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MANAGEMENT BRIEF

Flexible-Pass-Through Antennas for Half-Duplex Passive Integrated Transponder Tags in Medium to Large Rivers Used to Study Size-Selective Reservoir Passage

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Abstract
The use of passive integrated transponder (PIT) tags for studying fish behavior and demography in medium-large rivers is hindered by antenna designs that are susceptible to damage in those environments and low detection efficiencies. We designed a vertically oriented, flexible PIT tag antenna for half-duplex tags that is simple to construct and deploy, resilient to the dynamic river environment, retains the higher detection efficiency of pass-through antennas, and is suitable for rivers up to 30 m wide and 1.5 m deep. These "flexible-pass-through antennas" are economical to build and cost ~US$435 to $680 for a one- or two-winding antenna, respectively. We used two flexible-pass-through antennas to test for size-selective reservoir passage in juvenile steelhead *Oncorhynchus mykiss* (anadromous Rainbow Trout) and Rainbow Trout. We found that flexible-pass-through antennas withstood high flows and debris during a spring out-migration season and provided data to reject the hypothesis of size-selective fish passage at the Los Padres Dam and Reservoir on the Carmel River (California, USA).

The use of passive integrated transponder (PIT) tags in fisheries research has led to tremendous advances in the understanding of fish movements, survival, and life history patterns (Prentice et al. 1990; Gibbons and Andrews 2004). These small, battery-free tags can be used to track fish as small as 65 mm body length, and the tags can last a fish's lifetime (McKenzie et al. 2012). The application of PIT tags has not been without practical challenges, however, and one of the challenges has been monitoring PIT-tagged fish in medium-large rivers.

Passive integrated transponder tags must be relatively close (0.1–2 m) to a PIT tag antenna to be detected

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(McKenzie et al. 2012), which means that in-river studies must have in-river PIT tag antennas. In-river antennas are susceptible to damage from high flows, debris collision, or burial by sediment (Finlay et al. 2020). Researchers often want to monitor movements during these conditions, such as the high flows during spring smolt out-migration (e.g., Finlay et al. 2020). Passive integrated transponder tag antennas have their greatest detection distances when they are perpendicular to the tag orientation (which is typically perpendicular to the water surface), and tags move through the antenna, as opposed to over the antenna (Texas Instruments 1996; Bond et al. 2007; Burnett et al. 2013; Figures 1 and 2). Unfortunately, orienting an antenna perpendicular to the flow makes it especially susceptible to damage, but the greater detection distances are often critical for research in medium-large rivers. Therefore, to meet the needs of research in medium-large rivers, it is important that we improve the resilience of instream, perpendicular-to-flow PIT tag antennas.

To meet this need, we designed and tested a perpendicular-to-flow antenna that is flexible. Our "flexible-pass-through antenna" design is for half-duplex PIT tags, is easy to build with readily available materials, and can be used on medium-large sized rivers (up to 30 m wide and 1.5 m deep). In this management brief, we describe how we designed and built two flexible-pass-through antennas and how we used them to investigate the potential for size-selective passage in downstream-migrating juvenile steelhead *Oncorhynchus mykiss* (anadromous Rainbow Trout) and Rainbow Trout at the Los Padres Reservoir in the Carmel River, California, USA.

