A Study to Estimate Salmonid Survival through the Columbia River Estuary using Acoustic Tags, 2005

R. Lynn McComas,[1] Lyle G. Gilbreath,[1] Stephen G. Smith,[1] Gene M. Matthews,[1]
John W. Ferguson,[1] Geoffrey A. McMichael,[2] Jessica A. Vucelick,[2] and Thomas Carlson[2]

Report of research by

[1]Fish Ecology Division
Northwest Fisheries Science Center
2725 Montlake Boulevard East
Seattle, Washington, 98112-2097

and

[2]Battelle Pacific Northwest National Laboratory
620 SW 5th Ave., Suite 810
Portland, Oregon 97204

for

Portland District
U.S. Army Corps of Engineers
P.O. Box 2946
Portland OR 97208-2946
Delivery Order E86910060

and

Fish Ecology Division
Northwest Fisheries Science Center
National Marine Fisheries Service
National Oceanic and Atmospheric Administration
2725 Montlake Boulevard East
Seattle, Washington 98112-2097

October 2007

EXECUTIVE SUMMARY

In 2005, NOAA Fisheries, with Battelle Pacific Northwest National Laboratory and the U.S. Army Corps of Engineers, initiated the second phase of a multi-year project to estimate juvenile salmonid survival through the lower Columbia River and estuary. A total of 870 yearling and 1,217 subyearling run-of-the-river Chinook salmon *Oncohrhynchus tshawytscha* tagged with surgically implanted acoustic transmitters and passive integrated transponder (PIT) tags were released through the Bonneville Dam juvenile bypass facility outfall into the Columbia River. Yearling Chinook salmon were released 4 May–1 June (4 releases); subyearling fish were released 18 June–16 July (5 releases). Mean survival, assessed using the single-release estimation model, ranged from 0.564 (SE = 0.0683) to 0.873 (SE = 0.0545) for yearling release groups, and from 0.150 (SE = 0.245) to 0.748 (SE = 0.0497) for subyearling releases. Pooled across all releases, mean survival estimates were 0.754 (SE = 0.1797) for yearling Chinook salmon and 0.653 (SE = 0.2446) for subyearling Chinook salmon.

Median travel time by release from the outfall at river kilometer (rkm) 231.3 to the primary array (rkm 9) was 2.97 d (range 2.9-5.8 d) for yearling Chinook salmon, resulting in a migration rate of approximately 75.0 km/d. From PIT-tag detections using a pair trawl, the migration rate may have been differential for yearling smolts, which tended to slow on approaching the estuary. Subyearling Chinook salmon median travel time was 4.1 d, with a migration rate of about 53 km/d. The majority of detections occurred during daylight and across all tide stages for both species. Avian predation, evidenced by PIT-tag recoveries from estuary bird colonies, accounted for 4.5 and 4.4% of yearling and subyearling Chinook salmon mortality, respectively.

CONTENTS

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 outmigration 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 the 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 *O. kisutch*, sockeye *O. nerka*, and Atlantic salmon *Salmo salar*) move through estuaries and out to sea quickly, compared to the slower moving ocean-type salmon migrants.

Most of our knowledge of how salmonids utilize estuaries is limited to smaller systems that can be more readily sampled than the Columbia River estuary. 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. Reimers (1973) found that fall Chinook salmon (ocean type) 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 the fish sampled during July had resided in the estuary from 2 to 6 weeks (Jen Burke, Oregon Department of Fish and Wildlife, Pers. commun). Subyearling Chinook salmon attained 20 to 66% of their fork length while in the estuary.

In contrast, in more recent times, where hatchery fish dominated the juvenile population, Dawley et al. (1985) noted that movement rates through the estuary were similar to rates from the 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 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 for spring/summer Chinook salmon PIT tagged and released at Lower Granite Dam to migrate in-river, and fish transported to below Bonneville Dam and released. PIT-tagged fish detected at Bonneville Dam had significantly faster travel speeds (98 km/d) than those released from a transportation barge below Bonneville Dam (73 km/d). 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. Hydroelectric generation facilities (dams) have 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; 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 dam operations on migrant salmonids have not been evaluated.

The potential for delayed mortality in 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 2000). The authors found that 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. Use of smolt-to-adult ratios (SARs) calculated by the Plan for Analyzing and Testing Hypotheses (PATH) in the sensitivity analysis produced similar results (NMFS 2000).

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 in order 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, Battelle Pacific Northwest National Laboratories, and the U.S. Army Corps of Engineers 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 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 this size to assess survival through the lower Columbia River. These include 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 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 that would allow tracking and recapture of tagged individuals migrating through the entire study area.

Given the ostensibly 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 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 ≥92 mm (3.5 in) fork length (FL) at Bonneville Dam.

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). Termed the Juvenile Salmonid Acoustic Technology 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, approximate linear transects across the stream. Each transect is 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 the completion of development and evaluation in 2004, NOAA Fisheries, in partnership with Batelle's Pacific Northwest Laboratory, initiated the second phase of the multi-year project to estimate juvenile salmonid survival through the lower Columbia River and estuary. This paper is a report of initial assessments using micro-acoustic tags and fully populated primary and secondary JSATS detection arrays during 2005 to evaluate run-of-the-river yearling and subyearling Chinook salmon survival through the lower Columbia River and estuary.

METHODS

Study Area

The study area for this work includes the free-flowing mainstem Columbia River and its 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 low of 2,970 m^3s^{-1} during late summer and fall to 17,000 m^3s^{-1} during the spring freshet period, with a mean annual decrease of about 280-570 m^3s^{-1} due to irrigation removal and climate change. Sediment discharge under modern conditions is about 7.6×10^6 mt^3 y^{-1}, about 45% of which is sand (Sherwood et al. 1990). The authors 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 sea water is measurably diluted with fresh water derived from land drainage (Pritchard 1967). Though the upper limit of salt water incursion reaches slightly past Harrington Point at rkm 37 (Sherwood and Greagar 1990), tidal effects are observable as far inland as Longview, WA, (rkm 104) and measurable at Bonneville Dam (rkm 235). The estuary hosts four major bays and contains numerous islands of natural and man-made origin, as well as extensive intertidal and supratidal areas (Sherwood et al. 1990). Islands constructed of dredge spoils and extensive dikes are the most prominent man-made structures.

Collis et al. (2001) estimated that 9 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 spoils site at rkm 35, contained over 16,000 breeding pairs of terns, which were estimated to be dependant on salmonids for 74% of their diet (Collis et al. 2002). Subsequent relocation efforts successfully moved a majority of these birds to East Sand Island, another dredge spoils site at rkm 10, where a colony of about 8,500 breeding pairs were established by 2002.

In addition to the terns, Ryan et al (2005) cited 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. The colony of cormorants on Rice Island has decreased from 1,082 birds in 1998 (Collis et al. 2002) to no nesting pairs detected (Roby et al. 2005) over the same period.

Detection Arrays

Primary Array

To encompass the portion of the study area with the 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 (Figure 1) at approximately rkm 9. Initially, this deployment was comprised of 22 bottom-mounted nodes cabled to shore for power and data communications. Cabled nodes were 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). A second array 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).

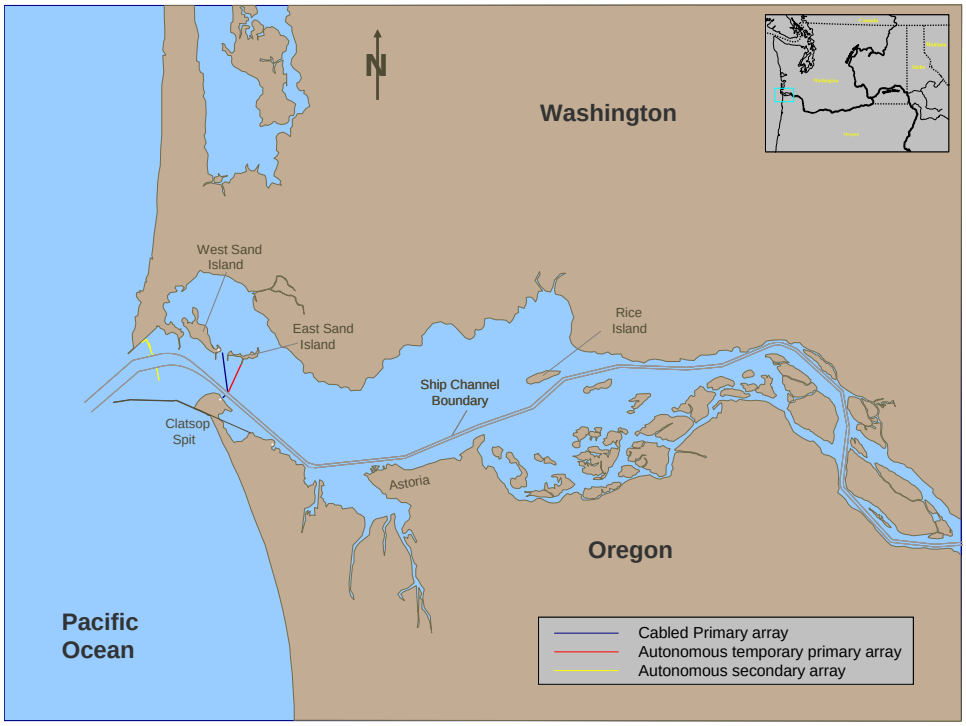


Figure 1. Columbia River estuary showing the locations of acoustic receiver arrays used to detect acoustically tagged juvenile Chinook salmon during studies to estimate juvenile salmonid survival through the lower Columbia River, 2005.

