Remote Monitoring of Fish in Small Streams: A Unified Approach Using PIT Tags

ABSTRACT: Accurate assessments of fish populations are often limited by re-observation or recapture events. Since the early 1990s, passive integrated transponders (PIT tags) have been used to understand the biology of many fish species. Until recently, PIT applications in small streams have been limited to physical recapture events. To maximize recapture probability, we constructed PIT antenna arrays in small streams to remotely detect individual fish. Experiences from two different laboratories (three case studies) allowed us to develop a unified approach to applying PIT technology for enhancing data assessments. Information on equipment, its installation, tag considerations, and array construction is provided. Theoretical and practical definitions are introduced to standardize metrics for assessing detection efficiency. We demonstrate how certain conditions (stream discharge, vibration, and ambient radio frequency noise) affect the detection efficiency and suggest that by monitoring these conditions, expectations of efficiency can be modified. We emphasize the importance of consistently estimating detection efficiency for fisheries applications.

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INTRODUCTION

Fisheries biologists use various marking techniques to investigate movement patterns, fish growth, and other life history characteristics (Parker et al. 1990). Most of these techniques (e.g., fin clips, freeze branding, coded wire tagging, and paint marks) lack the important feature of individual identification or have a limited longevity (e.g., radio and acoustic tags). Passive integrated transponders (PIT tags) overcome these obstacles. PIT tags are individually coded, have infinite life, are relatively inexpensive, are easily applied, are well retained, and have minimal effects on growth and survival (Gries and Letcher 2002; Zydlewski et al. 2003).

By necessity, many field applications of PIT tags have relied on physically recapturing tagged fish and placing the fish/tag next to a hand-held antenna. A tag must be close, typically within 1 m (Gibbons and Andrews 2004; Hill et al. 2006), to an antenna for decoding. Many innovative laboratory (e.g., Obedzinski and Letcher 2004; Zydlewski et al. 2005; Sigourney et al. 2005) and field (Hilderbrand and Kershner 2000; Bell et al. 2001; Letcher et al. 2002) studies have benefited from this technology. Notable application of the technology includes use of data in individually-based population dynamics models (van Winkle et al. 1993; Juanes et al. 2000).

Successes using PIT tags in semi-natural systems have been achieved despite the restriction of tag and antenna proximity. For example, fish passage has been monitored at hydroelectric facilities where fish can be directed through small orifices equipped with antennas (e.g., Castro-Santos et al. 1996; Giorgi et al. 1997; Prentice et al. 1990a,b). Because constrictions and orifices are known to alter natural behavior (Gowans et al. 1999), similarly-sized constrictions in fully natural systems may limit a biologist's ability to characterize natural movements. There are a few examples of successful field applications of continuous PIT tag monitoring (e.g., Zydlewski et al. 2001; Ibbotson et al. 2004; Zydlewski et al., unpublished); however, the efficiency of these systems has, at best, only been considered in an ad hoc fashion.

Maximizing recapture/observation events by developing methods to remotely monitor natural fish movements in streams has motivated our work. While developing PIT systems for this purpose, we faced the challenge of applying tag detection systems that were designed for use in fish passageways associated with dams. Difficulties included site choice, adapting electronics to field situations, designing and constructing antennas, determining environmental effects on electronic systems, and assessing equipment/detection efficiency. This article reviews techniques, problems, and solutions for constructing, maintaining, and handling data from in-stream PIT arrays based on our experiences over the last 10 years. Three case studies (independently operated by two laboratories) serve as examples for applying these techniques for ecological and management purposes: Abernathy Creek, Washington; Shorey Brook, Maine; and West Brook, Massachusetts.

