A Study to Estimate Salmonid Survival through the Columbia River Estuary using Acoustic Tags, 2006

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EXECUTIVE SUMMARY

In 2006, NOAA Fisheries, the Pacific Northwest National Laboratory (PNNL) and the U.S. Army Corps of Engineers (COE) continued the second phase of a multiyear project to estimate juvenile salmonid survival through the lower Columbia River and estuary. Also, a pilot study was initiated to determine the feasibility of estimating system-wide survival of fish released at Lower Granite Dam.

A total of 972 yearling and 1,957 subyearling Chinook salmon were surgically implanted with acoustic transmitters and passive integrated transponder (PIT) tags. River-run fish were collected from the Bonneville Dam juvenile bypass facility and released back into the Columbia River in groups of approximately 245. Yearling Chinook salmon were released during 2–27 May (4 releases), while subyearlings were released during 16 June-22 July (8 releases).

Estimates of survival ranged from 0.584 to 0.824 for yearling Chinook and from 0.185 to 1.005 for subyearling Chinook salmon. Pooled across all releases, estimated mean survival was 0.665 (SE = 0.055) and 0.632 (SE = 0.112) for yearling and subyearling fish, respectively. For yearling Chinook salmon, mean travel time from release (rkm 231.2) to the primary detection array (rkm 9) was 4.1 d (range 2.1–17.2 d), resulting in a mean migration rate of approximately 54.1 km d^{-1}. For subyearling Chinook salmon, mean travel time was 4.1 d, resulting in a migration rate of about 54.1 km d^{-1}. For both run types, a majority of first detections on the primary array occurred during daylight hours and during ebb tides. Avian predation, evidenced by PIT-tag recoveries from estuary bird colonies, accounted for at least 2.5 % of mortality for both yearling and subyearling Chinook salmon.

A total of 996 yearling river-run Chinook salmon were surgically implanted with acoustic transmitters and PIT tags and released from the Lower Granite juvenile bypass outfall into the Snake River on 6 and 13 May. Pooled across both releases, mean survival was estimated at 0.787 (SE = 0.0147) to the mouth of the Snake River, and 0.384 (SE = 0.0278) to the lower Columbia River estuary. Mean travel time from release at Lower Granite Dam to the Columbia River estuary was 13.0 d (range 6.6–35.3 d), resulting in a mean migration rate of approximately 52.8 km d^{-1}. For yearling Chinook salmon released at Lower Granite Dam, travel time from the primary array below Bonneville Dam to the primary array in the Columbia River estuary was similar to that of their cohorts released at Bonneville Dam. Yearling Chinook released at Lower Granite dam were detected in the estuary mainly during daylight hours and across all tide stages.

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INTRODUCTION

Mortality in the estuary and ocean comprises a significant portion of the overall mortality experienced by salmon throughout their life cycle, and seasonal and annual fluctuations in salmonid mortality in the estuarine and marine environments are a significant source of recruitment variability (Bradford 1995). Understanding the causes of juvenile salmonid mortality during their freshwater residence and downstream migration is essential to development of appropriate monitoring techniques and effective management strategies in support of mitigation efforts and conservation policies aimed at salmon population enhancement.

Recent studies have attempted to evaluate effects of estuarine conditions on salmon. Simenstad et al. (1992) suggest that estuaries offer salmonids three primary advantages: productive foraging, relative refuge from predators, and a physically intermediate environment in which the animal can transition from freshwater to marine physiological control systems. Thorpe (1994) reviewed information from three genera of salmonids (*Oncorhynchus, Salmo,* and *Salvelinus*) and concluded that salmonids are characterized by their developmental flexibility and display a number of patterns in estuarine behavior. He found that stream-type salmon migrants (some Chinook, coho, sockeye, and Atlantic salmon) move through estuaries and out to sea quickly, compared to ocean-type salmon migrants.

Most of our knowledge of how salmonids utilize estuaries is limited to smaller systems that can be more readily sampled. For example, Beamer et al. (1999) assessed the potential benefits of different habitat restoration projects on the productivity of ocean-type Chinook salmon in the Skagit River, Washington. They concluded that restoration of freshwater habitats (peak flow and sediment supply) to "functioning" levels "would provide limited benefits unless estuary capacity or whatever factor that limits survival from freshwater smolt to estuary smolt is also increased." They used productivity and capacity parameters to estimate that estuarine habitat restoration could produce up to 21,916 smolts ha^{-1}. Reimers (1973) found that fall Chinook salmon in the Sixes River, Oregon, used diverse estuary rearing periods and strategies.

Little information is available describing historic use of the Columbia River estuary by salmonid smolts. Rich (1920) found that 36% of juvenile yearling and subyearling Chinook salmon collected from 1914 to 1916 demonstrated extensive rearing in the estuary. As many as 70% of fish sampled during July over the 3 years of study had resided in the estuary from 2 to 6 weeks (Jennifer Burke, ODFW, personal communication). Subyearling Chinook salmon attained 20 to 66% of their fork length while in the estuary. In contrast, Dawley et al. (1985) found that more recently, when hatchery fish dominated the juvenile population, movement rates through the estuary were similar to those from a release site to the estuary, indicating limited use of the estuary by juvenile salmonids originating upstream from Jones Beach, OR (rkm 75).

Schreck and Stahl (1998) found mean migration speed of radio-tagged yearling Chinook salmon was highly correlated with river discharge, and averaged approximately 2 mph (3.7 kph) from Bonneville Dam to near the mouth of the Columbia River. Movement in the lower estuary was influenced by tidal cycles, with individuals moving downstream on the ebb tide and holding or moving upstream during the flood tide. They reported a high proportion of tagged animals were lost to piscivorous bird colonies located on dredge disposal islands.

Ledgerwood et al. (1999) also found that travel speed of PIT-tagged fish from Bonneville Dam to Jones Beach was highly correlated with total river flow. They observed significant differences in passage times at Jones Beach between PIT-tagged spring/summer Chinook salmon released at Lower Granite Dam to migrate in river and their cohorts transported and released below Bonneville Dam. Inriver migrating fish detected at Bonneville Dam had significantly faster travel speeds to Jones Beach (98 km d^{-1}) than those released below Bonneville Dam (73 km d^{-1}). These recent studies provide a cursory assessment of estuarine migration behavior.

Physical processes in the estuary, and thus estuarine habitat, are shaped by two dominant factors: channel bathymetry and flow. River flow is controlled by climate variation and anthropogenic effects such as water storage, irrigation, withdrawals, and flow regulation. The Federal Columbia River Power System (FCRPS) has altered the hydrology of the Columbia River estuary through flow regulation, timing of water withdrawals, and irrigation, which have affected the average flow volumes, timing, and sediment discharge (Bottom et al. 2001; NRC 1996; Weitkamp 1994; Simenstad et al. 1992; Sherwood et al. 1990). Annual spring freshet flows are approximately 50% of historical levels and total sediment discharge is roughly one third of levels measured in the 19th century. The direct effects of these changes to the estuary from FCRPS operations on migrant salmonids have not been evaluated.

The potential for delayed mortality on fish that migrate through the hydropower system is also a concern to fisheries managers and regional decision makers. Recent quantitative model studies have assessed the importance of survival downstream from Bonneville Dam to the overall life cycle, and sensitivity analyses have identified the life stages where management actions have the greatest potential to influence annual rates of population change, and priorities for research (NMFS 2000a). A reduction in mortality in the estuary/ocean and during the first year of life had the greatest effect on population growth rates for all spring/summer Chinook salmon stocks when a 10% reduction in mortality in each life stage was modeled. The Plan for Analyzing and Testing Hypotheses program calculated smolt-to-adult ratios (SARs) sensitivity analysis produced similar results.

These analyses suggest that salmonid recovery efforts will require an understanding of the important linkages between physical and biological conditions in the Columbia River estuary and salmonid survival. Indeed, Kareiva et al. (2000) concluded that modest reductions in estuarine mortality, when combined with reductions in mortality during the first year of life, would reverse current population declines of spring/summer Chinook salmon. Emmett and Schiewe (1997) concluded that survival must be separated between the freshwater, estuarine, and ocean phases to be able to answer these management questions.

In response to a dearth of information relating to smolt survival specific to the lower Columbia River, the estuary, and during the early marine experience, NOAA Fisheries, Pacific Northwest National Laboratory (PNNL), and the U. S. Army Corps of Engineers (COE) initiated a project in 2001 to develop tools to provide rigorous survival assessments for juvenile salmonids migrating through the Columbia River basin, estuary and near ocean. The statistical model introduced by Cormack (1964), Jolly (1965), and Seber (1965) and referred to as the CJS or single-release model was the most appropriate and practical statistical approach for this effort, and project goals were geared to assumptions of that architecture.

Three technologies have the potential for marking (tagging) individual fish of small size to assess survival through the lower Columbia River. These are radio tags, passive integrated transponder (PIT) tags, and acoustic tags. Since radio signals are quickly attenuated in salt or brackish water, radio tags cannot be used over significant portions of the study area. PIT tags are appropriate for implant into small salmonids and function in salt water environments. Unfortunately, maximum detection range for PIT tags is only about 610 mm (2 ft), making this technology suitable for sites where fish can be concentrated into a small sampling volume, such as in fish passage facilities at hydroelectric projects. Since the distal portion of the estuary involves fish movement through salt water, acoustic telemetry was the only existing technology with the combination of transmission range and medium independence suitable for tagging small fish. Acoustic tagging would allow detection of tagged individuals migrating through the entire study area.

