RECLAMATION

Managing Water in the West

Research Project: Summary of Freshwater Fisheries Telemetry Methods

Research and Development Office
Science and Technology Program
Final Report 2014-01-1219

Cathy Karp

Research and Development Office
Bureau of Reclamation
U.S. Department of the Interior

October 2014

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

REPORT DOCUMENTATION PAGE		*Form Approved* *OMB No. 0704-0188*
T1. REPORT DATE October 2014	**T2. REPORT TYPE** Scoping	**T3. DATES COVERED**
T4. TITLE AND SUBTITLE Summary of freshwater fisheries telemetry methods		**5a. CONTRACT NUMBER** RY1541EN201421219
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER 1541 (S&T)
6. AUTHOR(S) Cathy Karp, Bureau of Reclamation, Denver, CO		**5d. PROJECT 1219**
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER 85-829000
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Cathy Karp, Bureau of Reclamation, Technical Services Center, Fisheries and Wildlife Resources, Denver, CO 80225		**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Research and Development Office U.S. Department of the Interior, Bureau of Reclamation, PO Box 25007, Denver, CO 80225-0007		**10. SPONSOR/MONITOR'S ACRONYM(S)** R&D: Research and Development Office BOR/USBR: Bureau of Reclamation DOI: Department of the Interior
		11. SPONSOR/MONITOR'S REPORT NUMBER(S) 2014-01-1219

12. DISTRIBUTION / AVAILABILITY STATEMENT
Final report can be downloaded from Reclamation's website: https://www.usbr.gov/research/

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 words)*
Freshwater fisheries telemetry currently includes passive and active technologies. Passive telemetry (no internal power) includes Passive Integrated Transponder or PIT-tag technology in which the tag is powered through a process referred to as inductive coupling. Active telemetry is currently powered through an internal battery and includes acoustic telemetry and radiotelemetry. Acoustic telemetry uses transmission of low frequency sound while radiotelemetry uses higher frequency radio signal transmission. Each technology has its advantages and disadvantages and some studies use a mix of technologies to achieve study goals.

15. SUBJECT TERMS fish telemetry methods

16. SECURITY CLASSIFICATION OF: U			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON Cathy Karp**
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	**U**	24	**19b. TELEPHONE NUMBER** 303-445-2226

S Standard Form 298 (Rev. 8/98)
P Prescribed by ANSI Std. 239-18

PEER REVIEW DOCUMENTATION

Project and Document Information

Project Name:Summarize fish telemetry

WOID: X5437 and X1219

Document Summary of Fisheries Telemetry Methods

Document Author(s) Cathy Karp

Document date October 31 2014

Peer Reviewer several – see acknowledgements

Review Certification

Peer Reviewer: I have reviewed the assigned items/sections(s) noted for the above document and believe them to be in accordance with the project requirements, standards of the profession, and Reclamation policy.

Reviewer see acknowledgements Date reviewed September 2014
(Signature)

ACKNOWLEDGEMENTS

Joel Hubble (Reclamation, Upper Cascades Area Office, Yakima, WA), Josh Israel (Reclamation, Bay-Delta Office, Sacramento, CA), Colleen Sullivan (Hydroacoustic Technology, Inc., Seattle, WA), and Earl Prentice (Prentice & Associates, Port Orchard, WA) provided valuable comments on the draft manuscript.

Executive Summary

Ideally, biologists choose to study living animals in the natural world without disrupting their normal habits (Priede 1992). Development and improvements in use of electronic tags and telemetry techniques in fisheries in the last 30+ years has revealed much information about animal behavior. Active telemetry methods, acoustic telemetry and radiotelemetry, offer higher detection rates over long distance and more detailed location data, but have the disadvantage of costly equipment and data analyses. Thus, fewer individuals are tagged in active telemetry studies. Conversely, passive telemetry techniques, Passive Integrated Transponder, or PIT-tags, are permanent (as long as the tag is not shed by the tagged individual), offer the benefit of low cost, ease of tag implant, and long tag life. PIT-tags are more useful for studies involving high number of individuals while the active telemetry methods are more useful for study of individual behavior.