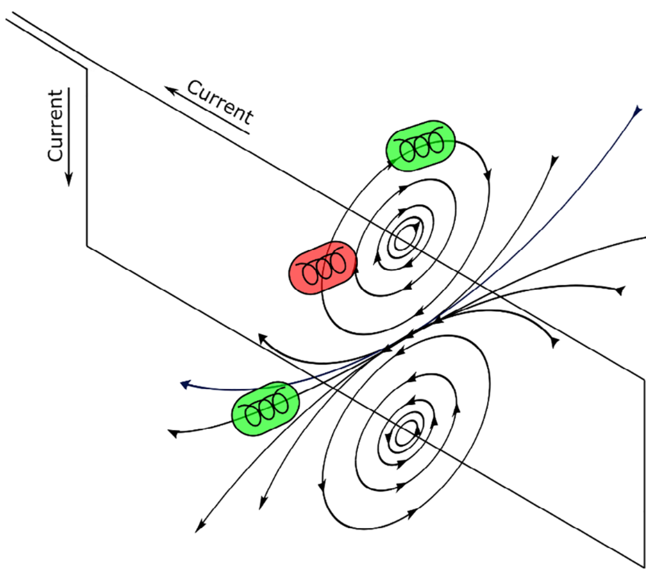

FIGURE 1. An electromagnetic field is generated around an antenna when current runs through the antenna wire. The shape of this particular electromagnetic field is depicted by the black flux lines. A PIT tag is activated and detected only when the electromagnetic flux lines pass longitudinally through the tag coils, as is the case for the green PIT tags. Passive integrated transponder tags will not be activated or detected when the electromagnetic flux lines pass vertically through the tag coils, as is the case for the red PIT tag. The maximum angle between a PIT tag and a flux line for activation and detection is ~45°; however, this depends on the size and strength of the electromagnetic field as well as the size of the PIT tag.

Fish passage through reservoirs is a topic of considerable management concern, as often the migratory success of fish through reservoirs and around dams is low (Jepsen et al. 1998; Pelicice et al. 2015; McLennan et al. 2018; Honkanen et al. 2021). Low passage rates are problematic because they can cause population declines (McClure et al. 2003), but they can also create a maladaptive selective environment if larger (or smaller) individuals are more likely to pass (Maynard et al. 2017). Measuring the degree to which size selection occurs at dams and reservoirs is important for quantifying the true impacts of dams and reservoirs as well as devising solutions to improve passage.

METHODS

The Los Padres Reservoir (36°22′30″N, 121°39′48″W) is located on the Carmel River at river kilometer (rkm) 42 and is ~1.55 km long and 0.17 km wide (Figure S1 in the Supplementary Materials available in the online version of this article). The reservoir is ~2,190 ML. Anadromous steelhead and resident Rainbow Trout are native to the watershed and share the reservoir with nonnative Brown Trout *Salmo trutta*. Juvenile steelhead migrate downstream during the spring either to smolt or rear in the lower river (Hayes et al. 2011). Steelhead migrants that originate upstream of the Los Padres Reservoir must make their way through the reservoir and past the Los Padres Dam to migrate downstream. The two routes of passage past the dam are over the spillway or through a downstream bypass. The downstream bypass is a floating weir collector located adjacent to the spillway crest.

To test the prediction that larger juvenile steelhead are more likely to pass through the Los Padres Reservoir, we captured juvenile steelhead with a rotary screw trap 0.2 rkm upstream of the reservoir and tagged them with half-duplex PIT tags. The rotary screw trap was operated 4 d per week from March 1, 2019, to May 31, 2019, except for March 11, 2019, when operations ceased due to high flows. All captured juvenile steelhead were measured and weighed, and individuals between 65 and 99 mm fork length (FL) were tagged with 12-mm PIT tags and individuals >100 mm FL were tagged with 23-mm PIT tags. All sample collections were conducted under a California Department of Fish and Wildlife Scientific Collection Permit (S-201120001-20,147-002) and the National Marine Fisheries Service's Endangered Species Act Section 10(a)(1)(A) Permit (17219-3R) for listed species. Fish handling followed protocols approved by the Institutional Animal

