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; Davidson 1965; Schweibert 1977].

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; Simmonds and MacLennan, 2005] were used from 1980 to 1999, and acoustic tag techniques were 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 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...
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], [2003]. 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]. 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),
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] and 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 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

<table>
<thead>
<tr>
<th>Release location (dam name)</th>
<th>Species</th>
<th>Number of acoustically tagged fish</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wells</td>
<td>Steelhead</td>
<td>500</td>
</tr>
<tr>
<td>Wells</td>
<td>Sockeye</td>
<td>1500</td>
</tr>
<tr>
<td>Rocky Reach</td>
<td>Steelhead</td>
<td>500</td>
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<tr>
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<td>1500</td>
</tr>
<tr>
<td>Rock Island</td>
<td>Steelhead</td>
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</tr>
<tr>
<td>Rock Island</td>
<td>Sockeye</td>
<td>500</td>
</tr>
<tr>
<td>Wanapum</td>
<td>Steelhead</td>
<td>1000</td>
</tr>
<tr>
<td>Wanapum</td>
<td>Chinook</td>
<td>1000</td>
</tr>
<tr>
<td>Priest Rapids</td>
<td>Steelhead</td>
<td>500</td>
</tr>
<tr>
<td>Priest Rapids</td>
<td>Chinook</td>
<td>500</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>8000</td>
</tr>
</tbody>
</table>

Table 2: Details of acoustic tagged smolt released in 2006 in the mid-Columbia river
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 (stream-trace) 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 regard-

<table>
<thead>
<tr>
<th>Dam</th>
<th>Fish species</th>
<th>Survival estimate</th>
<th>Standard error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rocky Reach</td>
<td>Steelhead</td>
<td>0.9598</td>
<td>0.0100</td>
</tr>
<tr>
<td>Rock Island</td>
<td>Steelhead</td>
<td>0.9396</td>
<td>0.0132</td>
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<tr>
<td></td>
<td>Sockeye</td>
<td>0.9600</td>
<td>0.0108</td>
</tr>
</tbody>
</table>

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.

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-
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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