Introduction

Many fish (freshwater, estuarine, and marine) exhibit movements and/or migrations during their life cycle. Our knowledge of these movements (long distance and localized) is critical to a more comprehensive understanding of fish behavior and habitat use, and to our ability to predict their response to environmental changes. However, acquiring this knowledge is challenging simply because fish live in a world different than our own.

Until the development of animal telemetry techniques, basic fisheries life history data was dependent on the use of observation and conventional mark-recapture studies in which various types of external tags or marks were attached/applied to some number of captured fish, followed by one or more fish recovery sampling efforts. These follow-up efforts were often limited and insufficient data was obtained. Beginning in the 1950's, development of electronic tag detection systems for fish allowed biologists to repeatedly, sometimes continuously, locate and identify individually tagged animals in a variety of habitat types. Considerable advances since then, and continuing today, with electronic tag technologies include development of receivers for passive tracking, transmitter miniaturization, improved battery technology and miniaturization, antenna design, use of pulsed and coded transmitter signals, etc. (Lucas and Baras 2000; Winter 1983, 1996; Cooke et al. 2013). This has enabled more in-depth studies of fish behavior and fish physiology in their natural habitat. Telemetry studies have greatly increased the understanding of fish habitat use, migration patterns, passage through or over manmade structures, and survival. Information learned from these studies is widely used in the management and conservation of protected, game and other fish species and determining the effectiveness of habitat restoration projects. The objective of this paper is to summarize existing telemetry technology used in studies of fish movements and behavior, migrations, and survival in freshwater systems, as these pertain to Bureau of Reclamation operations.

Literature and Technology Review

Biotelemetry is a generic term to describe the methodology used, among other things, to acquire remote or "difficult- to- collect" biological data on free-ranging animals. It enables scientists the ability to remotely acquire information from individually marked animals without having to directly observe or repeatedly handle them. Telemetry studies involve two basic components, a transmitter/transponder (i.e., a tag) and a listening system/receiver/reader, i.e., a receiver (Winter 1983, 1996). These technologies use the wireless underwater transmission of sound (e.g., acoustic telemetry) or electromagnetic energy (e.g., radiotelemetry, Passive Integrated Transponder, [PIT], tag telemetry) from a tag that has been attached or implanted in an individual fish, and, depends on that signal being detected by a receiver. The tag is attached to or implanted in the animal of study in one of several ways and the individual's movements are monitored for the life of the animal, life of the tag, or some intermediate period, e.g., bird predation removes tags from the aquatic environment and thus, often from the study. Telemetry studies can provide information on migration patterns, habitat use, size of home range, spawning locations, diel behavior, migration delay, route preference (up and downstream), predation sinks (mammal, bird, and fish), passage efficiency (success, duration, timing), etc.

Biotelemetry is the transmission of "unique" acoustic and radio signals at frequencies above the hearing range of fish (<7 kHz) and humans (<20 kHz). Acoustic signals are low frequency (20-300 kHz; i.e., 1000's of cycles/second) and radio signals relatively high frequency (27-300 MHz; i.e., millions cycles/sec). Use of electronic tag technology in freshwater systems currently includes passive (having no internal power) and active (battery powered) tag technologies. Passive telemetry tags (i.e., transponders) are powered through a process referred to as inductive coupling. The antenna coil within the PIT-tag couples to the electromagnetic field generated by the antenna and receiver system. In contrast, active telemetry requires a battery to power the transmission of data from the transmitter or tag to the detection system. Currently, PIT-tag technology is the only passive telemetry system available for fisheries studies, while radio, acoustic, satellite, and archival technologies are active telemetry as they require an internal battery. Fisheries biologists use either or some combination of these technologies depending on the objectives being addressed, species and age class, environmental conditions, scale of study, cost, and some acceptable level of the effectiveness of tag detection.