Individual cabled-array nodes were comprised of a node electronics assembly (NEA) enclosed in a cylindrical pressure vessel fitted with through-hull communications/power ports for cable and hydrophone connectors. The NEA was housed in an anchor to maintain proper upright attitude of the hydrophone located at the upper end of the pressure vessel (Figure 2).

Data was communicated to one of two shore stations located on Clatsop Spit (south array, 3 acoustic receiver nodes) and West Sand Island (north array, 19 acoustic receiver nodes). Each shore station consisted of two trailers housing batteries for powering the system, a computer center, and radio transmitters for external communications. Primary power was provided through the bank of 10 deep-cycle, lead-acid automotive batteries which were charged as necessary by a propane generator.

The south cabled array section functioned over the entire spring and summer juvenile migration period. However, the northern portion of the cabled primary array failed due to a short in the power connectors soon after deployment. To maintain project integrity, a temporary primary array of autonomous nodes was deployed as a replacement for the north section of the cabled array.

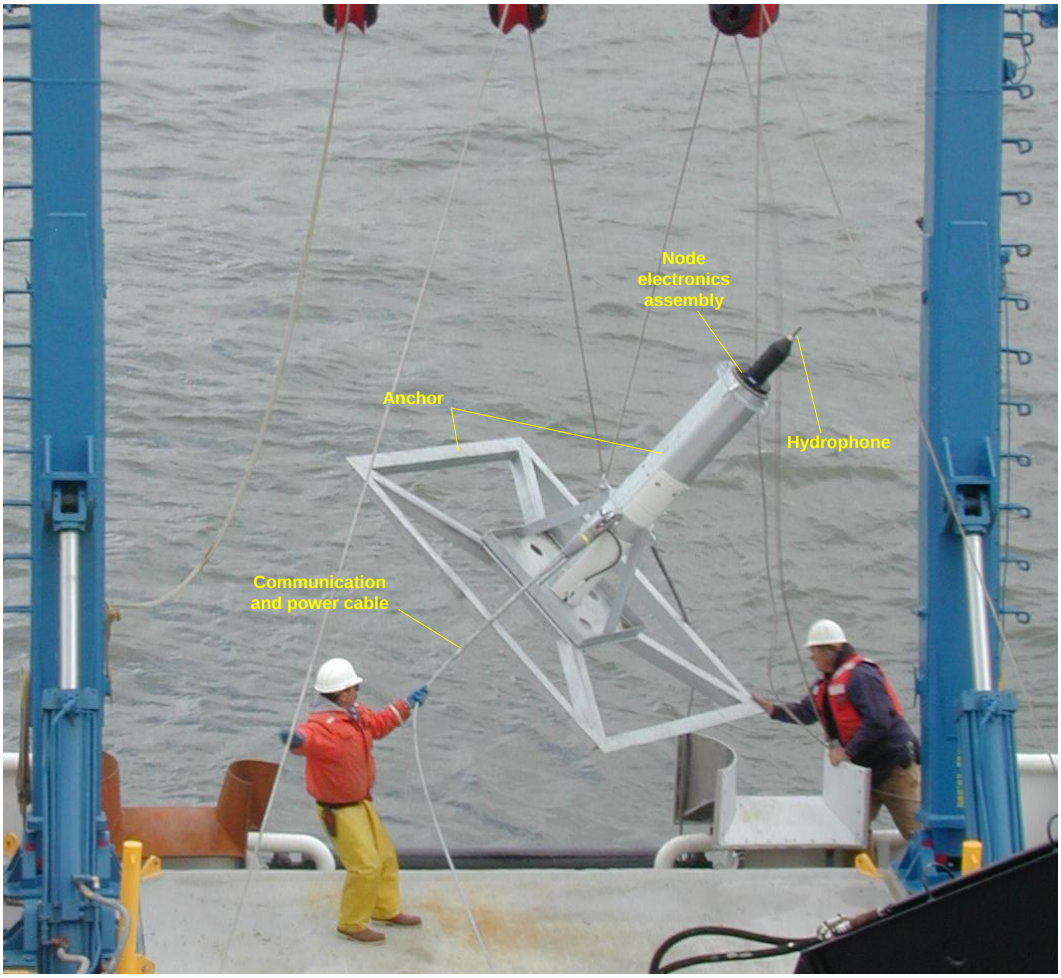


Figure 2. Major components of a cabled acoustic node used to detect signals from acoustically tagged, migrant juvenile Chinook salmon during survival studies in the Columbia River estuary, 2005. The illustration shows the node being placed in position from the deployment vessel.

Autonomous nodes consisted of electronics, on-board battery power (30-d battery life), data storage (256 MB CompactFlash), and hydrophones housed in 1.2-m-long × 15-cm-diameter PVC tubes. These were attached to 68-kg anchors with 3.7-m-long bungee moorings. An acoustic release (InterOcean Systems, Inc.[†] Model 111) coupled between the mooring and the node on a 0.9-m lead allowed the node and release to be retrieved for periodic servicing (data retrieval and battery replacement).

The node was attached to the lead by a 2.4-mm vinyl-coated stainless steel cable bridle. The acoustic release had a tag line canister containing 45 m of 4.7-mm-diameter line connecting the release to the anchor, which allowed the nodes to surface when the acoustic release was activated. From the node bridle, a 9.5-mm-diameter line ran to the surface and terminated in three 15.2-cm-diameter, 35.6-cm-long yellow surface buoys with 4.8 kg buoyancy each. A similar yellow subsurface buoy was placed on the same line approximately 5.5 m above the node. The total rigging length was designed to be approximately two times the depth at each site.

To preclude entanglement, the temporary replacement array was placed approximately 1 km upstream from the original cabled system (Figure 1). The replacement array consisted of 14 nodes deployed along a transect originating at the end of the easternmost pile dike on East Sand Island (46°14.9333’ N, 123°57.1949’ W) and ending at the ship channel near the southern terminus of the cabled array.

The temporary array was in place from early May through 13 July. The northern section of the cabled array was repaired and put back in service on 21 June and functioned well through August.

Secondary Array

The secondary array consisted exclusively of 29 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 8 nodes on the Oregon (south) side of the navigation channel, and the remaining 21 on the Washington (north) side of the channel (Figure 1).

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

To deploy the autonomous nodes, all rigging and equipment components except the anchor were assembled and loaded onto a 28-ft deployment vessel. Deployment locations were plotted on an electronic chart and located during physical deployment using the global positioning system (GPS) coordinates from the chart. 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 new GPS point was recorded.

To recover the equipment, we navigated to the GPS position and triggered the acoustic release. When the equipment came to the surface, we hooked the 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.

The 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. Table 1 shows the deployment, servicing, and removal schedule for autonomous nodes in 2005. The temporary primary array was removed approximately 2 weeks after the cabled array was repaired.

Table 1. Dates of autonomous node deployment, servicing, and removal during studies to evaluate juvenile salmonid survival from Bonneville Dam through the Columbia River estuary, 2005.

Array position	Initial deployment date	Service dates	Final retrieval date
Primary (temporary)	25-26 April, 2 May	23-25 May 21-23 June	6-10 July
Secondary	4-9 April	3-6 May 7-9 June 6-10 July	16-18 August

Tagging Operations

All Chinook salmon used to estimate survival through the lower estuary using acoustic tags in 2005 were captured, tagged, and released at the Bonneville Dam Juvenile Bypass Facility (JBF). Four groups of 250 yearling Chinook and five groups of 250 subyearling Chinook salmon were obtained from the run-of-the-river population passing through the JBF. Fish were collected by personnel of the Pacific States Marine Fisheries Commission Smolt Monitoring Program (SMP) on the day prior to acoustic tagging. On some collection dates, the SMP sample rate was increased to enable collection of the 250-fish groups. However, sufficient numbers of study fish were normally available so that the entire group was a subsample of the daily SMP sample without increasing the sample rate. Study fish were held overnight in a 455-L tank and supplied with flow-through river water prior to tagging.

Prior to surgery, fish were placed in an anesthetic bucket containing a solution of 80-100 mg/L tricane 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 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 incision approximately 8–10 mm in length was made 2-5 mm from and parallel to the mid-ventral line between the pelvic and pectoral girdles. A PIT tag (Biomark model TX1411ST 12.5 × 2 mm; 0.06 g) was inserted into the peritoneal cavity followed by an acoustic transmitter (Sonic Concepts model E101, 19 × 5 mm; 0.63 g in air; 0.4 g in water). 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 anesthesia, acoustically 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 2 gpm during the holding period. Between 7:00 and 10:00 am on the day following tagging, mortalities, if any, were removed from the holding containers, and a release group of study fish was released directly into the JBF flume, approximately 150 m upstream from the outfall into the Columbia River (Table 2).

Table 2. Numbers of acoustically tagged yearling and subyearling Chinook salmon released at the Bonneville Dam JBF outfall during studies to estimate juvenile salmonid survival through the lower Columbia River and estuary, 2005. All fish had acoustic and PIT tags concurrently implanted during surgery. The number of tags available on 24 May was reduced due to the theft of 84 acoustic tags.

