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Raft and Floating Radio Frequency Identification (RFID) Antenna Systems for Detecting and Estimating Abundance of PIT-tagged Fish in Rivers

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ARTICLE

Raft and Floating Radio Frequency Identification (RFID) Antenna Systems for Detecting and Estimating Abundance of PIT-tagged Fish in Rivers

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Abstract
Portable radio frequency identification (RFID) PIT tag antenna systems are increasingly being used in studies examining aquatic animal movement, survival, and habitat use, and their design flexibility permits application in a wide variety of settings. We describe the construction, use, and performance of two portable floating RFID PIT tag antenna systems designed to detect fish that were unavailable for recapture using stationary antennas or electrofishing. A raft antenna system was designed to detect and locate PIT-tagged fish in relatively long (i.e., ≥10 km) river reaches, and consisted of two antennas: (1) a horizontal antenna (4 × 1.2 m) installed on the bottom of the raft and used to detect fish in shallower river reaches (<1 m), and (2) a vertical antenna (2.7 × 1.2 m) for detecting fish in deeper pools (≥1 m). Detection distances of the horizontal antenna were between 0.7 and 1.0 m, and detection probability was 0.32 ± 0.02 (mean ± SE) in a field test using rocks marked with 32-mm PIT tags. Detection probability of PIT-tagged fish in the Cache la Poudre River, Colorado, using the raft antenna system, which covered 21% of the wetted area, was 0.14 ± 0.14. A shore-deployed floating antenna (14.6 × 0.6 m), which covered 100% of the wetted area, was designed for use by two operators for detecting and locating PIT-tagged fish in shorter (i.e., <2 km) river reaches. Detection distances of the shore-deployed floating antenna were between 0.7 and 0.8 m, and detection probabilities during field deployment in the St. Vrain River exceeded 0.52. The shore-deployed floating antenna was also used to estimate abundance of PIT-tagged fish. Results suggest that the shore-deployed floating antenna could be used as an alternative to estimating abundance using traditional sampling methods such as electrofishing.

Passive integrated transponder tag technology has many advantages over traditional marking techniques. They allow individual identification, have an infinite life as long as the tag is not damaged, are easily applied and well retained, and have minimal effects on growth and survival of fishes (Gries and Letcher 2002; Zydlewski et al. 2006; Ficke et al. 2012). Traditionally, the utility of PIT tagging has been limited to physical recapture events using methods such as electrofishing (Zydlewski et al. 2006). Stationary antennas allow passive recaptures of PIT-tagged fish and have recently been used to detect PIT-tagged fish in behavior studies, especially those examining habitat selection or movement (Nunnallee et al. 1998; Zydlewski et al. 2006; Bond et al. 2007; Compton et al. 2008; Connolly et al. 2008; Aymes and Rives 2009).

Stationary antennas are typically used to detect PIT-tagged fish, but the use of portable antennas is becoming more common. Portable antennas have been used in studies examining aquatic animal movement, survival, and habitat use, and their design flexibility permits application in a wide variety of settings. Initial technological advances in portable PIT tag antenna

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systems enabled effective detection in shallow, wadable rivers of salmonid fishes such as Atlantic Salmon *Salmo salar* (Roussel et al. 2000; Zydlewski et al. 2001), Brown Trout *S. trutta* (Cucherousset et al. 2005), and steelhead *Oncorhynchus mykiss* (anadromous Rainbow Trout) (Hill et al. 2006). Additionally, portable antennas have been developed to detect and locate age-0 Northern Pike *Esox lucius* (Cucherousset et al. 2007) and various age-classes of European Eel *Anguilla anguilla* and Common Dace *Leuciscus leuciscus* (Cucherousset et al. 2010). Previous designs of portable antenna systems have limited their effectiveness to shallow, wadable floodplains or small streams; however, a boat-mounted antenna system was recently developed for monitoring mussel populations in larger, nonwadable rivers (Fischer et al. 2012).

Portable antenna systems are limited by factors affecting detection efficiency including tag size, power source, tag orientation, antenna proximity if multiple antennas are used (Zydlewski et al. 2006), tag collision (Axel et al. 2005; O'Donnell et al. 2010), and disruption of the magnetic field by the presence of metal (Greenberg and Giller 2000; Bond et al. 2007). For example, tag orientation relative to the antenna field affects detection and is higher when the tag is oriented perpendicular rather than parallel to the antenna (Nunnallee et al. 1998; Morhardt et al. 2000; Zydlewski et al. 2006; Compton et al. 2008; Aymes and Rives 2009). Disruption due to antenna proximity can be reduced through the use of multiplexers (Aymes and Rives 2009), and disruption from metal can be reduced by utilizing noninductive materials such as epoxy coil encasements or nylon nuts and bolts (Fischer et al. 2012). Potential limitations should be accounted for during the design process, and we elaborate on the ways in which these limitations were accounted for in our portable antenna designs.

We describe the design and construction of two, portable, floating, radio frequency identification (RFID) PIT tag antenna systems: a raft antenna system and a shore-deployed floating antenna system. To assess the performance of each antenna system, we estimated detection distance and detection probability using both experimental and field data. Our research objective for the raft antenna system was to determine the location and fate of PIT-tagged fish in relatively long (i.e., ≥10 km) river reaches. For the shore-deployed floating antenna system, our research objectives were twofold. First, we wanted to compare abundance estimates to those obtained via electrofishing to determine whether the antenna could be used as an alternative for estimating abundance of PIT-tagged fish. Second, we wanted to determine the location and fate of fish that were not available for recapture via electrofishing due to movement from release locations in shorter (i.e., <2 km) river reaches.

METHODS

Raft Antenna System

Design and construction.—We designed a two-antenna array for detecting PIT-tagged fish in a relatively long (≥10 km) reach of the Cache la Poudre River, Colorado. The array was constructed using a 4.9-m, self-bailing, inflatable river raft. The first antenna was installed in the bottom of the raft (horizontal) and was designed for continuous deployment to detect fish in shallower (<1 m) sections of the river. The second antenna was a dropper antenna (vertical) designed for intermittent deployment to detect fish in deeper (≥1 m) pools.

Both antennas consisted of two, loosely bound, continuous loops of 12-gauge thermoplastic, high-heat-resistant, nylon-coated (THHN) wire. Binding of the wire occurred at specific attachment points with the raft (horizontal) or support beams used to maintain antenna shape (vertical). Between these points, the wire formed loose gaps of varying distances. The horizontal antenna was an elliptical antenna 4 × 1.2 m in size and located in the self-bailing channel of the raft (Figure 1). Antenna shape and loop proximity were maintained by threading the wire through sections of flexible plastic tubing secured to the self-bailing holes in the floor of the raft with soft nylon cord. The vertical antenna was a 2.7- × 1.2-m rectangle, maintained by four, 19-mm PVC crossbeams secured to the antenna wire with expandable spray-foam insulation (Figure 1). Holes were drilled in each crossbeam to allow water entry and 51-mm PVC caps filled with cement were attached to the lowermost crossbeam for ballast. Foam pipe insulation placed on the first crossbeam allowed the antenna to hang vertically in the water column while remaining at the water surface without becoming completely submerged. Connectors produced for welding applications were used to allow for a quick disconnection of the vertical antenna in the event that the antenna got entangled and caught on submerged rocks or vegetation while deployed. The vertical antenna design facilitated easy deployment at the head of a pool, retrieval at the tail end of the pool, and onboard storage in an accordion-like fashion for swift deployment on subsequent occasions.