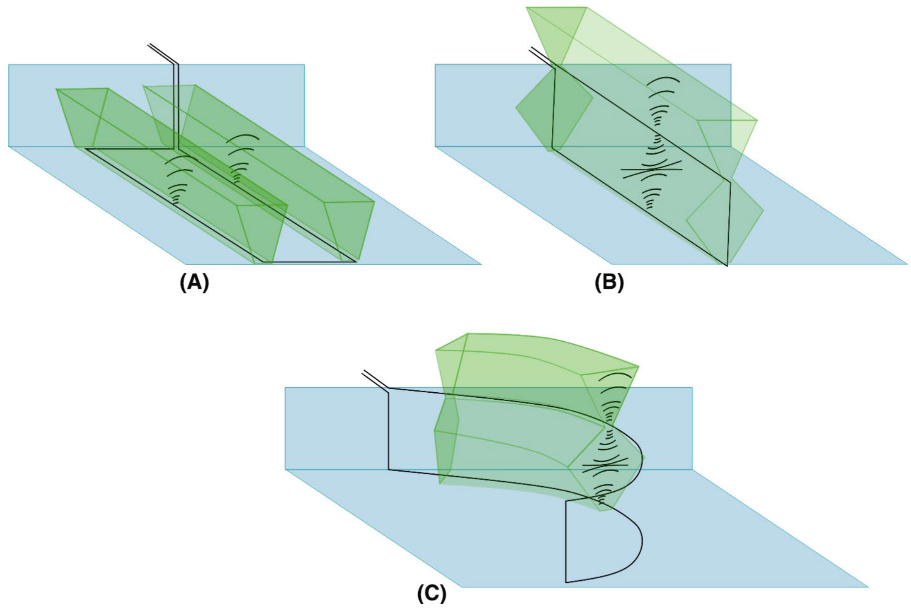

FIGURE 2. Detection volumes (green areas) for **(A)** rigid-pass-over, **(B)** rigid-pass-through, and **(C)** flexible-pass-through antennas. Only half of the detection volume is illustrated for the flexible-pass-through antenna for illustration clarity. The detection volume represents the area around the antenna in which a PIT tag traveling parallel with streamflow would be detected by the antenna. The differences between the detection volumes arise from the different antenna orientations and the interaction between the PIT tag and the electromagnetic flux lines. The flexible-pass-through antenna has the potential to lose detection ability on the perimeter of the antenna in extreme cases when the field lines are oriented at greater than 45° to the PIT tag. This is unlikely to be the case for flexible-pass-through antennas with relatively small arcs, but large arcs could experience some loss of detection ability at the perimeter.

Care and Use Committee of the University of California Santa Cruz (Permit ID: Kierj1904).

We monitored reservoir passage using two flexible-pass-through antennas in the river, as well as a rigid antenna on the downstream bypass exit pipe (Figure S1). One flexible-pass-through antenna was located in the river at the head of the reservoir, 100 m downstream of the rotary screw trap (Figures S1 and S2a). The other was located in the river 0.6 rkm downstream of the dam spillway (Figures S1 and S2b). We selected antenna sites with laminar flow (i.e., we avoided large riffles or rapids) because high-velocity, nonlaminar flow caused the antenna shape to change frequently, which changed the inductance and detection distance. We also avoided pool tails and other habitat features that increased the probability of individual tagged fish occupying the antenna field for long time periods, which can limit detection of other tagged individuals (O'Donnell et al. 2010; Schmidt et al. 2016). Additionally, we targeted sites with anchors on both sides of the river (see below) and where we had access to both sides during high flows. Access during high flows enabled us to reconnect antennas that were disconnected during high flow events.

Antenna construction.— We constructed flexible-pass-through antennas by connecting heavy-gauge wire at the bottom of the antenna to a lighter-gauge wire on top via electrical splices (Figures 3 and S3). We found that

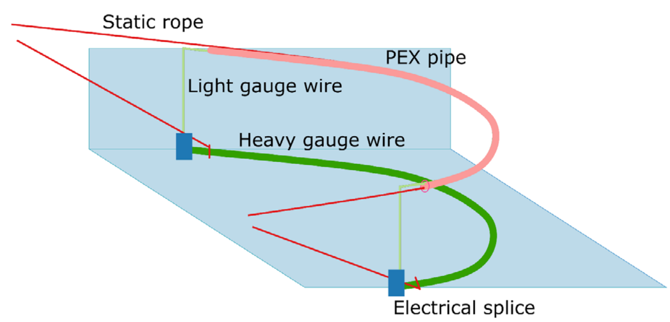

FIGURE 3. Flexible-pass-through antennas are made up of the following components: light-gauge top wire (pink wire) connected by electrical splices (blue rectangles) to heavy-gauge bottom wire (green wire), static rope (red lines) leading to anchors for the top and bottom wires separately, and PEX pipe covering the top wire and anchor rope.

waterproofing the connections was not necessary; however, that may not be the case in saline or turbid water. We dressed the connection with a combination of dielectric grease and self-vulcanizing electrical tape to keep fine sediment out of the connection, which made splice replacement easier. The heavy-gauge wire on the bottom conducted electricity and simultaneously acted as its own weighted line across the streambed. We found that highly flexible (multistrand), large-gauge (1 to 2/0 American Wire Gauge [AWG]) wire with robust rubber insulation, such as welding or diesel automotive wire, provided ideal weight and resilience to abrasion for the bottom wire (Table S2 in the Supplementary Materials available in the online version of this article). For the top wire, we used stranded household electrical wire (such as THHN insulated or Romex) in gauges ranging from 16 to 10 AWG (Table S2).

