Performance of a Full-Duplex Passive Integrated Transponder (PIT) Antenna System in Estuarine Channels

Author: Bass, Arthur L.

Source: Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science, 4(1) : 145-155

Published By: American Fisheries Society

URL: https://doi.org/10.1080/19425120.2012.676384

Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 4:145–155, 2012

ISSN: 1942-5120 online
DOI: 10.1080/19425120.2012.676384

ARTICLE

Performance of a Full-Duplex Passive Integrated Transponder (PIT) Antenna System in Estuarine Channels

Arthur L. Bass*
Department of Fisheries and Wildlife, Oregon State University, 104 Nash Hall, Corvallis, Oregon 97331-3803, USA; and Centre for Ecological and Evolutionary Synthesis, Department of Biology, University of Oslo, Post Office Box 1066 Blindern, Oslo, NO 0316, Norway

Guillermo R. Giannico
Department of Fisheries and Wildlife, Oregon State University, 104 Nash Hall, Corvallis, Oregon 97331-3803, USA

Gabriel T. Brooks
Northwest Fisheries Science Center, Fish Ecology Division, 2725 Montlake Boulevard East, Seattle, Washington 98112-2097, USA

Abstract
Passive integrated transponder (PIT) technology is rarely utilized in estuaries due to (1) saline water's attenuation of an antenna's electromagnetic field, (2) rapidly changing water properties and levels, and (3) the challenges of installing and maintaining antennas in silty, brackish conditions. We present methods for the construction and installation of antennas that can detect 12-mm full-duplex PIT tags in salinities up to 33‰. We evaluated their reading performance under variable water salinities, temperatures, and depths in the upper estuaries of three streams. We found that water depth, salinity, and temperature were all negatively correlated with antenna current, but that the relative importance of these variables varied depending upon aspects of the antenna deployment. Since our antennas held amperage levels adequate for maintenance of a complete electromagnetic field throughout all test conditions, we suggest that successful detection was more dependent upon the antenna system's coverage of the water column and the swimming path of fish through the antenna system than individual antenna performance. In addition to fish, this technology could be applied to studies of mammals, crustaceans, and particles transported through estuarine channels.

Recently, researchers have emphasized the need to better understand fine-scale estuarine habitat use by fish, particularly salmonids (Bottom et al. 2005; Koski 2009; Roegner et al. 2010). Estuaries provide critical habitats for multiple stages of salmonid life cycles by allowing rapid growth, acclimation to salinity, and the expression of multiple life histories, factors that may increase survival and population resilience (Reimers 1971; Tschaplinski 1982; Virtanen et al. 1991; Thorpe 1994). Because the deployment and use of some fish-tracking technologies is complicated or hampered in environments characterized by fluctuating water chemistry (including high salinity) and levels, much less is known about salmonid behavior and habitat use in estuarine marsh channels than in freshwater streams. Radiotelemetry, an important tool in the study of fish migrations, has had limited applicability in monitoring juvenile fish movements in brackish estuaries due to the attenuation of electromagnetic frequencies in saltwater. Acoustic tags work well in estuaries, and a smaller tag has recently been introduced that

Subject editor: Donald Noakes, Thompson Rivers University, British Columbia, Canada

*Corresponding author: arthurlb@ulrik.uio.no
Received July 28, 2011; accepted February 19, 2012

enables tagging of juvenile fish with a minimum fork length (FL) of 100 mm (Brown et al. 2010; McMichael et al. 2010). However, fine-scale movement studies with large population sizes will incur high costs, and the lifespan of the smallest tag is limited to 250 d.

Over the last two decades, passive integrated transponder (PIT) technology has enabled many important advances in fish biology and management (Prentice et al. 1990; Zydlewski et al. 2006). Biologists have used PIT tags to study fish movement in response to environmental variables, density-dependent spatial distribution, and ontogenetic shifts in habitat use (Armstrong et al. 1999; Zydlewski et al. 2005; Meynecke et al. 2008). In terms of fisheries management, PIT technology has been employed to understand impacts of reservoirs and dams, factors affecting smolt-to-adult recruit survival, and passage through culverts and fish ladders (Prentice et al. 1990; Castro-Santos et al. 1996; Sandford and Smith 2002). Passive integrated transponder tags have been especially useful for investigating the migrations of diadromous fishes and assessing the impacts of fish passage barriers. One limitation to the use of PIT technology in the study of diadromous fishes is the reduced performance of PIT antennas in brackish conditions. As water salinity increases an antenna's electromagnetic (energizing) field is attenuated, thus reducing tag detection range.

For PIT antennas to function in a brackish environment, they must be designed to maintain sufficient current at high salinities and ideally have the ability to self-tune to compensate for changing water level and properties (i.e., water chemistry and temperature). Two types of PIT antenna systems are in use: half duplex (HDX) and full duplex (FDX). Half-duplex antennas rapidly alternate between charging and reading phases, while FDX antennas simultaneously charge and read PIT tags. For many deployments, HDX technology is more appropriate than FDX due to lower costs, larger and more easily constructed antennas, and better read range. However, HDX PIT tags commonly in use (23 mm) have a minimum target fish size of 90-mm FL (Zydlewski et al. 2001). In 2011, 12-mm HDX tags became available, but we found no published third-party evaluations of their performance in brackish water. Regardless of the advantages and disadvantages of the two systems, in locations where a large number of FDX tags are in use (such as the Columbia basin, where over 1 million fish are tagged per year), FDX antenna systems must be employed if researchers wish to take advantage of the already tagged fish in the basin.

Half-duplex PIT antennas have been successfully used to track estuarine fish movement in brackish tidal channels, although some modifications are necessary to counteract the reduction in performance compared with freshwater deployments (Adams et al. 2006; Meynecke et al. 2008). Adams et al. (2006) installed a single antenna that covered the entire water column in an estuarine channel but found that the lower 40% of the antenna frame did not read PIT tags, apparently due to signal attenuation in brackish water (up to 28‰). Hering et al. (2010) used FDX technology to monitor subyearling Chinook salmon *Oncorhynchus tshawytscha* in a tidal salt marsh. To counter antenna field attenuation, they used commercially built, aluminum-shielded antennas; however, the high cost of such antennas can be prohibitive for many researchers, especially when a large number of antennas are required.

To monitor juvenile coho salmon *O. kisutch*, we constructed and installed low-cost FDX PIT antennas that could effectively operate in salinities as high as 33‰. In this article, we describe how to build and install this kind of antenna in upper estuarine channels and around tide gates. We also report in situ efficiency estimates of the antenna systems as well as antenna performance across a range of environmental conditions, information that is not readily available in the literature from previous studies that used PIT technology in brackish habitats.