Release date	Release location	Number released
	Yearling Chinook salmon	
4 May	Bonn II JBF outfall	244
12 May	Bonn II JBF outfall	240
24 May	Bonn II JBF outfall	161
1 June	Bonn II JBF outfall	245
Sbtotal		890
	Subyearling Chinook Salmon	
18 June	Bonn II JBF outfall	238
25 June	Bonn II JBF outfall	245
7 July	Bonn II JBF outfall	245
9 July	Bonn II JBF outfall	245
16 July	Bonn II JBF outfall	244
Sbtotal		1,217
Total		2,107

Of the total fish tagged on a given date, 5 were retained to evaluate long-term tagging effects and growth in length and weight. 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. To assess tag longevity, the function of acoustic tags explanted from retention fish was verified daily until failure.

Data Processing

Data collected by the autonomous nodes were recorded as a single text file on CompactFlash 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 on the flash media as they were received. Detection data included individual transmitter code, time stamp, received signal strength indicator (RSSI), and a calculated measure of background noise (RxThreshold). The file was transferred to a laptop computer following recovery from the node after 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 seemingly valid codes that did not meet criteria to be considered a valid detection), a series of rules was implemented during processing. This step-wise filter process included the following sequence of steps resulting in a file of valid detection data:

1) Each code detection was compared to a list (lookup table) of tags actually implanted and released. Only codes from tags that had been released were retained for the next step.
2) Only tag codes detected after they were released were retained.
3) Signal-to-noise ratio was analyzed as RSSI/RxThreshold. Only codes with an RSSI that was at least 0.75 times higher than the RxThreshold were retained.
4) Time of detections was calculated. To pass the final filter criterion required a) at least two consecutive detections with the correct time spacing (5 sec >spacing>4 sec) between detections, or b) 3 valid detections within 60 sec.

This final criterion applied to detections on only one node.

From the valid detection file, detection histories were analyzed 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-min 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 and secondary detection arrays. Counts of detections were then plotted on the same graph as the tides.

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 on either the primary or secondary arrays. A count of fish for each hour (independent of day or night) was then plotted. Day was considered to begin half an hour before sunrise and end half an 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 abandoned 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 conventional statistical models for mark-recapture data from a single group of marked animals (Cormack 1964; Jolly 1964; Seber 1965). This model is known by various names, including the CJS model and the single-release (SR) model. The model is simple when there are only two detection opportunities for each marked animal, as with the data for this study. For purposes of survival estimation, detection data are summarized in terms of the "detection history" of each marked fish. With only two opportunities for detection, the possible detection histories for tagged fish are:

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

To estimate survival for a release group, that is, a group of tagged fish released at a certain time, counts of fish in the group within each of the detection histories were used and denoted as n_{00}, n_{01}, n_{10}, and n_{11}, along with the total number of fish released, denoted as R.

The proportion of fish released and subsequently 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 were independent events, the joint probability of both events occurring was calculated as the simple product of the two probabilities. Thus, the proportion detected on the primary array was an estimate of SP.

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 was estimated independently by assuming that fish that survived to the secondary array and were detected there ($n_{01} + n_{11}$) represented a random sample of all fish from the group that were alive as they passed the primary array. Detection probability on the primary array was then estimated as the proportion of fish detected on the secondary array that had also been 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 surviving between the two arrays and detection on the secondary array.

Equipment Efficiency

For autonomous nodes, we examined the percentage of expected beacon detections vs. tide stage over short (2-4 tide cycles) and long (1 month) periods. We looked at signal-to-noise ratios of the autonomous nodes and compared our findings with data from the cabled array, especially where there was an autonomous node very near a node in the cabled array.

RESULTS AND DISCUSSION

Length and weight frequency distributions of Chinook salmon implanted with acoustic transmitters in 2005 are presented in Appendix Figures 1 and 2. Of the 896 yearling Chinook salmon released with implanted microacoustic tags, 475 (53%) were detected on acoustic receiver arrays in the lower Columbia River estuary (Table 3). Tagged yearling fish ranged from 116 to 226 mm FL, with a mean length of ≈153.8 mm (SE = 0.50). Mean length of yearling Chinook salmon detected in the estuary was significantly greater for detected (154.9 mm, SE = 0.523) than for non-detected fish (152.7 mm, SE = 0.721; $t = 2.16$, $P = 0.031$, $\alpha = 0.05$).

A total of 563 (46%) of the 1,212 acoustically tagged subyearling Chinook salmon were detected following release. Lengths ranged from 96 to 140 mm (mean = 109.4 mm, SE = 0.217), and as with yearling fish, mean length of subyearling Chinook salmon detected in the estuary (110.1 mm, SE = 0.327) was significantly greater that of fish not detected (108.7 mm, SE = 0.298; $t = 3.209$, $P = 0.001$, $\alpha = 0.05$).

With a 0.63-g tag, tag-weight (in air) to body-weight ratio ranged from 0.6 to 4.8% (mean = 2.1%, SE = 0.018) for yearling Chinook salmon, and from 2.0 to 7.9% (mean = 5.2%, SE = 0.028) for subyearling Chinook salmon. For subyearling fish, this was somewhat higher than the recommended 5% tag-weight to body-weight ratio. However, residual tag weight in water (0.4 g) to body-weight ratio ranged from approximately 0.4 to 3.0% (mean = 1.3%, SE = 0.012) for yearling Chinook and from 1.3 to 5.0% (mean = 3.3%, SE = 0.018) for subyearling Chinook.

Table 3. Descriptive statistics in length and weight by release date for acoustically 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, 2005.

		Release date										
		Yearling Chinook salmon					Subyearling Chinook salmon					
Variable	Descriptor	5/4	5/12	5/24	6/1	Total	6/18	6/25	7/2	7/9	7/16	Total
Length (mm)	n	244	240	161	245	890	238	245	245	245	244	1217
	minimum	127	122	116	127	116	98	96	97	96	98	96
	mean	145.7	154.2	154.3	161.2	153.8	109.8	107.7	105.8	111.3	112.4	109.4
	SE	0.52	1.01	1.31	0.93	0.50	0.45	0.37	0.33	0.53	0.61	0.21
	maximum	175	226	216	218	226	133	137	123	145	147	147
Weight (g)	n	244	240	161	244	890	238	245	245	245	244	1217
	minimum	18.9	14.8	13.2	18.9	13.2	9.0	8.1	8.0	8.2	9.0	8.0
	mean	29.2	32.8	30.9	35.9	32.3	13.5	11.8	11.1	13.1	13.9	12.7
	SE	0.33	0.76	0.95	0.71	0.35	0.17	0.13	0.11	0.21	0.23	0.08
	maximum	47.0	113.7	95.1	101.4	113.7	24.9	23.6	20.7	30.1	31.2	31.2

Survival Estimates

Single-release survival estimates for acoustically tagged Chinook salmon from Bonneville Dam JBF outfall through the lower Columbia River estuary ranged from 0.564 (SE = 0.0683) to 0.873 (SE = 0.0545) for yearling fish and from 0.150 (SE = 0.0245) to 0.748 (SE = 0.0497) for subyearling fish (Table 4). Weighted mean CJS estimates were 0.754 (SE = 0.179) and 0.653 (SE = 0.246) totaled across all yearling and subyearling Chinook salmon releases, respectively. Weighted mean detection probability at the primary array was substantially lower for spring (0.630, SE = 0.0771) than for summer release groups (0.896, SE = 0.0792). Detection histories for all acoustically tagged Chinook salmon are presented in Appendix Table 1.

Fish Behavior

Acoustically tagged yearling Chinook salmon from all spring releases were first detected on acoustic arrays over a variety of tidal conditions (Figures 3 and 4). The majority (68%) of first detections occurred during daylight hours (Figure 5), and detections were somewhat evenly distributed across the primary array (Figure 6). As with yearling fish, the majority of subyearling Chinook salmon (75%) were first detected during daylight hours (Figure 7) across all tide stages (Figures 8 and 9). However, there was a propensity for subyearling fish to pass near the center of the Washington side of the primary array (Figure 10).

Excluding outliers, median travel time for acoustically tagged yearling Chinook salmon by release (Figure 11) from Bonneville Dam to the primary array was 2.97 d (range 2.9-5.8 d, mean = 3.6 d, SE = 0.827). Median migration rate from release at the Bonneville Dam JBF outfall (rkm 231.3) to the primary estuary array was approximately 75.0 km/d (mean = 66.5 km/d, SE = 10.910, range 38.4–77.7 km/d).

Subyearling Chinook salmon travel times by release were somewhat longer than for yearling fish, ranging from 4.2 to 5.1 d (mean = 4.2 d, SE = 0.274), with a median of 4.1 d (Figure 11). Median migration rate was 53.0 km/d (mean = 53.4 d, SE = 3.163), and ranged from 43.5– 59.6 km/d across all 5 releases.

Table 4. Detection histories, primary array detection probabilities, and survival estimates to the primary detection array by release date for micro-acoustically tagged yearling (YCS) and subyearling (FC) Chinook salmon released to estimate juvenile salmonid survival from Bonneville Dam through the lower Columbia River estuary, 2005. Detection histories are denoted: 00--not detected following release, 10--detected only on the primary array, 01--detected only on the secondary array, and 11--detected on both arrays. Total values represent means weighted across all releases for yearling Chinook salmon (Subtotal, all YCS), subyearling Chinook salmon (Subtotal, all FC), and all acoustically tagged Chinook salmon released (Total).