CASE STUDIES

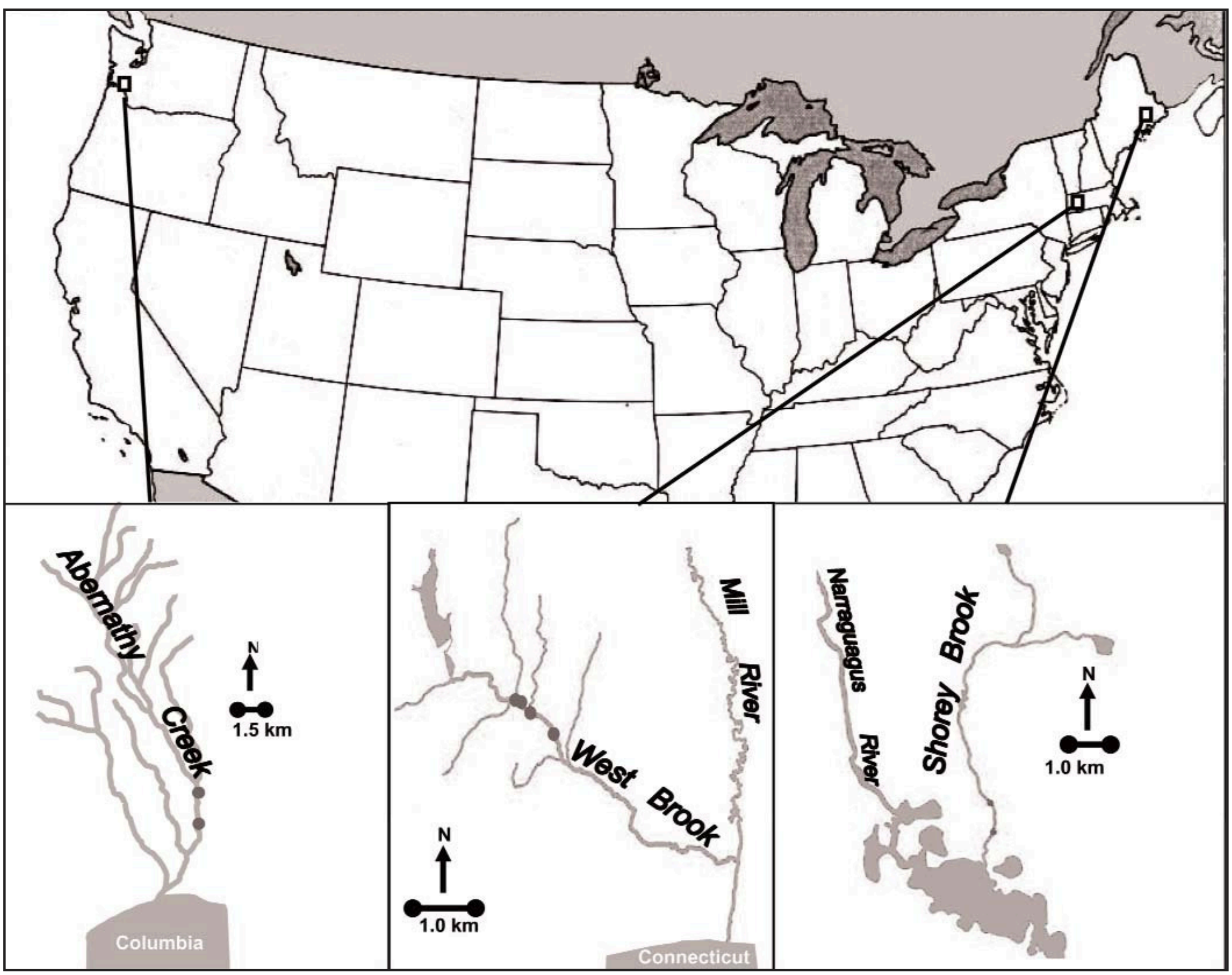
Case 1—Abernathy Creek (AB)

Abernathy Creek is a 3rd order tributary of the Columbia River, located 80 km from the ocean in Longview, Washington (Figure 1). PIT arrays (an antenna, or multiple antennas, which intersect a single stream cross-section) were established in 2001 to assess their feasibility in monitoring steelhead trout (*Oncorhynchus mykiss*) and coastal cutthroat trout (*O. clarki*) movement patterns and population dynamics. A 7.9 km reach (of the 17.5 km total stream length) was sampled by electrofishing annually from mid-September to early October in 2001–2003. Fish greater than 100 mm fork length were PIT tagged. Two PIT arrays monitored movements from 2001 to 2006. They were installed at bridges 3 km (lower—AB–DN) and 4 km (upper—AB–UP) from the creek mouth. Channel width at AB–UP was 11.0 m, requiring three antennas (3.5 m width x 1.9 m height, 3.7 m x 1.7 m, and 4.5 m x 1.3 m) to span the width of the creek (Photo 1). Channel width at AB–DN was 7.8 m, requiring only two antennas (4.0 m x 1.8 m and 4.0 m x 1.7 m).

Case 2—Shorey Brook (SH)

Shorey Brook is a 2nd order tributary of the Narraguagus River, located approximately 44 km from the ocean in Beddington, Maine (Figure 1). Movement, growth, and survival of

Figure 1. Geographic locations and site maps for PIT tag interrogation systems in the northeast and northwest USA. Black rectangles on United States map indicate the location of case study streams. Dots on inset maps indicate PIT tag monitoring sites.



Atlantic salmon (*Salmo salar*) and brook trout (*Salvelinus fontinalis*) were evaluated in this study. A 0.7 km stream reach (of the 2.7 km total stream length) was sampled by electrofishing seasonally each year to PIT tag fish. Three, single antenna PIT arrays were operated from 2001 to 2003. At river km 1.3 (upstream of the brook mouth), the single antenna (1.1 m x 0.3 m) was incorporated into a picket weir (Anderson and McDonald 1978; Figure 2a) spanning a width of 4 m. This design guided fish through the antenna. Two downstream arrays were located approximately 0.8 km upstream of the mouth (Figure 2b) approximately 3 m apart (one upstream of the other). Each array spanned a width of 2.5 m with a single antenna (2.2 m x 0.6 m). Sandbags and stream substrate were used to slightly constrict the overall

Photo 1. PIT tag interrogation systems on Abernathy Creek, Longview, WA, (Left panel: AB–UP and right panel: AB–DN). Arrays at both sites consisted of multiple antennas oriented such that they spanned the width of the stream channel.

Figure 2. Schematic of Northeast antenna placement: Shorey Brook (a. SH–UP and b. SH–DN) and West Brook (c. WB–UP and d. WB-DN). Panel a includes a depiction of weir panels that helped guide fish through SH–UP.

stream width and direct fish passage through the antenna (Figure 2b).