METHODS

Study sites.—Three creeks that drain into Coos Bay (43°21′15.47″N, 124°20′23.85″W), a 54-km^2 estuary on the southern Oregon coast, were used for this study, which took place from March to December 2009. Palouse Creek has a top-hinged tide gate at its mouth with two wooden doors (4.09 m wide × 2.56 m tall), Larson Creek has a side-hinged tide gate with two steel doors (3.20 m wide × 2.56 m tall), and Winchester Creek has no tide gate. The two tide-gated creeks are located in Haynes Inlet, at the north end of Coos Bay, 18.5 km northeast of the estuary mouth. Winchester Creek is located at the opposite end of the bay in South Slough, 7 km south of the estuary mouth. Coho salmon, sea-run cutthroat trout *O. clarkii*, Chinook salmon, and steelhead *O. mykiss* are present in all of these third-order streams.

Antenna construction.—Antenna construction followed the methods described in Zydlewski et al. (2006). Full-duplex PIT antennas were built using seven wraps of 10 AWG 1100/40 PVC-coated litz wire housed in a rectangular frame (inside dimensions = 3.0 × 0.6 m) made of schedule 80, 11.4-cm diameter PVC pipe. Litz wire consists of many small, individually insulated strands of wire woven together to provide greater conductance than standard copper wire by reducing both the skin and proximity effects (phenomena that increase the effective resistance of a conductor). To maintain their positioning within the PVC frame, strands of wire were threaded through adjacent slots of 8-mm channeled polycarbonate sheeting. Inductance of the coil alone was approximately 280 μH. For each antenna, a capacitor pack ranging from 4,850 to 4,980 pF was integrated into the coil (and housed within the PVC frame) to bring the antenna and transceiver to resonance at 134.2 kHz (Zydlewski et al. 2006). We used stainless steel underwater cable connectors (Teledyne Impulse, San Diego, California; part IE34) to ensure antennas could be disconnected from the cables for repair or in the event of a washout. To power each antenna and relay detections to the transceiver, we used a 30-m-long 10 AWG RG-8 coaxial cable with a waterproof coating (Belden, Richmond, Indiana; part 9913F7). We estimate material cost per antenna to be US$800–1,000 (not including labor).

At all sites, a Destron Fearing FS1001M multiplexing transceiver (St. Paul, Minnesota) operated up to six antennas. This transceiver is self-tuning, allowing it to adjust antenna capacitance to match environmentally caused changes in antenna inductance. This feature greatly improves the functional range of stationary antennas in tidal areas where water level, temperature, and salinity change rapidly. Six 100-Ah, 12-V deep-cycle batteries (connected as two groups in series to achieve 24 V) were used to power each transceiver and were replaced with newly charged batteries weekly (the transceiver's current draw is 0.8 Ah). The transceivers were programmed to record status reports that indicated antenna current, noise, and tuned phase at 2-h intervals. The FS-1001M records detections with 1-s resolution. Detections occurring within the same second were recorded in the order they were received, thus allowing for chronological identification of tag detections and prevention of mistaken passage events.

Antenna read range was tested in situ. Measurements are reported as "one-sided read range," defined as the distance from the center of the antenna plane to where a PIT tag (oriented perpendicularly to the antenna plane to imitate the trajectory of a fish passing through the antenna head-on) moving towards the antenna was first detected. Because tests with handheld PIT tags showed our antennas' fields to be nearly symmetrical, the total read distance over which a tag could be interrogated as it passed through an antenna was twice the one-sided read range plus the width of the PVC pipe (11.4 cm).

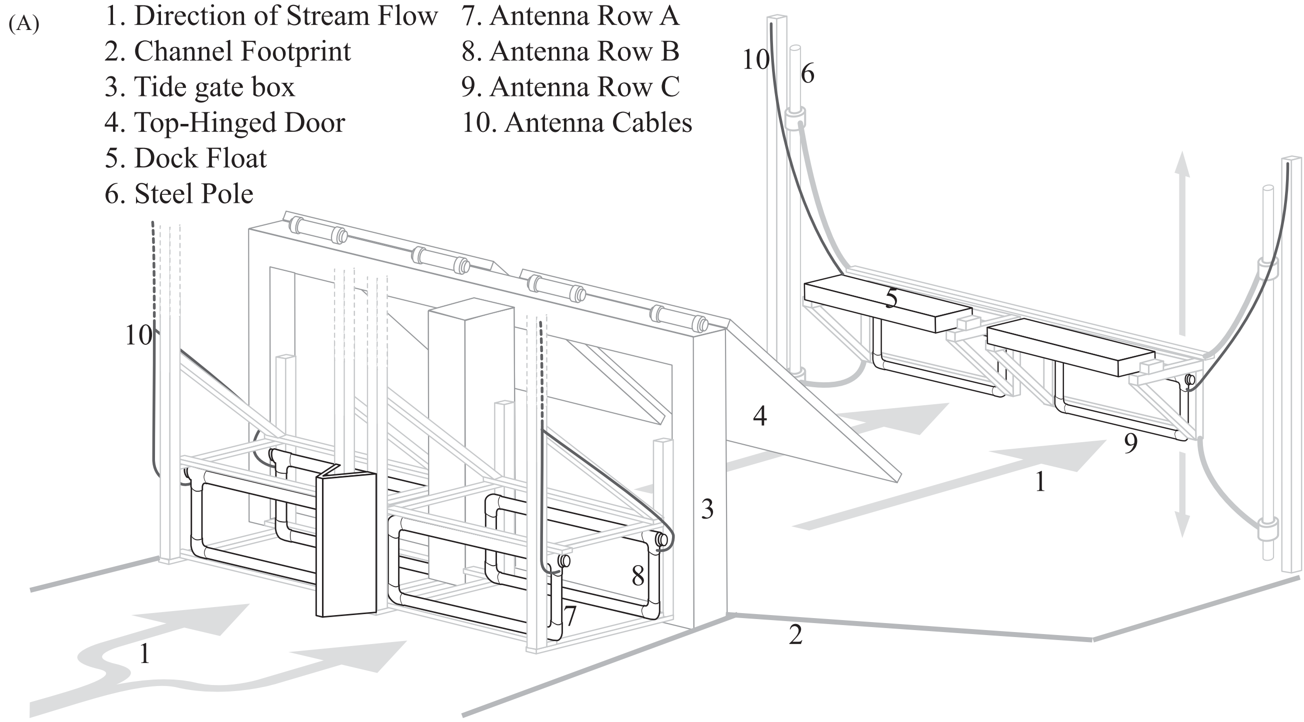
Antenna installation.—At the tide-gated sites, four antennas were placed in a 2 × 2 layout upstream of the tide gate doors and two antennas were placed downstream side by side in the bay (Figure 1A). A 2 × 2 layout allows determination of movement direction since detection timing is recorded to the nearest second and subsecond detections are recorded chronologically. All antennas were positioned vertically in the water column as "swim-through" frames oriented perpendicular to the flow of water (Zydlewski et al. 2006). The cross-sectional water column area covered by 12 of the 16 (see below: side-hinged gate) antennas' fields was 3.2 × 0.9 m (including the thickness of the PVC).