The horizontal and vertical antennas were both connected to an Oregon RFID half-duplex (HDX) multiplex reader (alternating read cycle of six times per second for each antenna), which helped prevent proximity detection errors (Aymes and Rives 2009). The HDX reader stored detections for the array along with date and time of detection. Two, 12-V, marine, deep-cycle batteries, connected in parallel, powered the raft antenna system. Batteries, tuner boxes, and the reader were placed in plastic, top-locking containers and strapped to a rigid plastic deck located on the floor of the raft, which prevented equipment shifts and submersion during deployment (Figure 1).

Detection distance.—To measure the detection distance of the horizontal antenna, the raft was elevated on stands, and detection distances were measured by running a 32-mm PIT tag in a perpendicular and parallel orientation past the antenna on horizontal, vertical, and 45° detection planes. The horizontal detection plane was defined as the plane extending 180° to the sides of the antenna, the same plane in which the antenna existed lying flat on the bottom of the raft, and was used to simulate detection of PIT-tagged fish near the water surface or in shallow

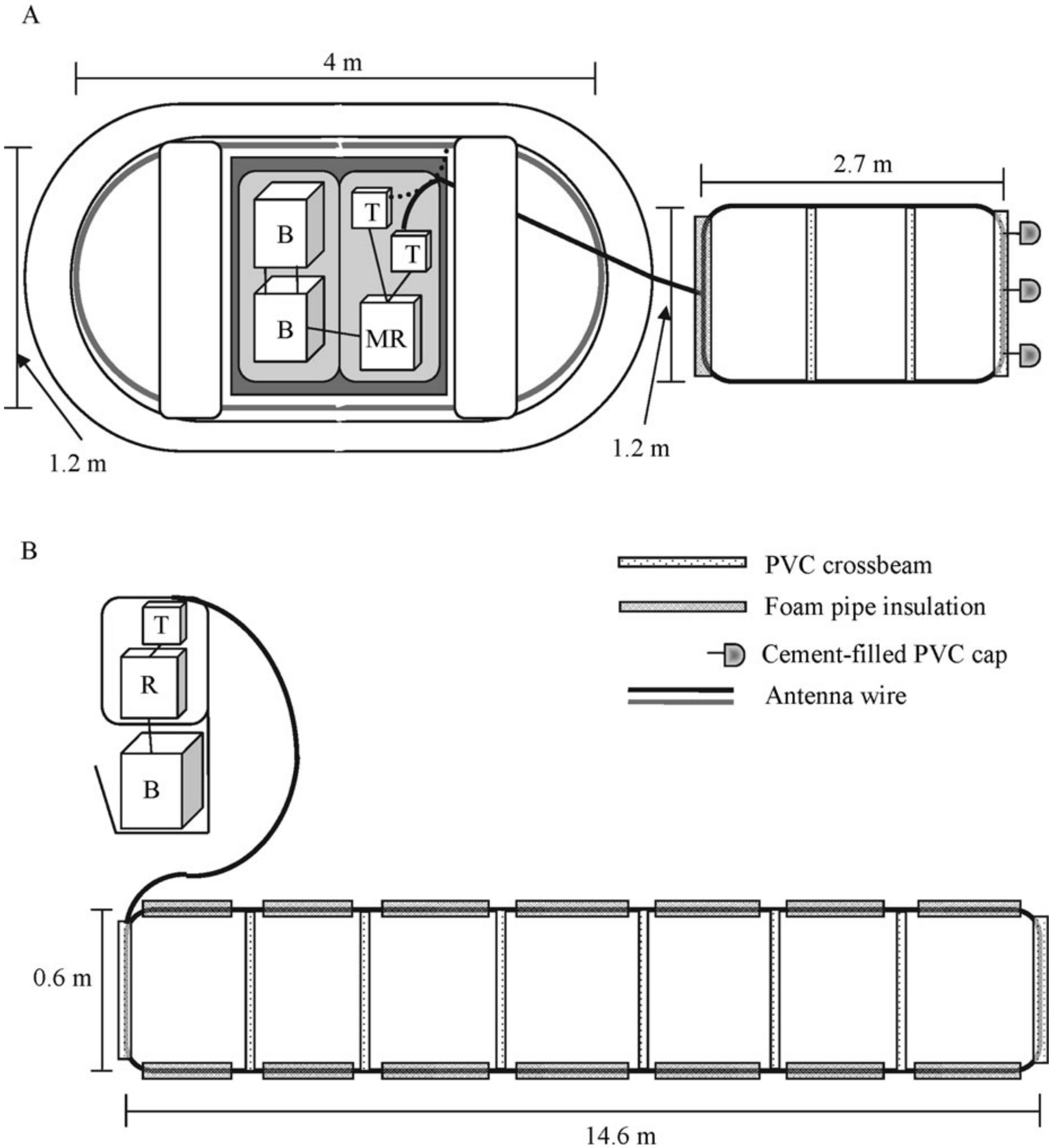

FIGURE 1. (**A**) Schematic representation of the raft antenna system (not to scale). Two continuous loops of 12-gauge THHN wire were used to create the horizontal (heavy dotted line) and vertical (heavy solid line) antennas. Both antennas were connected to tuning boxes (T), which were in turn connected to a multiplex reader (MR) and batteries (B) housed inside plastic, top-locking containers (light gray) and strapped to a rigid plastic deck (dark gray). (**B**) Diagram of the shore-deployed floating antenna system (not to scale). The antenna consisted of a single loop of 8-gauge, multistrand, speaker wire connected to a tuner box (T), which interfaced with the reader (R) and battery (B) enclosed in the sling-load backpack.

water on the edges of the river. The vertical detection plane was defined as the plane directly under the antenna, 90° to the bottom of the raft, and was used to simulate detection when passing directly over a PIT-tagged fish. The 45° detection plane was defined as the plane extending at a 45° angle to the bottom of the raft and was used to simulate detection of fish on the periphery of the antenna detection field. When the tag was detected, a piezoelectric buzzer connected to the reader produced an audible beep. Maximum continuous detection distance was defined as the distance between when a beep was heard for every movement of the tag past the antenna (100% detection rate) and when a lack of beep indicated that detections were being missed. The presence of a diamond-plated, floor-covering, aluminum oar frame was thought to affect the horizontal array as metal within the detection field had been shown to disrupt both detection occurrence and detection distance (Greenberg and Giller 2000; Bond et al. 2007). To test this, maximum detection distances were measured with and without the frame and compared.

To evaluate the effects of the oar frame, tag orientation, and detection plane on maximum detection distance, we used a general linear model (GLM) as implemented in SAS ProcGLM (SAS Institute 2010). We considered an intercept-only model as well as models that included effects of oar frame only, tag orientation only, detection plane only, additive effects between oar frame, orientation, and detection plane, and an interaction model. Models were ranked using Akaike's information criterion corrected for small sample sizes (AIC_c), compared using AIC_c differences (ΔAIC_c) and weights (w_i), and we report parameter estimates and associated SEs from the top-supported models (Burnham and Anderson 2002).

Detection probability.—To determine the detection probability of the horizontal antenna under riverine conditions, we epoxied fifty 32-mm HDX PIT tags to rocks and placed them in a 95.5-m (5.6 m average width) reach of an inlet stream located at Parvin Lake, Red Feather Lakes, Colorado. We divided the reach into transects ($N = 25$) and two rocks were placed on each transect. The first transect was located 6.8 m downstream from the raft put-in site, which allowed the raft to be underway before detection occurred. Subsequent transects were located at random distances from the first by using a random number generator. Depths and locations of the rocks were chosen deliberately to provide a variety of distances and depths for analysis. Rocks were placed such that PIT tags were oriented parallel to the banks, similar to the orientation of fish facing into the current. Distance from the south bank and water depth was recorded for each tag, and the metric distance from center (DFC) was calculated by dividing the transect length in half and subtracting the distance from south bank (Table 1).