Case 3—West Brook (WB)

West Brook is a 3rd order tributary of the Mill River which joins the Connecticut River, approximately 100 km from the ocean in Whately, Massachusetts (Figure 1). Movement, growth, and survival of Atlantic salmon (Letcher and Gries 2003; Letcher et al. 2002), brook, and brown trout (*Salmo trutta*; Carlson and Letcher 2003) were studied. A 1 km stream reach (of the 6.5 km total stream length) was sampled by electrofishing seasonally each year to PIT tag fish. Five, single antenna PIT arrays were operated from 2001 to 2005. Three of the arrays were installed at stream kilometers 4.8, 5.0, and 5.1 km (from the stream mouth). Even under base flows, none of these three arrays (antenna size 1.1 m x 0.4 m) was wide enough to span the width of the stream (average 4.4 m). Stream substrate was arranged to direct fish to swim through antennas (Figure 2c). Two downstream arrays (spaced 2.4 m apart) were located at a bridge at stream km 4.2. Width at the bridge abutments was constricted from 7.6 m to approximately 2.2 m using a partial sandbag weir to direct water and fish through a plywood flume and both arrays (Figure 2d).

EQUIPMENT: PIT SYSTEM CHOICE AND COMPONENTS

System Types

PIT systems (also known as RFID—radio frequency identification) allow the remote identification of tags through radio frequencies (RF). There are two distinct systems available: full duplex (FDX) and half duplex (HDX). Importantly, components are specific to each system and were not compatible between systems at the time of the studies (i.e., FDX tags could not be decoded on HDX transceivers and only a few FDX transceivers could decode HDX tags). HDX functions by having the powered transceiver generate a pulsed RF field. If a tag is in the field, the tag sends a signal back to the transceiver between the pulses and the code can be recorded. Read rate of the system is approximately 10–14 reads per second. Conversely, FDX systems emit a continuous RF field and tags may be decoded continuously, resulting in a faster read rate of 32 reads per second, which is important in high water velocity. This article draws on case studies using only FDX systems, but many of the considerations here are transferable (see Zydlewski et al. 2001 for HDX examples). The three components of PIT detection systems (tags, transceivers, and antennas) are discussed below.

Tags

PIT tags consist of a coil of wire wrapped around a ferrite core which generates electricity as it passes through the electromagnetic (EM) field of a matched antenna; this EM field is the power source for the tag. A microchip in the tag is programmed with a unique binary identification code that is displayed alphanumerically. Once in the EM field of an antenna, the tag disrupts the field to transmit the code to the transceiver. The code can then be logged to a computer with the time and date of detection.

Commercially available tags range in size from less than 12 to greater than 60 mm in length (2.0 to 20 mm in diameter; Photo 2). Most are encapsulated in glass or plastic. While available in multiple sizes, those used in fisheries applications are typically 12 mm and 23 mm long. PIT tags used in the case studies were Destron-Fearing (DF) 134.2 kHz FDX tags. All things being equal, a larger tag has a greater read range than a smaller tag. The larger the antenna coil in the tag the greater the ability to gather the necessary energy to power the microchip and disrupt the EM field in order to transfer the tag code. Note that similarly-sized tags of different models (e.g., DF tags TX1411ST and TX1411SGL) and manufacturers can significantly differ in read range. However, the effect of tag construction is less than the effect of tag size on read range given identical microchips and components that are proportional to the tag size. As this is not always the instance from one manufacturer to the next, it is important for researchers to procure tag samples to determine whether they have appropriate performance for a given study.

Larger tag coils generally allow longer read distances. As a result, the larger tags enable the use of larger antenna geometries. This consideration, along with the size of fish to be studied, drives the decision of tag size. In both Shorey Brook and West Brook, for example, 12 mm tags (12 mm long, 2 mm wide, 0.1 g in air) were used, allowing fish as small as 60 mm fork length to be tagged. This was important as the goal was to understand movements, growth, and survival of early life history stages. The compromise was in the size of antennas used (the largest being 2.2 m x 0.6 m). In contrast, a larger tag (23 mm long, 3.4 mm wide, 0.6 g in air) was chosen for the Abernathy Creek study, where the size of fish was compromised; fish

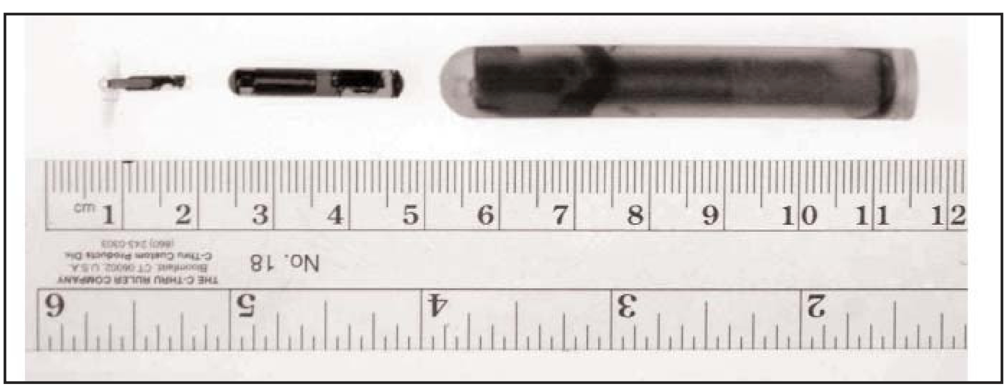


Photo 2. Commonly available passive integrated transponders (PIT tags). Left to right: 12 mm, 23 mm, 60 mm, approximately actual size.

greater than 100 mm could be tagged. The payoff, however, was the ability to build larger antennas, nearly twice as high and wide as the largest antennas used at West Brook and Shorey Brook. At Abernathy Creek this was important as the stream was much larger (channel width range from 7.8–11 m) and more susceptible to sudden and extreme changes in water level. In all three cases, surgical implantation of the tag was used as this has been demonstrated to result in excellent healing, retention, and survival (Zydlewski et al. 2001, 2003; Gries and Letcher 2002).