We placed the top wire into a cross-linked polyethylene (PEX) pipe to help shed debris and provide for protection from UV rays (Figures 3 and S2). The PEX also gives the top wire a modest positive buoyancy that keeps it floating just below the water surface. We ran a 5-mm-diameter static line (5.0 kN strength), with the top wire inside the tubing to attach to anchors on the streambank (Figure 3; Table S2). We added the same static line to the bottom wire and attached to the streambank anchors. The static line held the antenna in place and prevented tension on the electrical wire itself. A detailed part list is available in Table S2.

Antenna design.— We designed the above-reservoir antenna to work within the inductance range of the Oregon RFID (ORFID) reader, and the below-reservoir antenna for Biomark reader. The stock inductance range for ORFID readers is 8–80 μH and for Biomark IS1001 readers is 70–150 μH. To fit within these inductance ranges, our above-reservoir antenna had a single winding (i.e., loop) and our below-reservoir antenna had two windings. The two windings on the below-reservoir antenna each had heavy-gauge wire on bottom and lighter-gauge wire on top. We used a 10–2 AWG Romex wire for the top and placed it in a single PEX pipe with the static line. We zip-tied the bottom two wires and the static line together.

We designed the above-reservoir antenna to be 14.2 m long (the horizonal wire distance) and 0.9 m tall (the vertical distance between the top and bottom wires). The below-reservoir antenna was 14 m long and 0.9 m tall. However, because the water depths varied over the course of the study period, our antenna height varied as well because the top wire is mobile and can move as water depths change. We tested a range of distances between the top and bottom wires prior to installation and found that distances greater than 1.1 m usually created a zone between the wires where 12- and 23-mm PIT tags were not detected.

Both of our flexible-pass-through antennas had relatively large arcs; ~3–4 m from the straight-line distance between the two anchors (Figures 2 and S2). The arc decreased the force on the anchors and allowed the antenna to flex and shed debris. The optimal arc size was a trade-off between decreasing force on the antenna and tag detection. Larger arcs decreased force on the anchors, making them less likely to fail, which was critical for these flashy systems with lots of debris. However, arcs that were too large decreased the detection distance because tags approached the antenna at a less optimal angle (Figures 1 and 2). In general, antenna wires oriented more than 45° away from perpendicular to the tag have much smaller detection distances (Texas Instruments, Dallas, Texas, 1996; Burnett et al. 2013).

Anchoring.— We anchored the antennas by attaching the static line with carabiners to streambank anchors. The streambank anchoring options we used were trees and boulders with block anchors. We made tree anchors by wrapping static cord around a tree trunk 20–30 cm in diameter and using a carabiner to attach the antenna line (Figure S4a; Table S2). We anchored to boulders using concrete-block screw anchors and eye nuts (Figure S5; Table S2).

Installation.— We used a highline to reinstall the antennas after they broke during high flows and debris capture. A highline is a rope or cable that is attached to trees (or other objects on the bank) so that it spans the river well above the water line. We attached one end of the antenna to the highline and ferried the antenna across, then detached the antenna from the highline and attached it to the streambank anchor. This method increased the range of water levels where we could work with the antenna and eliminated the need for a person to wade into deep water.

Operations.— The ORFID antenna was tuned using an auto tuner 5 d per week for the duration of the study period. The Biomark antenna was set to automatically retune when the phase deviation threshold exceeded 60. Both flexible-pass-through antennas were operated using two 300-W solar panels wired in parallel, connected to Outback Power Systems FlexMax FM60 charge controllers and 12-V 90 ampere-hour absorbent glass mat batteries (Table S2). The ORFID and Biomark readers required 12- and 24-V power, respectively, so we used two 12-V batteries in parallel for the ORFID system and four 12-V batteries in series–parallel for the Biomark system.

Size-selective reservoir passage.— We compared the fork lengths of the juveniles detected on the above and below reservoir antennas, as well as the juveniles that were detected on the downstream bypass but were missed on the below-reservoir antenna. We tested for normal data distributions using a Shapiro–Wilk normality test and compared the median lengths using a Wilcox test. We conducted the analyses using R (R Core Team 2021).