Transmitters and Transponders

All fish telemetry studies require the attachment or insertion of the tag to the individual fish with the premise that the tag not alter or otherwise significantly change natural behavior. Many studies have been and continue to be conducted to determine a recommended tag weight to fish weight ratio (known as the tag burden) as a tag that is too large will either stress or kill the individual. Somewhat similarly, a tag that is too small may not be detected, or the battery could die before information is learned. It is generally accepted that the tag should weigh no more than 2% of the fish's body weight in air (or 1.25% of the weight in water; Winter 1983, 1996). This is known as the "2% rule" in telemetry studies and is based on the idea that a larger and heavier transmitter will affect the natural swimming behavior of the implanted fish. Miniaturization of batteries and transmitters in recent years, along with improvements in tag shape and form, has allowed more studies of juvenile and small bodied fish, and some recent studies suggest that larger transmitters may be used with some species (Adams et al. 1998; Brown et al. 1999, 2010). Transmitters may also be equipped with various types of sensors (e.g., temperature, depth) but are limited by the final tag size/weight and size of the study fish. Recent development in transmitter designs includes use of pulsed and coded transmitters (in comparison, radio stations continuously emit signals). Pulsed transmitters allow increased battery life, and for some tag types, the pulse interval can be used to identify and precisely locate specific transmitters. Development of coded transmitters in both radio and acoustic technologies allow for decreased scan time of the receiving system (thus increased tag detection).

The type of transmitter attachment (external, internal implant, gastric implant) depends on the species being studies, the size of the fish, and the type of system the fish resides in. Each type has pros and cons. External attachments require less anesthetization and the fish can be released more quickly, but, the attachment increases drag, may get fouled, torn off, and cause infection at the attachment site. Internal tags require a longer exposure to fish anesthetic, more invasive surgery, and the possibility of the tag being expelled either through the incision or digestive system. The trailing external antenna used in some radiotelemetry applications may cause some irritation at the exit site which can become lethal. Internal and gastric implants eliminate the risk of external fouling but may cause significant changes in normal fish behavior. PIT-tags are the smallest tag and may be implanted subcutaneously or into the body cavity with a syringe, scalpel, or semi-automated injection systems (Prentice et al. 1990c; may also be implanted abdominally if used in conjunction with acoustic/radio implant).

Passive Telemetry Methods

PIT-tag technology was first developed for use with juvenile salmon in the Columbia River Basin in the 1980’s in a joint effort by the National Marine Fisheries Service and Bonneville Power Administration (Prentice 1990). Since then, the technology has been widely used in studies of fish survival, juvenile and adult dam route passage, turbine passage, migration, river reach survival, hatchery practices, effectiveness of habitat restoration efforts, etc. in which large numbers of fish need to be monitored (multi-year or population level), or in which long-term “near real time” information on particular individuals is needed (Prentice et al. 1990b; Skalski et al. 1998; Gibbons and Andrews 2004; Zydlewski et al. 2006; Connolly et al. 2008; Downing et al. 2008; Smyth and Nebel 2013).

PIT-tags consist of a uniquely coded (alphanumeric) integrated circuit chip and a copper coiled antenna encased in glass, and range in size from about 8 -23 mm in length and 2 mm diameter (Prentice et al. 1990c; Gibbons and Andrews 2004). The PIT-tag is read (including date, time, and code) when the tagged individual passes near or through the tuned antenna receiver system. Tag shedding is uncommon, tags rarely fail, and PIT-tags do not significantly affect behavior of the tagged individual (Prentice et al. 1990a; Gibbons and Andrews 2004; Zydlewski et al. 2006).

There are two basic types of PIT tag systems, full duplex (FDX) and half duplex (HDX). In FDX systems, the tag modulates the amplitude of the 134.2 kHz electromagnetic field radiating from the antenna (a few FDX 125 kHz and 400 kHz tags are still in use but declining in popularity and availability). The energizing of the tag and modulating of the antenna field occurs at the same time using a process known as amplitude shift keying. In HDX systems, tags modulate the frequency from 134.2 kHz to 124.2 kHz. An HDX tag has a capacitor which is charged via inductive coupling to the antennas' electromagnetic field. When the charge cycle is terminated, the tag then modulates the frequency. HDX tags historically were larger than the common 12 mm FDX tags, but 12 mm long HDX tags are now available.