Given the ostensible high proportion of mortality occurring below Bonneville Dam, the potential positive response in population growth rates from changes to survival in this area, and uncertainty over the causal mechanisms of hydropower system delayed mortality, there is a need for detailed studies to evaluate juvenile salmonid survival and behavior through the lower Columbia River and through the Columbia River estuary. This is particularly true for subyearling Chinook salmon, which may utilize portions of the estuary for extended periods as rearing and transition habitat. However, these fish are small, with only 85% of the population at Bonneville Dam great than 92 mm (3.5 in) fork length. To effectively tag these smaller animals, a small, ergonomic transmitter was developed as part of an overall program to develop acoustic tools (McComas et al. 2005; McComas et al., in prep; McMichael et al. in press). Termed the Juvenile Salmonid Acoustic Telemetry System (JSATS), this tool is the current product of an ongoing, iterative process intended to provide regional researchers with acoustic transmitters and detection gear specifically designed to address local management needs.

The single-release model requires two successive points of detection which, in a riverine environment, were approximated by linear telemetry transects. Each transect was comprised of a succession of passive acoustic receivers, with overlapping reception ranges, spanning the river. Early in the development of the acoustic detection system for the Columbia River, design team consensus was that the most effective receiver gear for the upstream (primary) array would be a series of bottom mounted receiver nodes cabled to a shore station to provide power and data communications.

The ensuing JSATS development effort produced a cabled system capable of meeting design requirements, and sufficiently physically robust to meet demands for extended use in the estuarine environment (McComas et al. 2005). An autonomous node was developed for use lower in the estuary to function as the secondary array. With completion of development and evaluation in 2004, NOAA Fisheries, in partnership with PNNL, initiated the second phase of the multiyear project to estimate juvenile salmonid survival through the lower Columbia River and estuary.

Here we report survival assessments during 2006, which were based on microacoustic tag data from fully populated primary and secondary JSATS detection arrays. Survival was evaluated for river-run yearling and subyearling Chinook salmon through the lower Columbia River and estuary. In addition, a pilot study was conducted to estimate system-wide survival of yearling Chinook salmon from the tailrace of Lower Granite Dam in the Snake River through the Columbia River estuary.

METHODS

Study Area

The study area for this work included the free-flowing mainstem Columbia River and estuary from Bonneville Dam to the Pacific Ocean, a distance of approximately 234 river kilometers (rkm). Sherwood and Greagar (1990) described the annual hydrograph for the Columbia River as ranging from a late summer and fall low of 2,970 to 17,000 $m^3\ s^{-1}$ during the spring freshet period, with a mean annual decrease of about 280-570 $m^3\ s^{-1}$ due to irrigation removal and climate change. Sediment discharge under modern conditions is about $7.6 \times 10^6\ t^3\ y^{-1}$, about 45% of which is sand (Sherwood et al. 1990). Sherwood et al. noted that much of this finer material is transported in suspension during high river flow periods. Thus, both high flows and high suspended sediment loads coincide with the peak juvenile salmonid migration, particularly for yearling fish.

The Columbia River estuary conforms to the classic estuary definition as a semi-enclosed coastal body of water with a free connection to the open sea, and within which seawater is measurably diluted with freshwater derived from land drainage (Pritchard 1967). Though the upper limit of saltwater incursion reaches slightly past Harrington Point (rkm 37, Sherwood and Greagar 1990), tidal effects are observable as far inland as Longview, WA, (rkm 105) and are measurable at Bonneville Dam (rkm 235). The estuary hosts four major bays and contains numerous islands of natural and man-made or man-origin, as well as extensive intertidal and supratidal areas (Sherwood et al. 1990). Islands constructed of dredged sediment and extensive dikes are the most prominent man-made structures.

Collis et al. (2001) estimated that nine islands in the estuary supported up to 170,000 piscivorous waterbirds, including the largest aggregations of Caspian terns *Sterna caspia* and double-crested cormorants *Phalacrocorax auritus* in North America. Two of these islands were particularly important to survival studies for fish migrating through the study area. Rice Island, a dredge disposal site at rkm 35, contained over 16,000 breeding pairs of terns, which were estimated to be dependent on salmonids for up to 74% of their diet (Collis et al. 2002). Subsequent relocation efforts successfully moved a majority of these birds to East Sand Island, another dredge disposal site at rkm 10, where Collis et al. reported a colony of about 8,500 breeding pairs had been established by 2002. In addition to the terns, Ryan et al. (2002) cited the presence of a colony of about 8,000 breeding pairs of double-crested cormorants on a 15,000-m^2 area of rock jetty attached to East Sand Island. Relocation efforts reduced the colony of cormorants on Rice Island from 1,082 birds in 1998 to no nesting pairs by 2001 (Roby et al. 2005).

Detection Arrays: Autonomous Receiving System

Acceptance Testing

Autonomous receiving nodes consisted of electronics, on-board power (30-d battery life), data storage (1 GB compact flash (CF) memory card), and hydrophone housed in a 1.2-m-long × 15-cm-diameter PVC tube. Nodes were deployed to detect and record the presence of passing fish bearing JSATS microacoustic transmitters. Each receiver underwent rigorous acceptance testing by an independent contractor prior to delivery from the manufacturer and deployment in the field.

The first step of the test protocol was a gross examination to ensure that all parts were present and properly labeled. This included the upper and lower housings, bridle, battery-retaining device, board sets, CF card mount switch, stereo plug, hydrophone, and temperature and pressure sensors. The nodes were then activated and basic function evaluated: pressure and temperature sensors and the system clock were calibrated, and the ability to properly receive, decode, and store acoustic signals to the CF card was verified.

Finally, node performance was measured and the housings were tested for leaks. This was done in a large tank lined with anechoic material, using a signal generator and attenuator to simulate range. Each node was placed in the tank at a known distance from the signal generator element. An attenuation curve was created by calculating the percentage of transmissions correctly detected and decoded at each of 6 signal levels (-20, -30, -40, -45, -50, and -55 dB). Acceptance required a minimum detection efficiency of 80% at dB levels of -45 dB or higher (Figure 1). Nodes that failed any step of the test protocol were returned to the manufacturer for repair or replacement and retested for acceptance.

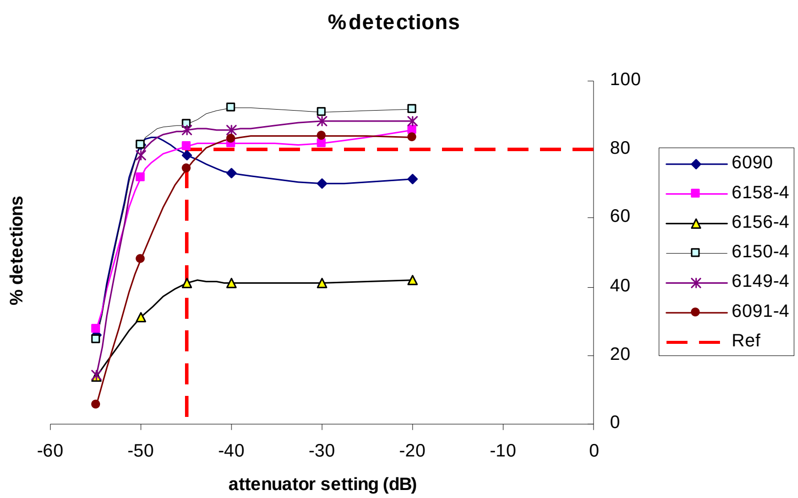

Figure 1. Example acceptance test data plot from autonomous receiver (node) showing percent detections decoded vs. signal strength (dB). Dashed lines delineate acceptance criteria: nodes that produced detection plots above and to the left of red lines were accepted. In this example, nodes 6156 4, 6090, and 6091 4 were not accepted, while all others were accepted.

Node Deployment and Servicing

Prior to deployment, each node was attached to an acoustic release (InterOcean Systems, Inc., San Diego, CA; model 111)[1] by a 0.9-m-long bridle made of 12.7-mm-diameter braided nylon rope (Figure 2). The release allowed nodes to be retrieved for periodic servicing (data retrieval and battery replacement). Each bridle end was terminated by a braided splice around a 9.5-mm SeaDog nylon thimble that was professionally braided. Three yellow buoys (Baolong BL 6, 16.5- × 12.4-cm, 1.45-kg buoyancy each) were threaded on the bridle between the node and release. Each acoustic release was shackled to a 68-kg anchor with a 1- to 3-m-long shock-corded mooring made of 125-mm braided nylon rope. The mooring assembly terminated with a 10-cm galvanized steel ring that was held by the acoustic release.

To deploy the autonomous nodes, all rigging and equipment components were assembled and loaded onto a 10-m deployment vessel. Deployment locations were plotted on an electronic chart and found using GPS navigation. Just prior to deployment, the assembly was attached to an anchor, and pertinent information was recorded on a data sheet (node serial number, acoustic release code, water depth, date, and time of deployment.). Once the boat was in position, two people hoisted the anchor to the gunwale and lowered it over the side. A third person fed the equipment over the side as the anchor was lowered to the bottom on a slip line. When the anchor reached bottom, the actual GPS point was recorded.

Figure 2. Autonomous acoustic telemetry receiver (top), acoustic release (middle), and anchor (bottom left) rigged as deployed in the Columbia River estuary.

