North American Journal of Fisheries Management 30:853–859, 2010

DOI: 10.1577/M09-143.1

[Management Brief]

Autonomous Acoustic Receiver Deployment and Mooring Techniques for Use in Large Rivers and Estuaries

P. SCOTT TITZLER,* GEOFFREY A. MCMICHAEL, AND JESSICA A. CARTER

Pacific Northwest National Laboratory, Ecology Group,
Post Office Box 999, Richland, Washington 99352, USA

Abstract.—Acoustic telemetry receivers are used across a range of aquatic habitats to study a diversity of aquatic species. The Juvenile Salmon Acoustic Telemetry System autonomous acoustic receiver system was deployed and moored in the Columbia River and its estuary. A high receiver loss rate during 2005 in the Columbia River estuary, an area with high water velocities and unstable substrates, prompted improvements to the receiver mooring system, and in 2006 the mooring system was redesigned. This change included elimination of surface buoys, a cable bridle, and an anchor tagline (for anchor recovery). The new mooring configuration, consisting of an acoustic receiver, acoustic release, and mooring line sections that were anchored to the riverbed, improved receiver recovery rates and crew safety. Additionally, a reward program was implemented to provide an incentive for people to return found receivers. The mooring design presented here performed well compared with previous acoustic receiver mooring methods used in the Columbia River system and should be useful for similar applications in large rivers and estuaries with high water velocities and shifting substrates.

The use of submersible acoustic receivers has become common worldwide to detect fish implanted with acoustic transmitters. Successful use of submersible acoustic receivers to detect large fish in the open ocean is well documented (e.g., Heupel and Hueter 2001; Comeau et al. 2002; Szedlmayer and Schroepfer 2005) and, to a lesser extent, in large river systems (Parsley et al. 2008; Holbrook et al. 2009). Acoustic telemetry has been used also to detect small fish (e.g., juvenile salmon) in the ocean where the use of radio telemetry is not feasible (Lacroix et al. 2005; Clemens et al. 2009; Rechisky et al. 2009). Most recently, acoustic telemetry has been used to detect juvenile Pacific salmon *Oncorhynchus* spp. ($<$140 mm) as they emigrate seaward through the Columbia River and its estuary (McMichael et al. 2010).

Understanding the temporal and spatial aspects of juvenile salmonid mortality during their seaward emigration is essential to the development of appropriate management strategies. This understanding supports mitigation efforts and conservation policies aimed at protecting and enhancing salmonid populations in the Columbia River basin. To address the need for more information on salmonid behavior and survival through the lower Columbia River and its estuary, especially with regard to juvenile fall Chinook salmon *O. tshawytscha*, the Juvenile Salmon Acoustic Telemetry System (JSATS) was developed (McMichael et al. 2010). As part of this development, a prototype of the JSATS autonomous acoustic receiver system was tested in 2004 near the mouth of the Columbia River and then deployed on a larger scale between 2005 and 2008.

Many environmental factors (e.g., river and tidal currents, large waves, substrate composition and stability, and underwater structures) can affect the success of mooring and recovering telemetry receivers in large rivers. The lower Columbia River and its estuary downstream from Bonneville Dam (235 km from the Pacific Ocean) constitute a particularly challenging environment due to the size of the river, high water velocities, variable substrate composition and stability, channel maintenance activities, commercial and recreational fishing, and vessel traffic. The most dynamic and challenging location is the mouth of the Columbia River where the river enters the Pacific Ocean (Figure 1). The physical characteristics of the Columbia River estuary are unique compared with other estuaries in the northwestern United States, as river discharge is relatively large (varies from about 2,970 to 17,000 m^3/s, which accounts for 77% of the freshwater drainage along the U.S. west coast north of San Francisco) and the river sediment is less stable (Fox et al. 1984; Sherwood and Greagar 1990; Hickey et al. 2005). Water elevation between the high and low tide varies by an average of 2.4 m in approximately 6 h (Fox et al. 1984). This tidal exchange and river discharge significantly influence water velocity and direction in the Columbia River estuary (Fox et al. 1984), where water velocity consistently reaches 2 m/s (CMOP 2010). The estuary substrate is composed mostly of sand that constantly shifts and builds sand waves that move in response to water flow and large waves (White 1970; Fox et al. 1984).