At the top-hinged gate, antenna row B was 15 cm upstream of the gate doors and row A was 1.5 m further upstream (Figure 1A). The antennas were attached with plastic strapping to a wooden frame and held stationary on the floor of the tide gate. Given the average water depth during the period of deployment (0.94 m), the upstream antennas covered, on average, 77% of the cross-sectional area of the water column. On the bay side of the top-hinged tide gate (Figure 1A), two antennas were mounted side by side (row C) vertically within an 8-m-long frame. These antennas were placed 3 m downstream of the doors, in the scour pool formed below the tide gate box. This pool was 2 m deep at the lowest tides and 5 m deep during the highest tides, and therefore the antennas were never able to cover the entire water column. The upper sides of these antenna frames were always at the water's surface. Foam dock floats were attached by outrigger arms to the floating structure to maintain the vertical position of the antennas during high-flow conditions. Metal cables attached to vertical poles on the sides of the scour pool kept these antennas oriented perpendicular to the prevailing flow direction as they rose and fell with the tides.

To fit the tide gate box, the four antennas upstream of the side-hinged tide gate doors had inside dimensions of 2.6 × 0.6 m and effective tag detection areas of 2.8 × 0.9 m each (due to similarities with the two other deployments, no illustration of this antenna system is included). Because the tide box floor elevation was lower than that of the top-hinged gate, water depths were often greater than the height of the antennas. Since we could not cover the entire water column, we chose to float the antennas to provide easier access for maintenance. They were mounted on two floating frames (two antennas on each) with a 60-cm space between each pair of antennas. Each frame was attached to two steel poles so that it could rise and fall with the water level inside the tide gate box. These antennas covered 47% of the water column's average cross-sectional area (average depth = 1.71 m). Unlike the top-hinged gate, each door was made of steel and when an antenna was within 55 cm of them, the antenna's electromagnetic field was reduced. Therefore, the antennas in row B were 76 cm upstream of each door. The two 3.0 × 0.6-m antennas on the bay side of the side-hinged gate were installed side by side on a floating frame. This frame moved vertically along steel poles that were held in place by horizontal wooden beams extending from the tide gate structure.

At the nongated stream, in the channel thalweg, a 2 × 2 antenna layout was mounted on a floating frame like that on the upstream side of the side-hinged gate (Figure 1B). A wooden exterior structure held three steel poles in place. This structure was attached to six 2.5-m-long fence posts (pounded 2 m into the sediment) and cabled to nearby trees from each of its four corners. The antennas floated at the surface in water up to 3 m deep (highest tides) and at low tides they rested on the stream bottom with their top half out of the water. Since the width of the side-by-side antennas only covered ~20% of the high-tide wetted-channel width, plastic aquaculture netting (3-mm mesh and 3-m height) was strung from the stream banks to the antennas at an approximately 45° angle (along the steel cables) like fyke nets. Within the opening between the fyke nets, the antennas covered on average 51% of the water column cross-sectional area (average depth = 1.76 m).

Measuring water depth, salinity, and temperature.—Water pressure transducers (nongated: YSI, Yellow Springs, Ohio [model 6600 EDS]; top-hinged and side-hinged: Onset [model U20-001-01-Ti]) were used to measure water depth (above-channel thalweg or tide gate floor) at 15- and 5-min intervals for nongated and gated sites, respectively. We measured temperature and salinity every 15 min with a data logger (Star-Oddi DST CT, Reykjavik, Iceland) submerged 1 m and attached to the lower horizontal beam of the antenna frame at the