[1] Use of trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

To recover the equipment, we navigated to the GPS position of a receiver and triggered the acoustic release. When the equipment came to the surface, we captured the bridle line with a boat hook and brought the equipment on board. Occasionally the gear became fouled, preventing the node from detaching from the anchor when the acoustic release was triggered. When this happened, we used a weighted steel cable towed along the bottom between two boats to drag for the nodes. In most cases this was successful in severing the node from its mooring.

Autonomous nodes required servicing about every 28-30 d. During servicing, batteries were replaced, data was downloaded, and nodes that were missing or malfunctioning were replaced. The deployment schedule for autonomous nodes in 2006 is presented in Table 1.

Table 1. Name, location (physical landmark description and river kilometer from the mouth of the Columbia River), and deployment and recovery dates of JSATS acoustic telemetry arrays in the Snake and Columbia River systems used to detect acoustic-tagged juvenile Chinook salmon released during studies to estimate survival through the Columbia River estuary, 2006.

Array Code	River kilometer	Physical site description	Date deployed	Date retrieved
LMDF	589.2	Lower Monumental reservoir boat restricted zone (BRZ)	26 Jul	25 Sep
LMDT	578.5	Lower Monumental tailrace	12 Apr	26 Sep
IHDF	538.1	Ice Harbor forebay BRZ	11 Apr	26 Sep
IHT1	525.2	Ice Harbor tailrace primary	10 Apr	26 Sep
IHT2	524.0	Ice Harbor tailrace secondary	10 Apr	26 Sep
JDAE	339.2	John Day egress	12 May	5 Jun
JDA1	325.6	John Day tailrace primary	10 May	20 Sep
JDA2	324.2	John Day tailrace secondary	10 May	20 Sep
JDA3	312.4	John Day tailrace tertiary	10 May	20 Sep
TDA1	275.6	The Dalles tailrace primary	12 May	16 Sep
TDA2	238.4	The Dalles tailrace secondary	May	Sep
TDA3	236.4	The Dalles tailrace tertiary	8 May	6 Sep
TDA4	235.2	The Dalles tailrace quaternary	1 Jun	7 Aug
BONC	235.1	Bonneville Spillway cabled array	3 Jul	7 Aug
BON1	208.8	Bonneville tailrace primary	2 May	21 Sep
BON2	204.0	Bonneville tailrace secondary	2 May	21 Sep
BON3	193.8	Bonneville tailrace tertiary	2 May	21 Sep
EST1	8.3	Estuary primary	17 Apr	27 Sep
EST2	2.8	Estuary secondary	17 Apr	27 Sep

Primary Array

To encompass the portion of the study area with most probable predation impact from piscivorous birds on East Sand Island, the primary array for survival estimation was deployed along a transect from West Sand Island to Clatsop Spit at approximately rkm 9 (Figure 3). This deployment was comprised of 22 autonomous nodes deployed in two separate arrays to avoid crossing the ship channel. One array of 19 nodes was deployed south from the southern end of West Sand Island (46°15.8581’ N, 124°0.0539’ W) to the north side of the ship channel (46°14.3907' N, 123°59.5947' W). The second was deployed north from Clatsop Spit (46°14.1897' N, 123°59.7871' W) to the south border of the ship channel (46°14.2574' N, 123°59.7029' W).

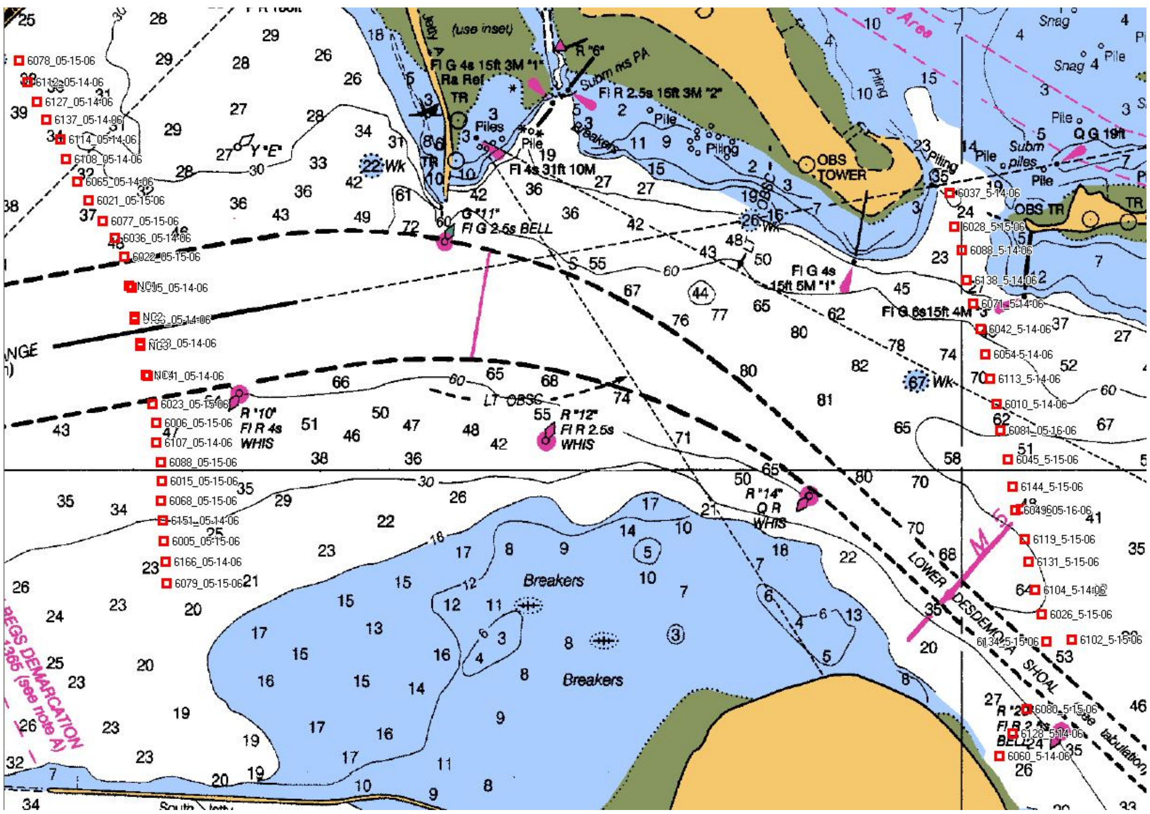

Figure 3. Columbia River estuary showing the locations of acoustic receiver arrays used to detect acoustic-tagged juvenile Chinook salmon during studies to estimate juvenile salmonid survival through the lower Columbia River, 2006.

Secondary Array

For the majority of the season, the secondary array consisted of 21 autonomous nodes similar to those described for the temporary primary array. These were located on a north-south transect at approximately rkm 2.8 with 10 nodes on the Oregon (south) side of the navigation channel, and the remaining 11 on the Washington (north) side of the channel. Two times during the season, 4 nodes were deployed temporarily (for 2 d each time) in the navigation channel (Figure 3) to increase detection efficiency during the time when fish were expected to be migrating through the area.

Other Arrays

To detect fish coming down the Snake River from Lower Granite Dam, eight nodes were placed in the Snake River. An array of three nodes was placed in Lower Monumental Dam forebay. A similar array was placed in Ice Harbor Dam forebay, and two arrays were placed downstream from Ice Harbor Dam near the confluence of the Snake and Columbia Rivers. The first of these contained three nodes and was located at Columbia rkm 525.2; the second, contained two nodes and was placed at rkm 524. This study also benefited from nodes deployed for other acoustic telemetry projects (Table 1).

Tagging Operations

All Chinook salmon used to estimate survival through the lower estuary in 2006 were captured, tagged, and released at the Bonneville Dam Juvenile Bypass Facility (JBF). Four groups of 250 yearling and 8 groups of 250 subyearling river-run Chinook salmon were collected from the population passing through the JBF. Fish were taken on the day prior to tagging from the Smolt Monitoring Program sample, which was collected by Pacific States Marine Fisheries Commission personnel. Sufficient numbers of fish were usually available so that the study fish group could be subsampled from the daily smolt monitoring sample without increasing the collection rate. However, on some dates the SMP sample rate was increased to enable collection of 250 fish per group. Study fish were held overnight in a 455-L tank supplied with flow-through river water prior to tagging.

Prior to surgery, fish were placed in an anesthetic bucket containing a solution of approximately 80 mg L^{-1} tricaine methanesulfonate (MS-222). After equilibrium loss, the animal was weighed to the nearest gram, measured to the nearest millimeter, and placed on the surgery table. A maintenance dose of approximately 40 mg L^{-1} solution MS-222 was administered via a tube inserted into the fish's mouth during surgery.

Fish were tagged using procedures similar to those of Adams et al. (1998): with the fish facing ventral side up, an 8- to 10-mm incision was made 2 to 5 mm from and parallel to the mid-ventral line between the pelvic and pectoral girdles. A passive integrated transponder (PIT) tag (Destron Fearing model TX1411ST, 12.5 × 2 mm; 0.06 g) was inserted into the peritoneal cavity followed by an acoustic transmitter (Sonic Concepts model E101, 17 × 5.5 mm; 0.63 g in air; 0.35 g in water, Figure 4).