The use of a deployment and mooring method that

---

* Corresponding author: scott.titzler@pnl.gov

Received September 15, 2009; accepted May 12, 2010

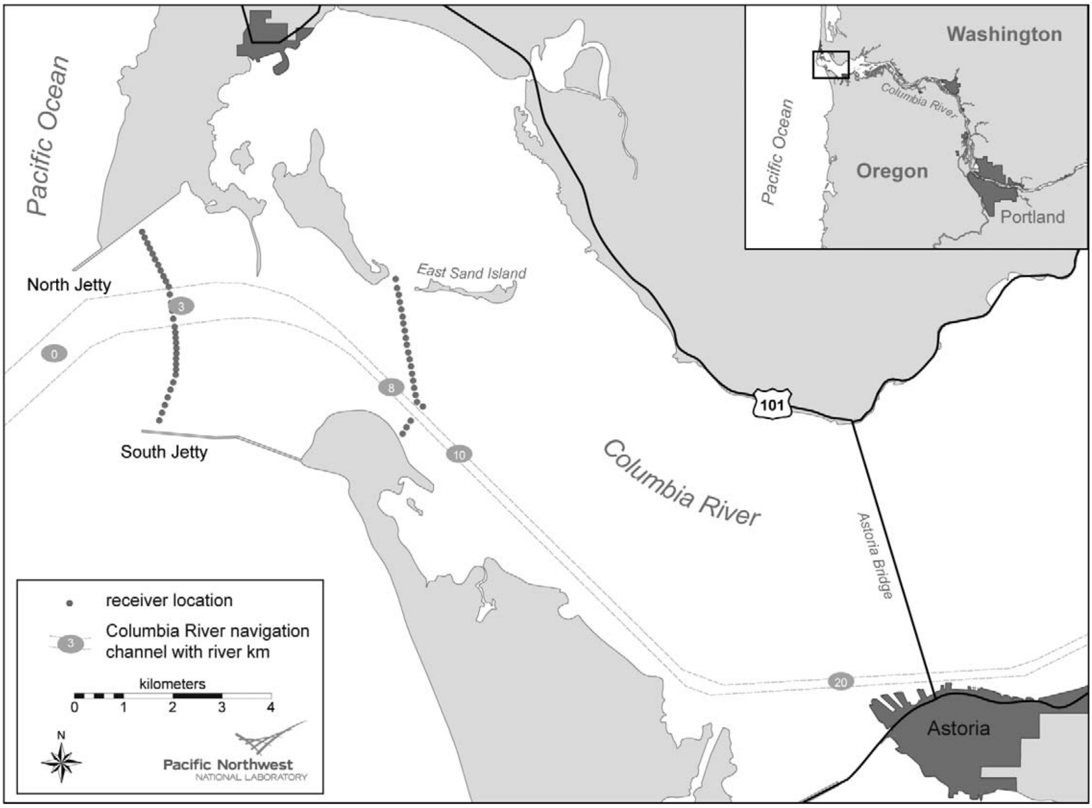

FIGURE 1.—Map of the mouth of the Columbia River and its estuary showing the locations of the north and south jetties and two Juvenile Salmon Acoustic Telemetry System autonomous acoustic receiver arrays (rkm 3 and 8).

minimizes loss of acoustic receivers and data they contain is critical to the success of behavior and survival studies of fish using acoustic telemetry (Domeier 2005). For example, single-release survival models commonly used in the Columbia River to estimate seaward survival of juvenile salmonids are based on several assumptions, the most relevant of which is that each marked fish in the population has an equal probability of being detected (Cormack 1964; Jolly 1965; Seber 1965). Lost receivers represent lost transmitter-detection data, which may result in violations of survival model assumptions.

The first large-scale JSATS study using autonomous acoustic telemetry receivers near the mouth of the Columbia River in 2005 had lower-than-expected recovery rates along two arrays (at river kilometers [rkm] 3 and 8; Figure 1). Other researchers using autonomous acoustic telemetry receivers near the mouth of the Columbia River also have experienced high rates of equipment loss (Clements et al. 2005). Despite the widespread use of acoustic telemetry technology, few sources in the literature outline protocols and methods related to acoustic receiver mooring configurations in large rivers and estuaries (Clements et al. 2005). This paper describes a system developed for deploying and mooring autonomous acoustic receivers to improve receiver recovery success in large rivers with high water velocities and shifting substrates, such as those in the lower Columbia River and its estuary.