RESULTS

We successfully operated our flexible-pass-through antennas from February 1 to July 1, 2019. Flows over the antenna operations period ranged from 23 to 796 ft^3/s at the below-reservoir antenna (Figure 5; Monterey Peninsula Water Management District, unpublished data). Flows above the reservoir were measured on three occasions at a site 1-rkm upstream of the above-reservoir antenna and were consistent with flows measured below the reservoir (Figure 5; Monterey Peninsula Water

Management District, unpublished data). The Los Padres Dam operates as a "run of river" dam after the reservoir has filled from winter storms, such that the reservoir spills approximately the same amount of water entering the reservoir. All of our antenna operations occurred after the reservoir had filled and before the last day of spill, which occurred on August 8, 2019. The below-reservoir antenna was operational for all of the flows; however, the 796-ft^3/s flow event at the above-reservoir antenna caused a boulder anchor to break. We were able to reattach the antenna using the highline and drilling new anchors within 3 d of the break.

The water depths over the study period ranged from 0.3 to 1.5 m, and because the top wire of the antenna is slightly buoyant, it followed the water height and maximized detection efficiency by similarly moving from ~0.3 to 1.5 m depth. The inductance on the single-winding, above-reservoir antenna ranged from 30 to 42 μH, and the inductance on the double-winding, below-reservoir antenna ranged from 112 to 146 μH. Detection distances for 23-mm tags were generally the full distance between the top and bottom wires, whereas the detection distances for the 12-mm tags were 0.15–0.3 m away from the top and bottom wires. The single-loop ORFID antenna cost roughly US$435, while the double-loop Biomark antenna cost roughly $680 (Table S2).

We captured 397 juvenile steelhead at the rotary screw trap, and 87% were large enough to tag. In all, 257 were tagged with 12-mm tags and 88 were tagged with 23-mm tags. We detected 261 (191 of 12-mm tagged and 70 of 23-mm tagged) of the tagged individuals on the above-reservoir antenna between March 1 to July 1, 2019. We assumed that all juveniles detected on the above-reservoir antenna entered the reservoir. We detected 24 juveniles on the below-reservoir antenna and 8 juveniles on the downstream bypass antenna that were not detected on the below-reservoir antenna.

The length data was not normally distributed for juveniles detected on the above-reservoir antenna (Shapiro–Wilk test, $W = 0.78$, $P < 0.001$) or on the below-reservoir antenna ($W = 0.91$, $P = 0.04$). The length data for juveniles uniquely detected on the downstream bypass was normally distributed ($W = 0.93$, $P = 0.52$). There was no size difference between the juveniles detected on the below-reservoir antenna and those detected only on the downstream bypass antenna (Wilcoxon rank sum test, $W = 67.5$, $P = 0.22$), so we combined those groups to compare with the fish entering the reservoir. We found no size difference between the juveniles that entered the reservoir and those that passed through the reservoir during the study period (Wilcoxon rank sum test, $W = 4{,}276$, $P = 0.80$) (Figure 4). The median FL for juveniles that entered the reservoir was 90 mm FL (innerquartile [IQ] range: 81–100 mm) and median FL for fish that passed through the reservoir was 89 mm (IQ range: 79–101 mm) (Figure 4).