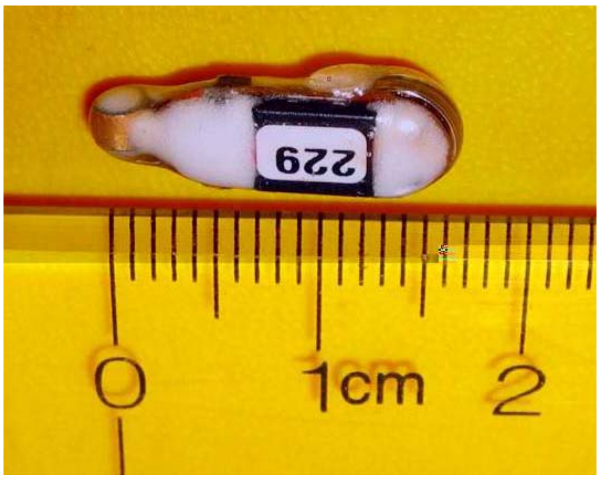

Figure 4. JSATS microacoustic transmitter used for implant into yearling and subyearling Chinook salmon during studies to evaluate juvenile salmonid survival through the Columbia River estuary, 2006.

Both tags were positioned parallel to the longitudinal axis of the fish, and the incision was closed using two simple, interrupted sutures (Ethicon 5-0 absorbable braided Vicryl sutures with FS-2 needle). Following surgery, fish were placed in a recovery bucket with fresh, oxygenated river water and monitored to ensure that they recovered equilibrium before they were transferred to the holding/release container.

Following recovery from anesthetic, acoustic-tagged fish were moved to a 120-L container and held for a minimum of 14 h (overnight) in groups of up to 25 fish per container to assess short term tagging mortality. Holding containers were supplied with continuous flow-through river water at a rate of approximately 7.6 L min^{-1} during the holding period. On the day following tagging, mortalities (if any) were removed from holding containers, and study fish were released directly into the JBF flume approximately 150 m upstream from its outfall into the Columbia River (Table 2). The first three groups were released between 0700 and 1000 PDT. Beginning with the fourth group of yearling Chinook salmon, the release time was changed to hours of darkness (between 2000 and 0400) due to concerns about avian predation at the JBF outfall.

At Lower Granite Dam on the Snake River, 996 yearling Chinook salmon were tagged and released on two dates (Table 2) to evaluate the feasibility of using JSATS tags to estimate survival through the entire FCRPS, including the lower Columbia River and estuary (system-wide survival). Tagging methods at Lower Granite Dam were similar to those at Bonneville, and fish were released through the Lower Granite JBF outfall.

Of the total fish tagged on a given date at Bonneville Dam, five were retained (retention fish) to evaluate longer-term tagging effects. Retention fish were held by tag date in separate containers on river water in the JBF for a minimum of 2 weeks, after which surviving fish were sacrificed. Sacrificed fish were weighed and measured, and necropsies were performed to evaluate incision healing, suture loss, encapsulation and adhesion development, and internal abnormalities. Function of acoustic tags explanted from retention fish was verified daily until tag failure.

Table 2. Numbers of acoustic-tagged yearling and subyearling Chinook salmon released at Lower Granite Dam and Bonneville II JBF outfall during studies to estimate juvenile salmonid survival in 2006. All fish had acoustic and PIT tags concurrently implanted during surgery.

Release location	Release date	Number released
Yearling Chinook		
Lower Granite	6 May	238
Lower Granite	13 May	758
Total		996
Bonneville	2 May	239
Bonneville	11 May	245
Bonneville	19 May	244
Bonneville	27 May	244
Total		972
Subyearling Chinook		
Bonneville	17 Jun	245
Bonneville	22 Jun	245
Bonneville	27 Jun	245
Bonneville	2 Jul	245
Bonneville	7 Jul	243
Bonneville	12 Jul	245
Bonneville	17 Jul	244
Total		1,957
Combined total		3,925

Data Processing

Data collected by the autonomous nodes were recorded as a single text file on CF memory cards. Physical data (date, time, pressure, water temperature, tilt, and battery voltage) were written to a file every 15 seconds. Valid detection data were recorded as they were received and included individual transmitter code, time stamp, receive signal strength indicator (RSSI), and a calculated measure of background noise (RxThreshold). Each data file was transferred to a laptop computer following servicing or retrieval events.

Data files from all nodes were coded with the node location and stored in a database developed specifically for storing and processing acoustic telemetry data. To remove 'false positives' (detections of otherwise valid tag codes that were not in the set of codes implanted in fish), a filtering program was implemented. This program was comprised of a sequence of steps. First, each tag-code record was compared to a list of tag codes released, and records of tags that had not been released were excluded. Second, the detection date was compared to the release date, and any detection dated prior to the release date was excluded. Finally, records were excluded if less than four detections occurred within one 60-second period.

From the valid detection file, a detection history was created for each fish. Detection histories were analyzed to estimate survival (described below) as well as to determine the relationships between detections and tides, cross channel distribution, and travel time from point of release to point of detection for each release group.

To evaluate relationships between detections and tides, a count of detections for fish from each release group was made over 5-minute intervals. Using the tide generating software WXTIDE32 (http://www.wxtide32.com/), we produced tide elevation plots for periods during which tagged fish were migrating past the primary detection array between East and Island and Clatsop Spit. Counts of detections were then plotted against the change in tide along that transect.

Cross-channel distribution was determined separately for yearling and subyearling fish by plotting valid tag observations at each node location for each release group. From this, the number of valid codes observed at each location was calculated by year class for all release groups combined.

Arrival times were defined as the first observation (detection) of each fish observed on an array. A count of fish for each hour (independent of day or night) was then plotted. Day was considered to begin one-half hour before sunrise and end one-half hour after sunset.

Rates of avian predation in Chinook salmon tagged with acoustic tags were determined from data gathered by the NOAA Fisheries avian predation project (Ryan et al. in prep). That project evaluates the impacts of predation by Caspian terns and double crested cormorants on juvenile salmonids through electronic detection of PIT tags on piscivorous water bird nesting colonies in the Columbia River Basin (Ryan et al. 2001, 2003). Recovery files downloaded for all bird predation interrogation sites in the Basin were queried for intersection with tagging files specific to this study.

Survival Estimation

Survival estimates were derived from the CJS model for mark/recapture data from a single release group (Cormack 1964; Jolly 1964; Seber 1965). This model was well suited for data from this study, wherein only two detection opportunities were available for each marked animal. For survival estimates, detection data were summarized by "detection history" for each marked fish. With only two opportunities, the possible histories were:

00 – never detected
10 – detected on primary detection array but not on secondary array
01 – detected on secondary array but not on primary array
11 – detected on both arrays

To estimate survival for a group of tagged fish released at a certain time (a "release group"), counts of fish within each detection history category are used, denoted n_{00}, n_{01}, n_{10}, and n_{11}, along with the total number of fish released, denoted R.

The proportion of fish released detected on the primary array $[(n_{10} + n_{11})/R]$ is an estimate of the combined, or joint probability that a fish survived from release to the primary array (*s*) and that the fish was detected, given that it survived (*p*). Assuming that survival to the primary array and detection on that array are independent events, the joint probability of both events occurring is the simple product of the two probabilities. Thus, the proportion detected on the primary array is an estimate of $s \times p$.

To separate the two probabilities in the product requires a method to estimate either of the probabilities individually. The estimate of the remaining probability can then be obtained by dividing the joint estimate by the estimate of the first. The probability of detection on the primary array can be estimated independently by making the assumption that fish that survived to the secondary array and were detected there (n_{01} + n_{11}) represent a random sample of all fish from the group that were alive as they passed the primary array. The estimated detection probability on the primary array is then the proportion of the sample that were detected on the primary array [$n_{11}/(n_{01} + n_{11})$].

Survival between the primary and secondary arrays cannot be estimated separately from the detection probability on the secondary array, because without a third detection opportunity there is no way to construct the sample from which to estimate detection separately. Thus, we can estimate only the joint probability of survival between the two arrays and detection on the secondary array.

RESULTS AND DISCUSSION

Length and weight descriptive metrics for Chinook salmon implanted with acoustic transmitters and released to the tailraces of LGR or BON in 2006 are presented in Table 3.

Of the 996 yearling Chinook salmon implanted microacoustic tags and released at LGR, 234 (23%) were detected on acoustic receiver arrays in the lower Columbia River estuary. Fork lengths of these fish ranged from 105 to 160 mm (mean = 137.8 mm, SE = 0.28). Mean length for yearling Chinook salmon released at Lower Granite Dam and subsequently detected in the estuary was 138.0 mm (SE = 0.573), and was not significantly greater than the mean length of 136.7 mm (SE = 0.321) for non-detected fish (t = 1.89, P = 0.058, α = 0.05).

Of the 972 yearling Chinook salmon released at Bonneville Dam, 607 (62%) were detected in the estuary (Table 3). Tagged yearling fish ranged from 116 to 218 mm FL about a mean of 149.7 mm (SE = 0.49). Mean length of yearling Chinook salmon detected in the estuary (150.6 mm, SE = 0.603) was significantly greater (t = 2.42, P = 0.016, α = 0.05) than for non detected fish (148.2 mm, SE = 0.810).

A total of 1,112 (57%) of the 1,957 acoustic-tagged subyearling Chinook salmon were detected following release. Lengths ranged from 94 to 155 mm (mean 109.8 mm, SE = 0.18), and as with yearling fish, mean length of subyearling Chinook salmon detected in the estuary (110.9 mm, SE = 0.228) was significantly different (t = 7.05, P < 0.001, α = 0.05) than those not detected (108.3 mm, SE = 0.287).