Methods

Autonomous acoustic receivers (Model N201, Sonic Concepts, Inc., Bothell, Washington) were used for JSATS salmonid survival studies from 2005 through 2008. The JSATS receiver consisted of a hydrophone, pressure and temperature sensors, electronic components, and compact flash (CF) card mounted in a 1.2-m-long × 15-cm-diameter yellow cylindrical polyvinyl chloride (PVC) plastic housing. The autonomous receiver (with battery power for 30 d) weighed approximately 9.6 kg in air and had approximately 3.0 kg net buoyancy in freshwater. Each receiver also carried an acoustic beacon and a label. The acoustic beacon transmitted a unique code every 15 s; the label included manufacturer identification, researcher contact information, indication of a reward for return if found, a serial number, and a lithium battery warning.

Receiver mooring design.—The initial 2005 JSATS autonomous acoustic receiver mooring design included three surface buoys, a standard-length 3.7-m-long anchor line, a receiver bridle made of two vinyl-coated 4.75-mm-diameter stainless steel cables terminated to the receiver housing by two stainless steel thimbles, and a tagline connecting an acoustic release to the anchor. Surface buoys marked the receiver location, and the tagline was intended to provide an opportunity to recover anchors. In 2006 and subsequent study years, the same receiver was used, but due to problems encountered while recovering receivers in 2005 (e.g., lost surface buoys and receivers, safety concerns while attempting to recover anchors), surface buoys, bridle, and tagline were eliminated from the mooring system.

In 2006, each receiver housing was fitted with a polystyrene fin (later replaced with polyethylene) to reduce drag and increase receiver stability under high-velocity conditions. Each receiver housing also incorporated a single-point attachment to the mooring line, replacing the bridle attachment (Figure 2). The receiver single-point attachment consisted of a stainless steel band that held a 9.5-mm-diameter nylon thimble incorporated into the top end of the 1.5-m-long × 9.5-mm-diameter buoy line (Samson Tenex, Samson Rope Technologies, Ferndale, Washington). The thimble was secured to the stainless steel band by a stainless steel bolt, allowing the thimble to pivot freely along the axis of the receiver housing. The bottom end of the buoy line was attached to the top end of an acoustic release (10.2 cm in diameter × 84 cm long; Model 111, InterOcean Systems, Inc., San Diego, California). Extra buoyancy was added between the receiver and release with three yellow buoys (12.4 cm in diameter × 16.5 cm long, each with 1.45 kg buoyancy; Bao Long Industrial Ltd., Taiwan, Republic of China) threaded onto the buoy line (Figure 2). The bottom end (releasing end) of the acoustic release held a 10-cm-diameter galvanized steel ring that was incorporated into the top end of a shock-corded mooring (anchor line) made from 9.5-mm-diameter Samson Tenex line. The length of the anchor line was dependent on water depth at the deployment location. In areas greater than 12 m deep, a 3.7-m anchor line was used. In areas less than 12 m deep, a 1.5-m anchor line was used. The bottom end of the anchor line was terminated by a 9.5-mm nylon thimble attached to a 57-kg or 34-kg steel anchor by a galvanized carbon steel high-strength shackle (workload limit of 2,000 kg). Anchor design and size were selected based on the deployment location. In areas of low velocity (<2 m/s), a 34-kg brick-style anchor was used; in areas of high velocity (≥2 m/s), a 57-kg disk-shaped anchor was used.

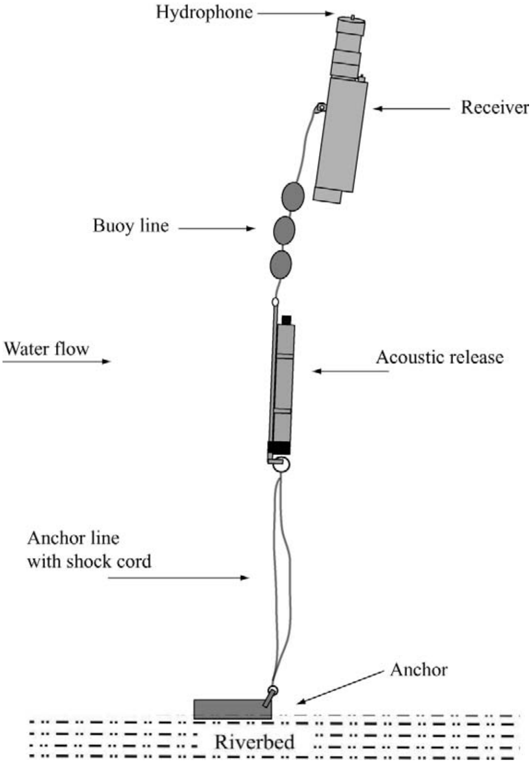

FIGURE 2.—Mooring design for the 2006–2008 Juvenile Salmon Acoustic Telemetry System autonomous acoustic receivers.