Ten passes were conducted to estimate detection probability. A crew of three was used to operate the raft, and the raft was maneuvered down the center of the inlet stream on each pass to reduce bias because the raft operators were the same people that placed the tagged rocks. Additionally, approximately the same course was followed on all 10 passes to reduce bias. The raft was maneuvered at a 45° angle to the banks, providing a detection field roughly 4.2 m wide, including both the 1.2- and 4-m axes of the antenna, and allowing raft operators to maneuver through meanders and avoid obstacles. Unfortunately, the shallow nature of the inlet stream precluded the use of the vertical antenna in the detection probability field test. Detection probability for the raft antenna system, including continuous deployment of the horizontal antenna and intermittent deployment of the vertical antenna, was later estimated following deployment and PIT-tagged fish detection in the Cache la Poudre River.

Detection probability (p) for the horizontal antenna was estimated using the Huggins closed capture–recapture estimator in program MARK (White and Burnham 1999). The Huggins closed capture–recapture estimator differs from a traditional closed capture–recapture estimator in that only two parameters, capture or detection probability (p) and recapture probability (c) are included in the likelihood; N is conditioned out of the likelihood and estimated as a derived parameter using estimates of p (Huggins 1989). This quality allows individual covariates affecting p to be included in Huggins estimator (Huggins 1991). Primary assumptions are that tags are not lost, are correctly identified, and that the system is closed.

TABLE 1. Placement of rocks marked with PIT tags, with regard to transect number (T), depth (cm), and distance from center (DFC; cm), of the 50 rocks (two on each of 25 transects) used in the raft antenna system detection probability experiment conducted in the Parvin Lake inlet stream.

T	Depth	DFC	T	Depth	DFC	T	Depth	DFC
1	38.1	53.3	10	34.3	94.0	19	5.1	346.7
1	38.1	190.5	10	20.3	82.6	19	30.5	19.1
2	64.8	22.9	11	16.5	330.2	20	25.4	171.5
2	25.4	257.8	11	34.3	25.4	20	22.9	224.8
3	53.3	20.3	12	45.7	180.3	21	25.4	36.8
3	35.6	147.3	12	30.5	53.3	21	12.7	450.9
4	44.5	121.9	13	33.0	104.1	22	15.2	237.5
4	48.3	138.4	13	30.5	195.6	22	53.3	616.0
5	52.1	85.1	14	33.0	190.5	23	38.1	2.5
5	48.3	82.6	14	39.4	144.8	23	27.9	271.8
6	33.0	269.2	15	41.9	180.3	24	47.0	22.9
6	39.4	55.9	15	35.6	94.0	24	26.7	205.7
7	44.5	90.2	16	22.9	342.9	25	33.0	381.0
7	25.4	214.6	16	30.5	358.1	25	17.8	15.2
8	17.8	299.7	17	35.6	108.0			
8	25.4	35.6	17	30.5	257.8			
9	17.8	194.3	18	22.9	298.5			
9	44.5	293.3	18	29.2	158.8			

Encounter histories were constructed for each rock such that if it were detected on a pass, it would be given a value of 1, and if it were not detected, it would be given a value of 0. Depth and DFC were included as individual covariates for each rock, and models in which p was constant, varied by depth, DFC, or the additive combination of the two, were included in the model set; p equaled c in all models, as c was not expected to be affected by previous detection. Models were ranked using AIC_c, compared using ΔAIC_c and w_i (Burnham and Anderson 2002), and a model-averaged parameter estimate and unconditional SE were reported (Anderson 2008). Information from all models with $w_i > 0$ were included in the model-averaged parameter estimate. In addition, cumulative AIC_c weights were used to assess the relative importance of each covariate.

Location and fate of PIT-tagged fish.—Our objective was to detect and locate PIT-tagged fish that had been marked and released in the Cache la Poudre River near Glen Echo, Colorado, during a previous study (Fetherman 2013). We were primarily

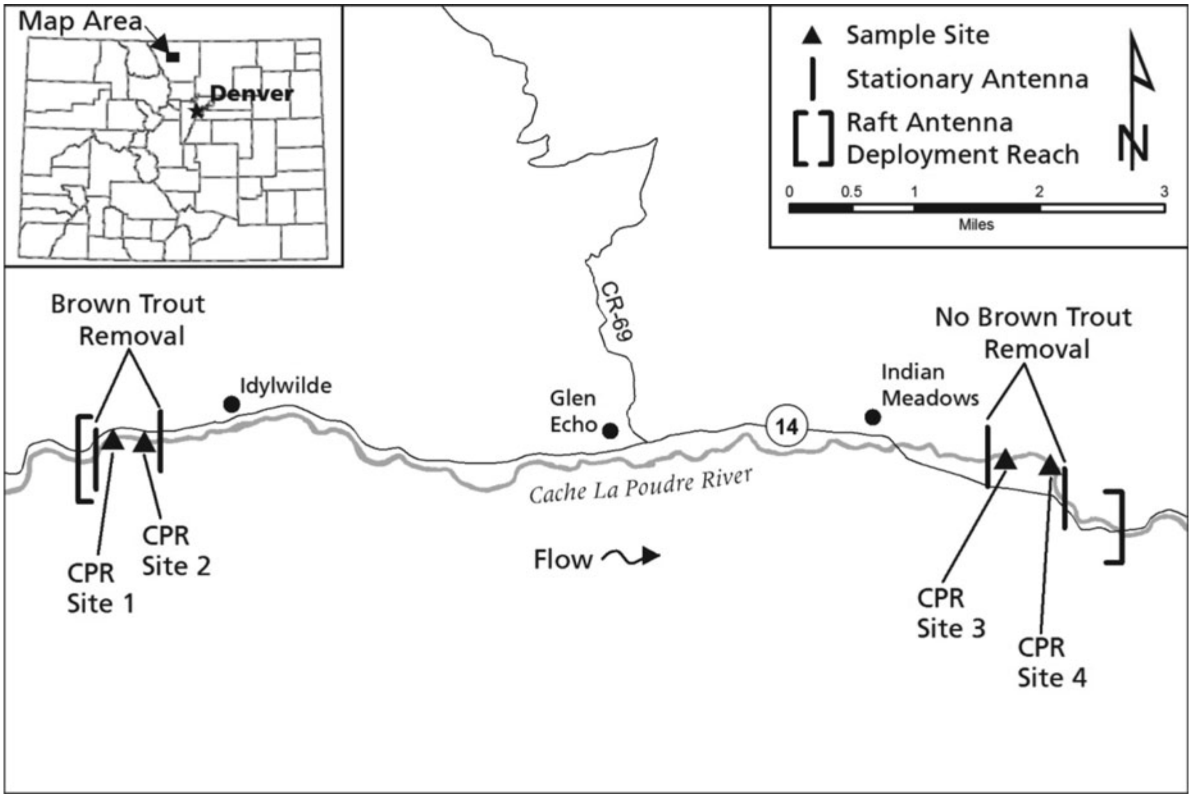

FIGURE 2. Study area in the Cache la Poudre River, Colorado. The map shows the reach in which the raft antenna system was deployed to determine PIT-tagged fish location and fate, the locations where Brown Trout were and were not removed from the river as part of the study conducted by Fetherman (2013), the stationary antenna locations, and the four study segments (CPR1, CPR2, CPR3, and CPR4) in which abundance was estimated using both the shore-deployed floating antenna system and electrofishing.

interested in fish that were not available for detection by stationary antennas deployed in the river because they had migrated from the initial study sections, or they remained in the study sections and could not be detected by the stationary antennas.