Species	Release date	Number released	Detection histories				Estimated detection probability on primary array	Standard error of detection probability estimate	Estimated survival to primary array	Standard error of survival estimate
			00	10	01	11				
YCS	5/5/2005	244	146	55	18	25	0.581	0.0752	0.564	0.0683
YCS	5/12/2005	240	98	62	24	56	0.700	0.0512	0.702	0.0475
YCS	5/24/2005	161	96	21	27	17	0.386	0.0734	0.611	0.0944
YCS	6/1/2005	245	75	68	40	62	0.608	0.0483	0.873	0.0545
Subtotal, all YCS		890	415	206	109	160	0.630	0.0771	0.754	0.1797
FC	6/18/2005	238	80	64	14	80	0.851	0.0367	0.711	0.0358
FC	6/25/2005	245	85	109	9	42	0.824	0.0534	0.748	0.0497
FC	7/2/2005	245	177	34	7	27	0.794	0.0693	0.314	0.0360
FC	7/9/2005	245	103	60	5	77	0.939	0.0264	0.595	0.0333
FC	7/16/2005	244	209	21	1	13	0.929	0.0688	0.150	0.0245
Subtotal, all FC		1217	654	288	36	239	0.896	0.0792	0.653	0.2446
Total		2107	1069	494	145	399	0.852	0.2548	0.690	0.2338

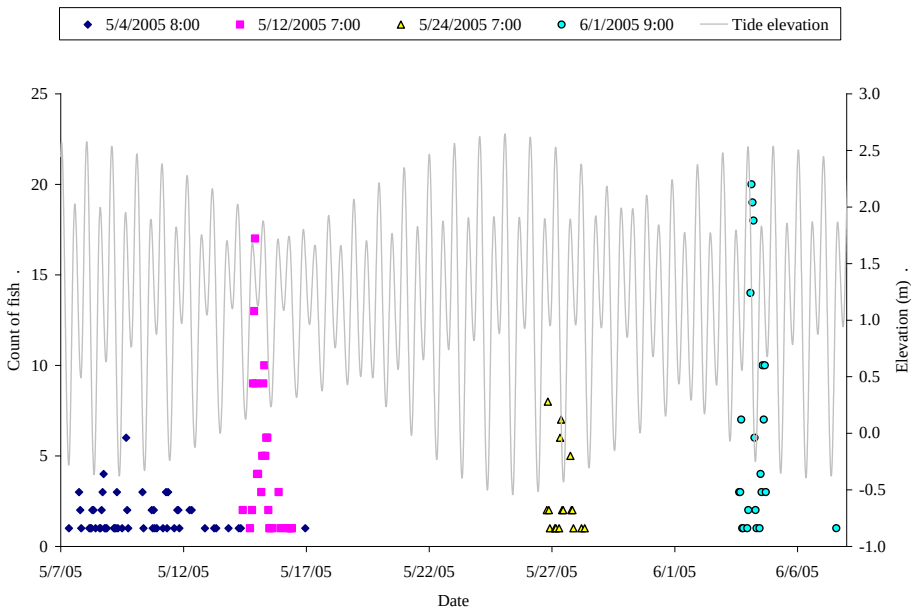


Figure 3. Hourly detections of yearling Chinook salmon on the primary array by release group and tide elevation for fish released from Bonneville Dam to estimate juvenile salmonid survival through the Columbia River estuary, 2005.

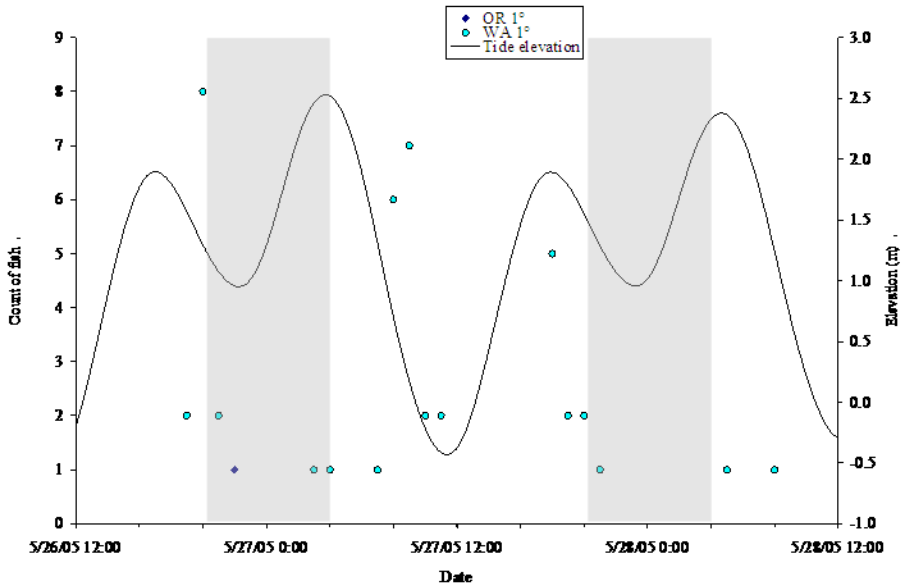


Figure 4. Detections of yearling Chinook salmon from the third release group on the primary array by nodes located on the Washington (WA 1) or Oregon (OR 1) side of the navigation channel during evaluation of juvenile salmonid survival through the lower Columbia River estuary, 2005. Shaded areas represent hours of darkness. Tide elevation is represented by the solid line.

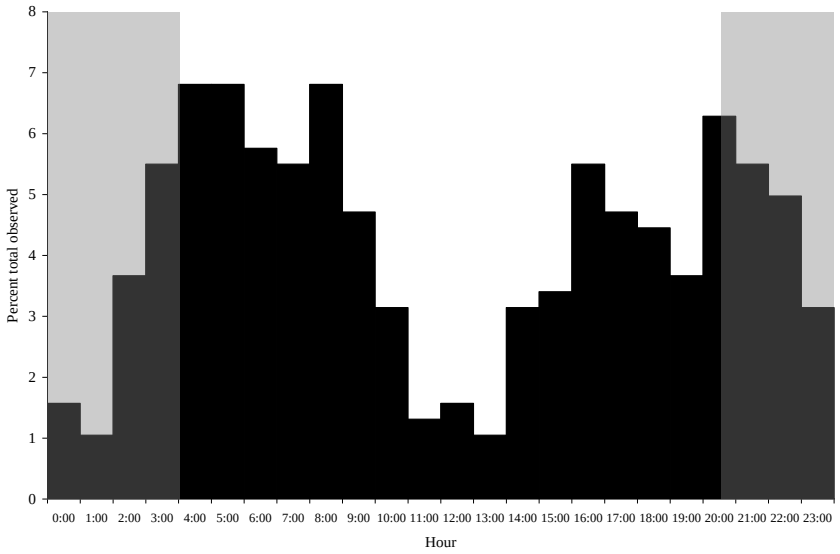


Figure 5. Percentage of acoustically tagged yearling Chinook salmon observed on the primary array receivers by hour during evaluation of juvenile salmonid survival through the lower Columbia River, 2005. Shaded areas represent approximate hours of darkness.

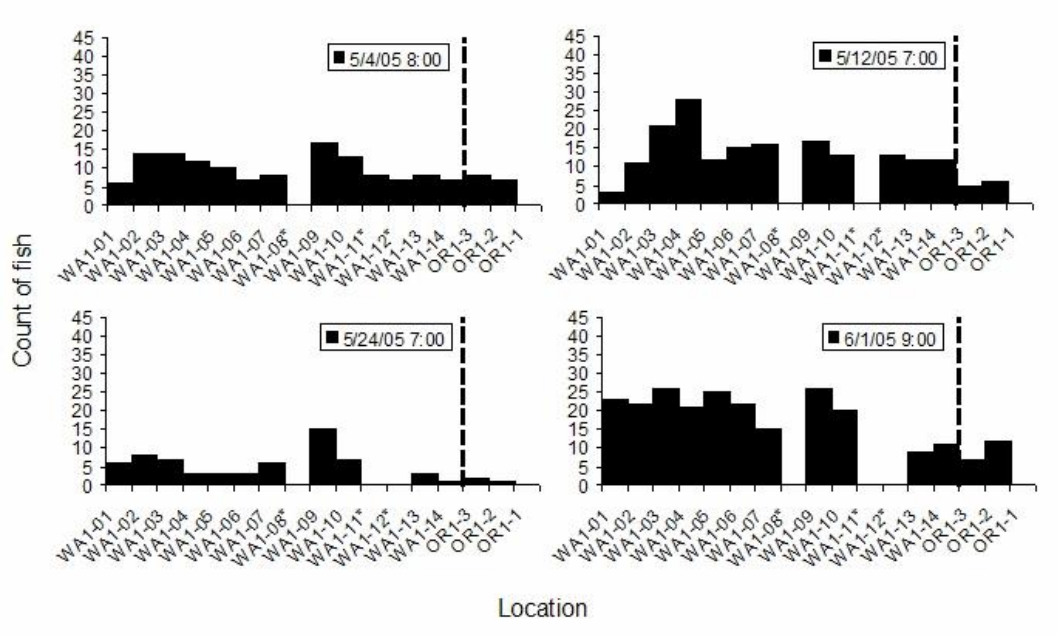


Figure 6. Cross channel distribution of acoustically tagged yearling Chinook salmon detected on the primary receiver array during studies to evaluate juvenile salmonid survival through the Columbia River estuary, 2005. The vertical dashed line represents the navigation channel.