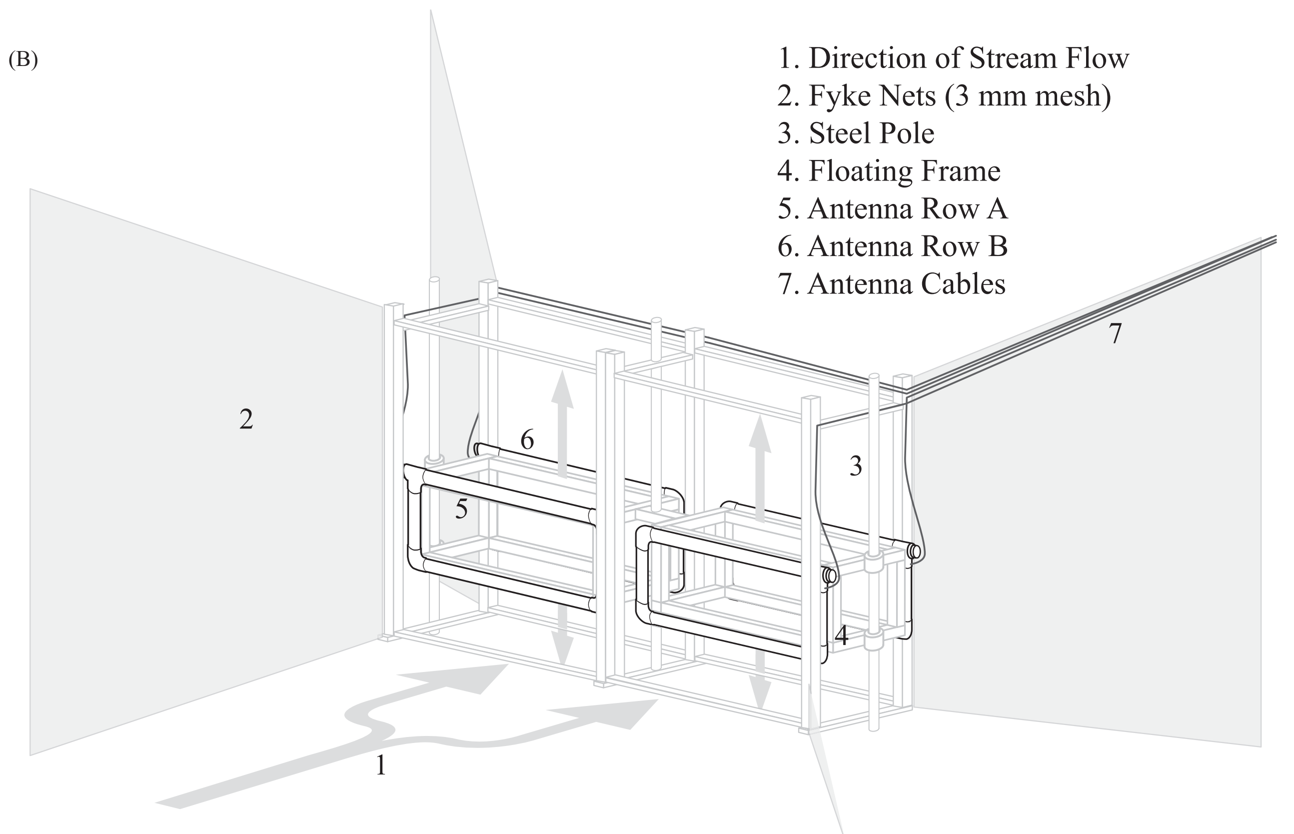


FIGURE 1. Illustrations of antenna systems described in our study. (**A**) Deployment at the top-hinged gate. The walls and ceiling of the tide gate box, as well as the accompanying dike (which would extend sideways from the tide gate box), have been removed for clarity. The four antenna on the upstream side of the tide gate were stationary on the tide gate box floor, while the floating antenna on the bayside were tethered to two steel poles by cable. (**B**) Antenna deployment at the nongated channel. Antennas floated with tidal level and the channel was constricted by fyke nets.

TABLE 1. Fish numbers, species, and life stages used in the n_{indep} group for estimating in situ efficiency (in 2009). The total number of fish tagged upstream of the three antenna systems in 2008 and 2009 is also provided.

	Species				
Site	Sea-run cutthroat trout	Coho salmon smolt	Coho salmon subyearling	Coho salmon adult	n_{indep}
			Used upstream		
Top-hinged	1	5	21	13	40
Side-hinged	4	11	1		16
Nongated	5	11	1		17
			Used downstream		
Top-hinged	3	68	3		74
Side-hinged	6	30	8		44
Nongated	5	9		1	15
			Total tagged 2008		
Top-hinged	145	487	1,193		
Side-hinged	42		282		
Nongated					
			Total tagged 2009		
Top-hinged	28	742	2,807		
Side-hinged	11	375	493		
Nongated	13	171	17		

nongated channel. At the top-hinged and side-hinged gates, the temperature–salinity logger was attached in the same fashion to the bayside antenna frame at each site. The temperature and salinity data could be applied to the antennas on both the upstream and downstream sides of the top-hinged gate because the dike underneath the tide gate box leaked, and many spot measurements during antenna installation showed that the conditions were similar on both sides. At the side-hinged gate, there was very little intrusion of bay water and conditions were very different between both sides of the gate. Salinity and temperature data for the upstream antennas was recorded by a logger positioned 0.5 km upstream of the antennas. Environmental variables for all sites were matched with antenna current values (A) recorded by each transceiver's status reports (every 2 h).

In situ efficiency.—Both free-swimming, PIT-tagged (Biomark TX1411SST; 12.5 × 2.07 mm, 0.102 g) cutthroat trout and coho salmon (at various life stages) were used to estimate efficiency. Fish were tagged throughout each study stream in every month of 2008 and 2009 for other studies underway in the streams (see Table 1 for number of fish tagged), and data used to estimate efficiency were recorded from March through December 2009. When using free-swimming, PIT-tagged fish, it is only possible to determine what Zydlewski et al. (2006) refer to as "in situ" efficiency, which is a cumulative result of "antenna efficiency" (the likelihood that a tag that passes through an antenna field will be detected) and "path efficiency" (the likelihood that a fish passing an antenna will physically move through that antenna and not around it). To test antenna efficiency, we occasionally passed PIT tags connected to a measuring tape (and oriented perpendicular to the antenna plane) through the antennas.

We calculated in situ efficiency for the antenna systems at each site in two different ways, and, in addition, we calculated in situ efficiency for each antenna row of each antenna system. For all efficiency estimates the sample size was n_{indep}, defined as the number of free-swimming, PIT-tagged fish known to pass the antenna system independently of detection during passage (Zydlewski et al. 2006). Fish could be included in the n_{indep} group (Table 1) if (1) they were captured or detected on one side of the gate and subsequently recaptured or detected on the opposite side (including at other antenna systems), or (2) they were captured or detected upstream of the gate and detected in 2010 as adults (coho salmon smolts only). Detections by the antenna array at a tide gate could be used to establish presence on one side, but only if the gate doors had been closed for at least 1 h. Since there were few recaptures or detections independent of the antennas at the nongated antenna system, independently known passage events occurred when fish were detected passing twice in the same direction in a 48-h period. For instance, if a smolt was detected passing downstream twice in 48 h, it must have passed upstream once during this period. For each individual with multiple passes, one occurrence of independently known passage in each direction (where available) was randomly selected for calculating efficiency.

The first method for the in situ efficiency of an antenna system, titled E_{detect} here, is similar to a common method based on releasing a number of PIT-tagged fish on one side of an antenna system and determining the proportion that are detected at least once as they pass through (Adams et al. 2006; Meynecke et al. 2008; Hering et al. 2010). The difference is that we used n_{indep} as the sample group, which ensured that efficiency estimates would not be biased by mortality or fish that stay on one side of the antenna, E_{detect} being defined as

$$E_{\text{detect}} = d_{\text{detect}}/n_{\text{indep}},$$

where E_{detect} is the in situ efficiency of an antenna system from 0 to 1, n_{indep} is the sample group as defined above, and d_{detect} is the number of fish from n_{indep} that were detected at least once at any antenna in that antenna system. This efficiency estimate was very similar to the E_{combined} in situ efficiency estimate defined by Zydlewski et al. (2006), but we did not use this method because the close proximity of our antenna rows would have resulted in inflated estimates due to spatial dependency. E_{detect} is a useful efficiency estimate because it allows us to compare our efficiency estimates with those of other studies as well as to adjust our survival estimates for fish migrating through the system (i.e., coho salmon smolts).

We created the second estimate of in situ efficiency for an antenna system, E_{conf}, to apply to "confirmed passage" events. A confirmed passage occurred when a PIT-tagged fish was detected at more than one antenna row in a sequence that suggested directional movement with no more than 5 min between detections. Like E_{detect}, E_{conf} is given as a simple proportion, expressed as

$$E_{\text{conf}} = d_{\text{pass}}/n_{\text{indep}},$$

where E_{conf} is the in situ efficiency from 0 to 1, n_{indep} is the sample group as defined above, and d_{pass} is the number of fish from the n_{indep} group with confirmed passage. Since the E_{conf} estimate requires detection by more than one row of antennas sequentially and within 5 min, it is lower than typical efficiency estimates, where the goal is simply to detect each fish at least once. We created E_{conf} so that we could estimate the true number of fish passing in both directions based on confirmed passage events.