Mooring line length and material were modified based also on water depth and substrate characteristics. For shallow-water moorings (<5 m), the acoustic release was attached directly to the handle of the anchor, or a 0.30-m-long anchor line was used with the release or buoy line, or both, tied parallel with the receiver. In areas where there was concern for mooring line failure due to abrasion (e.g., areas with substrate composed of angular basalt boulders), a 1.5-m-long × 4.75-mm-diameter wire rope was substituted for the nylon anchor line.

Receiver deployment.—Similar deployment procedures were used for all JSATS autonomous acoustic receivers used in the Columbia and Snake rivers from 2005 through 2008. Receivers were deployed individually or in transect arrangements (arrays) spanning the width of the river to meet study detection requirements. Locations (waypoints) for each receiver were determined prior to deployment. All waypoints were created with Fugawi navigation software (Northport Systems, Inc., Toronto, Ontario) and navigated to using Fugawi and a global positioning system (GPS) receiver. Before each receiver was deployed, equipment and mooring sections were examined to ensure that all parts were present, operational, and labeled properly. Receiver serial number, deployment location, and acoustic release code were recorded on data sheets prior to deployment. Once the research vessel was positioned as close as possible to the predetermined waypoint, the anchor and receiver assembly (receiver, acoustic release, and short buoy-line section) were lowered to the river bottom on a slip line. When the anchor reached the bottom, a receiver waypoint was recorded. Immediately after each deployment, additional information was recorded, including the waypoint name, latitude and longitude, date, time, and depth (from vessel sonar).

Receiver recovery.—To download tagged-fish detection data and replace batteries, an effort was made to recover JSATS autonomous acoustic receivers no more than 28–30 d after deployment. To recover JSATS receivers, we used an InterOcean Systems model 1100E command control unit (DC-operated transponder interrogator and receiver) to transmit a unique acoustic signal to each release. This code signaled the acoustic release to open, allowing the positively buoyant receiver assembly to ascend to the surface, leaving the anchor behind. To minimize data loss due to temporary absence of a receiver at a recovery location, a previously activated receiver was deployed immediately (typically within <5 min) after the recovery of each receiver. Occasionally the receiver and (or) mooring became fouled, preventing the receiver assembly from detaching from the anchor when the acoustic release was activated. When this happened, alternative methods were used to retrieve the receiver. In most cases, a grappling hook or pinch bar was dragged in an effort to snag the anchor or receiver assembly and then a davit with a hydraulic winch was used to lift it to the surface.

Results

Receiver loss decreased dramatically after the change in mooring design in 2006. We make a distinction between receivers that are never recovered (permanently lost receivers) and those not recovered during the initial recovery attempt but subsequently recovered or found and returned (temporarily lost receivers). Permanent receiver loss resulted in lost data, while temporary receiver loss resulted in a percentage of lost data or no loss at all. In our initial 2005 study, 161 JSATS receiver deployments were made in two arrays near the mouth of the Columbia River (rkm 3 and 8; Figure 1) over a 5-month period (April–August). Twelve of the 161 (7.5%) receivers deployed were permanently lost. During subsequent study years (2006–2008), receivers were again deployed near the same two arrays (rkm 3 and 8) for a 6-month period (April–September), and receivers permanently lost decreased each year, even as the number of receiver deployments increased (Table 1). Permanent receiver loss decreased to 1.6% by 2008.