Transceiver

The transceiver energizes an antenna. When the EM field of an antenna is disrupted (by a tag modulating the field) the transceiver decodes the binary identification as an alphanumeric sequence. Two types of Destron-Fearing 134.2 kHz FDX transceivers were used our in case studies: DF Multiple Transceiver Systems (MTS—Model FS1001A) and DF Portable Transceiver Systems (PTS—Model FS2001F). For the case studies each transceiver powered one antenna.

The MTS is a stand-alone transceiver enabling multiple transceiver combinations (Photo 3) and was used at Abernathy Creek (both arrays), and the lower two arrays at Shorey Brook and West Brook. AB–UP and antennas in the lower two Shorey Brook arrays were energized with 120 V AC powered MTS units. After difficulty eliminating interference, conversion of Shorey Brook units to 24 V DC powered MTS solved the problem (see discussion of RF noise below). AC power was converted to DC using an AC/DC power supply (Condor, Oxnard, CA, Model F24-12-A+). Antennas in close proximity result in mutual interference of tag detection. To overcome this problem, multiple MTS units within Abernathy Creek arrays were synchronized (via cable); likewise the lower Shorey Brook and West Brook arrays (operated in close proximity to one another) also required synchronization. Data from MTS units were transferred via fiber optics to computers that ran software (MiniMon, Pacific States Marine Fisheries Commission—PSMFC, www.ptagis.org) to continuously record date, time, and PIT code of all passing fish. Data collected from each array (including MTS diagnostics) were periodically (6–12 h) uploaded via direct Internet connection (AB–UP), satellite modem (AB–DN), and telephone modem (West Brook) to offsite databases.

The upper arrays on Shorey Brook and West Brook used PTS transceivers powering custom antennas. These units are generally used as portable units, but because of low power requirements they lend themselves to stationary and remote applications where AC power may not be available. Units were powered by 12 V deep cycle marine batteries connected in parallel; battery life for each PIT array was approximately

Photo 3. PIT tag transceiver (a), computer (b), satellite modem (c), AC/DC converter (d), and isolation transformer (e) used on Abernathy Creek, Longview, WA, AB–DN; each antenna was connected to one transceiver (note black cable in the bottom left corner of each transceiver).

seven days. The PTS is not capable of synchronization, limiting the ability to have multiple antennas in close proximity. Tag detections were date/time stamped by the PTS, saved on the PTS, and data were uploaded on occasion with a portable laptop computer.

Power, data access, and physical location (with respect to the antenna and water) guided transceiver choice and installation location. Access to commercial power is a major consideration. Because of the power required by the MTS unit (110–220 V AC, 2 amps) and necessity for a data logging device (computer), powering with batteries can be logistically challenging. These factors resulted in the choice of DC-powered PTS systems for upper arrays at Shorey Brook and West Brook. Batteries at the upper site on Shorey Brook (the most remote of all sites monitored) were trickle charged with a solar charging system to extend visit intervals. PTS-based systems had internal storage limitations, necessitating site visits for downloading data. Another important limitation of PTS transceivers is the inability to store transceiver diagnostic information (e.g., RF noise).

Antennas

There are three components to an antenna: the coil, the cable, and the capacitor pack. Although all of our antennas were custom-built, assembly "kits" and prefabricated antennas that meet many needs are available from various manufacturers. Generally, the antenna coil is a continuous loop of wire. The coil is encased in a watertight chamber (Figure 3), connected to a shielded low capacitance/resistance two-conductor cable which is connected to the transceiver. One lead of the coil is attached to a fixed capacitor pack (preferably temperature stable capacitors, Negative-Positive-Zero [NPO] type) located at the antenna. The pack is matched to the inductance of the antenna. Multiple capacitors in parallel should be used to achieve the desired capacitance so that component damage due to the current through the antenna can be avoided. For the MTS transceiver, there is an adjustable capacitor (in addition to the fixed capacitor pack at the antenna) that can be used to fine-tune the resonance frequency of the system. Cables with built in tuning modules are available for PTS transceivers (in addition to the fixed capacitor pack at the antenna) and were used at Shorey Brook and West Brook.