PIT-tag antennas may be hand-held (portable) or stationary (fixed). Antenna geometry varies from round to rectangular depending on application. Tag detection range (i.e., read distance or read range) is based on the size and quality of the antenna, reader design, ambient and self-generated electromagnetic interference, orientation of the tag to the antenna field, and other factors (E. Prentice, Prentice & Associates, personal communication). Read range of PIT-tags is much less than with active telemetry technologies and varies from about 0.5 m in FDX to < 1 meter for HDX. Best PIT-tag detection occurs when the tag is perpendicular to the antenna. Tag collision is a phenomenon that can occur when multiple PIT-tags enter the antenna's interrogation field at the same time, thereby preventing any tag from being read. Installation of multiple antennas in a row and reducing the number of tags released near the antenna field increases the probability of the tag being read.

Stationary or fixed PIT-tag antennas are either pass-through, pass-by, or hybrid (Downing et al. 2008). Pass-through antenna systems are oriented vertically to the flow, detect tagged fish as they move through the antenna, but are vulnerable to high flows and debris. Pass-by or flat plate antennas are anchored to the stream bottom and are best suited for more shallow systems with bottom oriented species. The tagged individual is detected as it swims over the antenna. Hybrid antennas are anchored to the stream bottom at the upstream end but float on the downstream side so that the antenna system fluctuates in height with changes in flow. Tagged fish may be detected as they pass through the antenna at higher flow or over at low flows. A new design uses a surface mounted antenna for use in shallow systems (McKinstry 2013). Detection efficiency (i.e., proportion of tagged fish passing through the area) of the PIT-tag antenna array is generally recommended prior to the start of a study because of potential tag collision and other tag detection issues.

Active Telemetry Methods

Acoustic Telemetry

Acoustic telemetry was originally developed for use with marine systems but is also widely used in freshwater to evaluate habitat use, fish passage timing, route selection, and survival at hydroelectric dams, in deep water habitats (movement and migration studies), and in rivers with higher conductivity (survival studies). This technique is generally more effective in areas of low turbulence as entrained air bubbles and other noise/electric inference may interfere with correct acoustic signal reception. Early studies were relatively labor intensive in that hand-held directional listening devices (i.e., hydrophones) and boat mounted electronics were used to actively track the tagged fish (Kessel et al. 2014). Development of stand-alone receiver systems in the 1980's allowed for more complex positioning types of studies using multiple hydrophones (Heupel and Webber 2011).

Acoustic (also known as ultrasonic and sonic) telemetry involves the transmission of low frequency sound signals (30-417 kHz) to an underwater antenna or hydrophone and above water receiver (Stasko and Pincock 1977; Winter 1983, 1996). The acoustic tag contains a transducer, circuit board, and battery, and is encapsulated in epoxy resin (there is no antenna). Tag electronics allow for the conversion of battery powered electrical energy to sound energy (Pincock and Johnston 2012). The hydrophone then converts the acoustic signal back to an electrical signal for detection and decoding in the receiver. Transmitters emit pulsed signals consisting of short bursts of sound waves. Pulsed signals may extend battery life by minimizing power consumption and may be separated in time by as little as 0.1 msec. Signal coding methods have advanced greatly and allows for significantly more unique tags potentially available and more sophisticated tag positioning determinations.

Detection of the acoustic signal can be affected by ambient underwater noise, electrical noise from nearby equipment, underwater structure, etc. (Pincock and Johnston 2012). There are different types of tag identification methods that will affect the distance over which tags can be detected and identified. Location of the acoustic tag is determined from time-of-arrival detections on a single or an array of hydrophones, each detection having a date and time stamp. Sound can travel through water for over 1km but can be reduced by natural (e.g., air bubbles, structure, vegetation) and man-made (e.g., boat motors) noise. A limitation of acoustic telemetry is that sound signals do not pass the water-air interface and thus, detection systems only use underwater antennas.