During the initial tagging event (Fetherman 2013), we PIT-tagged 5,271 Rainbow Trout and Brown Trout with 32-mm HDX tags, inserted posterior to the pectoral fin through the midventral body wall into the peritoneal cavity using a hypodermic needle (Prentice et al. 1990; Acolas et al. 2007). At the time of tagging, Rainbow Trout averaged 177 mm TL, ranging from 116 to 236 mm TL, and Brown Trout averaged 274 mm TL, ranging from 107 to 500 mm TL. Fish were marked 1 year prior to raft antenna deployment.

The raft antenna system was deployed in an 11.3-km section of the Cache la Poudre River (19.6 m average width; Figure 2). Prior to deployment, the horizontal and vertical antennas were tuned and tested with a PIT tag to ensure proper operation. A crew of six was used to maneuver the raft: a captain, four paddlers, and a person to operate the antenna equipment and deploy the vertical antenna in pools. Four paddlers were needed because previous research indicated that a metal oar frame would interfere with the operation of the antennas (Greenberg and Giller 2000; Bond et al. 2007). In assessing our antenna systems, we also documented a decrease in detection distance associated with the metal oar frame (see below). The raft antenna system was deployed in low-water conditions, which were conducive to higher detection probabilities but made maneuvering the raft difficult; however, we attempted to maneuver the raft within the river's thalweg. The horizontal antenna was deployed continuously to detect fish in shallower reaches (<1 m), while the vertical antenna was intermittently deployed in pools ≥ 1 m deep.

Two passes were made through the 11.3-km reach on subsequent days. Raft course, restricted within the deeper water of the thalweg, and vertical antenna deployment within deep pools were similar among the passes. Before the start of each pass, operators' watches were synchronized with the PIT tag reader clock. We recorded start and stop times, as well as times at which recognizable landmark features adjacent to the river were passed, allowing us to pair PIT tag detection times and locations for analysis.

Following deployment in the Cache la Poudre River, two-pass detection data from the horizontal and vertical antennas were pooled to obtain an overall estimate of p and c for the raft antenna system using the Huggins closed capture–recapture estimator in program MARK. To meet the closure assumption, passes were made on consecutive days over a relatively long stretch of river, making it unlikely that fish died or moved out of the study section between passes. Although fish were previously marked with PIT tags and released, the raft antenna deployment was treated as a traditional mark–recapture study in which the first pass was the "mark" pass and the second pass was the "recapture" pass. Encounter histories were constructed for each fish such that fish encountered only on the first pass had a history of "10," fish encountered only on the second pass had a history of "01," and fish encountered on both passes had a history of "11." To estimate p and c, the model set included models in which p and c were constant and equal, constant but not equal, or varied by species. Models were ranked using AIC_c, compared using ΔAIC_c and w_i, and we report model-averaged parameter estimates and associated SEs (models with $w_i > 0$).

Locations of PIT-tagged fish detected by the raft antenna system were determined by comparing the times at which the fish were detected to the times at which recognizable landmark features adjacent to the river were passed. To determine fate, tag numbers detected by the raft antenna system were compared with the release information associated with the initial PIT tagging event and the tag numbers obtained from the stationary antennas deployed in the Cache la Poudre River. Numbers of fish detected by the raft antenna system, fish location, and fish fate are reported.

Shore-deployed Floating Antenna System

Design and construction.—We designed a river-spanning, shore-deployed, floating antenna system for detecting PIT-tagged fish in shorter (i.e., <2 km) river reaches. The antenna was designed to not only determine the location and fate of fish that were not available for detection via electrofishing, but also to test its utility for use in place of traditional methods, such as electrofishing, for estimating the abundance of PIT-tagged fish.

The shore-deployed floating antenna was rectangular in shape (14.6 × 0.6 m) and consisted of a single loop of insulated, 8-gauge, multistrand, copper speaker wire. Antenna shape was maintained by threading the wire through foam pipe insulation (used for flotation) and 13-mm PVC crossbeams, located every 1.8 m along the length of the antenna (Figure 1). Floating nylon rope was threaded through the upstream side of the foam pipe insulation, allowing operators to maintain tension and antenna shape during deployment. An Oregon RFID HDX single reader and tuner box, located in the top compartment of a plastic-framed, sling-load pack and a 12-V, marine, deep-cycle battery, secured to the pack via the sling, were used to power the antenna (Figure 1).

Antenna design facilitated two-person deployment, with both operators walking along the banks of the river to avoid scaring fish out of the study segments by wading during deployment. One person carried the sling-load pack and was the primary guide for the antenna. The second person retained tension on the nylon rope in order to maintain antenna shape and guide the antenna over obstacles. The fully extended antenna was maneuvered downstream, allowing the river current to carry the antenna over the majority of obstacles, primarily large boulders.

Detection distance.—Detection distance was tested by running a 32-mm PIT tag over the antenna in the horizontal, vertical, and 45° detection planes, holding the tag at both a perpendicular and parallel orientation to the antenna. Both sides of the antenna were tested to determine whether there were differences in detection symmetry. When the tag was detected by the reader, a piezoelectric buzzer attached to the reader produced an audible beep. Maximum continuous detection distance was determined as the distance between when a beep was heard for every movement of the tag past the antenna (100% detection rate); when an audible beep was not produced, this indicated that detections where being missed.

To evaluate antenna symmetry and influence of detection plane on maximum detection distance, we used a general linear model (GLM) as implemented in SAS ProcGLM. We considered an intercept-only model, as well as models that included effects of side only and detection plane only and models with additive and interactive effects between side and detection plane. Models were ranked using AIC_c and compared using ΔAIC_c and w_i, and we report parameter estimates and associated SEs from the top supported models.

Abundance estimation.—One of our primary objectives was to determine whether the shore-deployed floating antenna could be used to estimate abundance of PIT-tagged fish. To accomplish this, we compared estimates obtained from antenna detection data with traditional electrofishing estimates. We deployed the antenna in 10 river segments, four segments in the Cache la Poudre River (Figure 2) and six segments in the St. Vrain River, Lyons, Colorado (Figure 3). Passive integrated transponder-tagged fish within the Cache la Poudre River were the same as those previously described for the raft antenna system (N = 5,271). Rainbow Trout and Brown Trout in the St. Vrain River were PIT-tagged and released 1 year prior to abundance estimation (N = 1,569). At the time of tagging, Rainbow Trout averaged 192 mm TL, ranging from 113 to 272 mm TL, and Brown Trout averaged 190 mm TL, ranging from 120 to 480 mm TL. Fish that were PIT-tagged within the St. Vrain River were being used to evaluate and compare movement rates through a whitewater park reach (WWP) containing artificially constructed flow-control structures and through a natural reach (natural) where no such flow-control structures existed.