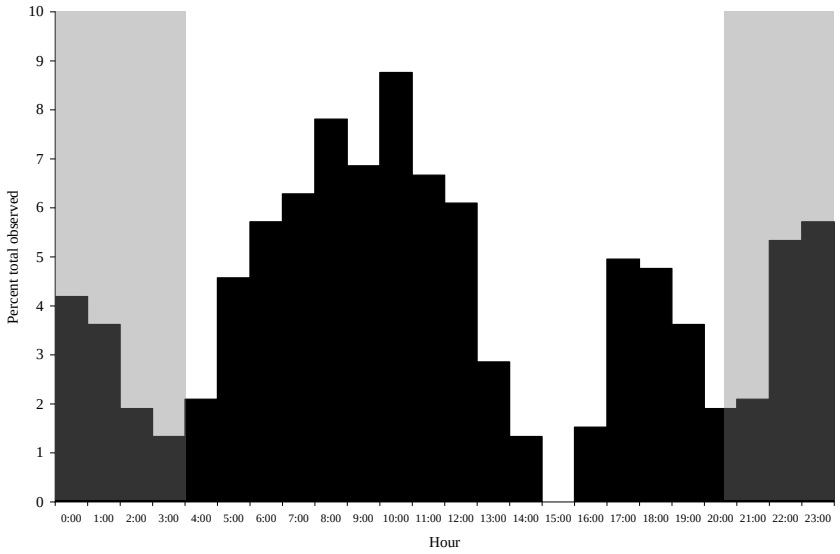


Figure 7. Percentage of acoustically tagged subyearling Chinook salmon observed on the primary array receivers by hour during evaluation of juvenile salmonid survival through the lower Columbia River, 2005. Shaded areas represent approximate hours of darkness.

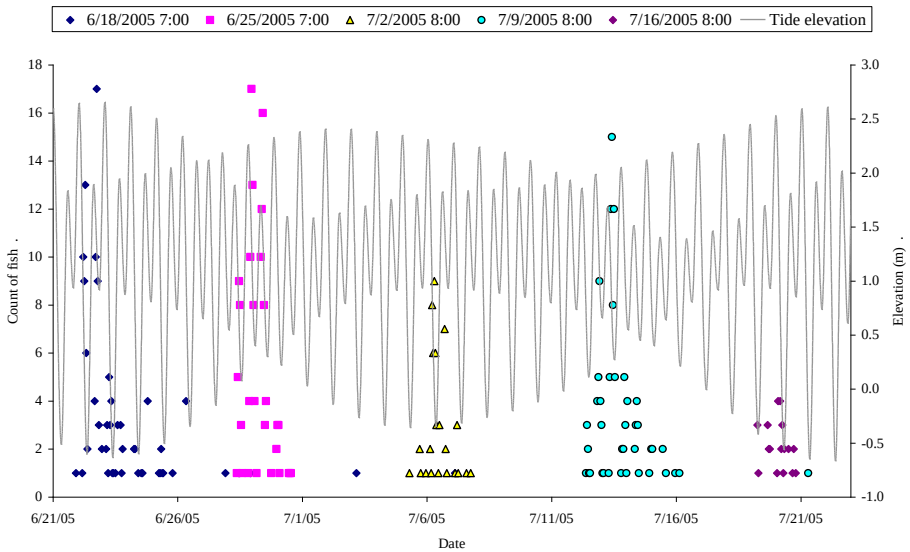


Figure 8. Hourly detections of subyearling Chinook salmon on the primary array by release group and tide elevation for fish released from Bonneville Dam to estimate juvenile salmonid survival through the Columbia River estuary, 2005.

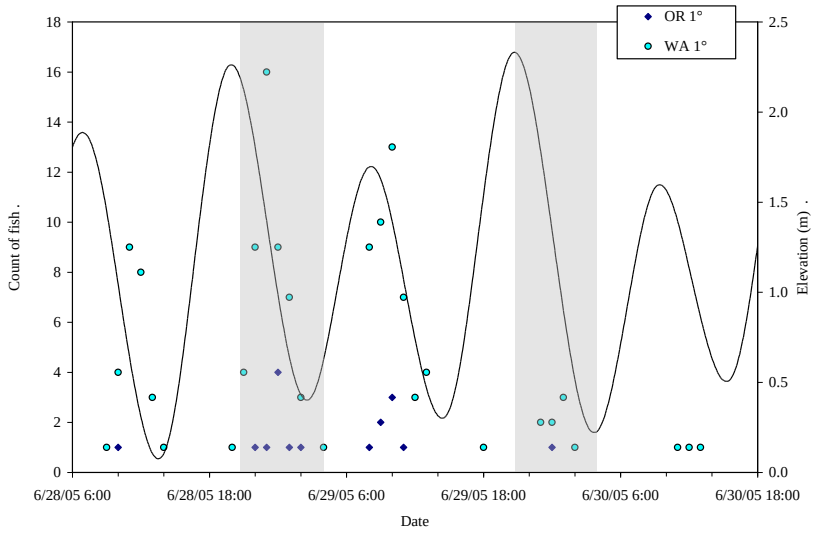


Figure 9. Detections of subyearling Chinook salmon from the third release group on the primary array by nodes located on the Washington (WA 1) or Oregon (OR 1) side of the ship channel during evaluation of juvenile salmonid survival through the lower Columbia River estuary, 2005. Shaded areas represent hours of darkness. Tide elevation is represented by the solid line.

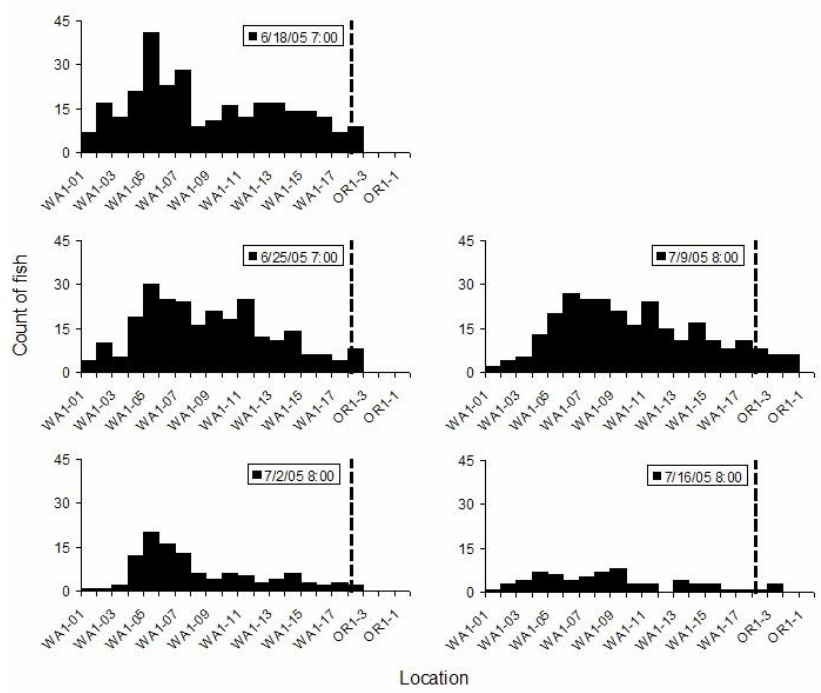


Figure 10. Cross-channel distribution of acoustically tagged subyearling Chinook salmon detected on the primary receiver array during studies to evaluate juvenile salmonid survival through the Columbia River estuary, 2005. The vertical dashed line represents the navigation channel.

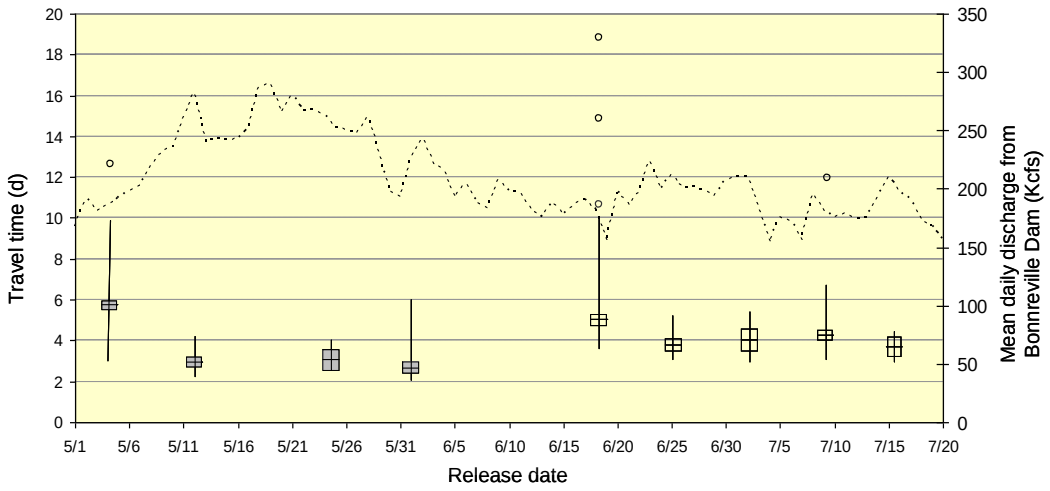


Figure 11. Mean travel time in days (horizontal bar) for acoustically tagged yearling (grey boxes) and subyearling (clear boxes) Chinook salmon from Bonneville Dam JBF outfall (rkm 232) to the primary detection array (rkm 9) by release date, 2005. Boxes about the mean indicate standard error, vertical bar indicates range for each group (without outliers), and outliers are indicated by circles. Dashed line is mean daily discharge (kcfs) from Bonneville Dam.