Acoustic telemetry may be used to determine fish presence/absence, and to obtain a continuous record of a fish's movements. Thus, this technology is ideal for "real time" fine-scale studies in which time-stamped tag detections are used to measure a tagged fish's movements (for example, evaluating fish behavior in front of and through a barrier). One technology uses pulsed signals in which the emitted signal pulses are uniformly spaced with high precision (i.e., the length of the pulse and interval between successive pulses is precisely repeated). This allows determination of accurate fish identification and position data (fine-scale 2D and 3D) using multiple listening stations in small spatial scale (e.g., directionality of movement, holding behavior, or cessation of tag movement suggesting tag expulsion or predation/defecation, Tracy Fish Collection Facility, CA studies, Karp et al. 2014). In more wide ranging presence/absence studies, tag detection on multiple listening stations set up over a large area (generally linear) can be used to monitor the sequential location of the tag (e.g., tracking outmigration success of juvenile steelhead and Chinook salmon in the San Joaquin-Sacramento Delta, CA, J. Israel, personal communication). Through coordinated deployment of receivers in multiple facilities, some studies are also yielding survival estimates for tagged fish passing through a particular fish collection facility (J. Israel, personal communication). Acoustic telemetry can also be used to track juvenile salmonids in the interface between freshwater and near shore marine environments (McMichael et al. 2013).

Radiotelemetry

Radiotelemetry was first developed for terrestrial use and more recently modified for aquatic animals in the 1990's (Cooke and Thorstad 2011). Radiotelemetry has been widely used in shallow and turbulent rivers with low conductivity (< 500uS/cm). Radiotelemetry uses a relatively high frequency radio signal transmission and either hand-held or mounted aerial antennas (30-300 MHz; Sisak and Lotimer 1998; Hockersmith and Beeman 2012; Stasko and Pincock 1977; Winter 1996). Tags may be separated by frequency or signal pulse rates within a frequency which allows for reduced scan time and increased tag detection. Radiotransmitters use a quartz crystal (to control frequency), battery, and an antenna that may be coiled and encased within the tag package, or left out and trailing from the fish, to transmit information. Internal antenna transmitters have lower signal strength than the external antenna configurations. However, the external antennas may get fouled and/or cause infection, etc. (reviewed in Bridger and Booth 2003). As with acoustic transmitters, radio transmitters need to be waterproofed and are encased in resin or epoxy.

Radio signals propagate in all directions and are not affected by vegetation and turbulence. However, signal strength is reduced with depth and conductivity. These signals easily pass through the air-water interface and can be tracked by land based antenna systems (e.g., airplane, boat, and truck mounted antennas). Thus, radiotelemetry has typically been the method of choice for highly mobile species over large watersheds in shallow, low conductivity systems. Radiotelemetry is also best suited for engineered fishways at dams, ice covered rivers, for situations with heavy aquatic vegetation or debris because antennas may be mounted on various devices (airplanes, towers, hand-held) and the radio signal is far-ranging. Antennas may be omni or uni-directional and a variety of shapes and sizes are used. The tags' location is determined from repeated efforts using hand-held directional antenna from different angles (i.e., triangulation) and from fixed site receiving stations typically located on the stream bank. As with acoustic telemetry, radiotelemetry can provide "real time" information.

Combined radio acoustic telemetry

Technology is available to track fish that move between freshwater and near-shore marine environments using transmitters that combine acoustic and radiotelemetry components (CART technology). The more complex CART transmitters are able to sense the conductivity of the ambient water and activate the correct technology (Cooke et al. 2013).

Types of errors in active telemetry

Various types of transmission-detection errors may occur with biotelemetry systems due basically to differences between what was transmitted and the signal received. Errors include tag read errors (false positives and false negatives) and location/position errors. False positives may occur when a tag is recorded when it should not have been and false negatives occur when a valid tag is not recorded when it should have been. These may occur when multiple tags are in the area, interference from ambient noise, collisions among transmitters in the detection area, and obstructions between the tag (fish) and the receiving antenna (Beeman and Perry 2012). Another type of tag identification error can occur when a tagged fish is predated by another. Prior to defecation, the tag signal can still be detected within the predator fish and tag behavior may then be erroneously interpreted as that of the original tagged individual.