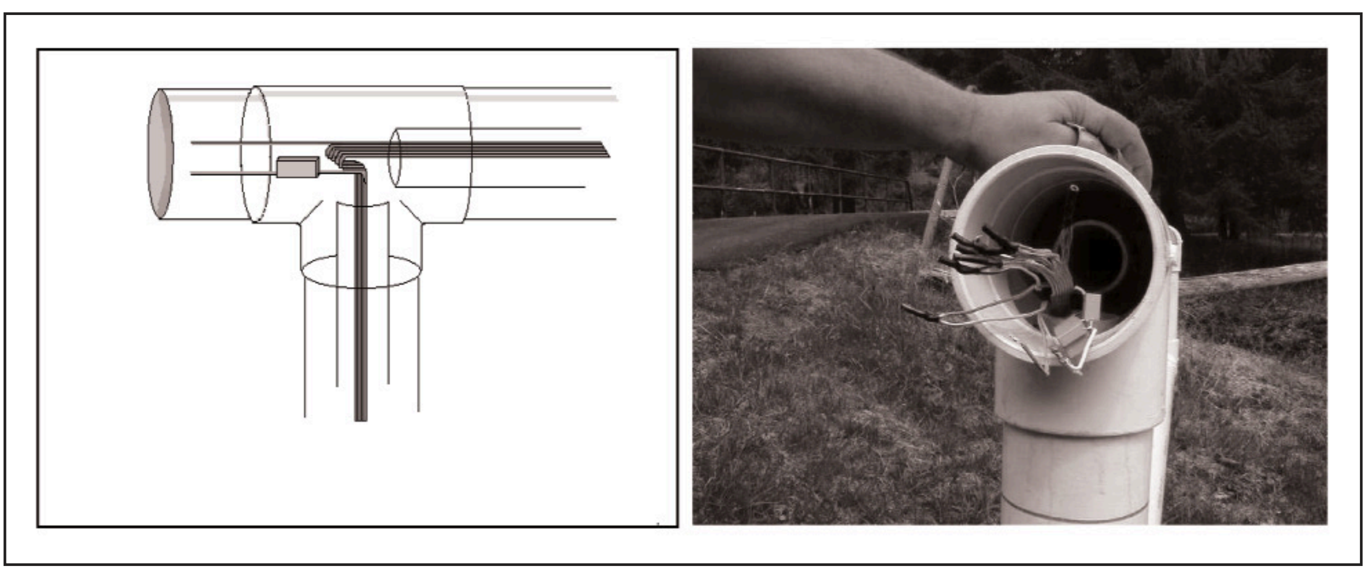
Typically, antennas are constructed so that the coil inductance was between 275 and 400 μH. The capacitance of the fixed pack must then be determined empirically using the following general relationship (as a starting point for MTS transceivers):

$$C = -13.92 \times I + 7610$$

where C is capacitance and I is the antenna inductance. Optimum capacitance can change with cable length or shielding. In practice, antenna construction is simple but can be time consuming.

Antennas used in the case studies were custom-designed for specific field applications and consisted of different sizes depending on the type of transceiver and tag size with which they were designed to work. For larger antenna sizes used with the MTS transceivers, antennas were constructed by threading the coil through a small diameter PVC pipe (3.5 cm inside diameter), and then centering this frame within a larger diameter PVC pipe (10.2 cm inside diameter) that was then sealed to keep water out (Figure 3). This design reduced the problem of "loading" that arises when water and wire are in close proximity. Smaller-sized

Figure 3. Schematic of antenna construction and photograph of antenna coil in PVC pipe. Antenna wires were fed through the smaller diameter PVC pipe (5.1 cm) centered within a larger diameter PVC pipe (10.2 cm). Wires were not overlapped or twisted when feeding the coil through the PVC pipe.



antennas were used with the PTS; the coils were housed in a single 3.5 cm (inside diameter) PVC pipe. Loading is less of a problem for the smaller antennas.

For both antenna types, antenna coils were constructed from 9-strand, 18 gauge ribbon cable. Wires were terminated to form a continuous loop at one corner of the PVC structure (Figure 3). The number of loops could be increased or decreased by including or excluding wires on the ribbon-cable to adjust the inductance of the coil during construction. The appropriate capacitors were attached between the coil and the cable. Cable length to the transceiver was limited to less than 15 m to ensure enough power to the antennas. In practice, longer cables (up to 50 m) are possible but may result in a reduction in efficiency.

Antenna choice (design, size, and shape) can vary as much as the application. Limiting factors for antenna size are tag size and the ability to generate enough power to create an efficient EM field to decode a tag. The EM field can be visualized in three dimensions as extending both upstream and downstream of the antenna plane (antenna plane is defined as the plane formed within the interior of the antenna opening). Large antennas require increased energy to enable detection throughout the entire plane of the antenna. Tag orientation in the antenna's field greatly affects the ability to be decoded successfully. The optimal tag orientation is where the long axis of the tag is orthogonal to the plane of the antenna, such that the long axis of the tag approaches the plane of the antenna.

Antenna orientation must be considered before construction. Antennas in all case studies were constructed and oriented with a swim-through design (Figure 2). Morhardt et al. (2000) first suggested the use of "swim-through" PIT tag antennas in streams because of increased detection range afforded by this design. An alternate design is to orient the antenna as a "flat plate" (Armstrong et al. 1996) flush with the stream bottom so that tags could be detected as fish swim over top of the antenna. This design has the advantage of an increased ability to withstand high flow events; however, detection "off the plane" of a flat plate antenna is limited if fish can swim high enough in the water column to escape detection. While other designs (Ibbotson et al. 2004) have been used and have advantages (e.g., negligible debris loading) these elaborate designs are more expensive. Our designs present cost-effective solutions that may result in some antenna loss, especially at high flows, but allow inexpensive replacement.

ENVIRONMENTAL EFFECTS ON EQUIPMENT

Because PIT systems use RF, any array is susceptible to interference from ambient RF signal at or near the operating frequency (or harmonics of the frequency) of the system. Such ambient RF signal is interpreted as RF "noise" by the transceiver. Electrical switching can cause a similar effect. At Abernathy Creek, for example, the upper site was impacted by RF noise caused by electrical switching at the U.S. Fish and Wildlife Service Abernathy Fish Technology Center. At AB-DN, switching noise generated by a computer transformer contributed to RF noise and ultimately required an isolation transformer to remove interference. The transceiver cannot decode multiple tags simultaneously, therefore, a tag in close proximity of the antenna will generate what is recorded as noise and can preclude other tags from being decoded. When building an array, a spectrum analyzer can be used to analyze ambient noise at 134.2 $\pm$ 10 kHz, but for most cases that is excessive. Building a large antenna and temporarily running a transceiver at the chosen field site provides a good check of background interference.