PIT tags from 37 acoustically tagged Chinook salmon were detected by the pair trawl operating at the upper end of the estuary near Jones Beach, Oregon (rkm 75). Of these 37, 33 were yearling Chinook. By release group, the numbers of yearling (YCS) and subyearling (SYCS) Chinook salmon detected on the pair trawl were:

Release date	Number released	Number detected on pair trawl	Percent detected
	Yearling Chinook salmon		
4 May	244	5	2.0
12 May	240	12	5.0
24 May	161	10	6.2
1 June	245	6	2.4
	Subyearling Chinook salmon		
18 June	238	1	0.4
25 June	245	--	--
7 July	245	--	--
9 July	245	3	1.2
16 July	244	--	--

For all yearling Chinook salmon detected on the pair trawl, travel time from the outfall at Bonneville Dam to Jones Beach ranged from 1.5–3.7 d (mean = 1.9 d, SE = 0.085), with a median of 1.7 d. From median travel times from Bonneville Dam JBF outfall to Jones beach and median travel times across all tagged fish to the estuary acoustic arrays, yearling Chinook salmon required approximately 1.3 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 82 km/d for yearling fish detected on the pair trawl from all 4 spring releases combined. The estimated mean migration rate over the remaining distance from Jones Beach to the primary array (66 km) was approximately 51 km/d.

Median travel time for the four acoustically tagged subyearling Chinook salmon detected on the pair trawl was 3.1 d from Bonneville Dam JBF outfall to detection on the pair trawl, and ranged from 2.5–3.7 d (mean = 3.1 d, SE = 0.363), yielding a migration rate of approximately 50 km/d. Estimated median travel rate from Jones Beach to the primary acoustic array for subyearling smolts was about 66 km/d.

Avian Predation

Of acoustically tagged fish released at Bonneville Dam to assess survival through the lower Columbia River, PIT tags from 40 yearling and 53 subyearling Chinook salmon were detected from 2 bird colonies on East Sand Island in the lower Columbia River estuary, which represented 4.5 and 4.4% of the total numbers of yearling and subyearling fish released, respectively (Table 5). Detections of PIT tags on bird colonies were remarkably consistent across release groups, with yearling Chinook salmon ranging from 6 to 14 (mean = 10, SE = 1.94) detections per release, and subyearling fish ranging from 7 to 14 (mean 10.6, SE = 1.30) detections.

Twenty-four acoustic tags (26%) associated with the 93 PIT-tag detections on bird colonies were previously detected on acoustic detection arrays. Of the 24 tags detected on acoustic arrays, 9 were from yearling Chinook and 15 were from subyearling releases. Seven of the acoustic tags from yearling fish (78%) and 9 tags from subyearling fish (60%) were detected only on the primary array. The remaining tags (two from yearling and seven from subyearling Chinook salmon) were seen at least one time on each array. One acoustic tag from a subyearling fish remained in the area of the arrays for nearly 5.5 d following arrival, during which time it was detected on several nodes in both arrays. It is unclear whether this represented movement of a piscivian predator after having ingested a tagged smolt or whether the smolt did not enter the ocean immediately.

Table 5. Numbers of acoustic tags from yearling and subyearling Chinook salmon released at Bonneville Dam (Bonn II JBF outfall) that were subsequently recovered from piscivorus bird colonies during studies to estimate juvenile salmonid survival through the lower Columbia River and estuary, 2005.

Release date	Total released	Number recovered	Percent total released
	Yearling Chinook salmon		
4 May	244	11	4.51
12 May	240	9	3.75
24 May	161	6	3.73
1 June	245	14	5.71
Subtotal	890	40	4.49
	Subyearling Chinook salmon		
18 June	238	14	5.88
25 June	245	10	4.08
7 July	245	12	4.90
9 July	245	7	2.86
16 July	244	10	4.10
Subtotal	1,217	53	4.35
Total	2,107	93	4.41

Equipment Performance

Detection efficiency of the autonomous nodes was lower than had been expected. During periods of small tidal exchange, the percentage of beacon detections increased (Fig. 12), indicating that the higher velocities associated with larger tidal exchanges caused noise around the autonomous nodes that impacted their efficiency for detecting tags. Nodes were not completely deafened, but their effective range was decreased by an unknown amount. Figure 13 shows similar data over a 2-d period. During the maximum ebb portion of the tide cycle, the effective range was most substantially reduced.

The cabled array suffered diminished performance over the spring outmigration period. In particular, the northern portion of the array became inoperable prior to the first tagging date and remained in that state until repairs could be incorporated following the yearling sampling period. The fault was evinced as burnt pins on cable connectors conducting power to the system. The cause of the malfunction is under investigation at this writing.

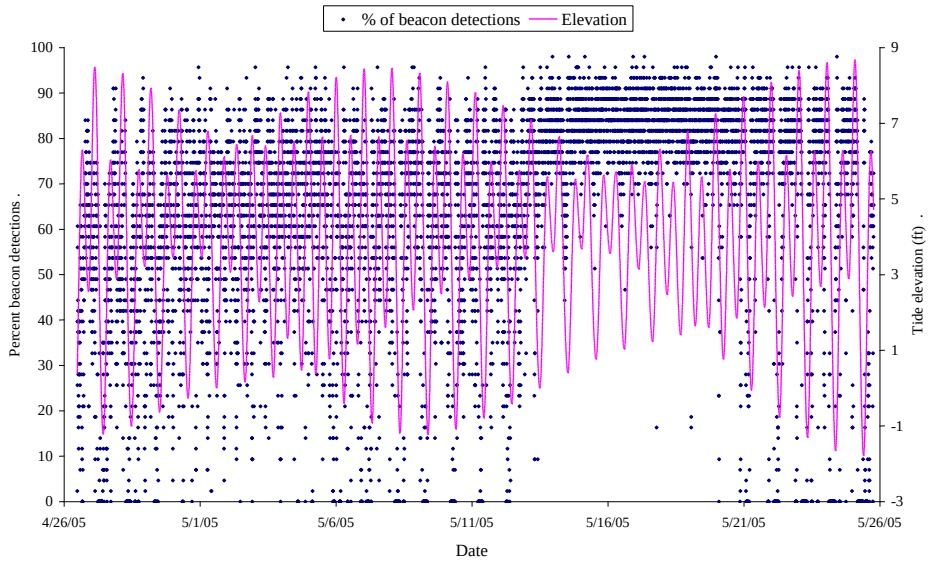


Figure 12. Percent autonomous node beacon detections in 5-min blocks versus tide elevation.

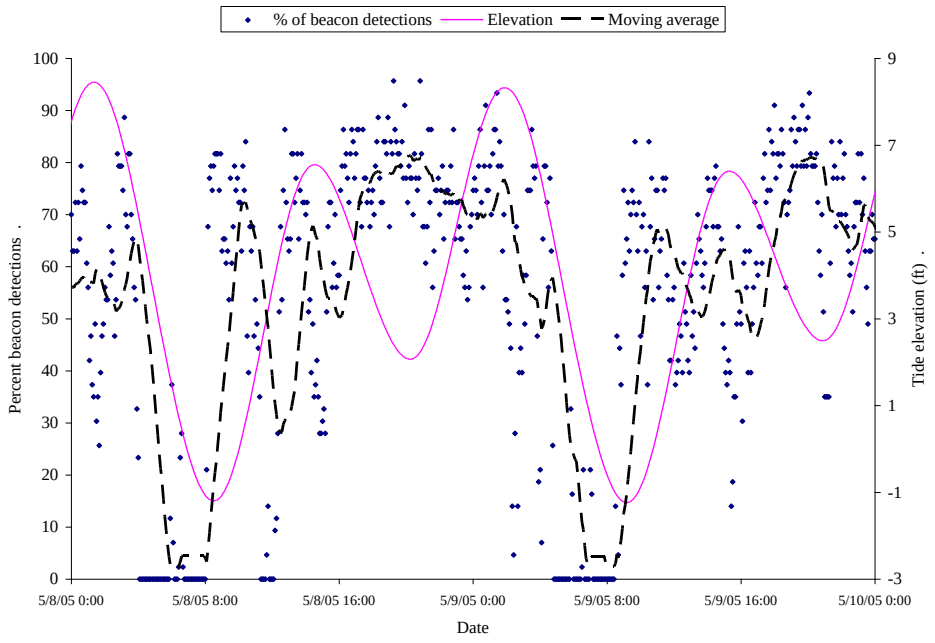


Figure 13. Percent of expected beacon detections on autonomous nodes in 5-min blocks versus tide elevation.

CONCLUSIONS

1. Based on pooled estimates from this study, acoustically tagged yearling Chinook salmon survival through the lower Columbia River and estuary (0.754, SE = 0.179) was similar to survival estimated using PIT tags from Lower Granite Dam through Bonneville Dam (Smith et al. 2004).

2. Pooled, acoustically tagged subyearling Chinook salmon survival was estimated at 0.653 (SE= 0.246).

3. Median travel times from Bonneville Dam through the mouth of the Columbia River estuary were 2.97 d and 4.2 d for yearling and subyearling Chinook salmon, respectively.

4. Avian predation on acoustically tagged yearling (4.5%) and subyearling (4.4%) Chinook salmon was almost double the predation rate for PIT-tagged yearling Chinook salmon, and approximately three times higher than for PIT-tagged subyearling Chinook salmon migrating past Bonneville Dam reported by Ryan et al. (2005).