Other Active Telemetry Technologies

Telemetry studies using satellite technology are not commonly used with freshwater fish because the individual needs to spend some time at the surface for the signal to be transmitted. Archival or data storage tags (PSAT= pop-up satellite archival tag) are dependent on tag recovery for full data retrieval. The tag is typically hooked into the dorsal musculature (may be implanted but these need to be recovered for data access) and data is transmitted to the ARGOS (Advanced Research and Global Observation Satellite) system when the tagged individual is at the surface or the tag is released. After a preset amount of time, the tag disengages from the fish and floats to the surface where it can be recovered (more recent technology sends a signal to aid tag recovery). Another satellite tag system is SPOT (Smart Position/Temperature Transmitting) that improves the likelihood of tag retrieval as the satellite sends tag location data to the researcher. A newer concept is the use of cellular technology to track animal movements, using cell tower network in the area of study. The downside to these technologies for use with freshwater fish is that most species under study do not generally use near surface or surface habitats. However, advances in this type of remote tracking in the future will create new options.

Discussion and Future

Fisheries biologists and water resource managers need to be able to measure the response of fish populations to environmental change (whether it be fishing pressure, flow alteration, dam construction and blockage of migration routes, dewatering, silting and sedimentation, lake turnover, food supply, poisons, disease, etc.), keeping in mind that needs may vary by life history stage (i.e., larvae, juvenile, adult). The development of fishery telemetry techniques has greatly expanded collection of basic biological data. In selecting the type of telemetry system, the appropriate tool depends on the species, life history stage, habitat (e.g., benthic, pelagic, resident or migratory), resolution required, sample size, size of the study area, time over which data is required, personnel availability and experience, and budget (see Table 1 for method summary). Furthermore, tag technology used is sometimes dependent on other ongoing telemetry projects and fixed station equipment in the study area.

Although no method is 100% effective, each telemetry technology has specific capabilities and limitations. All three techniques (PIT, acoustic, and radio tag) are used in studies of fish survival at dams (or other in- river structure), fishways, and in river reaches. Acoustic telemetry traditionally was better suited for freshwater studies in deeper areas with little turbulence, but advances in signal detection and data interpretation now reduces interference from ambient noise and the technology is more widely used throughout freshwater environments. Radiotelemetry continues to be used in shallow river systems where turbulence and thus, air entrainment may be high, conductivity is relatively low, in systems with dense aquatic vegetation, winter studies and ice cover, and in large watersheds (Cooke and Thorstadt 2011). Radiotelemetry also has the advantage of enabling detection of a tagged fish that has predated (bird or mammal) and left the aquatic environment. PIT-tag systems are best suited for large scale studies of passage/migration success and in individual long-term studies in which the animal may be recaptured (e.g., razorback sucker population estimates in the lower Colorado River).

The two active telemetry methods allow for a wider detection range (up to 1 km) whereas PIT-tags can only be detected either with hand-held devices or when within < 1 m of a tuned antenna. Acoustic and radio telemetry methods are limited by the size of the study animal (although battery and tag miniaturization is ongoing) but allow study of fine-scale movements and individual behavior. Acoustic telemetry systems use an underwater antenna (hydrophone) to detect acoustic signals while aerial antennas are used in radiotelemetry. Both systems use portable (mobile) and fixed receivers to collect and decode the received signal. Both radio and acoustic transmitters may be fitted with sensors to record temperature, depth, salinity, and muscle activity. Both active telemetry systems may be used to track fish passage (up and downstream), route preferences, route survival, timing and delay, etc., and both systems are uniquely vulnerable to noise interference (e.g., lightning, radio stations for radiotelemetry; boat motors, turbulence for acoustic systems).

Advantages for active telemetry systems are that transmitter detection rates are higher and location data is more precise than in PIT-tag systems, but, both transmitters and data analyses are relatively expensive and the life of the transmitter is relatively short. PIT-tag systems have the advantage of being the smallest available electronic tag with least invasive surgical implant procedure, almost infinite number of unique codes, having little or no effect on individual's behavior, lower cost, and having a long life (e.g., consumed PIT-tags have been recovered from meter thick waste piles underneath some bird rookeries, Sebring et al. 2010; J. Hubble, personal communication). PIT-tags can act as a lifetime barcode if the tagged individual remains alive, tag is not shed, and is recaptured or detected (Smyth and Nebel 2013).