With a 0.63 g tag (in air), tag-to-body weight ratio ranged from 0.7 to 4.4% (mean = 2.2%, SE = 0.019) for yearling Chinook salmon, and from 1.9 to 8.8% (mean = 5.2%, SE = 0.024) for subyearling Chinook salmon. For subyearling fish this was slightly higher than the recommended 5% ratio. However, because tag weight in water was slightly lower (0.35 g on average), wet tag-to-body weight ratio ranged from approximately 0.4 to 2.4% (mean = 1.2%, SE = 0.011) for yearling Chinook salmon, and 1.0 to 4.9% (mean = 2.9%, SE = 0.013) for subyearling Chinook.
s

Table 3. Descriptive statistics in length and weight by release date for acoustic-tagged yearling and subyearling Chinook salmon released through the Bonneville Dam JBF outfall to evaluate juvenile salmonid survival through the lower Columbia River and estuary, 2006.

Release	Fork Length (mm)					Weight (g)				
date	n	min	max	mean	SE	n	min	max	mean	SE
Yearling Chinook, Lower Granite Dam releases										
16 May	238	113	159	137.0	0.59	238	12.6	37.7	24.4	0.32
13 May	758	105	160	137.1	0.32	758	10.5	39.0	23.7	0.16
Total	996	105	160	137.1	0.28	996	10.5	39.0	23.9	0.15
Yearling Chinook, Bonneville releases										
2 May	239	116	202	149.0	1.11	239	14.4	84.8	33.1	0.79
11 May	245	119	203	151.4	1.06	245	15.6	78.8	31.9	0.73
19 May	244	124	202	147.1	0.74	244	16.6	82.6	29.5	0.49
27 May	244	122	218	151.2	0.92	244	14.8	93.8	31.0	0.71
Total	972	116	218	149.7	0.49	972	14.4	93.8	31.4	0.35
Subyearling Chinook, Bonneville releases										
16 Jun	245	97	134	109.4	0.42	245	8.3	22.9	12.7	0.15
22 Jun	245	95	141	111.2	0.63	245	8.2	28.2	13.6	0.24
27 Jun	245	96	128	110.6	0.34	245	8.4	20.9	12.8	0.13
2 Jul	245	97	131	111.1	0.42	245	8.2	24.7	12.7	0.15
7 Jul	243	96	136	110.0	0.36	243	8.6	23.5	12.1	0.13
12 Jul	245	94	141	107.5	0.52	245	7.2	27.6	12.0	0.20
17 Jul	244	96	148	109.9	0.62	244	8.1	30	12.6	0.23
22 Jul	245	94	155	108.5	0.64	245	8.3	33.5	12.3	0.25
Total	1957	94	155	109.8	0.18	1,957	7.2	33.5	12.6	0.07

Survival Estimates

Survival estimates from the JBF outfall at Bonneville Dam through the lower Columbia River estuary ranged from 0.573 to 0.841 for yearling Chinook and from 0.179 to 1.005 for subyearling Chinook (Table 4). Mean survival pooled across all releases was 0.665 (SE = 0.0542) for yearling and 0.632 (SE = 0.1122) for subyearling Chinook salmon. Mean detection probability at the primary array was not statistically different between spring (0.819, SE = 0.0316) and summer release groups (0.770, SE = 0.0381; $t = 0.822$, $P = 0.215$, $\alpha = 0.05$).

Pooled survival for the two releases of yearling Chinook salmon from the tailrace of Lower Granite Dam was 0.787 (SE = 0.0147) to the Snake River mouth (Ice Harbor Dam tailrace secondary array), and 0.488 (SE = 0.0351) from the Snake River through the estuary. Estimated FCRPS system-wide survival from release at Lower Granite Dam through the estuary primary array was 0.384 (SE = 0.0278) for the pooled total of both releases.

Table 4. Detection probabilities (*p*), and survival estimates (*s*) to the primary detection array by release date for acoustic-tagged yearling and subyearling Chinook salmon released to estimate survival from Lower Granite and Bonneville Dam through the lower Columbia River estuary, 2006.

Release date	Number released	Array name	Probability of detection on "estimation array"		Estimated survival to primary array	
			p	SE	*s*	SE
Yearling Chinook Lower Granite releases						
06 May	238	Ice Harbor secondary	0.893	0.0268	0.835	0.0281
13 May	758	Ice Harbor secondary	0.905	0.0151	0.772	0.0172
06 May	238	Estuary primary	0.686	0.0758	0.409	0.0492
13 May	758	Estuary primary	0.590	0.0540	0.379	0.0341
Yearling Chinook Bonneville releases						
02 May	239	Estuary primary	0.935	0.0312	0.657	0.0351
11 May	245	Estuary primary	0.833	0.0407	0.573	0.0362
19 May	244	Estuary primary	0.833	0.0393	0.841	0.0378
27 May	244	Estuary primary	0.862	0.0453	0.623	0.0403
Subyearling Chinook Bonneville releases						
17 June	245	Estuary primary	0.848	0.0360	0.914	0.0341
22 June	245	Estuary primary	0.730	0.0402	0.837	0.0376
27 June	245	Estuary primary	0.703	0.0434	1.005	0.0458
02 July	245	Estuary primary	0.802	0.0384	0.856	0.0367
07 July	243	Estuary primary	0.761	0.0445	0.671	0.0397
12 July	245	Estuary primary	0.741	0.0596	0.481	0.0428
17 July	244	Estuary primary	0.950	0.0487	0.194	0.0264
22 July	245	Estuary primary	0.615	0.1349	0.179	0.0410

Fish Behavior

For yearling Chinook salmon released at LGR, travel time from release to the primary array in the lower Columbia River estuary ranged from 6.7 to 35.3 d, with a mean of 13.0 d (SE = 0.23, Figure 5). Travel rate generally increased as fish moved downstream (Figure 6). Travel time from the Bonneville primary array (BON1) to the estuary arrays was similar for yearling Chinook salmon released at LGR and BON (Figure 7). BON1 was located approximately 22 km downstream of the Bonneville Dam JBF.

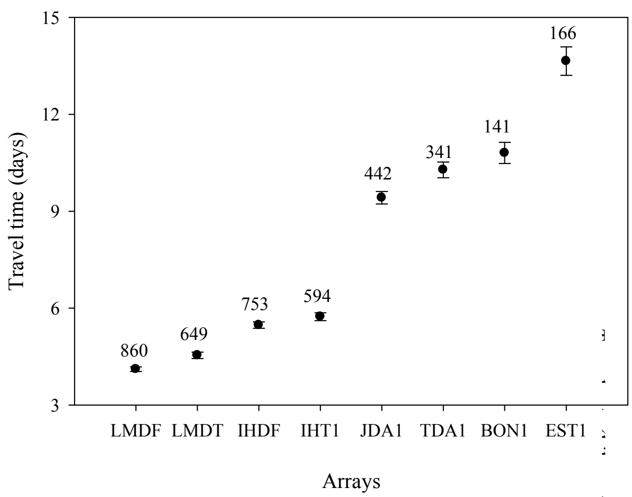

Figure 5. Mean travel time (days ± 1.96 × SE) for yearling Chinook salmon released at Lower Granite Dam to detection arrays in the Snake and Columbia Rivers. Numbers indicate sample sizes. Abbreviations listed below.

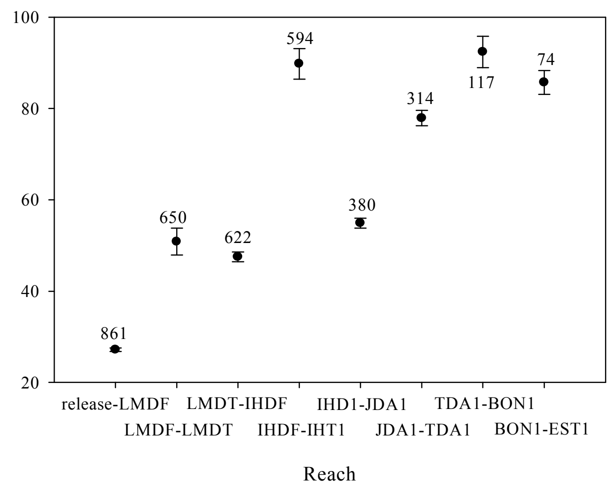

Figure 6. Mean travel rate (± 1.96 × SE) in kilometers per day for yearling Chinook salmon released at Lower Granite Dam through the various reaches on the Snake and Columbia Rivers. Numbers indicate sample sizes. Abbreviations listed below.