5. Reduced receiver efficiency may have contributed to detection variability and decreased detection efficiency.

RECOMMENDATIONS

1. This study provides only a first attempt at producing 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 inter-annual variation in survival and behavior. Releases from the Bonneville Dam JBF outfall should be compared to mid-river releases at the same rkm.

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

3. Mobile tracking capability should be developed and protocols established as tools to monitor tagged-fish behavior (migration routes, estuarine habitat use, etc.) in the lower river. Mobile tracking could play a role in determining whether some fish reside in the system past the life of the acoustic tag, or exploring specific areas to determine causes of increased local mortality.

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

ACKNOWLEDGEMENTS

We express our gratitude to Dean Ballinger and the smolt monitoring crew at Bonneville Dam for their conscientious collection of fish for this study. We also thank Lila Charlton and Laura Leighton for their support in data collection, fish releases, and tag activation. The surgical skills of Brad Ryan, Michelle Rub, and Kate Deters were invaluable in implanting tags, and Blaine Ebbert's efforts at funding and study guidance were appreciated.

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. Hayman. 1999. Fiscal Year 1999 Skagit River chinook restoration research. Project performance report. Skagit System Cooperative, LaConner, Washington.

Bottom, D. and eight co-authors. 2001. Salmon at river=s end: the role of the estuary in the decline and recovery of Columbia River salmon. Available from Northwest Fisheries Science Center, 2725 Montlake Blvd. E, Seattle, WA 98112.

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, 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. 313 pp.

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, 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, Oregon.

NMFS (National Marine Fisheries Service). 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. Pages 3-5 *in* G. H. Lauff, editor. Estuaries. American Association for the Advancement of Science Publication 83. Washington DC.

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. Bulletin of the United States Bureau of Fisheries, No. 37.

Ryan B. A., J. W. Ferguson, R. D. Ledgerwood, and E. P. Nunnallee. 2001. Detection of passive integrated transponder tags from juvenile salmonids on piscivorous bird colonies in the columbia river basin. North American Journal of Fisheries Management 21:417–421, 2001

Ryan B. A., S. G. Smith, J. M. Butzerin, and J. W. Ferguson. 2003. Relative vulnerability to avian predation of juvenile salmonids tagged with passive integrated transponders in the columbia river estuary, 1998–2000. Transactions of the American Fisheries Society 132: 275-288.

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, Washington.

Roby, D., K. Collis, J. Adkins, C. Couch, B. Courtot, R. Lord, D. Lyons, Y. Suzuki, A. Evans, and M. Hawbecker. 2005. Research, monitoring, and evaluation of avian predation on salmonid smolts in the lower and mid-Columbia River. Report of Real Time Research, Inc. to the U.S. Army Corps of Engineers. Available at http://columbiabirdresearch.org/Seasonal_Summary_2005/Seasonal_Summary_2005.htm

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.

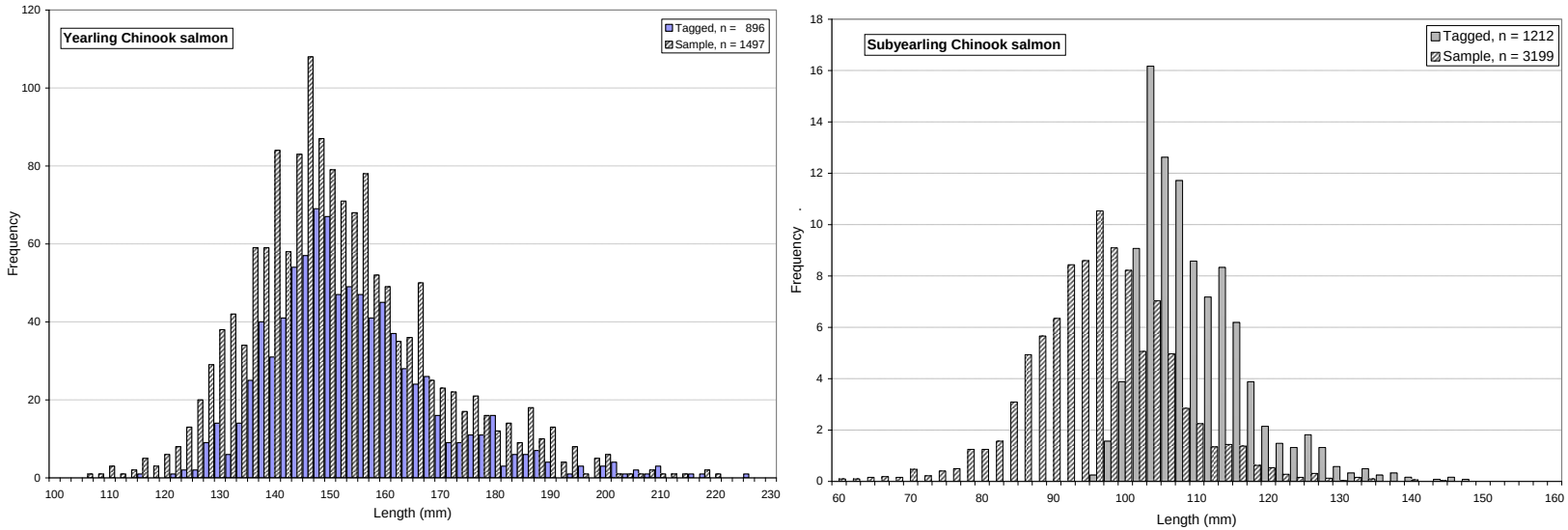
Simenstad, C. A., D. A. Jay, C. R. Sherwood. 1992. Impacts of watershed management on land-margin ecosystems: the Columbia River estuary as a case study. Pages 266-306 *in* R. Naimen, editor. New perspectives for watershed management: balancing long-term sustainability with cumulative environmental change, Springer-Verlag, New York.

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. Report of the National Marine Fisheries Service to the Bonneville Power Administration, Portland, Oregon.

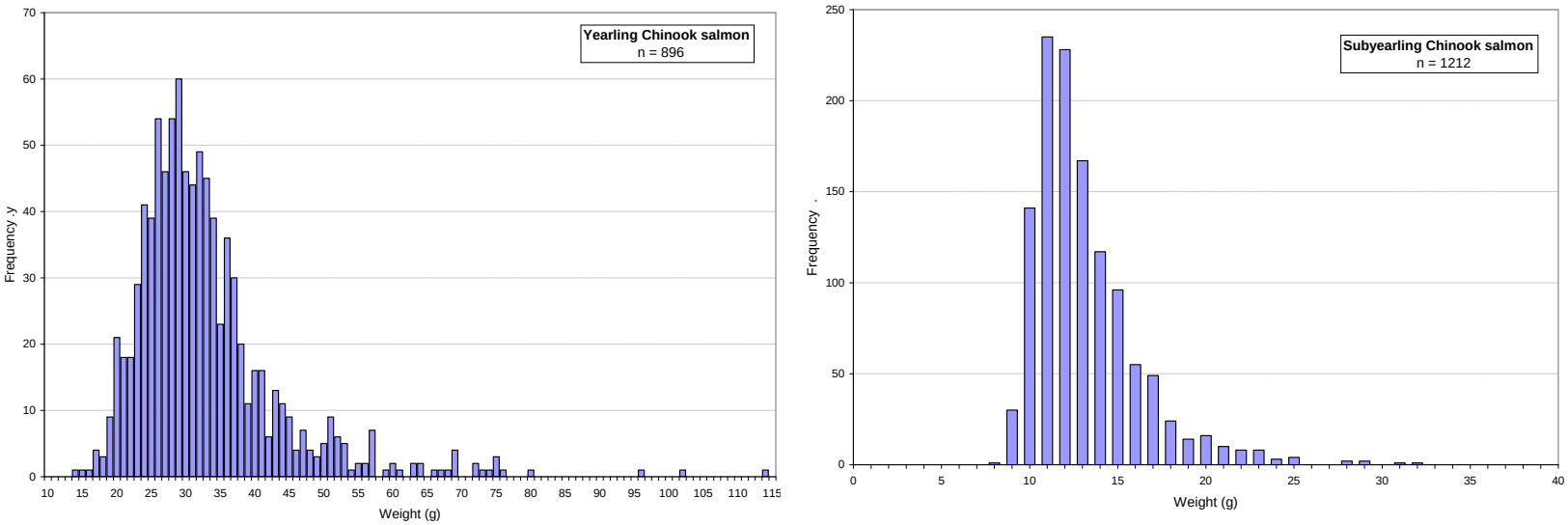
Thorpe, J. E. 1994. Salmonid fishes and the estuarine environment. Estuaries. 17(1A):76-93.

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.

APPENDIX



Appendix Figure 1. Length frequency distribution for acoustically tagged (Tagged) yearling and subyearling Chinook salmon released to evaluate survival from Bonneville Dam through the lower Columbia River and estuary, 2005. Length frequency distributions of untagged fish measured by smolt monitoring personnel over the timeframe when tagging was being done (Sample) are included for comparison.



Appendix Figure 2. Weight frequency distribution for acoustically tagged (Tagged) yearling and subyearling Chinook salmon released to evaluate survival from Bonneville Dam through the lower Columbia River and estuary, 2005.