The main limitations of PIT-tag systems are the relatively low detection range, high occurrence of tag collisions when multiple tags pass near the antenna at the same time (one technique used to increase detection is the use of multiple antenna systems spread longitudinally down the river or fishway), the high costs of some antenna installations, the inability to install PIT-tag antennas in some locations due to technical constraints, and vulnerability of in-river antenna systems to high flows and debris. There is a higher likelihood of tag expulsion in radio/acoustic surgically and gastrically implanted tags than with PIT-tags.

All aquatic fisheries methods may be used singly or in combination. All have some inherent problems. Tags can fail (more likely with acoustic and radio tags), fish can pass undetected (e.g., tag collisions in PIT-tag systems), and errors occur in tag identification (more often with acoustic and radio). Future technology may include microminiaturization of components and sensors to allow smaller fish to be studied, development of larger PIT-tag antenna systems, development of new tag technology (e.g., predation tag, K. Kumagai, personal communication), development of new receiver technology, and improvements in processing tag detection errors.

Literature Cited

Adams, N. S., D. W. Rondorf, S. D. Evans, J. E. Kelly, and R. W. Perry. 1998. Effects of surgically and gastrically implanted radio transmitters on swimming performance and predator avoidance of juvenile Chinook salmon (*Oncorhynchus tshawytscha*). Canadian Journal of Fisheries and Aquatic Sciences 55:781–787.

Beeman, J. W. and R. W. Perry. 2012. Bias from false-positive detections and strategies for their removal in studies using telemetry. Pages 505-517 *in* N. S. Adams, J. W. Beeman, and J. H. Eiler, editors, Telemetry Techniques: A User Guide for Fisheries Research. American Fisheries Society, 2012.

Bridger, C. J. and R. K. Booth. 2003. The effects of biotelemetry transmitter presence and attachment procedures on fish physiology and behavior. Reviews in Fisheries Science, 11(1):13-34.

Brown, R. S., S. J. Cooke, W. G. Anderson, and R. S. McKinley. 1999. Evidence to challenge the "2%" rule for biotelemetry. North American Journal of Fisheries Management 19:867-871.

Brown, R. S., R. A. Harnish, K. M. Carter, et al. 2010. An evaluation of the maximum tag burden for implantation of acoustic transmitters in juvenile Chinook salmon. North American Journal of Fisheries Management 30:499-505.

Connolly, P. J., I.G. Jezorek, K. D. Martens et al. 2008. Measuring the performance of two stationary interrogation systems for detecting downstream and up-stream movement of PIT-tagged salmonids. North American Journal of Fisheries Management 28:402-417.

Cooke, S.J. and E. B. Thorstad. 2011. Is radio telemetry getting washed downstream? The changing role of radio telemetry in studies of freshwater fish relative to other tagging and telemetry technology. American Fisheries Society Symposium 76:1-21.

Cooke, S. J., S. G. Hinch, M. C. Lucas, and M. Lutcavage. 2013. Chapter 18 – Biotelemetry and biologging. Pages 819-860 in A. V. Zale, D. L. Parrish, and T. M. Sutton, editors. Fisheries Techniques, Third Edition. American Fisheries Society, Bethesda, Md.

Downing, S.L., E. F. Prentice, B. F. Jonasson and G. T. Brooks. 2008. Development and evaluation of passive integrated transponder tag technology (December 2006-November 2007). Project 1983-319-00, Bonneville Power Administration, Portland, Oregon.

Gibbons, J.W. and K.M. Andrews. 2004. PIT tagging: Simple technology at its best. Bioscience 54:447-454.

Heupel, M. R. and D. M. Webber. 2011. Trends in acoustic tracking: where are the fish going and how will we follow them. Pages 219-231 in McKenzie, J., B. Parsons, Seitz, R. Keller Kopf, M. Mesa, and Q. Phelps, editors. Advances in Fish Tagging and Marking Technology. American Fisheries Society Symposium 76.

Hockersmith, E.E., and Beeman, J. W., 2012, A history of telemetry in fisheries research: Pages 7-20 in N.S. Adams, J.W. Beeman, and J.H. Eiler, editors. Telemetry techniques: a user guide for fisheries research: American Fisheries Society, Bethesda, Maryland.

Hubble, J. 2014. Personal communication. Bureau of Reclamation.