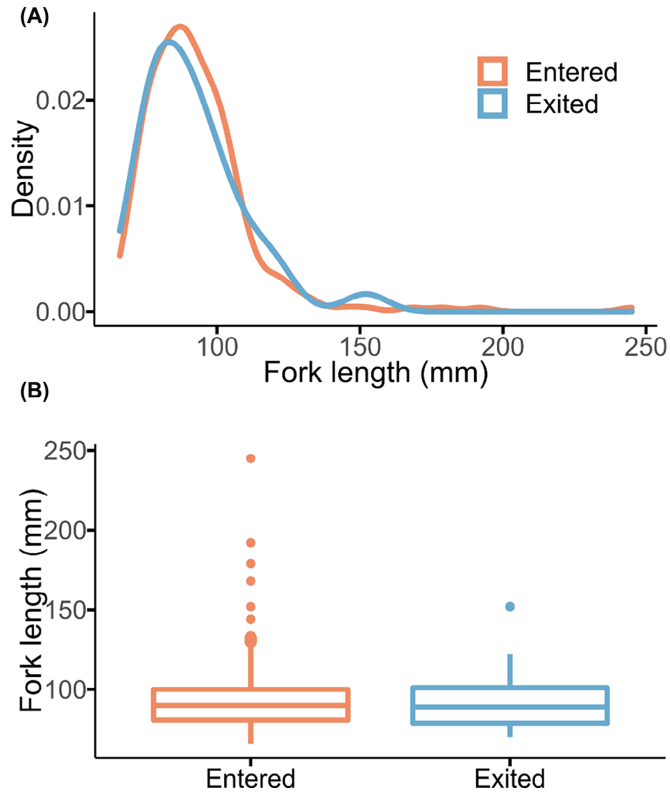

FIGURE 4. The **(A)** fork length distributions and **(B)** median values are not different between the PIT-tagged juvenile steelhead that entered the reservoir and those that exited. In panel A, density is the number in each 1-mm FL bin, scaled to integrate to 1.

DISCUSSION

The flexible-pass-through design allowed us to successfully and effectively operate in-river PIT tag antennas for the spring outmigration season in the upper Carmel River. The antennas withstood high flows (Figure 5) and considerable debris load, and on the occasion that one broke, we were able to reinstall it with relative ease and safety.

The detection efficiencies on both of the flexible-pass-through antennas were relatively high. We estimated the antenna detection efficiencies using a Bayesian state-space mark–recapture model as part of a larger fish passage study in the Carmel River (Ohms et al. 2022). The detection probability on the above-reservoir antenna was 94–96% (95% confidence intervals 90–97% and 94–98%) for 12- and 23-mm tags, respectively (Ohms et al. 2022). Detection probability on the below-reservoir antenna was 64–68% (95% confidence intervals 54–74% and 56–82%) for 12- and 23-mm tags, respectively (Ohms et al. 2022). These relatively high detection capabilities are especially

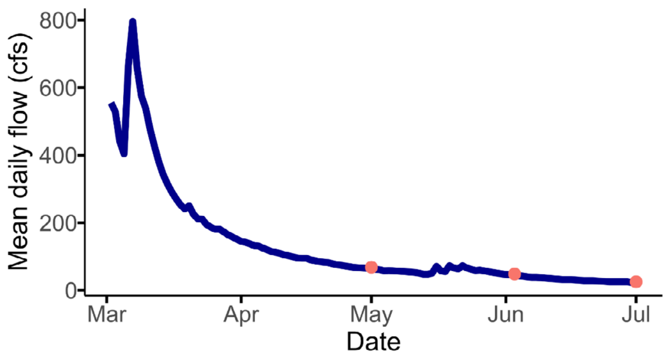

FIGURE 5. Mean daily flows from March 1 to July 1, 2019, measured 0.5-rkm upstream of the below-reservoir antenna (blue line). The orange points show flows that were measured on three occasions 1-rkm upstream of the above-reservoir antenna. Data collected by the Monterey Peninsula Water Management District (unpublished).

beneficial for studies where sample sizes are small or movement among different groups is relatively low.

The cost to build a flexible-pass-through antenna varies considerably, depending on the antenna size (which is determined by the stream size), the number of windings in the antenna, and the gauge of the bottom wire. Larger antennas or more windings increase the amount of wire needed and therefore the cost. The bottom wire gauge is also highly influential on the cost; the price of the bottom wire ranged from $4.79 for 1 AWG to $10.76 for 2/0 AWG (Table S2). The gauge of the bottom wire should be chosen based on the site conditions. Antennas at sites with relatively slow-moving water, low flow volumes, and fine sediments can be built with the smaller-sized (1 AWG) bottom wire, whereas sites with fast water, high or turbulent flows, and coarse sediments will require larger-sized (up to 2/0 AWG) bottom wires. The additional costs for the reader, power source, and equipment boxes will also vary, depending on what is chosen (Table S2). The approximate additional cost for our Biomark site (everything but the antenna) was $3,255, and for our ORFID site was $5,110 (Table S2). Nearly half of the additional cost was from the solar power system; if AC power was available, the cost would have been considerably less.

