach and Rock Island dams were 94 per cent to 96 per cent, with low standard errors of approximately 1 per cent (see Table 3). ◊

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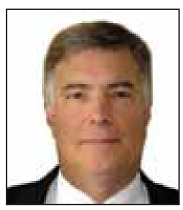

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