As in Zydlewski et al. (2006), we also included in situ efficiency estimates for each antenna row at each antenna system, which were simply the proportion of fish from the n_{indep} group that were detected. We provided these estimates since the antenna rows at the tide gate antenna systems were installed very differently and might therefore detect different proportions of fish.

Analysis.—For each antenna deployment, we used multiple linear regression to evaluate the relationship between antenna current (data from status reports) and the explanatory variables of depth, salinity, and temperature. Since the antennas were deployed differently upstream and downstream of the doors at the tide-gated sites, we created separate models for each side. We also modeled the nongated site a second time, without salinities under 1‰, since there was a large cluster of points around zero that we thought might be due to logger inaccuracy at low salinities. We used the antenna current from one antenna in each group since similarly positioned antennas behaved nearly identically. We calculated Pearson correlation coefficients for associations between explanatory variables at each site. While we only report data from additive models here, we tested each group of antennas with all possible two-variable interactions. All analyses were performed in R (R Development Core Team 2010).

As all environmental variables were likely to affect antenna current, it was more informative to determine the relative importance of the variables. We used proportional marginal variance decomposition (PMVD) to hierarchically partition the variance in antenna current among the explanatory variables (decomposes the multiple R^2; Grömping 2007). Proportional marginal variance decomposition was calculated using the R package relaimpo (Grömping 2006). We plotted the relationship between antenna current and the explanatory variable with the highest PMVD for each model.

RESULTS

Various antennas broke or failed at different times during the duration of this study. Twelve months after installation, antenna row C at the top-hinged gate failed in multiple places. The underwater cable connectors corroded at the plugs and several prongs broke off. The wood around fastening points on the frame failed due to the burrowing activity of estuarine invertebrates (including the introduced burrowing isopod *Sphaeroma quoianum*). Antenna rows A and B at the top-hinged gate continued to function after 12 months, although one antenna broke free of the plastic strapping during a period of high flow. The antenna system at the side-hinged gate remained intact after 12 months. However, the fact that antennas of different dimensions were run by a single transceiver that provides a common current for all antennas led to problems selecting the proper current setting at the transceiver. Increasing the current to compensate for low current at row C lead to high current at rows A and B that caused the transceiver to overload and fail, thus requiring repair. The antenna system at the nongated channel was removed after 8 months and did not experience any problems throughout its deployment.

The average antenna efficiency based on 16 occasions when PIT tags were passed through antennas in the field was 0.90. In situ efficiency estimates varied considerably between antenna systems and were typically higher for upstream passage (Table 2). At both gates, in situ efficiency was particularly low (0.06–0.13) at the bayside antennas (Table 2: E_{RowC}). E_{detect} yielded higher estimates of in situ efficiency than E_{conf}, which requires

TABLE 2. In situ efficiency estimates for upstream and downstream passage at three antenna systems including in situ efficiency estimates for individual antenna rows and E_{detect} and E_{conf} for each antenna system.

Site	n_{indep}	E_{RowA}	E_{RowB}	E_{RowC}	E_{detect}	E_{conf}
Upstream						
Top-hinged	40	0.75	0.65	0.13	0.85	0.55
Side-hinged	16	0.31	0.31	0.06	0.31	0.31
Nongated	17	0.82	0.82		0.82	0.47
Downstream						
Top-hinged	74	0.62	0.51	0.12	0.78	0.37
Side-hinged	44	0.39	0.41	0.11	0.43	0.23
Nongated	15	0.47	0.40		0.47	0.40

multiple sequential detections. Where antennas were arranged in a floating 2 × 2 layout (nongated channel, and rows A and B at the side-hinged gate), a fish detected in one row was very likely to be detected in the other (Table 2).

During testing prior to installation, we found that at the highest salinity tested, 33‰, fully submerged antennas were capable of reading PIT tags with a one-sided read range from 3 to 20 cm. Antenna read range was correlated with antenna current, and test tags were read consistently (no gaps in the antenna field) at antenna currents down to 1 A and slightly below (Figure 2). The smaller antennas installed at the side-hinged gate had greater read ranges than the larger antennas at other sites and displayed consistently higher antenna current in the field (Figure 3C). The antennas deployed at all three sites generally maintained antenna