Noise can also be caused by detuning because of environmental conditions. Daily summaries of array noise demonstrate that each system has a unique pattern of RF noise. As a result, RF records can serve as a diagnostic tool for assessing the status of an array and probing the effects of environmental conditions within and among sites. Changes in water level affected noise and resulted in a seasonal pattern of recorded background noise that was generally positively correlated with water depth. As water discharge increases, electronic noise levels increase due to increased "loading" on the antenna. Increasing stream velocity associated with higher discharges can also cause tuning to change (noise to increase) due to vibration. In many cases, new tuning optima can be reached for the latest condition (after which antenna efficiency should be assessed). As a result, noise levels are dependent on system maintenance as well as environmental conditions.

DETECTION EFFICIENCIES

Like other sampling methods, the utility of detection data from stationary PIT tag monitoring efforts depends on the ability to estimate "capture" probability. While simple in concept, much of the discussions of the authors have centered on how to define and characterize efficiencies in a manner inclusive of just three case studies. Such difficulty underscores the challenge in developing useful and consistent terminology. For the types of efficiencies we outline, the most accurate characterization is generated through the use of live, free swimming fish of the target species. For some estimates, this may be practical while for others it may not. In some cases the practicality may depend on study design.

For purposes of standardization, the functional unit of assessment is defined as an "array," which is an antenna (or multiple antennas) that intersects a stream at a single cross-section. At Abernathy Creek, a single array consisted of two or three antennas. A number of arrays can be arranged serially (one downstream from another) at differing distances. For example, at Shorey Brook and West Brook, lower arrays were arranged <3 m apart whereas arrays at Abernathy Creek were separated by kilometers.

The type of efficiency that perhaps has the most universal application is what we term in situ efficiency ($E_{\text{in situ}}$). In situ efficiency is the ratio of fish detected at an array that are known to pass the array. For each array, $E_{\text{in situ}}$ is the product of two probabilities:

1. The fish passes through an array antenna (path efficiency, E_{PATH}) and
2. The antenna successfully detects and decodes the tag (antenna efficiency, $E_{ANTENNA}$; Figure 4):

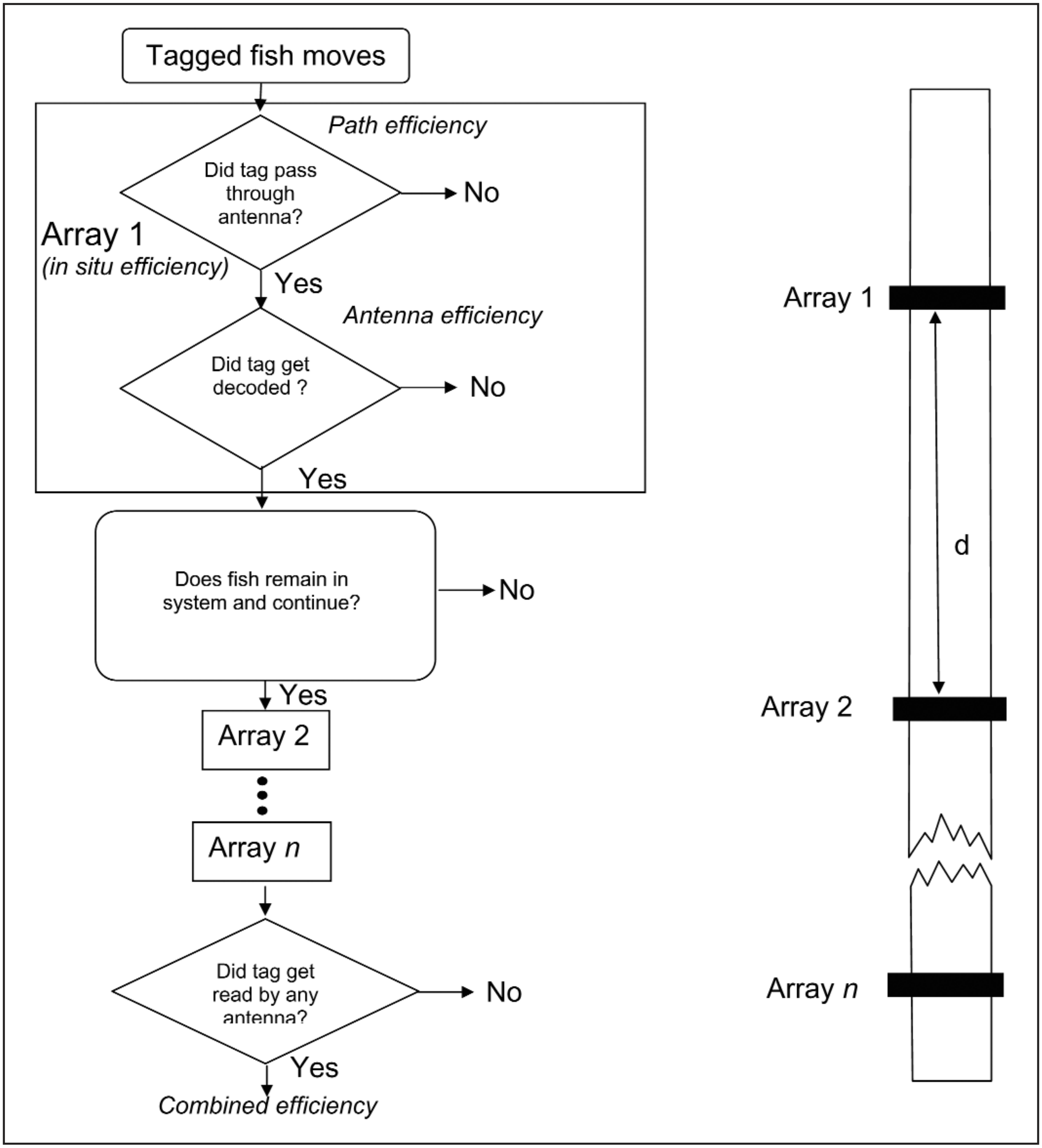
$E_{in\ situ} = E_{PATH} \times E_{ANTENNA}$