When permanent receiver loss rates were compared among different river environments, study sites near the mouth of the Columbia River (rkm 3–8) and the unimpounded Columbia River downstream from Bonneville Dam (rkm 29–113) consistently produced higher rates of receiver loss than did the impounded sections of the Columbia and Snake rivers (Table 1). Between 2006 and 2008, a combined 718 receiver deployments between the Bonneville Dam tailrace and John Day Dam reservoir (rkm 193–351) in a 6-month period resulted in only five receivers permanently lost (0.7% loss). For the same study period in the lower Snake River (rkm 2–105), 909 JSATS receiver deployments resulted in only four permanently lost receivers (0.4% loss).

Between 2005 and 2008, an additional 38 JSATS receivers were temporarily lost, some of which resulted in time lost collecting data (Table 1). Based on pressure data (indicating when the receiver ascended) and the last tag detections from each temporarily lost receiver, average time loss for all 38 temporarily lost receivers was 41%. Time loss for a single receiver varied from 0% to 98%.

Discussion

The physical environment and human activities in different marine and riverine locations may substantially influence how researchers design acoustic receiver mooring systems and deploy and successfully recover acoustic receivers. For example, in warmwater marine regions, researchers deploy and moor their acoustic receivers in ocean conditions that are more conducive to use of divers (e.g., low water velocity, good visibility). This allows researchers to use scuba divers to deploy and (or) recover receivers (Domeier 2005; Szedlmayer and Schroepfer 2005). In contrast, researchers using acoustic receivers in large rivers and estuaries of the northwestern coastal region of North America face more challenges due to frequent unfavorable water and weather conditions. In most cases, using SCUBA divers to recover receivers is not an option in the lower Columbia River and its estuary due to high water velocities and poor visibility. Additionally, researchers using autonomous acoustic receivers along the continental shelf of western North America experience receiver loss due to the annual commercial

TABLE 1.—Number of Juvenile Salmon Acoustic Telemetry System receiver deployments, (D), permanent losses (PL), and temporary losses (returned by others) (TL) by year and study location on the Columbia and Snake rivers; NA = not applicable.

	Downstream of Bonneville Dam					Bonneville and John Day dams		Lower Snake River	
	Rkm 3–8		Rkm 29–113						
Year	D	PL	D	PL	TL	D	PL	D	PL
2005	161	12	NA		12	NA		NA	
2006	267	9	NA		8	264	2	236	2
2007	332	6	154	0	10	193	1	540	2
2008	248	4	124	3	8	261	2	130	0

bottom trawl fishery (e.g., Rechisky et al. 2009). Researchers mooring acoustic receivers in the ocean, large rivers, or estuaries should consider strong tidal currents, substrate movement, and commercial activities (e.g., fishing, ship traffic) when designing a receiver mooring system.

During the initial full-scale deployment of JSATS autonomous acoustic receivers in the Columbia River estuary in 2005, we experienced challenges with our mooring system and learned many valuable lessons. In 2005, we learned that a custom-designed disk anchor worked well to hold the JSATS receivers in place. However, the 4.75-mm-diameter stainless steel bridle cables that connected the receivers to the mooring lines did not withstand the side-to-side motion of the receivers when subjected to water current and consequently developed stress corrosion (Kirby 1995; King et al. 2008). Corrosion then led to failure of the bridle cable, which resulted in both permanent and temporary receiver loss. Breakage occurred at the two thimbles or along either arm of the bridle. The 2005 surface-buoy mooring system was subjected to high water velocities, debris accumulation, shipping traffic, recreational boating, and commercial and recreational crabbing, all of which contributed to receiver loss. The use of taglines to retrieve anchors also contributed to permanent and temporary receiver loss, as tagline canisters frequently released a tagline prematurely, which then became entangled with the receiver and prevented the equipment from surfacing after the acoustic release command was transmitted. Finally, receivers deployed with a standard-length anchor line in shallow areas (<12 m) were sometimes damaged or destroyed by boat propellers, or, in a few cases, data were lost when the hydrophone floated above the water surface at extreme low tides.