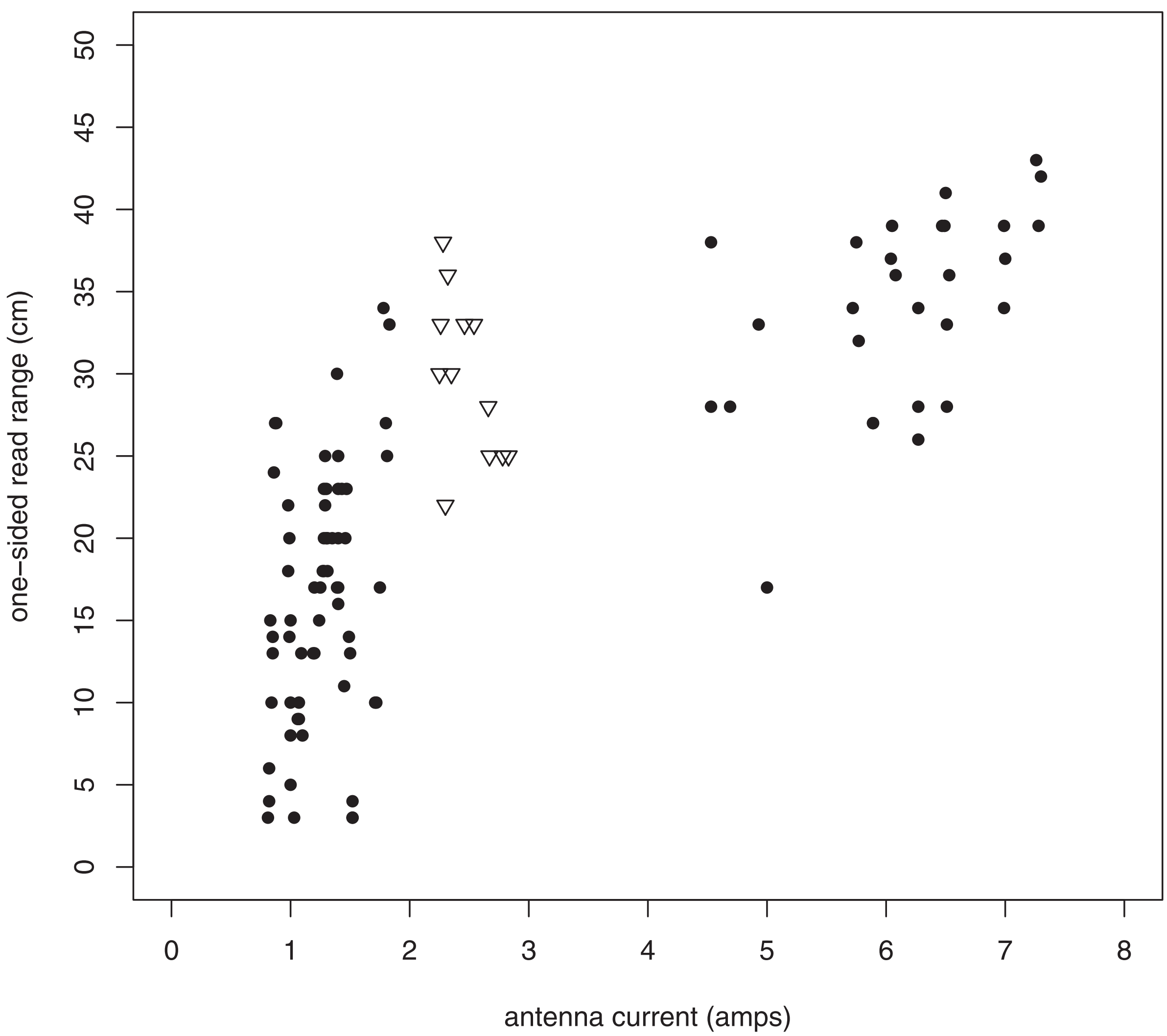


FIGURE 2. Relationship between antenna current and one-sided read range of FDX litz wire PIT antennas. Data were recorded during in situ antenna tests at all three arrays. Black circles were measurements recorded at the 10 larger antennas (all sites), white triangles were recorded at the four smaller antennas (upstream of the side-hinged gate).

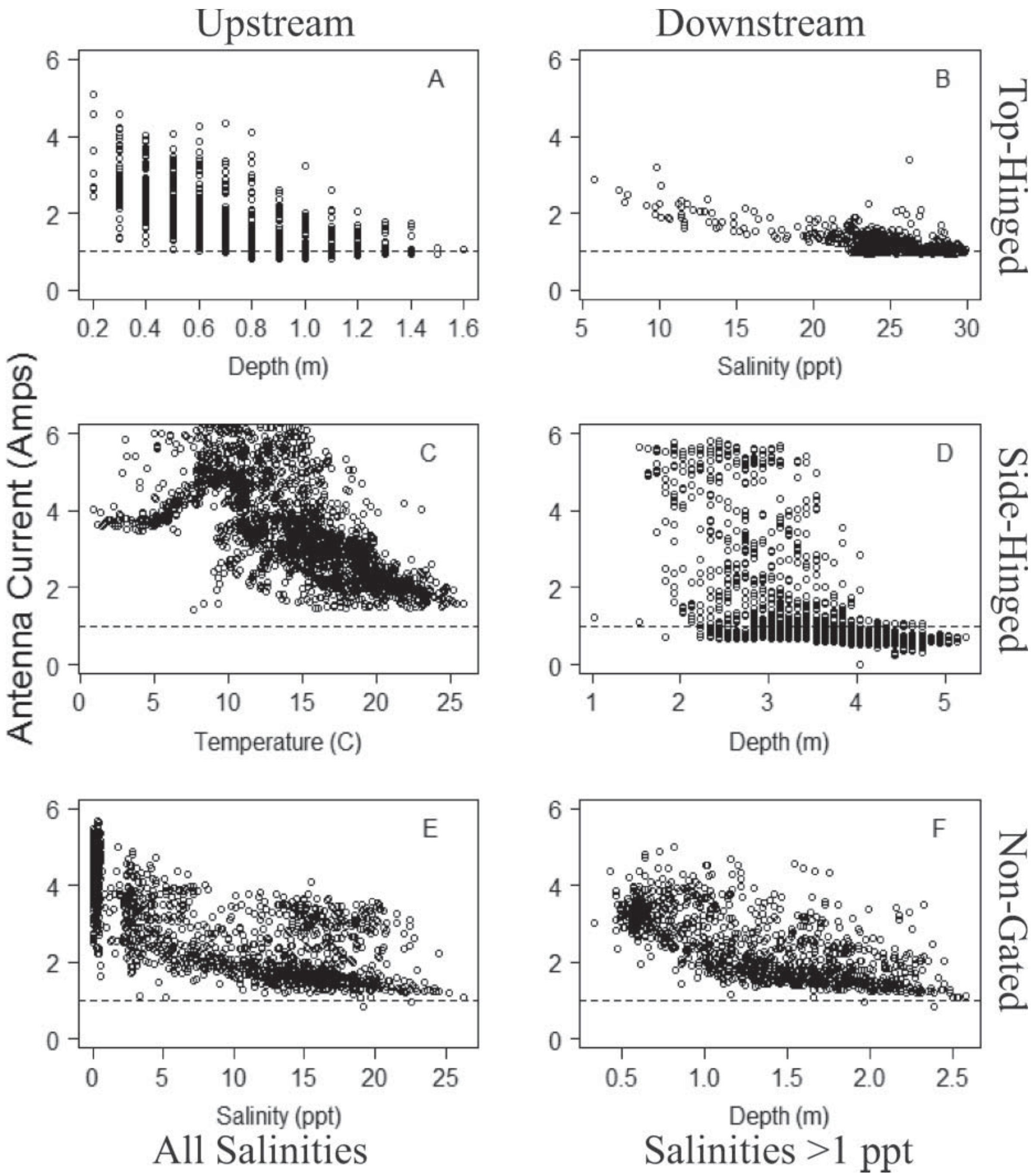


FIGURE 3. Relationship between antenna current (recorded in transceiver status reports) and the most important environmental variable (determined by PMVD) at each different antenna deployment: **(A)** upstream top-hinged gate, **(B)** downstream top-hinged gate, **(C)** upstream side-hinged gate, **(D)** downstream side-hinged gate, **(E)** nongated channel, and **(F)** nongated channel where salinity was > 1‰. The dotted horizontal line indicates an antenna current of 1 A.

currents above 1 A except for the antennas located downstream of the side-hinged gate (Figure 3D).