Abbreviations used for array location in Figures 5 and 6:		rkm
LMDF	Lower Monumental reservoir boat restricted zone (BRZ)	589.2
LMDT	Lower Monumental tailrace	578.5
IHDF	Ice Harbor forebay BRZ	538.1
IHT1	Ice Harbor tailrace primary	525.2
IHT2	Ice Harbor tailrace secondary	524.0
JDAE	John Day egress	339.2
JDA1	John Day tailrace primary	325.6
TDA1	The Dalles tailrace primary	275.6
BON1	Bonneville tailrace primary	208.8
EST1	Estuary primary	8.3

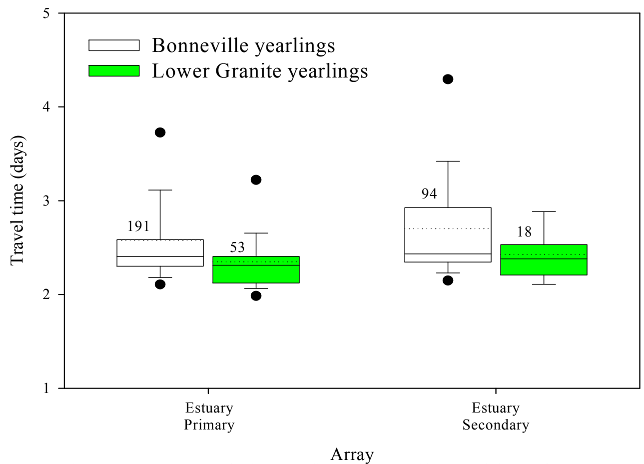

Figure 7. Travel time (d) for yearling Chinook salmon released downstream of Bonneville and Lower Granite Dams from the Bonneville primary array to the estuary arrays. Solid lines within boxes represent medians, dotted lines represent means, upper and lower limits of the box represent the 25th and 75th percentiles, whiskers represent the 10th and 90th percentiles, and dots represent the 5th and 95th percentiles. Numbers adjacent to boxes are sample sizes.

Cross-channel distribution of yearling Chinook salmon migrating past the estuary primary array was similar for fish released at Lower Granite and Bonneville Dam. The majority of yearling Chinook salmon were detected near the middle of the Washington side of the estuary primary array (Figure 8) and were detected primarily during daylight hours (Figure 9). Yearling Chinook salmon release at Lower Granite Dam were detected on the estuary primary array across all tide stages (Figure 10), although 67% of the fish were first detected during an outgoing tide (Table 5).

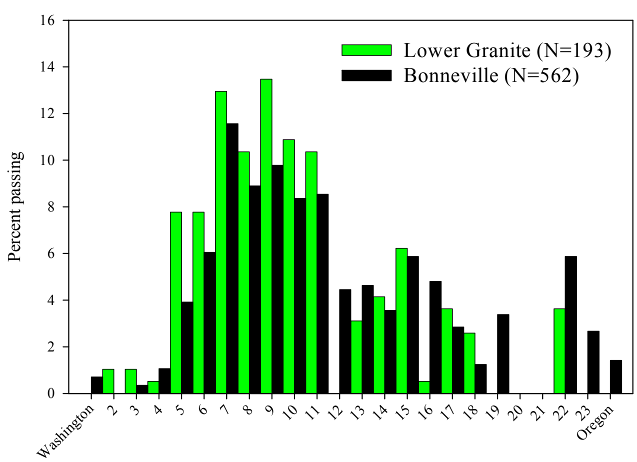

Figure 8. Cross-channel distribution of detections on the estuary primary array for yearling Chinook salmon released downstream of Lower Granite and Bonneville Dams.

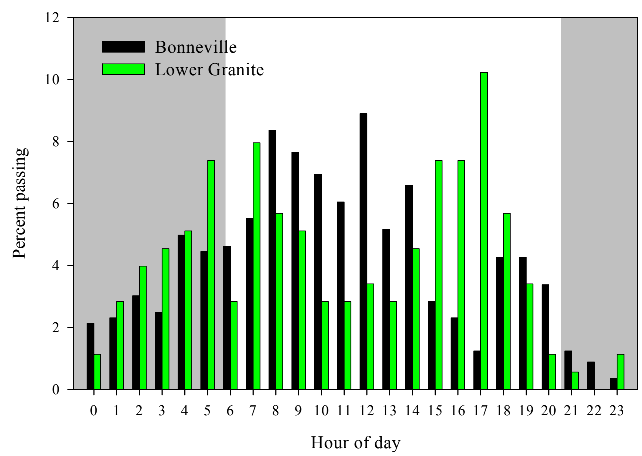

Figure 9. Time of arrival (24-h scale) of Bonneville and Lower Granite release groups of yearling Chinook salmon at the estuary primary array. Shaded areas represent approximate hours of darkness.

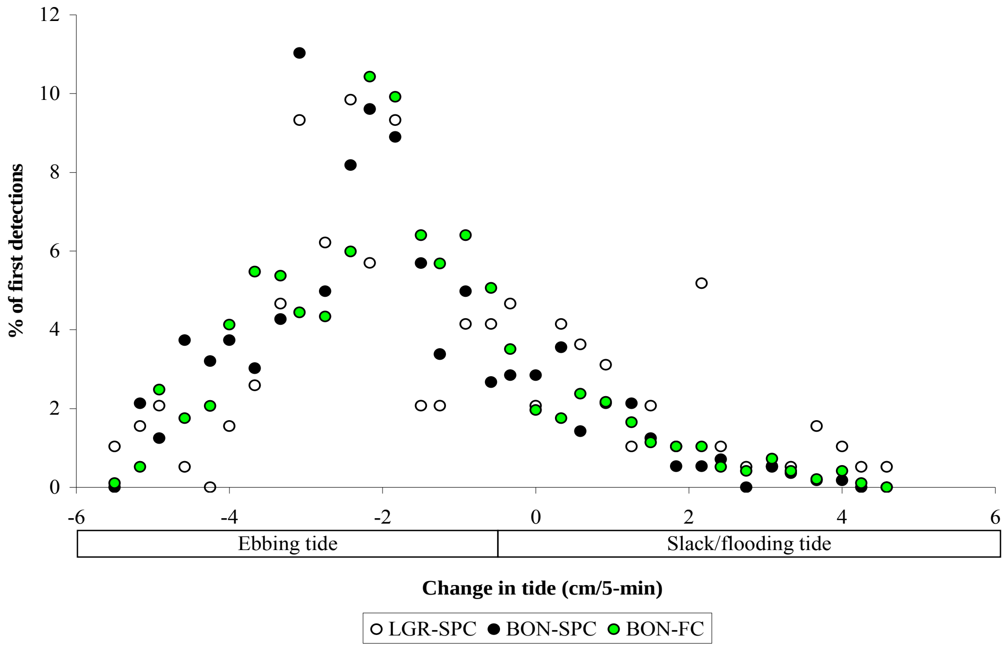

Figure 10. Percentage of first detections for yearling and subyearling Chinook salmon released below Bonneville Dam, and yearling Chinook salmon released below Lower Granite Dam, on the estuary primary array vs. change in tide elevation.

Table 5. Numbers and percentages of Chinook salmon detected on the primary array vs. tide conditions.

		Ebb tide		Flood tide	
Run type	Release location	n	%	n	%
Yearling	Lower Granite	129	66.8	64	33.2
Yearling	Bonneville	454	80.8	108	19.2
Subyearling	Bonneville	780	80.6	188	19.4
Total		1,363	79.1	360	20.9

Travel times for acoustic-tagged yearling Chinook salmon from release at Bonneville Dam to the primary array in the estuary ranged from 2.1 to 17.2 d (mean 4.1 d; SE = 0.1). Both variability of and mean travel time decreased over the season (Figure 11). For fish release from Lower Granite Dam, travel times from the primary array below Bonneville Dam (BON1) to the estuary primary array ranged from 2.0 to 3.4 d (mean 2.4 d, SE = 0.04). As with yearling Chinook salmon from Lower Granite Dam, yearling Chinook salmon released at Bonneville were first detected on acoustic arrays over a variety of tidal conditions, although 84% of first detections occurred during outgoing tides (Figure 10). Also like the their cohorts released from Lower Granite, the majority of yearling Chinook released from Bonneville (80%) were first detected during daylight hours (Figure 9), and detections were oriented towards the middle of the Washington side of the primary array (Figure 8).

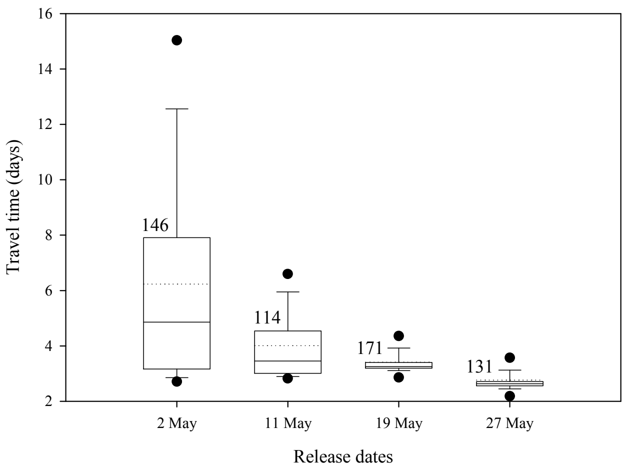

Figure 11. Travel time (d) from release to the estuary primary array for acoustic-tagged yearling Chinook salmon, 2006. Solid lines represent medians, dotted lines represent means, boxes show 25th and 75th percentiles, whiskers represent 10th and 90th percentiles, and dots represent 5th and 95th percentiles. Numbers adjacent to boxes are sample sizes.