Sampling segments varied in length, width, and habitat characteristics. In the Cache la Poudre River, the two most upstream segments (CPR1: 114 m long × 17 m wide; CPR2: 165 × 12 m) were characterized by slower-velocity pool habitat with higher-velocity riffles on the upstream end. The two most downstream segments (CPR3: 91 × 21 m; CPR4: 124 × 19 m) were both characterized by moderate riffle habitat with higher-velocity riffle habitat on the upstream end (Figure 2). The Cache la Poudre River was sampled at an average discharge of 3.4 m^3/s, and average segment depth was 0.6 m. Segments within the St. Vrain River consisted of naturally occurring and artificially

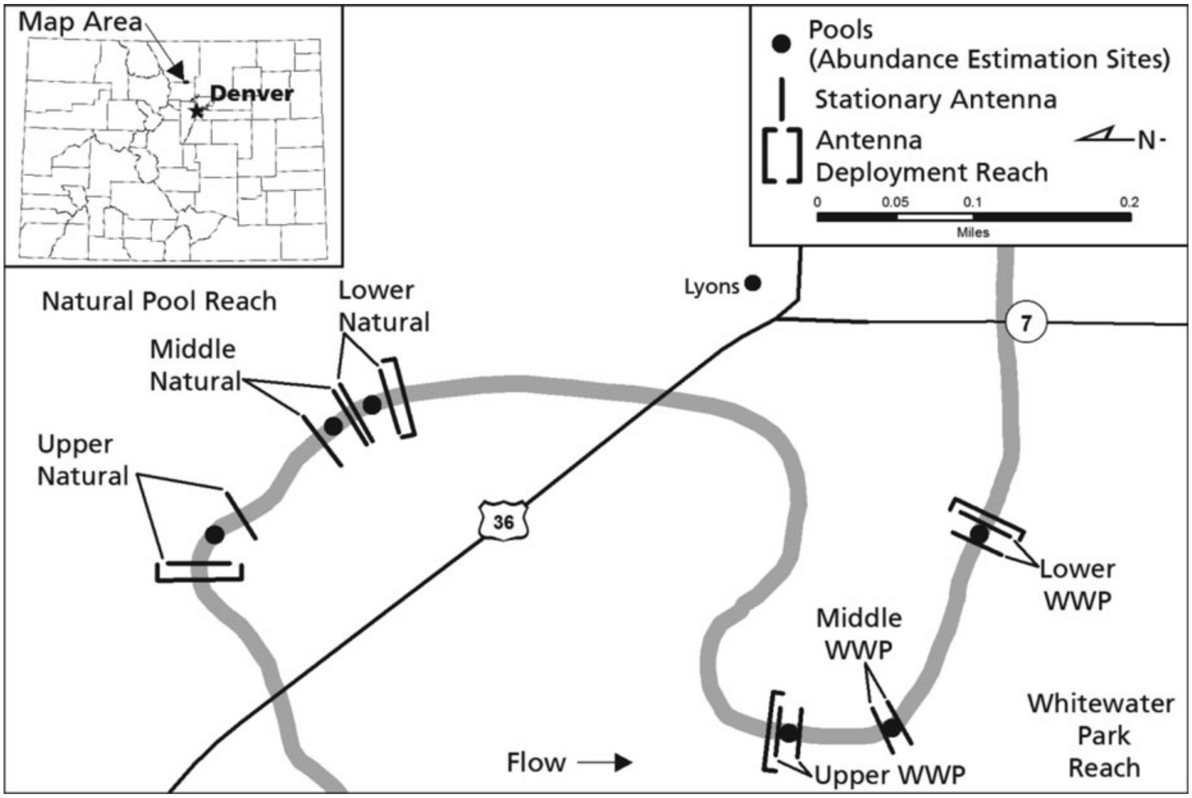

FIGURE 3. Study area in the St. Vrain River, Colorado. The map shows the two 0.8-km reaches in which the shore-deployed floating antenna system was deployed to determine PIT-tagged fish location and fate, and the six study segments in which abundance was estimated using both the shore-deployed floating antenna system and electrofishing.

constructed pools of varying depth. The three artificial pools (lower, middle, and upper WWP) were 1.6, 1.4, and 2.1 m deep, respectively, and the three natural pools (lower, middle, and upper natural) were 0.5, 0.4, and 1.0 m deep, respectively (Figure 3). Average width of segments was 7.6 m, and the segments were sampled at an average discharge of 0.7 m^3/s.

Fish abundance was estimated by making two passes with the fully extended, shore-deployed, floating antenna through a study segment; the antenna was folded up and returned to the top of the segment between passes. The first pass with the antenna was considered the "mark" pass, while the second pass acted as the "recapture" pass. In the St. Vrain River, closure for the estimates was achieved by using block nets at both the upstream and downstream ends of the study segments. In the Cache la Poudre River, we used stream features, such as high-velocity riffles on the upstream end of the segments, to restrict fish movement during the estimates. Use of natural barriers is the protocol currently used by Colorado Parks and Wildlife to conduct electrofishing population estimates, and we wanted to use a similar protocol when deploying the antenna. However, we realized that we were assuming closure and it was not guaranteed. As in the St. Vrain River, passes were conducted one immediately after the other, and wading was avoided to prevent scaring fish from the segment.

Abundance estimates of PIT-tagged fish per segment were obtained using the Huggins closed capture–recapture estimator in program MARK. Encounter histories and model set were constructed similar to those described for estimating detection probability of the raft antenna system. Data for each segment was analyzed separately (10 analyses in total). Models were ranked using AIC_c and compared using ΔAIC_c and w_i, and we report model-averaged parameter estimates and associated SEs (models with $w_i > 0$).

Estimates of PIT-tagged fish abundance obtained from the shore-deployed floating antenna were compared with those obtained from the same study segment using electrofishing. Immediately following antenna deployment, two-pass (Cache la Poudre River) or three-pass (St. Vrain River) removal abundance estimates were conducted in the same segment using a bank electrofishing unit with four electrodes. All fish captured were weighed, measured, and scanned for PIT tags using a handheld reader. Tag numbers were compared with those recorded by the shore-deployed floating antenna to determine whether the same fish were detected by both gears.

Abundance estimates were similarly obtained from the electrofishing data using the Huggins closed capture–recapture estimator in program MARK, with the exception that c was fixed to zero in all models because fish were removed after capture

TABLE 2. Model selection results for factors influencing maximum detection distance for the horizontal antenna of the raft antenna system. The maximized log-likelihood [log(L)], the number of parameters (K) in each model, and AIC_c values are shown. Models are ranked by their AIC_c differences (Δ_i) relative to the best model in the set and Akaike weights (w_i) quantify the probability that a particular model is the best model in the set given the data and the model set.

Model	R^2	log(L)	K	AIC_c	Δ_i	w_i
Orientation × Frame × Plane	0.90	−207.46	12	441.30	0.00	1.00
Orientation + Plane	0.87	−225.11	5	460.65	19.35	0.00
Orientation + Frame + Plane	0.87	−224.22	7	463.25	21.96	0.00
Orientation	0.84	−237.02	2	478.13	36.83	0.00
Orientation + Frame	0.84	−236.27	4	480.82	39.52	0.00
Intercept only	0.00	−370.24	1	742.52	301.22	0.00
Plane	0.02	−368.50	3	743.16	301.86	0.00
Frame	0.00	−370.13	2	744.34	303.04	0.00
Frame + Plane	0.03	−368.38	5	747.19	305.89	0.00

(Hense et al. 2010; Saunders et al. 2011). Encounter histories were constructed for only PIT-tagged fish and were constructed such that fish captured on the first pass had a history of "10" and fish caught on the second pass had a history of "01." Rainbow Trout and Brown Trout were included as groups in the same analysis and p was modeled as constant or varied by length, species, or both. Models were ranked using AIC_c and compared using ΔAIC_c and w_i, and we report model-averaged parameter estimates and associated 95% CIs (models with $w_i > 0$). Abundance estimates obtained with the two gear types were compared within each study segment, and differences between the gears were determined by a lack of overlap in 95% CIs.

Location and fate of PIT-tagged fish.—Another primary objective of the shore-deployed floating antenna was to determine the location and fate of PIT-tagged fish that were not available for recapture via electrofishing in the St. Vrain River study segments. To address this objective we deployed the antenna in two 0.8-km reaches of the St. Vrain River (Figure 3). In the natural reach, the antenna was deployed just upstream from the upper natural study segment to just downstream from the lower natural study segment. In the WWP reach, the antenna was deployed just upstream from the upper WWP study segment to just downstream from the lower WWP study segment. All six of the previously described study segments were contained within the two reaches. Shallow riffle habitat constituted the majority of the habitat between study segments in both reaches.