All environmental variables in all regression models were significantly negatively correlated with antenna current ($P \leq 0.02$; Table 3), except in the case of depth on the upstream side of the side-hinged gate, which was positively correlated. Proportional marginal variance decomposition values indicated that the most important environmental variable varied among deployments (Table 3; Figure 3). Few explanatory variables had Pearson correlations with other explanatory variables greater than 0.40 (nongated: salt $\times$ temperature $= 0.57$; side-hinged upstream: temperature $\times$ depth $= 0.43$). There were no

TABLE 3. Results from multiple linear regression of antenna current and environmental variables at all different antenna deployments. The PMVD estimate for the variable in each model that accounts for the greatest amount of variance is in bold italics.

	Top-hinged upstream	Top-hinged downstream	Side-hinged upstream	Side-hinged downstream	Nongated	Nongated, salinity > 1
Intercept	6.89	3.17	6.65	4.29	5.44	4.90
Depth β1 (SE)	***−1.62 (0.03)***	−0.07 (0.006)	0.14 (0.06)	***−1.00 (0.03)***	−0.73 (0.03)	***−1.05 (0.03)***
PMVD	0.42	0.05	0.01	0.35	0.09	0.45
Salinity β2 (SE)	−0.09 (0.003)	***−0.05 (0.001)***	−0.03 (0.002)	−0.03 (0.002)	***−0.12 (0.003)***	−0.06 (0.003)
PMVD	0.15	0.42	0.03	0.05	0.59	0.22
Temperature β3 (SE)	−0.07 (0.003)	−0.04 (0.002)	***−0.19 (0.007)***	−0.11 (0.006)	−0.03 (0.005)	−0.03 (0.004)
PMVD	0.10	0.12	0.39	0.10	0.01	0.02
Multiple R^2	0.67	0.58	0.43	0.49	0.70	0.69
Number of observations	1,809	1,320	2,184	2,004	1,778	1,093

interaction terms with higher PMVD values than any of the explanatory variables alone for any models. At the nongated site, when salinities below 1‰ were included in the model, salinity was the most important explanatory variable (based on PMVD), but at salinities above 1‰ water depth became more important (Table 3).

DISCUSSION

We constructed full-duplex PIT antennas that were capable of detecting 12-mm PIT tags through a range of conditions, most notably in salinities up to 33‰. We developed methods for installing these antennas that were appropriate for short-term monitoring. The efficiency estimates for our antenna systems were fairly low compared with many freshwater PIT antenna deployments, but the in situ efficiency estimates, E_{detect}, at the top-hinged gate for both passage directions and for upstream passage at the nongated channel were comparable to similarly measured in situ efficiency estimates from other estuarine PIT antenna studies (Adams et al. 2006; Meynecke et al. 2008; Hering et al. 2010; 0.67, 0.60, 0.69–1.00, respectively). We found that water depth, salinity, and temperature were all negatively correlated with antenna current, but that the impact and nature of this relationship varied depending upon aspects of the antenna deployment. Most antennas maintained current that was necessary to generate an electromagnetic field that completely covered the antenna frame (1A). However, since read range is correlated with antenna current, the likelihood of detecting fish at higher swimming speeds decreases as antenna current decreases. Our results corroborate the usefulness of homemade antennas for monitoring fine-scale fish movement in brackish, tidally influenced environments, for which little information exists.

We believe that our installation methods could be improved to create more-robust structures that last longer. To counteract corrosion, we recommend the use of stainless steel hardware. The failure at the antenna cable plug, due to corrosion, might have been avoided by periodic application of a protective grease or by positioning the cable connection point so that it was not submerged. Treated or plastic lumber would better resist boring invertebrate colonization than the standard fir we used (Cragg et al. 1999).

Our finding that water depth was an important environmental variable affecting antenna current, especially when antennas became fully submerged, is consistent with the results of Hering et al. (2010). At the side-hinged gate downstream antennas, the structure upon which the floating antennas ascended and descended with the tide was constructed in a way that imposed an upper limit so that antennas became completely submerged at a water depth of 3.85 m, at which point there is a noticeable change in antenna current (Figure 3D). Current output from the transceiver could not be increased at this site (as mentioned above), although it might have compensated for the decrease in antenna current if it were possible. Submersion at the top-hinged upstream antennas, which were affixed to the tide gate floor, occurred at 0.8-m depth (Figure 3A). At the nongated channel, the antenna frames filled and began to float at 0.8-m depth (Figure 3F). Another potential explanation for the decrease in current at this site could be inundation of the antenna cables at this depth. When installing PIT antennas in tidally affected areas, it is important for researchers to understand local tidal patterns and how inundation will affect antenna performance.

To our knowledge, this is the first peer-reviewed article presenting the effects of salinity on PIT antenna performance. At salinities up to 30‰, our deployed antennas maintained an antenna current sufficient for producing an electromagnetic field covering the entire antenna frame. For two of the floating antenna deployments (nongated channel and downstream top-hinged gate), we found salinity to be the environmental variable most strongly associated with antenna current. However, from the two analyses we performed for the nongated channel (with and without salinity values < 1‰), it appears that the antennas performed very differently in freshwater compared with low salinity water. When data recorded in freshwater conditions was removed from the analysis, depth became more important and the effect of salinity on antenna current was halved, becoming similar to the effect of salinity at the floating antenna at the top-hinged gate (which did not include data recorded in freshwater conditions; Table 3). Furthermore, the change in mean antenna current between 5‰ and 25‰ (Figures 3B, E) is much less than the change in mean antenna current between 0‰ and 5‰ (Figure 3E). Based on these results, we suggest that conventional FDX antennas may not be adequate even in conditions where only low salinities (under 10‰) are expected and we recommend the use of litz wire antennas.

On the upstream side of the side-hinged gate, temperature was the environmental variable most strongly associated with antenna current. Rising temperature increases resistance in antenna wire and could therefore be expected to reduce antenna current. Alternatively, this relationship could be explained by the fact that the salinity and temperature data were recorded 0.5 km upstream from the tide gate. Salinity recorded at this location could have been much lower than at the location of the upstream antennas (which might have been correlated with the temperature we recorded).

In situ efficiency estimates tended to be higher for fish passing upstream than downstream, except at the side-hinged gate. Fish swimming against the current are more likely to maintain a body orientation ideal for tag detection (perpendicular to antenna plane) than those moving with the current. At the nongated channel, upstream passage almost always occurred at low tides, when the antennas would have greater water column coverage. This was not the case at the side-hinged gate, where efficiency estimates might be lower if fish tended to pass upstream at greater depths and therefore under the antennas. Because our antennas generally maintained current levels required for a complete reading field, we suspect that detections often failed as a result of the path that fish took through the antenna system rather than due to antenna performance. The similarities between average cross-sectional water column area covered by each antenna row A (top-hinged = 77%, side-hinged = 44%, nongated = 51%) and the in situ efficiency estimates for row A (downstream passage) at each site (0.62, 0.39, 0.47) lend some anecdotal support to this possibility. Perhaps the greatest limitation of our antennas is their size, especially when installed in locations such as the large scour pool downstream of the tide gates. If the number of PIT-tagged fish is large, path efficiency is less of a concern unless a subset of the population consistently uses a specific path through the antenna system. For example, if body size was associated with swimming depth, the floating antennas might record data biased towards a specific size-class. For this reason, it would have been preferable, at a site such as the nongated channel, to rotate the antennas 90° and gain full water column coverage at the expense of a narrower passage window.