Other researchers using a surface buoy system to moor autonomous acoustic receivers in the lower Columbia River and its estuary experienced problems with receiver loss similar to those we encountered in 2005. On the lower Columbia River, Parsley et al. (2008) were forced to abandon one of their seven receiver locations due to problems with persistent equipment loss. During 2001–2003, Clements et al. (2005) made 217 receiver deployments that resulted in the loss of 38 receivers (17%) near the mouth of the Columbia River within an 8-month period. Clements et al. (2005) attributed the primary cause of their receiver loss to boat traffic. We initially had an overall loss rate of 15%, but half of the lost JSATS receivers subsequently were recovered and returned. Three important distinctions between JSATS receivers and those used by Clements et al. (2005) are that they used different receivers and different receiver recovery methods and moored a proportion of their receivers in the near-shore ocean. They moored receivers composed of two arrays; one array extended west 8 km from the south jetty and the second extended west 8 km from the north jetty (Clemens et al. 2009). We did not deploy JSATS receivers in this environment. Additionally, the positive buoyancy of JSATS receivers (+3 kg) allowed receivers that became detached from moorings to be found floating in the water or washed up on a shoreline. Conversely, VR2 receivers (Vemco AMIRIX Systems, Inc., Halifax, Nova Scotia) used by Clemens et al. (2009) were negatively buoyant (−0.17 kg) and would sink to the bottom if detached from the buoys, making them more difficult to recover. Finally, Clements et al. (2005) used surface buoys to mark the location of their receivers and provide a means to recover receiver data without removing the anchor from the riverbed. Conversely, JSATS receivers were removed from their mooring to recover receiver data and a previously activated receiver then was immediately deployed to take its place.

The reward program implemented in 2005 provided an incentive for people to return found receivers (temporarily lost receivers), which we deemed very successful. Each receiver was painted bright yellow and carried a label advertising a reward if returned. The number of receivers found and returned by others compared with the number lost and not returned (Table 1) shows that the reward program worked well. Although the reward program probably reduced permanent receiver loss, some data were permanently lost once a receiver was removed from its mooring before another receiver was deployed to take its place. The time interval between when a temporarily lost receiver was displaced from its mooring and when a new receiver was deployed to take its place was considered lost time (or data). This time interval was variable. For example, no data were lost when a temporarily lost receiver was displaced from its mooring (e.g., May 17, 2006) after another receiver was redeployed to take its place (e.g., May 10, 2006) or a large percentage of data were lost when a temporarily lost receiver was displaced from its mooring only a few hours after it was deployed.

Permanent loss rates for JSATS autonomous acoustic receivers were much lower after our initial 2005 JSATS study and lower than those reported in other studies. By discontinuing the use of surface buoys and taglines in 2006, many of the causes of receiver loss experienced in 2005 were eliminated. Receiver loss due to stress corrosion and bridle breakage was reduced by switching to a single-point-attachment bridle made of 9.5-mm-diameter braided nylon line; adding the polyethylene fin helped to stabilize the receiver in the current and reduce abrasion. Adapting the length of the receiver anchor line to keep the receiver well below the water surface during the lowest tide also helped decrease equipment and data loss.

We made additional improvements to our deployment and mooring methods between 2006 and 2008 to maximize receiver recovery. In addition to the reward program, we were able to decrease equipment and data loss by communicating with other river and estuary users in our work areas. We contacted commercial fishers, informed them about our work and equipment, and avoided areas where they focused most of their fishing effort. To avoid receiver loss from dredging activities, we worked with the U.S. Army Corps of Engineers' channel maintenance staff responsible for maintaining the shipping channels. We also gained experience by learning the patterns of shipping traffic (i.e., areas where ships tended to stray from the marked navigation channel). To limit receiver loss, we avoided deploying in areas of high vessel traffic (large ships and barges), popular fishing grounds (recreational and commercial), navigation channels, and near known obstacles.

The Columbia River system presents unique challenges to the successful deployment, mooring, and safe recovery of acoustic telemetry equipment. Knowledge gained from our efforts and past acoustic telemetry studies led to the development of an improved autonomous acoustic receiver mooring system and procedures described in this paper. The benefits made to the JSATS autonomous acoustic receiver mooring design described here are improved crew safety, receiver recovery success, and data quality while using acoustic telemetry receivers in the Columbia River system. The successes and failures with using autonomous acoustic receivers in the lower Columbia River and its estuary will hopefully guide other researchers in the design and implementation of studies that deploy equipment in large rivers and estuaries.

Acknowledgments

Funding for these JSATS studies was provided by the U.S. Army Corps of Engineers (Portland and Walla Walla districts). We particularly thank Blaine Ebberts of the Portland District for his involvement with these projects. Many people at the Pacific Northwest National Laboratory have been instrumental in the development of these methods. We sincerely appreciate the dedication and hard work of Gary Dennis, Kate Hall, Brian Bellgraph, Rich Brown, Kate Deters, Ryan Harnish, Ian Welch, and others. The Pacific Northwest National Laboratory is operated by Battelle for the U.S. Department of Energy under contract DE-AC05-76RL01830.