Two passes with the antenna were made through each reach. Due to the narrow width of the reaches, the array was deployed at a 45° angle to the stream banks, allowing full extension of the array for proper tuning. Before the start of each pass, operators' watches were synchronized with the reader clock. We recorded start and stop times, as well as times at which recognizable landmark features adjacent to or within the river were passed, allowing us to pair PIT tag detection times and locations for analysis; average deployment time was roughly 45 min per pass. To determine PIT-tagged fish fate, tag numbers were compared with the release information associated with the initial PIT tagging event and tag numbers of fish captured via electrofishing. Numbers of fish detected by the shore-deployed floating antenna system, fish location, and fish fate are reported.

Detection probability for the shore-deployed floating antenna was estimated for each reach following deployment. Encounter histories and model sets were constructed similar to those described for estimating detection probability of the raft antenna system. Models were ranked using AIC_c and compared using ΔAIC_c and w_i, and we report model-averaged parameter estimates and associated SEs (models with $w_i > 0$).

RESULTS

Raft Antenna System

Detection distance.—Tag orientation, oar frame presence, and detection plane had the largest influence on hand-held PIT tag maximum detection distance of the horizontal antenna of the raft antenna system (AIC_c weight = 1.00; Table 2). Average detection distance was greater for tags oriented perpendicular than for those oriented parallel to the antenna. The presence of the oar frame affected detection distance along the vertical, horizontal, and 45° detection planes for tags oriented perpendicular to the antenna. Detection distance in the vertical detection plane was affected by the presence of the oar frame for tags oriented parallel to the antenna, but were not affected by oar frame presence in the horizontal or 45° detection planes (Figure 4).

Detection probability.—The use of PIT-tagged rocks in the Parvin Lake inlet stream showed that both DFC and depth affected p of the horizontal antenna of the raft antenna system (model = DFC + Depth; AIC_c weight = 0.99). A negative relationship was observed between DFC and detection probability ($\hat{\beta} = -0.011 \pm 0.001$) indicating that the farther a tag was from the center of the inlet stream, and consequently the center of the antenna's detection field, the less likely it was to be detected. Interestingly, there was a positive relationship between p and depth ($\hat{\beta} = 0.02 \pm 0.005$). This relationship likely occurred because tags located near the center of the inlet stream were

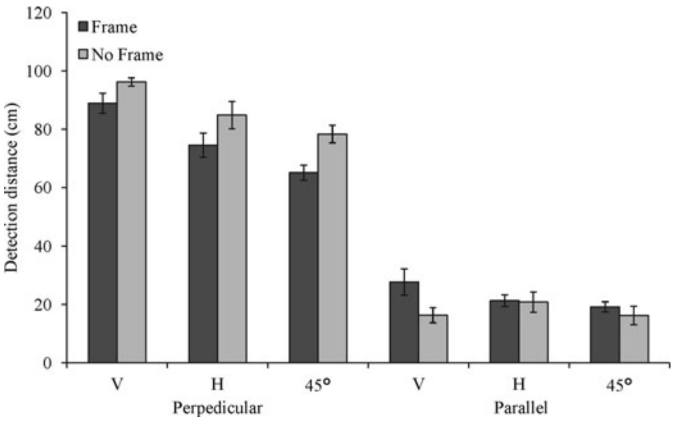

FIGURE 4. Maximum detection distances for the horizontal antenna of the raft antenna system with and without the aluminum oar frame and with tags oriented perpendicular and parallel to the antenna in the vertical (V), horizontal (H), and 45° detection planes. Error bars represent SE.

deeper than those placed closer to the banks and, thus, more likely to be detected regardless of depth. The model-averaged estimate of p for the horizontal antenna was 0.32 ± 0.02 (mean ± SE).

Location and fate of PIT-tagged fish.—A total of 44 PIT-tagged fish (32 Rainbow Trout and 12 Brown Trout) were detected by the 4.2-m-wide antenna detection field (21% of the wetted area) over the 11.3-km reach of the Cache la Poudre River. Two unique fish were detected by the intermittently deployed vertical antenna, whereas 42 unique fish were detected by the continuously deployed horizontal antenna. Three fish were detected on both passes, which allowed both p and c to be estimated for the raft antenna system. Detection probability of the raft antenna system, including continuous deployment of the horizontal antenna and intermittent deployment of the vertical antenna, was 0.14 ± 0.14, and for c was 0.13 ± 0.07.

Twenty-seven of the fish detected had never been detected by the stationary antennas after their release 1 year prior to deployment of the raft antenna system. Of these, 15 were detected in their release location and had never moved past the stationary antennas. The remaining 12 fish had moved upstream or downstream, but were not detected by the stationary antennas. The complementary use of the raft antenna system enabled us to locate and determine the fate of those fish not detected by the stationary antennas.

The other 17 fish detected by the raft antenna system had been previously detected by the stationary antennas. Detections at stationary antennas occurred between 8 and 12 months prior to detection by the raft antenna system, and use of the system allowed us to confirm the new locations of these fish. Fish moved both upstream and downstream from their release locations. On average, fish were located within 1.2 km of the locations from which they had been released; however, several fish were detected farther from their release location including one fish located over 4 km upstream from its release site.

Shore-deployed Floating Antenna System

Detection distance.—Detection plane had the largest influence on hand-held PIT tag maximum detection distance for the shore-deployed floating antenna (model 1 = Plane, AIC_c weight = 0.48; model 2 = Side + Plane, AIC_c weight = 0.44; Table 3). On average, tags in the vertical detection plane were detected at a greater distance (79.9 ± 0.8 cm) than tags in the horizontal or 45° detection planes. Horizontal (71.6 ± 0.7 cm) and 45° (72.3 ± 0.8 cm) detection planes exhibited average maximum detection distances. There was some evidence that detection distances were not symmetrical about the antenna (model 2 = Side + Plane, AIC_c weight 0.44; Table 3). However, average maximum detection distances did not appear to differ between the right (75.3 ± 1.2 cm) and left (74.0 ± 0.9 cm) sides of the antenna.

Abundance estimation.— Abundances of PIT-tagged fish obtained from the shore-deployed floating antenna were similar to those obtained via electrofishing, as indicated by overlapping 95% CIs, in two of the four study segments in the Cache la Poudre River (CPR2 and CPR3; Figure 5). However, it is important to note the 95% CIs overlapped in these two segments because of large 95% CIs for the electrofishing estimates (CPR2) or the antenna estimates (CPR3), suggesting that the estimates were fairly imprecise, likely due to the low numbers of PIT-tagged fish detected in these segments. In CPR2, 19 PIT tags were detected by the antenna, whereas eight PIT-tagged fish were detected via electrofishing; four PIT-tagged fish were detected by both gear types. In CPR3, seven PIT tags were detected by the antenna, whereas five PIT-tagged fish were detected via electrofishing; two PIT-tagged fish were detected by both gear types.

Abundance estimates differed in two of the four study segments in the Cache la Poudre River (CPR1 and CPR4; Figure 5). The estimate of PIT-tagged fish abundance in CPR4 was higher with electrofishing than with the antenna, which was potentially a function of differences in maneuverability of the gear types around the large boulders located within this study segment. In CPR4, six PIT tags were detected by the antenna, whereas 11 PIT-tagged fish were detected via electrofishing; two PIT-tagged fish were detected by both gear types. Abundance estimation via electrofishing was not possible in CPR1 due to depletion failure (i.e., three PIT-tagged fish caught on both passes); however, abundance estimates were obtainable using the antenna (Figure 5). In CPR1, 11 PIT tags were detected by the antenna, whereas six PIT-tagged fish were detected via electrofishing; five PIT-tagged fish were detected by both gear types.