It should be noted that our flexible-pass-through antennas were designed to detect half-duplex (HDX) tags only. Although there are vertically oriented flexible-antenna designs that are used to detect full-duplex (FDX) tags (Holcombe et al. 2020), these antennas must operate with less-rapid shape change and wire movement than our flexible-pass-through antennas experience. Specifically, the top wire of a flexible-pass-through antenna will bounce and move with the water current. Large changes in water depth and antenna height ($\geq \sim 15$ cm) can be accommodated by retuning the antenna, so long as the antenna remains within the inductance range of the reader. The smaller, more-rapid changes caused by the top wire moving in the stream current limit the antenna use for FDX tags. The limited application of our flexible-pass-through antenna design to FDX tags is due to the differences in tag signal transmission between FDX and HDX systems. Full-duplex systems rely on amplitude modulation (AM) transmission between the tag and the antenna. Rapid movement of the antenna wires can cause corresponding shifts in the antenna current amplitude and mask the AM transmission from the tag, thus leaving the tag undetected (International Organization for Standardization 1996). In contrast, HDX systems rely on frequency modulation (FM) transmission between the tag and antenna, which are not masked by changes in antenna current amplitude due to wire movements (International Organization for Standardization 1996). In this way, HDX systems are more "forgiving" to wire movement and shape changes. There are limits, however, and deploying flexible-pass-through antennas into highly turbulent sites (i.e., with rapids) will likely limit detection distances of HDX tags.

We found that tree anchors were especially effective as streambank anchors; however, not all sites will have suitable riparian trees for anchoring. In these cases, deadman anchors can be effective. Deadman anchors are constructed by running steel cable through one to three pieces of wood and stacking cobble on top (Figure S4b). Fast-growing riparian trees (i.e., alders) can be planted on top of the anchor to increase long-term strength. These various anchoring options allow flexible antennas to be deployed under a broad variety of site conditions using onsite materials and negligible streambed alteration.

We did not find evidence for size-selection on PIT-tagged juvenile steelhead passing through the Los Padres Dam and Reservoir. There was no observed size difference between the PIT-tagged juvenile steelhead that entered the reservoir and those that exited downstream. Our finding was in contrast to previous studies that have documented higher migration survival for larger steelhead (Ward et al. 1989; Bond et al. 2008) and in other salmonid smolts in the ocean (Henderson and Cass 1991; Miyakoshi et al. 2001; Irvine et al. 2013), higher likelihood of maturation for larger juvenile steelhead (Sloat and Reeves 2014) that could cause them to remain in the reservoir, and higher predation rates on smaller Pink Salmon *Oncorhynchus keta* and Masu Salmon *Oncorhynchus masou* fry (Hasegawa et al. 2021). Our results suggest that these size-selective mechanisms did not occur in the Los Padres Reservoir, despite relatively low reservoir passage overall (Ohms et al. 2022). One reason may be that all juvenile steelhead, regardless of size, had difficulty navigating through the Los Padres Reservoir. This hypothesis is supported by the observation that other juvenile salmonids struggle to navigate through both natural lakes and man-made reservoirs and that successful passage appears to be largely by chance (Beeman and Adams 2015; Honkanen et al. 2021).

Although the lack of evidence for size selection was clear, our study had some limitations that are important to consider. We had a relatively small sample size of fish that passed through the reservoir (n = 32), a single study year, and a species with considerable life history plasticity. Additionally, juvenile steelhead <65 mm FL could have had different reservoir passage rates that we were unable to measure because those fish were too small to tag, and lower detection probabilities for 12-mm tags below the dam could have led us to overestimate the mean length of fish that passed through the reservoir. Each of these limitations may have constrained our ability to detect size-selective reservoir passage. Future studies that address these limitations would be worthwhile.

Our study demonstrates how flexible-pass-through antennas can be a valuable tool for monitoring the movements and survival of half-duplex PIT-tagged fish in medium to large rivers. In addition to the two flexible-pass-through antennas we describe here, we have built and operated several others in a range of sizes (Table S1). In general, we have found that flexible-pass-through antennas are effective for sites up to 30 m wide and 1.5 m deep (Table S1). The resilience, ease of construction, and effectiveness of flexible-pass-through antennas make them a great option for studies in medium to large rivers. We encourage further development and testing of these useful in-river PIT tag antennas.

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SUPPORTING INFORMATION

Additional supplemental material may be found online in the Supporting Information section at the end of the article.