The small tide gate box at the side-hinged gate required us to place the two upstream antennas in fairly close proximity to one another. This design was repeated at the nongated channel due to ease of construction and for consistency between the sites. While this design functioned well in recording passage events, some fish lingered in the antenna fields for prolonged periods, perhaps using the structures as cover. While PIT-tagged individuals reside in the field of an antenna, other PIT tags cannot be interrogated by that antenna. We recommend increasing the space between the antenna rows, especially in nongated channels where space is not a limitation.

We believe that the technology and installations we used will enable researchers to gain a better understanding of the migratory behavior and habitat selection of many species of fish and other aquatic organisms. Floating objects and other materials transported by tidal activity could also be PIT-tagged to remotely monitor tidal dynamics. Finally, our techniques can be applied to research efforts to understand how tide gates and culverts in tidal areas impact organism passage.

ACKNOWLEDGMENTS

This project was funded by the Oregon Watershed Enhancement Board research grant 208-8004-5778. The Coos Watershed Association performed initial fieldwork in Palouse and Larson creeks, and was very generous with field equipment and support. The following individuals performed invaluable fieldwork: Adam Weybright, Justin Arriola, Andrew McClary, John Winkowski, Dave Nelson, and Donald Danesi. Bruce Hansen and Chris Jordan provided support with antenna production and supplies. Thanks to Earl Prentice for advice on antenna design and to Daniel Leventhal for producing the illustrations depicted in Figure 1.

REFERENCES

Adams, A. J., R. Wolfe, W. E. Pine, and B. L. Thornton. 2006. Efficacy of PIT Tags and an autonomous antenna system to study the juvenile life stage of an estuarine-dependent fish. Estuaries and Coasts 29:311–317.

Armstrong, J., F. Huntingford, and N. Herbert. 1999. Individual space use strategies of wild juvenile Atlantic salmon. Journal of Fish Biology 55:1201–1212.

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

Brown, R., R. Harnish, K. Carter, J. Boyd, K. Deters, and M. Eppard. 2010. An evaluation of the maximum tag burden for implantation of acoustic transmitters in juvenile Chinook salmon. North American Journal of Fisheries Management 30:499–505.

Castro-Santos, T., A. Haro, and S. Walk. 1996. A passive integrated transponder (PIT) tag system for monitoring fishways. Fisheries Research 28:253–261.

Cragg, S., A. Pitman, and S. Henderson. 1999. Developments in the understanding of the biology of marine wood boring crustaceans and in methods of controlling them. International Biodeterioration and Biodegredation 43:197–205.

Grömping, U. 2006. Relative importance for linear regression in R: the package relaimpo. Journal of Statistical Software 17:1–27.

Grömping, U. 2007. Estimators of relative importance in linear regression based on variance decomposition. American Statistician 61:139–147.

Hering, D., D. Bottom, E. Prentice, K. Jones, and I. Fleming. 2010. Tidal movements and residency of subyearling Chinook salmon (*Oncorhynchus tshawytscha*) in an Oregon salt marsh channel. Canadian Journal of Fisheries and Aquatic Sciences 67:524–533.

Koski, K. V. 2009. The fate of coho salmon nomads: the story of an estuarine-rearing strategy promoting resilience. Ecology and Society [online serial] 14(1):4. Available: http://www.ecologyandsociety.org/vol14/iss1/art4/. (February 2012).

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

Meynecke, J., G. Poole, J. Werry, and S. Lee. 2008. Use of PIT tag and underwater video recording in assessing estuarine fish movement in a high intertidal mangrove and salt marsh creek. Estuarine Coastal and Shelf Science 79:168–178.

Prentice, E. F., T. A. Flagg, C. S. McCutcheon, and D. F. Brastow. 1990. PIT-tag monitoring systems for hydroelectric dams and fish hatcheries. Pages 323–334 *in* N. C. Parker, A. E. Giorgi, R. C. Heidinger, D. B. Jester Jr., E. D. Prince, and G. A. Winans, editors. Fish-marking techniques. American Fisheries Society, Symposium 7, Bethesda, Maryland.

R Development Core Team. 2010. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Rome. Available: http://www.R-project.org. (March 2012).

Reimers, P. E. 1971. The length of residence of juvenile fall Chinook salmon in Sixes River, Oregon. Doctoral dissertation, Oregon State University, Corvallis.

Roegner, G., E. Dawley, M. Russell, A. Whiting, and D. Teel. 2010. Juvenile salmonid use of reconnected tidal freshwater wetlands in Grays River, lower Columbia River basin. Transactions of the American Fisheries Society 139:1211–1232.

Sandford, B., and S. Smith. 2002. Estimation of smolt-to-adult return percentages for Snake River basin anadromous salmonids, 1990–1997. Journal of Agricultural, Biological, and Environmental Statistics 7:243–263.

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

Tschaplinski, P. J. 1982. Aspects of the population biology of estuary-reared and stream-reared juvenile coho salmon in Carnation Creek: a summary of current research. Pages 289–307 *in* G. F. Hartman, editor. Proceedings of the Carnation Creek workshop, a 10-year review. Pacific Biological Station, Nanaimo, British Columbia.

Virtanen, E., L. Soderholm-Tana, A. Soivio, L. Foreman, and M. Muona. 1991. Effect of physiological condition and smoltification status at smolt release on subsequent catches of adult salmon. Aquaculture 97:231–257.

Zydlewski, G., A. Haro, and S. McCormick. 2005. Evidence for cumulative temperature as an initiating and terminating factor in downstream migratory behavior of Atlantic salmon (*Salmo salar*) smolts. Canadian Journal of Fisheries and Aquatic Sciences 62:68–78.

Zydlewski, G., A. Haro, K. G. Whalen, and S. D. Mccormick. 2001. Performance of stationary and portable passive transponder detection systems for monitoring of fish movements. Journal of Fish Biology 58:1471–1475.

Zydlewski, G. B., G. Horton, T. Dubreuil, B. Letcher, S. Casey, and J. Zydlewski. 2006. Remote monitoring of fish in small streams: a unified approach using PIT tags. Fisheries 31:492–502.