There are considerable logistical and theoretical challenges in separating these two components of $E_{in\ situ}$. Nevertheless, it is important to recognize that both may significantly contribute at different times in different ways to $E_{in\ situ}$; the relative role of each building block should be considered.

Path efficiency (E_{PATH})

For a single array, path efficiency is the ratio of tags that *physically moved through* an array antenna (as opposed

Figure 4. Flow chart depicting the concepts of (a) path, antenna, in situ, and combined PIT tag detection efficiencies. Panel (b) depicts a potential spatial continuum of arrays.



to around the array) to those known to have passed the array (Figure 4). Whether or not fish swim within a detection field depends in a complex way on fish behavior and what proportion of the cross-sectional stream area is covered by the detection field. While fish behavior cannot be controlled, some aspects of antenna conditions in the stream can be modified. For example, antenna location relative to the stream channel can influence the proportion of cross-sectional stream area captured by the antenna. At Abernathy Creek, both arrays covered the stream "bank to bank" in all but the highest water conditions; presumably path efficiency approached 100%. At Shorey Brook and West Brook, antennas were installed knowing that path efficiency was less than 100%, even under low water conditions. Efforts to improve path efficiency included placement of structures (sand bags, rocks, weirs) to direct fish movements. Extremes in stream discharge, however, likely influenced path efficiency (and therefore its relative contribution to $E_{in\ situ}$). Characterizing the proportion of the cross-sectional stream area "sampled" under different flow conditions is the best index of path efficiency.

Antenna efficiency ($E_{ANTENNA}$)

For a single array, antenna efficiency is the ratio of tags *detected successfully* by an array antenna to the known number of tags to have followed a path through that array antenna. Antenna efficiency is a function of the array antenna(s), transceiver(s), environmental conditions, tag velocity, and tag orientation as the tag moves through the detection field. Therefore, like path efficiency, this value and its contribution to $E_{in\ situ}$ is not fixed over time. In spite of this, antenna efficiency assessment remains an important tool for adjusting array performance over time. At all three streams, efficiency tests were performed at regular intervals (in some cases, daily). The simplest method to assess antenna efficiency is the use of a drone. Some "body" (drone) is tagged and passed through array antenna(s) multiple times and the proportion of successful attempts is assessed. Even then, differences in the geometry or "behavior" of drones as they pass through the antennas can lead to estimates that are not directly comparable. Drones used in case studies included wooden blocks, oranges, tennis balls, rope, and dead fish. It is important to remember that multiple tags should be used to assess antenna efficiency, as repeated jostling of an individual tag over long periods of time can cause changes in tag performance. For a neutrally buoyant drone drifted through an antenna (such as an orange), the tag rotates freely so that orientation is not fixed. On the other extreme, rectangular wooden blocks tended to orient the same way to the flow, each time resulting in near perfect tag orientation to the detection field (orthogonal). Each method has its own biases; hence standardization is important for long term assessment. For example, at Shorey Brook a "tagged" wooden block was routinely drifted through the antennas ($E_{ANTENNA}$ ranged from 94–98%). At Abernathy Creek, a nylon rope was used as a means to float a PIT tag and then pull it back through an antenna (standardizing tag orientation to the antenna). Trials of 10 antenna passes were conducted weekly ($E_{ANTENNA}$ ranged from 55–100%).

In situ efficiency ($E_{in\ situ}$)

Unfortunately neither component of in situ efficiency (path or antenna) is directly calculable in a field setting without additional monitoring. In situ efficiency for live, free-swimming fish can be calculated, but this requires multiple capture opportunities and entails either the operation of multiple arrays or coordination with more conventional detection techniques (e.g., trapping, electrofishing). This calculation requires knowing the number of tagged fish moving past an array and the number of tags detected beyond an array (upstream or downstream). To generalize:

$$E_{in\ situ\ ARRAY\ 1} = (d_{COMMON\ TO\ ARRAYS\ 1+2}) \times (d_{UNIQUE\ TO\ ARRAY\ 2} + d_{COMMON\ TO\ ARRAYS\ 1+2})^{-1}$$

where "d" is the number of tags decoded. To illustrate, consider a stream with two arrays (such that Array 1 is upstream of Array 2) and 100 PIT tagged salmonid smolts (i.e., downstream migrants) are released upstream of Array 1. Of the 80 fish later detected at Array 2, 60 were also detected at Array 1 ($d_{COMMON\ TO\ ARRAYS\ 1+2}$) and 20 were unique to Array 2 ($d_{UNIQUE\ TO\ ARRAY\ 2}$). In situ efficiency of Array 1 is then calculated as 0.75. This calculation has two critical assumptions:

1. The probability of a tagged fish being decoded by the first array is independent of the probability of it being decoded by the second array (otherwise the estimate will be inflated); and
2. The tagged fish moving through the first array continues to move in the direction of the next array.