The shore-deployed floating antenna failed to obtain comparable abundance estimates to those obtained by electrofishing in the WWP study segments in the St. Vrain River (Figure 5), which was likely a function of segment depth. The shallowest study segment (middle WWP, 1.4 m) exceeded the maximum read range of the array by 0.6 m. All three PIT tags detected by the antenna in the lower and middle WWP segments were not detected via electrofishing.

TABLE 3. Model selection results for factors influencing maximum detection distance for the shore-deployed floating antenna system. The maximized log-likelihood [log(*L*)], the number of parameters (*K*) in each model, and AIC_c values are shown. Models are ranked by their AIC_c differences (Δ_i) relative to the best model in the set and Akaike weights (w_i) quantify the probability that a particular model is the best model in the set given the data and the model set.

Model	R^2	log(*L*)	*K*	AIC_c	Δ_i	w_i
Plane	0.64	−43.43	3	93.49	0.00	0.48
Side + Plane	0.66	−42.27	4	93.63	0.14	0.44
Side × Plane	0.68	−41.33	6	97.06	3.57	0.08
Intercept only	0.00	−64.98	1	132.05	38.56	0.00
Side	0.02	−64.57	2	133.45	39.96	0.00

Similar abundance estimates were obtained in the lower natural and middle natural study segments in the St. Vrain River (Figure 5). Maximum pool depth in these study segments did not exceed 0.5 m. In the lower natural segment, 20 PIT tags were detected by the antenna, whereas 18 PIT-tagged fish were detected via electrofishing; six PIT-tagged fish were detected by both gear types. In the middle natural segment, 11 PIT tags were detected by the antenna, whereas 10 PIT-tagged fish were detected via electrofishing; four PIT-tagged fish were detected by both gear types. In the upper natural segment, which had a maximum depth of 1 m and exceeded the maximum read range of the antenna by 0.2 m, the abundance estimate obtained using the antenna was lower than that obtained by electrofishing (Figure 5). Twelve PIT tags were detected by the antenna in the upper natural segment, whereas 21 PIT-tagged fish were detected via electrofishing; only two PIT-tagged fish were detected by both gear types.

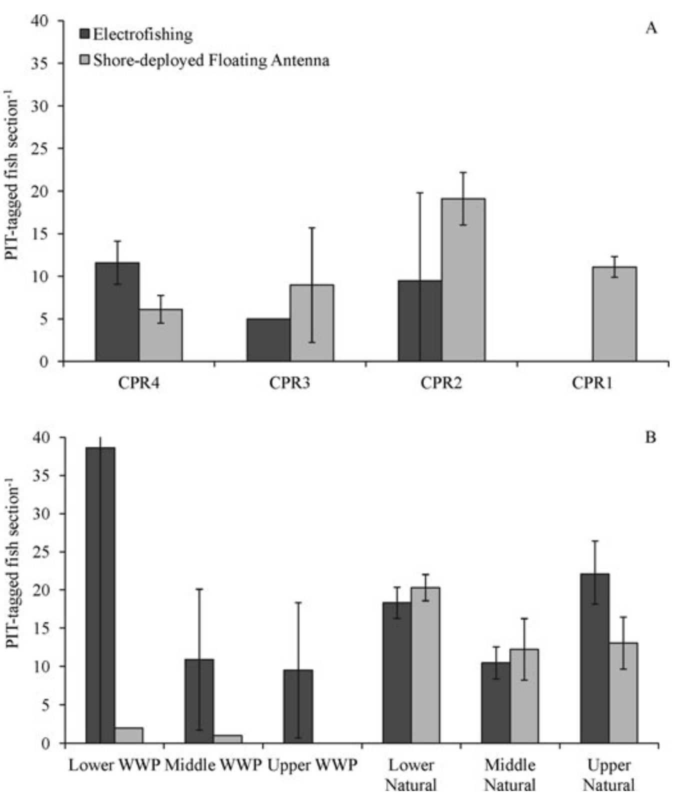

FIGURE 5. Estimated number of PIT-tagged salmonids per section estimated via electrofishing (Cache la Poudre River: two passes; St. Vrain River: three passes) and the shore-deployed floating antenna (two passes) within the study segments in (**A**) the Cache la Poudre River and (**B**) the St. Vrain River. Error bars represent 95% CI.

Location and fate of PIT-tagged fish.—Thirty-two PIT-tagged fish—16 Rainbow Trout and 16 Brown Trout—were detected by the shore-deployed floating antenna, which covered 100% of the wetted area within the 0.8-km natural reach of the St. Vrain River. In the 0.8-km WWP reach, 49 PIT-tagged fish were detected by the shore-deployed floating antenna: 18 Rainbow Trout and 31 Brown Trout. Estimated *p* for the shore-deployed floating antenna did not differ between the reaches: $p = 0.52 \pm 0.15$ in the natural pool reach and $p = 0.60 \pm 0.10$ in the WWP reach.

Of the 32 fish detected by the shore-deployed floating antenna in the natural reach of the St. Vrain River, 12 were detected in the location to which they had been released 6 to 12 months prior to antenna deployment. Eighteen of the 32 fish that had been released within the reach exhibited upstream and downstream movements, and were detected in locations that differed from their release location. Six of these fish were located within the lower, middle, or upper natural segments and were available for detection, whereas the other 12 fish were located between study segments and were not available for detection via electrofishing. The new locations of these fish would not have been known had they not been detected by the shore-deployed floating antenna. Finally, two of the fish that had been released in the WWP reach 12 months earlier were located between study segments and were not available for detection via electrofishing. The detection of these fish confirmed that fish were able to navigate the artificial structures of the WWP and move upstream, an observation that was only made possible because the locations of these fish were confirmed by the shore-deployed floating antenna.

Of the 49 fish detected by the shore-deployed floating antenna in the WWP reach of the St. Vrain River, 31 were detected in the location in which they had been released. Twelve of the 49 fish were detected downstream from where they had been released within the WWP reach. Two fish had been released in the natural reach upstream from the WWP reach and had exhibited downstream movement into the WWP reach. Four fish were detected upstream from the location in which they had been released, again confirming that fish were able to navigate the artificial structures of the WWP. All four were located between the WWP study sections and as such were not available for detection via electrofishing. Therefore, the shore-deployed floating antenna helped confirm upstream movement through the WWP structures, which would not have been confirmed using traditional sampling methods.

DISCUSSION

Both our raft and shore-deployed floating antenna systems allowed us to determine the location and fate of PIT-tagged fish that had not moved, moved but had not been detected by stationary antennas or electrofishing, or had migrated from the release location entirely. Our raft antenna system was deployed over an 11.3-km section of the Cache la Poudre River, detecting fish in locations that would not have otherwise been sampled using traditional sampling methods in shorter study segments. Our shore-deployed floating antenna allowed us to obtain estimates of PIT-tagged fish abundance in shorter study segments in both rivers and determine the location and fate of fish in two 0.8-km reaches of the St. Vrain River. Overall, the raft and shore-deployed floating antenna systems have overcome limitations recognized with other portable systems, namely antenna size, stream distance surveyed, coverage, and detection distances.