Appendix Table 1. Individual detection histories by release date for groups of juvenile Chinook salmon tagged with acoustic transmitters (Nominal tag code) and released through the Bonneville Dam smolt bypass facility outfall to evaluate juvenile salmonid survival through the lower Columbia River and estuary, 2005.[a] Records without detection data (--) indicate fish which were not detected following release.

Nominal Tag code	Full tag message transmitted	First detection site name	First detection date	First detection time	First detection latitude	First detection longitude	Last detection site name	Last detection date	Last detection time	Last detection latitude	Last detection longitude
Released on 4 May at 0800 PST											
4044	7240441C	---	---	---	---	---	---	---	---	---	---
404F	72404F3C	---	---	---	---	---	---	---	---	---	---
4053	72405302	---	---	---	---	---	---	---	---	---	---
405A	72405A9E	---	---	---	---	---	---	---	---	---	---
405B	72405BC0	WA1-03-A	12-May	08:28:18	46.253261	-123.983868	WA1-03-A	12-May	08:30:24	46.253261	-123.983868
4063	724063BC	WA1-14-A	9-May	16:49:39	46.241428	-123.992285	WA1-14-A	9-May	16:51:42	46.241428	-123.992285
4064	7240643F	WA1-03-A	8-May	18:44:01	46.253261	-123.983868	WA1-03-A	8-May	18:44:56	46.253261	-123.983868
4067	724067DD	---	---	---	---	---	---	---	---	---	---
4069	724069C2	---	---	---	---	---	---	---	---	---	---
406B	72406B7E	---	---	---	---	---	---	---	---	---	---
4075	724075FC	---	---	---	---	---	---	---	---	---	---
4080	724080B7	WA2-07-A	8-May	06:53:42	46.264828	-124.066102	WA2-07-A	8-May	06:54:13	46.264828	-124.066102
4084	724084D6	WA1-07-A	13-May	20:22:38	46.249078	-123.987085	OR2-03-A	13-May	21:27:57	46.248328	-124.059769
408E	72408EA8	---	---	---	---	---	---	---	---	---	---
4093	724093C8	---	---	---	---	---	---	---	---	---	---
4097	724097A9	WA1-05-A	8-May	07:40:32	46.251161	-123.985752	WA1-06-A	8-May	07:44:43	46.250178	-123.986269
409D	72409DD7	OR1-02-C	10-May	22:33:31	46.236495	-123.996452	OR1-02-C	10-May	23:13:40	46.236495	-123.996452
40A2	7240A228	---	---	---	---	---	---	---	---	---	---
40A5	7240A5AB	---	---	---	---	---	---	---	---	---	---
40AE	7240AE8B	---	---	---	---	---	---	---	---	---	---
40B3	7240B3EB	---	---	---	---	---	---	---	---	---	---

[a] This table shows only the first 75 records to limit printed document volume. Full electronic copies of this file can be obtained from the authors.

Appendix Table 1. Continued.

Nominal Tag code	Full tag message transmitted	First detection site name	First detection date	First detection time	First detection latitude	First detection longitude	Last detection site name	Last detection date	Last detection time	Last detection latitude	Last detection longitude
Released on 4 May at 0800 PST (Continued)											
40C2	7240C24D	--	--	--	--	--	--	--	--	--	--
40C3	7240C313	OR1-03-C	8-May	16:47:34	46.237578	--123.995048	OR1-03-C	8-May	16:48:12	46.237578	-123.995048
40C9	7240C96D	--	--	--	--	--	--	--	--	--	--
40F3	7240F3AD	--	--	--	--	--	--	--	--	--	--
40F5	7240F570	--	--	--	--	--	--	--	--	--	--
40F7	7240F7CC	--	--	--	--	--	--	--	--	--	--
4118	724118A0	WA1-09-A	12-May	08:46:20	46.246911	-123.988485	OR2-03-A	12-May	09:39:51	46.248328	-124.059769
4131	7241311F	--	--	--	--	--	--	--	--	--	--
417C	72417CA4	WA2-01-A	8-May	04:04:44	46.271045	-124.070669	WA2-01-A	8-May	04:05:12	46.271045	-124.070669
4183	72418391	--	--	--	--	--	--	--	--	--	--
418C	72418CD0	--	--	--	--	--	--	--	--	--	--
418E	72418E6C	WA1-12-A	8-May	18:41:48	46.243545	-123.991085	WA1-12-A	8-May	18:42:36	46.243545	-123.991085
4190	724190EE	--	--	--	--	--	--	--	--	--	--
4195	724195D1	WA1-14-A	9-May	16:44:32	46.241428	-123.992285	OR2-03-A	9-May	17:26:05	46.248328	-124.059768
4197	7241976D	WA2-02-A	8-May	06:55:46	46.270045	-124.069952	WA2-20-A	8-May	07:20:12	46.267445	-124.078135
419C	72419C4D	--	--	--	--	--	--	--	--	--	--
41C7	7241C7B6	--	--	--	--	--	--	--	--	--	--
41C9	7241C9A9	WA1-02-A	11-May	07:27:32	46.254511	-123.983352	WA1-02-A	11-May	07:27:52	46.254511	-123.983352
41CA	7241CA4B	WA1-10-A	7-May	18:25:05	46.245695	-123.989335	WA1-01-A	7-May	20:52:00	46.255511	-123.982602
41CB	7241CB15	--	--	--	--	--	--	--	--	--	--
41D1	7241D1F6	--	--	--	--	--	--	--	--	--	--
41DC	7241DC0B	--	--	--	--	--	--	--	--	--	--
41DF	7241DFE9	--	--	--	--	--	--	--	--	--	--
41E1	7241E148	--	--	--	--	--	--	--	--	--	--
41E3	7241E3F4	WA1-12-A	8-May	08:58:09	46.243545	-123.991085	WA1-14-A	8-May	09:32:14	46.241428	-123.992285
41EB	7241EB36	WA1-01-A	10-May	08:37:03	46.255511	-123.982602	WA1-01-A	10-May	08:38:04	46.255511	-123.982602
41F2	7241F237	--	--	--	--	--	--	--	--	--	--

Appendix Table 1. Continued.

Nominal Tag code	Full tag message transmitted	First detection site name	First detection date	First detection time	First detection latitude	First detection longitude	Last detection site name	Last detection date	Last detection time	Last detection latitude	Last detection longitude
Released on 4 May at 0800 PST (Continued)											
41FD	7241FD76	--	--	--	--	--	--	--	--	--	--
41FF	7241FFCA	WA1-03-A	11-May	18:38:59	46.253261	-123.983869	WA1-03-A	12-May	00:07:25	46.253261	-123.983869
4226	72422654	WA1-03-A	14-May	06:57:56	46.253261	-123.983869	WA1-03-A	14-May	06:59:03	46.253261	-123.983869
4229	72422915	WA2-04-A	9-May	04:54:46	46.268111	-124.068302	WA2-04-A	9-May	04:55:32	46.268111	-124.068302
4231	7242314A	WA1-04-A	16-May	23:29:04	46.252411	-123.984852	OR2-08-A	17-May	02:06:47	46.253295	-124.060385
4234	72423475	--	--	--	--	--	--	--	--	--	--
4239	72423988	--	--	--	--	--	--	--	--	--	--
4243	7242430E	--	--	--	--	--	--	--	--	--	--
4249	72424970	WA1-07-A	8-May	06:17:52	46.249078	-123.987085	WA1-06-A	8-May	06:19:29	46.250178	-123.986269
424B	72424BCC	--	--	--	--	--	--	--	--	--	--
424F	72424FAD	--	--	--	--	--	--	--	--	--	--
4252	724252CD	--	--	--	--	--	--	--	--	--	--
425F	72425F30	--	--	--	--	--	--	--	--	--	--
4260	724260CF	WA2-14-A	9-May	06:20:03	46.268595	-124.067002	WA2-03-A	9-May	06:22:31	46.269011	-124.068835
4261	72426191	WA1-10-A	9-May	16:29:00	46.245695	-123.989335	WA1-10-A	9-May	16:30:20	46.245695	-123.989335
4265	724265F0	--	--	--	--	--	--	--	--	--	--
426B	72426BEF	WA1-13-A	11-May	08:26:27	46.242345	-123.991719	OR2-08-A	11-May	09:12:05	46.253295	-124.060385
426C	72426C6C	--	--	--	--	--	--	--	--	--	--
4274	72427433	--	--	--	--	--	--	--	--	--	--
4290	724290BB	--	--	--	--	--	--	--	--	--	--
4295	72429584	WA1-04-A	12-May	21:05:53	46.252411	-123.984852	WA1-05-A	12-May	21:10:02	46.251161	-123.985752
429A	72429AC5	OR1-03-C	8-May	17:39:47	46.237578	-123.995048	OR1-03-C	8-May	17:40:13	46.237578	-123.995048
429B	72429B9B	WA1-04-A	8-May	18:53:48	46.252411	-123.984852	WA1-03-A	8-May	18:56:01	46.253261	-123.983869
42A2	7242A2B9	WA1-06-A	9-May	07:19:06	46.250178	-123.986269	WA1-05-A	9-May	07:22:27	46.251161	-123.985752
42A6	7242A6D8	--	--	--	--	--	--	--	--	--	--
42A8	7242A8C7	WA1-14-A	9-May	16:57:42	46.241428	-123.992285	WA1-14-A	9-May	16:58:33	46.241428	-123.992285
42C3	7242C382	--	--	--	--	--	--	--	--	--	--