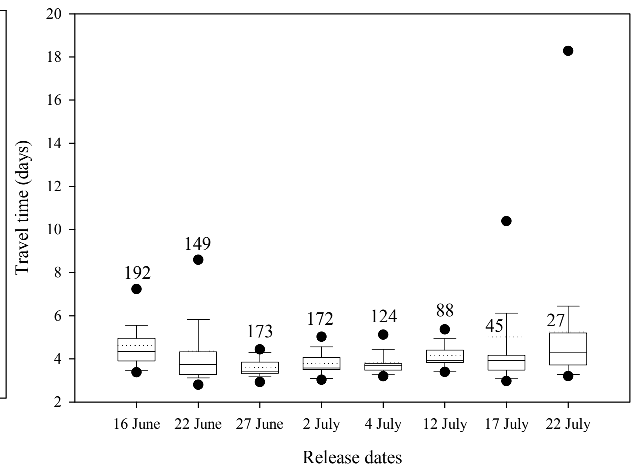

Figure 12. Travel time (d) from release through Bonneville Dam JBF to the estuary primary array for acoustic-tagged yearling Chinook salmon, 2006. Solid lines represent medians, dotted lines represent means, boxes show 25th and 75th percentiles, whiskers show 10th and 90th percentiles, and dots show 5th and 95th percentiles. Numbers adjacent to boxes are sample sizes.

Travel time for subyearling Chinook salmon from release at Bonneville Dam to the estuary primary array was 4.1 d on average (range = 2.5-25.6, SE = 0.04; Figure 12). Like yearling Chinook, the majority of subyearling Chinook salmon (74%) were first detected during daylight hours (Figure 13). Subyearling Chinook salmon also displayed a propensity for passing near the center of the Washington side of the primary array (Figure 14). PIT tags from 50 acoustic-tagged Chinook salmon were detected on the pair trawl operating at the upper end of the estuary near Jones Beach, Oregon (rkm 75). Of these 50 detections, 36 were yearling Chinook. Numbers of yearling and subyearling Chinook salmon detected on the pair trawl by release group are presented in Table 6.

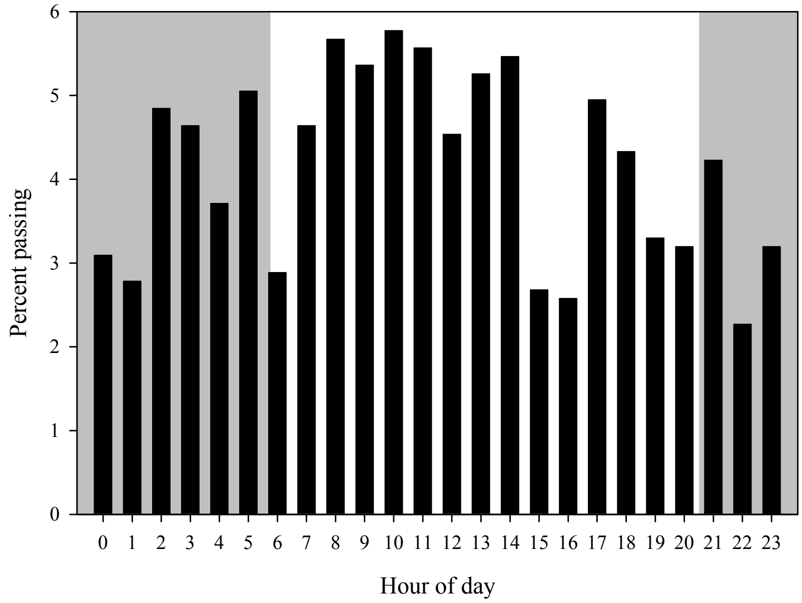

Figure 13. Percentage of acoustic-tagged subyearling Chinook salmon observed on the primary array receivers by hour during evaluation of juvenile salmonid survival through the lower Columbia River, 2006. Shaded areas represent approximate hours of darkness.

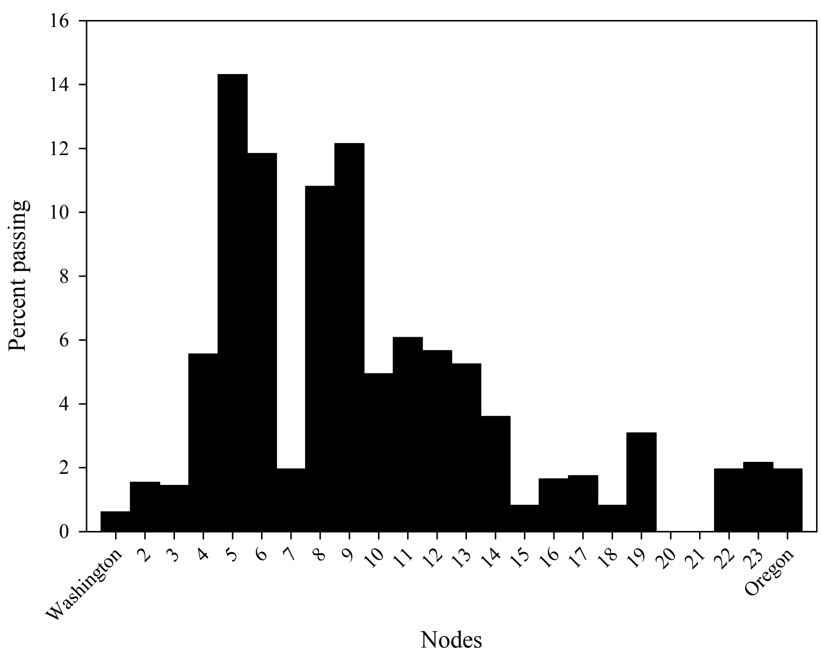

Figure 14. Cross-channel distribution of acoustic-tagged subyearling Chinook salmon detected on the primary receiver array during studies to evaluate juvenile salmonid survival through the Columbia River estuary, 2006. The navigation channel is between nodes 19 and 20.

Table 6. Numbers of Chinook salmon released at Lower Granite or Bonneville Dam and subsequently detected on the pair trawl in the upper Columbia River estuary near Jones Beach, Oregon (rkm 75) in 2006.

Release location (dam)	Release date	Number released	Number observed in pair trawl	Percent observed in pair trawl
Yearling Chinook				
Lower Granite	6 May	238	2	0.9
Lower Granite	13 May	758	4	0.5
Bonneville	2 May	239	3	1.3
Bonneville	11 May	245	12	4.9
Bonneville	19 May	244	4	1.6
Bonneville	27 May	244	11	4.5
Subyearling Chinook				
Bonneville	16 Jun	245		
Bonneville	22 Jun	245	8	3.3
Bonneville	27 Jun	245	3	1.2
Bonneville	2 Jul	245		
Bonneville	7 Jul	243		
Bonneville	12 Jul	245		
Bonneville	17 Jul	244	3	1.2
Bonneville	22 Jul	245		

For all yearling Chinook salmon detected on the pair trawl, travel time from the outfall at Bonneville Dam to Jones Beach ranged from 1.4 to 2.9 d (mean = 1.7 d, SE = 0.055) with a median of 1.6 d. Based on median travel times from Bonneville Dam to Jones Beach and from release to the estuary across all tagged fish groups, yearling Chinook salmon required approximately 1.7 d to travel between Jones Beach and the lower estuary. Mean migration rate over the first 156 km from the Bonneville Dam JBF outfall to Jones Beach was approximately 98 km d^{-1} for yearling fish detected on the pair trawl from all 4 spring releases combined. Estimated mean migration rate over the remaining 66 km from Jones Beach to the primary array was approximately 39 km d^{-1}, indicating that migration rate slowed as fish approached the estuary.

Median travel time for the 14 acoustic-tagged subyearling Chinook salmon detected on the pair trawl was 2.2 d from Bonneville Dam JBF outfall to detection on the pair trawl, and ranged from 1.9 to 2.3 d (mean = 2.1 d, SE = 0.037), yielding a mean migration rate of approximately 74 km d^{-1}. Estimated median travel rate from Jones Beach to the primary acoustic array for subyearling smolts was about 41 km d^{-1}.

Avian Predation

Of the 996 acoustic-and PIT-tagged yearling Chinook salmon released at Lower Granite Dam, PIT tags from 24 fish (2.4%) were recovered from five bird colonies on three islands: two in the mid-Columbia River and one in the estuary (Table 7).

Of acoustic- and PIT-tagged fish released at Bonneville Dam, PIT tags from 24 yearling and 49 subyearling Chinook salmon were recovered from two bird colonies on East Sand Island in the lower Columbia River estuary. These detections comprised 2.5% of the total number of yearling and total number of subyearling fish released (Table 7). Because less than 100% of PIT tags from fish consumed by birds are recovered, the 2.5% represents a minimum estimate of avian predation.

Table 7. Numbers of PIT tag codes from acoustic-tagged yearling Chinook salmon released to the tailrace of Lower Granite Dam with tags subsequently detected on piscivorous bird colonies, 2006.

	Yearling Chinook salmon released at Lower Granite Dam					
Release date	Number released	Crescent Island	Foundation Island	East Sand Island	Total	Total percent recovered
06 May	238	1	3	2	6	2.55
13 May	758	7	2	9	18	2.37
Totals	996	8	5	11	24	2.42

Of the 97 PIT-tag detections on bird colonies, 20 of these (25%) were from fish tagged with acoustic tags that had been previously detected on arrays in the estuary. Of these 20 tags, 2 were from yearling Chinook released at Lower Granite Dam, 2 were from yearling Chinook released at Bonneville Dam, and 16 were from subyearling Chinook released at Bonneville Dam. All 4 acoustic tags from yearling fish (100%) and 6 tags from subyearling fish (38%) had been detected only on the primary array. The remaining 10 tags from subyearling fish has been detected on both the primary and secondary arrays.