This assumption can be made with more or less certainty depending on the species and life history characteristics being studied and the distance between the two arrays.

The degree to which the tags decoded on any two arrays are independent is greatly influenced by the distance between them. At Shorey Brook and West Brook lower sites, two arrays were placed approximately 3 m apart (Figure 2b and d). An individual moving downstream through the upper of the two arrays (for example) would have a higher probability of moving through the lower array than a fish that swam around. In the case of West Brook, the plywood weir virtually assured that a fish passing through one array would pass through the second. In this case, using tag detections from one array to calculate in situ efficiency for the other array would result in an estimate that was biased high. As the distance between two arrays increases (Figure 4b; upper arrays at West Brook, Shorey Brook, and at Abernathy), the assumption of independence of detection between arrays is more appropriate.

The assumption that a tagged fish continues moving through a series of arrays is the second critical consideration. The validity of this assumption varies with both the life history stage (e.g., smolt vs. non-smolts) and species of fish being studied. Clearly, most salmon smolts display rapid and directed downstream movements (McCormick et al. 1998) but not all fish fit this pattern. Ward and Slaney (1988) reported up to 3% of presumptive steelhead smolts transported above a trap did not move downstream. For non-migratory movements, tag detection at an individual array may indicate movement past the array or simply an excursion near the array. Even when the assumption of directed fish movement may hold, fish losses due to mortality (e.g., predation) subsequent to detection on one array but prior to detection on a serial array can bias efficiency estimates. Constructing arrays in close proximity has clear value in such cases. This arrangement has the benefits of demonstrating direction of movement and making the assumption of remaining in the system a robust one. The cost of this arrangement may be a failure to meet the assumption of independence for the arrays; although, if both path and antenna efficiencies are high, these issues are less critical.

Combined efficiency

"Combined efficiency" is defined as the proportion of tags known to have transitioned through the stream that were detected by at least one array. In the case studies presented here, estimating smolt emigration was a goal. Toward this end, if a tagged fish was detected at any array (during the period of downstream migration) it could be assumed to be a migrant. Hence data from multiple arrays can be used in combination as given below.

$$E_{COMBINED} = 1 - [(1 - E_{\textit{in situ}\ \text{ARRAY}\ 1}) \times (1 - E_{\textit{in situ}\ \text{ARRAY}\ 2}) \times \ldots (1 - E_{\textit{in situ}\ \text{ARRAY}\ n})]$$

Abernathy Creek, for example, $E_{combined}$ was estimated as 83–97%. Such a calculation is obviously helpful in estimating survival or the total number of migrants.

INSIGHTS

Data from PIT tag detection systems in small streams allows high recapture probabilities (approaching 100% in some cases) that can better inform research and management questions associated with fish movement and population dynamics. While it is tempting to apply these techniques to every small stream situation, our experiences have indicated that along with careful choice of system type and site adequacy, rigorous protocols for examining detection efficiency need to be established.

The case studies described overcome many challenges reported for PIT tag system operations (Gibbons and Andrews 2004). Swim-through arrays enabled monitoring of fish populations with no (or minimal) disruption to fish behavior. A significant logistical challenge was physically supporting the array antennas under high water conditions; site choice is important. Stream characteristics at a wide range of water levels and availability of structure for anchoring antennas (e.g., bridges) guide construction. Other considerations include ambient RF noise, power access, and stream channel width. The size of the tag used determines both the lower size limit of fish tagged and feasible antenna size, which may limit the stream size that can be monitored.

Study objectives may not necessitate arrays to interrogate the entire width of a system. Modest in situ efficiencies (e.g., using a single antenna) may be adequate to provide descriptive data for many needs such as describing the timing of migration in smolting salmonids. In most cases, operation of multiple arrays, even if they do not span the stream width, can greatly increase combined efficiency while providing movement direction.

Recent developments in FDX technology have included multiplexing (allowing the operation of more than one antenna from a single transceiver) and auto-tuning. While these systems are still being tested, they will offer great advantages to using PIT technology in small streams. Multiplexer transceivers switch power among multiple antennas that can be in close proximity. At our case sites, these multiplexer transceivers would have greatly reduced cost and allowed more flexibility in study designs. Auto-tuning accommodates changes in environmental conditions that affect antenna efficiency (e.g., increasing water depth/discharge) without user intervention. Advances in PIT tag construction are likely to allow greater read range of small tags. For example, improvements in newer tag models have already led to greater read distances over earlier generations of tags, a trend which will allow construction of even larger antenna sizes for a given tag size.

Regardless of developing technologies, there remains a need to characterize the efficiencies of PIT tag systems. PIT arrays have allowed biologists to assess movements of fish and population metrics that were not feasible in recent times. Just as with other, more traditional fish capture techniques, PIT arrays are subject to inefficiencies resulting from environmental and biological factors. The same basic principles applied to fisheries trapping methods decades ago must still be remembered. Maximizing and characterizing efficiencies are at the center of the challenge to applying this tool to its fullest potential.

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