Detection distances for both antenna systems were between 0.7 and 1.0 m and can be partially attributed to using 32-mm tags (Zydlewski et al. 2006). Other studies have used 12- or 23-mm tags, which resulted in lower detection distances (Roussel et al. 2000; Zydlewski et al. 2001; Cucherousset et al. 2005; Hill et al. 2006). However, one possible disadvantage of greater detection distance is an increased chance of multiple tags being present in the detection field of the array, resulting in no tags being detected (tag collision; Axel et al. 2005; O'Donnell et al. 2010). In addition, greater detection distance could result in the detection of ghost tags, i.e., tags lodged in the substrate through a combination of tag loss, predation, and natural mortality (O'Donnell et al. 2010). Finally, although detection distances were greater than other portable antenna designs, both the raft and the shore-deployed floating antenna systems were still limited to use in shallow (<1 m) river reaches. The utility of both antenna systems for use in deeper river reaches could be increased by manipulating voltage or adjusting wire arrangement (e.g., multiple loops or adjusting spacing between loops) to increase their detection distance.

Despite greater detection distances, detection probability for the raft antenna system was relatively low. Low p could be a result of the coverage of the raft antenna system relative to the width of the river. In the Parvin Lake field test, the raft antenna system covered an average of 32% of the wetted area of the inlet stream. Consequently, p for the horizontal antenna was 0.32, and modeling indicated that p was affected by tag distance from the detection field of the raft, which suggests that if coverage had been wider, p would have been higher. Coverage was less in the Cache la Poudre River where the raft antenna system covered only 21% of the wetted area. This resulted in a lower p (0.14) than that of the Parvin Lake field test. Rafting technique, e.g., pointing the nose of the raft straight downriver versus maintaining the raft at a 45° angle to the banks, could also affect coverage and therefore p of the raft antenna system.

In contrast, the shore-deployed floating antenna system, which covered 100% of the wetted area, produced higher estimates of p during deployment, and p was similar between the natural and WWP reaches in the St. Vrain River. Similarities in p were likely a result of where fish were detected in these reaches. In the natural reach, depths rarely exceeded the read range of the antenna, which allowed nearly all fish in the reach to be available for capture on one or both passes. In the WWP reach, fish were most commonly detected in the shallow riffle habitat between the deeper study segments, the depth of which did not exceed the read range of the antenna. Estimation of p requires that at least one fish needs to be detected on both passes (White et al. 1982). In this study repeat detections on subsequent passes occurred in the shallower sections of the WWP reach. Fish in the deeper study segments were generally unavailable for detection on either pass, which likely artificially inflated the estimates of p in the WWP reach. Overall, p could be increased by increasing the number of passes made through a study section. However, a balance is needed between the number of passes made, the time it takes to make a pass, and the information gained by adding more passes to the study.

Only two fish were detected by the vertical antenna of the raft antenna system, potentially contributing to the low p. Linnansaari and Cunjak (2007) suggested that there may be a fright bias associated with larger submerged antennas if fish are tracked in their active state. Therefore, our vertical antenna may have caused some behavioral avoidance when deployed in pools. In addition, the vertical antenna was tuned fully extended prior to deployment. Antenna shape may have differed when deployed in pools, or intermittent deployment and storage may have caused the antenna to become detuned, thereby reducing detection distance of the vertical antenna upon deployment. The small number of fish detected by the vertical antenna suggests that antenna contributed little to the overall detection of fish by the raft antenna system. However, the utility of the vertical antenna could be increased by correcting issues regarding detuning of the antenna by constructing a more rigid frame that maintains antenna shape during deployment.

Despite potential issues with detection probability, the ability to determine the location and fate of PIT-tagged fish over short (0.8 km) and long (11.3 km) distances is a major advantage of these antenna systems relative to other portable antenna designs. Most portable antenna designs, with the exception of the boat-mounted antenna for monitoring mussels (Fischer et al. 2012), have been constrained to use in shallow, wadable streams; as a result, survey length was limited by the length of river an operator could walk. Here, we demonstrated that both antenna systems could detect and locate fish that had migrated from smaller study segments and were no longer available for detection by stationary antennas or electrofishing. In several cases, we were able to document upstream movement of fish through structures thought to be a barrier to movement (i.e., WWP structures in the St. Vrain River), and over long distances (up to 4 km in the Cache la Poudre River). However, little inference can be made regarding fish fate from tags that were detected in the same location or downstream from where they had been released. Ghost tags (O'Donnell et al. 2010) could potentially be detected by these antenna systems, leading to incorrect interpretations of the data regarding fish location and fate. Ghost tag detections cannot be removed from the data without locating the tags using a smaller wand-type antenna or electrofishing to confirm whether tags were retained or lost by the fish to which they are associated.

Portable PIT-tag antenna systems are fairly accurate in estimating abundance of PIT-tagged fish in small streams (O'Donnell et al. 2010; Sloat et al. 2011). Portable antennas have the advantage of allowing frequent sampling for abundance estimation and fish location without subjecting the fish to excessive handling stress or mortality, and by minimizing disturbance to individuals (Sloat et al. 2011). However, this feature also excludes the ability to examine fish for growth or physiological parameters (Zydlewski et al. 2001) or to estimate the overall abundance (marked and unmarked) of fish within a designated area. Our results suggest that if estimates of tagged fish are desired, and handling fish (beyond tagging) is not necessary to collect individual information (e.g., fish size or signs of disease), portable antennas such as the shore-deployed floating antenna present an alternative to traditional sampling methods such as electrofishing. However, estimates may be imprecise. In addition, detection distance limitations must be considered, as abundance may be greatly underestimated in deeper study segments, e.g., those of the WWP reach. Finally, our data regarding the small number of tags detected by both gears suggest that ghost tags (O'Donnell et al. 2010) could influence abundance estimates obtained with the shore-deployed floating antenna system.

The shore-deployed floating antenna system overcomes some of the limitations observed with other antenna systems, such as antenna size, or those caused by lack of operator experience and fish behavior (O'Donnell et al. 2010). Many of the previously described portable antenna systems were small, designed to be operated by one person in a small stream (Roussel et al. 2000; Cucherousset et al. 2005; Hill et al. 2006), and as such, antenna coverage was small relative to the width of the river. Our shore-deployed floating antenna is the largest two-person portable antenna described to date, as previous two-person antennas did not exceed 5 m in length (Linnansaari and Cunjak 2007). Submersion of the antenna is not required, theoretically reducing the chance of a behavioral response to an antenna located within the water column. Although overhead stimuli may also illicit an avoidance response, especially when conditions are such that shadows are cast by the antenna (e.g., sunny days; Ellis et al. 2013), fish are less likely, relative to smaller designs, to move completely out of the detection field due to antenna coverage (i.e., 100% of the wetted area). The effect of operator experience is also reduced due to antenna coverage as the operator is not required to identify specific locations or habitats to sample. However, fish located directly behind large boulders or other obstacles may not be detected by the floating antenna when passing over these obstacles.

The design flexibility of these antenna systems provides an opportunity to potentially combine designs and create a larger detection field for greater river coverage. For example, wing-like floating antennas could be combined with the raft antenna system to create a larger array that could cover more of the wetted area over long distances. Multiplexers, or a well-designed master–slave set-up, could be used to power the system and prevent proximity detection errors (Aymes and Rives 2009). However, the larger size of the system could potentially result in a greater chance of entanglement with obstacles such as boulders or submerged trees, and this would need to be considered during the design of these larger systems.

Our portable antenna systems provide noninvasive methods that minimize disturbance to individual fish for determining the fate of PIT-tagged fish in both small (hundreds of meters) and large (kilometers) river reaches. Through the use of marker tags, accurate timing devices, and submeter GPS, the location of fish can be determined fairly accurately using these systems. In addition, the shore-deployed floating antenna provides an alternative to traditional sampling methods for estimating PIT-tagged fish abundance. More research is needed to examine the effects of ghost tags on inferring the fate of fish without physical recaptures, to assess fish behavioral responses to antenna systems, and to determine ways to increase p and reduce variability in abundance estimates.

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