Table 8. Numbers of PIT-tag codes from acoustic-tagged yearling and subyearling Chinook salmon released at Bonneville Dam (Bonn 2 JBF outfall) that were subsequently recovered from piscivorous bird colonies on East Sand Island. 2006.

Release date	Number released	Observed on avian colony	
		n	(%)
Yearling Chinook			
2 May	239	7	2.9
11 May	245	4	1.6
19 May	244	2	0.8
27 May	244	11	4.5
Total/mean	972	24	2.5
Subyearling Chinook			
16 June	245	5	2.0
22 June	245	5	2.0
27 June	245	3	1.2
2 July	245	5	2.0
7 July	243	7	2.9
12 July	245	8	3.3
17 July	244	11	4.5
22 July	245	5	2.0
Total/mean	1,957	49	2.5
Combined total/overall mean	2,929	73	2.5

CONCLUSIONS

1. The pilot study to determine system-wide survival for acoustic-tagged yearling Chinook salmon released from Lower Granite Dam was successful. Mean survival of these study fish to the Columbia River estuary was 0.384 (SE = 0.028).

2. Based on pooled estimates from this study, acoustic-tagged yearling Chinook salmon survival through the lower Columbia River and estuary was 0.665 (SE = 0.055). This result was similar to survival estimated using PIT tags from Lower Granite Dam through Bonneville Dam (Smith et al. 2003).

3. Mean survival for acoustic-tagged subyearling Chinook salmon was estimated at. 0.632 (SE = 0.112).

4. Mean travel time from release at Bonneville Dam through the mouth of the Columbia River estuary was 4.1 d for both yearling and subyearling Chinook salmon.

5. Avian predation on acoustic-tagged yearling (2.5%) and subyearling (2.5%) Chinook salmon was similar to the predation rate for PIT-tagged yearling Chinook salmon. This was slightly higher than rates observed for PIT-tagged subyearling Chinook salmon, reported by Ryan et al. (2002).

RECOMMENDATIONS

1. This study provides only a second attempt at rigorous survival estimates for juvenile salmonids through the lower Columbia River. Continued effort over a number of years is essential to understanding the role of interannual variation in survival and behavior. Releases from the Bonneville Dam JBF outfall should be compared to mid-river releases at the same rkm.

2. Continuous testing, development, upgrade, and repair of acoustic receivers is needed. Autonomous nodes will benefit from internal electronics improvements to increase detection efficiency and improve mooring capability. The cabled array should be repaired and returned to service as soon as possible to facilitate real time, in-season monitoring capability.

3. Mobile tracking capability should be developed and protocols for mobile tracking established. These tools are needed to monitor fish behavior (migration routes, estuarine habitat use, etc.) in the lower river. Mobile tracking can help to determine whether some fish reside in the system past the life of the acoustic tag and to identify specific areas to determine causes of increased local mortality.

4. Consideration should be given to partitioning the lower river to determine whether mortality is consistent throughout the area or more confined to specific reaches.

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REFERENCES

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

Beamer, E. M., R. E. McClure, and B. A. Hyman. 1999. Fiscal Year 1999 Skagit River chinook restoration research. Project performance report of the Skagit System Cooperative. LaConner, Washington.

Bottom, D. L., C. A. Simenstad, J. Burke, A. M. Baptista, D. A. Jay, K. K. Jones, E. Casillas, and M. H. Schiewe. 2005. Salmon at river's end: the role of the estuary in the decline and recovery of Columbia River salmon. NOAA Technical Memorandum NMFS NWFSC 68.

Bradford, M. J. 1995. Comparative review of Pacific salmon survival rates. Canadian Journal of Fisheries and Aquatic Sciences 52:1327 1338.

Collis, K., D. D. Roby, D. P. Craig, B.A. Ryan, and R. D. Ledgerwood. 2001. Colonial waterbird predation on juvenile salmonids tagged with passive integrated transponders in the Columbia River estuary: vulnerability of different species, stocks, and rearing types. Transactions of the American Fisheries Society 130:385–396.

Collis, K., D. D. Roby, D. P. Craig, S. Adamany, J. Adkins, and D. E. Lyons. 2002. Colony size and diet composition of piscivorous waterbirds on the lower Columbia River: implications for losses of juvenile salmonids to avian predation. Transactions of the American Fisheries Society 131:537–550.

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

Dawley, E. M., R. D. Ledgerwood, T. H. Blahm, C. W. Sims, J. T. Durkin, R. A. Kim, A. E. Rankin, G. E. Monan, F. J. Ossiander. 1985. Migrational characteristics, biological observations, and relative survival of juvenile salmonids entering the Columbia River estuary, 1966 1983. Report of the National Marine Fisheries Service to the Bonneville Power Administration. BPA, Portland, Oregon.

Emmett, R. L., and M. H. Schiewe. 1997. Estuarine and ocean survival of Northeastern Pacific Salmon: proceedings of the Workshop. NOAA Technical Memorandum NMFS NWFSC 29.

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

Kareiva, P., M. Marvier, and M. McClure. 2000. Recovery and management options for spring/summer chinook salmon in the Columbia River basin. Science 290:977 979.

Ledgerwood, R. D., B. A. Ryan, E. P. Nunnallee, and J. W. Ferguson. 1999. Estuarine recovery of PIT tagged juvenile salmonids from the Lower Granite Dam transportation study, 1998. Report of the National Marine Fisheries Service to the U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington.

McComas, R. L., D. Frost, S. G. Smith, and J. W. Ferguson. 2005. A study to estimate juvenile salmonid survival through the Columbia River estuary using acoustic tags, 2002. Report of the National Marine Fisheries Service to the U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

McComas, R. L., L. Gilbreath, S. G. Smith, G. Matthews, J. W. Ferguson, G. A. McMichael, J. A. Vucelick, and T. Carlson. 2007. A study to estimate salmonids survival through the Columbia River Estuary using acoustic tags, 2005. Report of the National Marine Fisheries Service to the U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

McMichael, G. A., T. J. Carlson, J. A. Vucelick, R. S. Brown, G. R. Ploskey, R. L. McComas, E. E. Hockersmith, and B. P. Sandford. In review. Development of a new tool to investigate juvenile salmon movement and survival: the juvenile salmon acoustic telemetry system (JSATS). Fisheries.

National Marine Fisheries Service (NMFS). 2000. A standardized quantitative analysis of risks faced by salmonids in the Columbia River Basin. Cumulative Risk Initiative draft report, 7 April 2000. NOAA NMFS, Northwest Fisheries Science Center, Seattle, Washington.

Pritchard, D. W. 1967. What is an estuary; a physical viewpoint. American Association for the Advancement of Science 83:3–5.

Reimers, P. E. 1973. The length of residence of juvenile fall chinook in Sixes River, Oregon. Research Report of the Fisheries Commission of Oregon 4(2):43 p.

Rich, W. H. 1920. Early history and seaward migration of chinook salmon in the Columbia and Sacramento Rivers. U.S. Bureau of Fisheries, Bulletin 37:1 74.

Ryan B. A., A. S. Cameron, E. P. Nunnallee, and J. W. Ferguson. 2005. Detection of passive integrated transponder (PIT) tags on piscivorous bird colonies in the Columbia River Basin, 2002. Report of the National Marine Fisheries Service to the U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington.

Roby D. D., K. Collis, J. Y. Adkins, C. Couch, B. Courtot, R. Lord, A. Evans, M. Hawbecker, D. E. Lyons, and Y. Suzuki. 2005. Research, monitoring, and evaluation of avian predation on salmonid smolts in the lower and mid-Columbia River: Draft 2005 season summary. Available at http://columbiabirdresearch.org (March 2008).

Schreck, C. B. and T. P. Stahl. 1998. Evaluation of migration and survival of juvenile salmonids following transportation; MPE W 97 4. Draft annual report for 1998. Oregon Cooperative Fish and Wildlife Research Unit, Corvallis, OR, 50 p.

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

Sherwood, C. R. and J. S. Greagar. 1990. Sedimentary geology of the Columbia River estuary. Progress in Oceanography 25:15 79.

Sherwood, C. R., D. A. Jay, R. B. Harvey, P. Hamilton, and C. A. Simenstad. 1990. Historical changes in the Columbia River estuary. Progress in Oceanography 25:299 357.

Simenstad, C. A., D. A. Jay, C. R. Sherwood. 1992. Impacts of watershed management on land margin ecosystems: the Columbia River estuary as a case study. *In*: R. Naimen, ed., New Perspectives for Watershed Management—Balancing long term Sustainability with Cumulative Environmental Change, Springer Verlag, New York, pp. 266 306.

Smith, S. G., W. D. Muir, R. W. Zabel, D. M. Marsh, R. McNatt, J. G. Williams, and J. R. Skalski. 2004. Survival estimates for the passage of spring migrating juvenile salmonids through Snake and Columbia River dams and reservoirs, 2003 2004. Report of the National Marine Fisheries Service to the Bonneville Power Administration, Portland, Oregon. Available www.efw.bpa.gov/searchpublications/ (April 2008).

Thorpe, J. E. 1994. Salmonid fishes and the estuarine environment. Estuaries. 17(1A):76 93.

Weitkamp, L. A. 1994. A review of the effects of dams on the Columbia River estuarine environment, with special reference to salmonids. Report of the National Marine Fisheries Service to the Bonneville Power Administration, Portland, Oregon.