References

Clemens, B. J., S. P. Clements, M. D. Karnowski, and D. B. Jepsen. 2009. Effects of transportation and other factors on survival estimates of juvenile salmonids in the unimpounded lower Columbia River. Transactions of the American Fisheries Society 138:169–188.

Clements, S., D. Jespen, M. Karnowski, and C. B. Schreck. 2005. Optimization of an acoustic telemetry array for detecting transmitter-implanted fish. North American Journal of Fisheries Management 25:429–436.

CMOP (Center for Coastal Margin Observations and Prediction). 2010. Columbia River ecosystem observatory network. CMOP. Available: stccmop.org/datamart/observation_network. (April 2010).

Comeau, L. A., S. E. Campana, and M. Castonguay. 2002. Automated monitoring of a large-scale cod (*Gadus morhua*) migration in the open sea. Canadian Journal of Fisheries and Aquatic Sciences 59:1845–1850.

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

Domeier, M. L. 2005. Methods of the deployment and maintenance of an acoustic tag tracking array: an example from California's Channel Islands. Marine Technology Society Journal 39:74–80.

Fox, D. S., S. Bell, W. Nehlsen, and J. Damron. 1984. The Columbia River estuary: atlas of physical and biological characteristics. Columbia River Estuary Data Development Program, Columbia River Estuary Study Task Force, Astoria, Oregon.

Heupel, M. R., and R. E. Hueter. 2001. Use of an automated acoustic telemetry system to passively track juvenile blacktip shark movements. Pages 217–236 *in* J. R. Silbert and J. L. Nielsen, editors. Electronic tagging in marine fisheries. Kluwer Academic Publishers, Dordecht, The Netherlands.

Hickey, B. M., S. Geier, N. Kachel, and A. MacFadyen. 2005. A bi-directional river plume: the Columbia in summer. Continental Shelf Research 25:1631–1656.

Holbrook, C. M., J. Zydlewski, D. Gorsky, S. L. Shepard, and M. T. Kinnison. 2009. Movements of prespawn adult Atlantic salmon near hydroelectric dams in the lower Penobscot River, Maine. North American Journal of Fisheries Management 29:495–505.

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

King, A., G. Johnson, D. Engelberg, W. Ludwig, and J. Marrow. 2008. Observations of intergranular stress corrosion cracking in a grain-mapped polycrystal. Science 321:382–385.

Kirby, G. N. 1995. Fight chloride corrosion in aqueous systems. Chemical Engineering Progress 91:47–53.

Lacroix, G. L., D. Knox, and M. J. W. Stokesbury. 2005. Survival and behavior of post-smolt Atlantic salmon in coastal habitat with extreme tides. Journal of Fisheries Biology 66:485–498.

McMichael, G. A., M. B. Eppard, T. J. Carlson, J. A. Carter, B. D. Ebberts, R. S. Brown, M. Weiland, G. R. Ploskey, R. A. Harnish, and Z. D. Deng. 2010. The juvenile salmon acoustic telemetry system: a new tool. Fisheries 35:9–22.

Parsley, M. J., N. D. Popoff, B. K. Van der Leeuw, and C. D. Wright. 2008. Seasonal and diel movements of white sturgeon in the lower Columbia River. Transactions of the American Fisheries Society 137:1007–1017.

Rechisky, E. L., D. W. Welch, A. D. Porter, M. C. Jacobs, and A. Ladouceur. 2009. Experimental measurement of hydrosystem-induced delayed mortality in juvenile Snake River spring Chinook salmon (*Oncorhynchus tshawytscha*) using a large-scale acoustic array. Canadian Journal of Fisheries and Aquatic Sciences 66:1019–1024.

Seber, G. A. F. 1965. A note on the 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.

Szedlmayer, S. T., and R. L. Schroepfer. 2005. Long-term residence of red snapper on artificial reefs in the northeastern Gulf of Mexico. Transactions of the American Fisheries Society 134:315–325.

White, S. M. 1970. Mineralogy and geochemistry of continental shelf sediments off the Washington–Oregon coast. Journal of Sedimentary Petrology 40:38–54.