Karp, C., B. Wu, A. Schultz et al. 2014 (In prep). Evaluation of Chinook salmon and Central Valley steelhead facility losses at the Tracy Fish Collection Facility. Bureau of Reclamation, Technical Services Center, Denver, CO.

Kessel, S. T., S. J. Cooke, M. R. Heupel et al. 2014. A review of detection range testing in passive acoustic telemetry studies. Rev. Fish. Biol. Fisheries, 24: 199-218.

Kumagai, K. 2014. Personal communication. Hydroacoustic Technology, Inc.

Israel, J. 2013. Personal Communication. Bureau of Reclamation.

Lucas, M. C. and E. Baras. 2000. Methods for studying spatial behavior of freshwater fishes in the natural environment. Fish and Fisheries, 1:283-316.

McKinstry, M. 2013. New antenna system to detect tagged fish. Bureau of Reclamation. The Knowledge Stream Research Update Bulletin 2013-06.

McMichael, G. A., A. C. Hanson, R. A. Harnish et al. 2013. Juvenile salmon migratory behavior at the mouth of the Columbia River and within the plume. Animal Biotelemetry 2013, 1:14.

Pincock, D. G., and S. V. Johnston. 2012. Acoustic Telemetry Overview. Section 7.1 in N. S. Adams, J. W. Beeman, and J. H Eiler (eds.) Telemetry Techniques: A user guide for fisheries research. American Fisheries Society, Bethesda, Maryland.

Prentice, E.F. 2014. Personal communication. Prentice & Associates.

Prentice, E. F. 1990. A new internal telemetry tag for fish and crustaceans. Marine Farming and Enhancement, NOAA Technical Report NMFS 85.

Prentice, E. F., T. A. Flagg, and C. A. McCutcheon. 1990a. Feasibility of using implantable passive integrated transponder (PIT) tags in salmonids. Pages 317-322 *in* N.C. Parker, A.E. Giorgi, R.C. Heidinger, D.B. Jester, Jr., E.D. Prince, and G.A Winans, editors. American Fisheries Society, Symposium 7, Bethesda, Maryland.

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

Prentice, E. F., T. A. Flagg, C. A. McCutcheon et al. 1990c. Equipment, methods, and an automated data-entry station for PIT tagging. Pages 335-340 *in* N.C. Parker, A.E. Giorgi, R.C. Heidinger, D.B. Jester, Jr., E.D. Prince, and G.A Winans, editors. American Fisheries Society, Symposium 7, Bethesda, Maryland.

Priede, I. G. 1992. Wildlife Telemetry: an introduction. Pages 1-25 *in* Priede, I. G. and S. M. Swift editors. Wildlife Telemetry, Remote Monitoring and Tracking of Animals. Ellis Horwood Limited.

Sebring, S. H. R. D. Ledgerwood, B. P. Sandford et al. 2010. Detection of passive integrated transponder (PIT) tags on piscivorous avian colonies in the Columbia River Basin, 2008. U.S Army Corps of Engineers, Contract 2RL4SPTP00.

Smyth, B. and S. Nebel. 2013. Passive integrated transponder (PIT) tags in the study of animal movement. Nature Education Knowledge 4(3):3.

Stasko, A. B., and D. G. Pincock. 1977. Review of underwater biotelemetry, with emphasis on ultrasonic techniques. Journal of Fisheries Research Board of Canada. 34(9): 1261-1285.

Sisak, M. M. and J. S. Lotimer. 1998. Frequency choice for radio telemetry: the HF vs. VHF conundrum. Hydrobiologia 371/372:53-59.

Skalski, J. R., S. G. Smith, R. N. Iwamoto et al. 1998. Use of passive integrated transponder tags to estimate survival of migrant juvenile salmonids in the Snake and Columbia rivers. Canadian Journal of Fisheries and Aquatic Sciences 55:1484-1493.

Winter, J. D. 1983. Underwater biotelemetry. Pages 371-395 *in* L. A. Nielsen and D. L. Johnson, eds., Fisheries Techniques. American Fisheries Society, Bethesda, Maryland.

Winter, J. D. 1996. Advances in underwater biotelemetry. Pages 3555-585 *in* B. R. Murphy and D. W. Willis, eds., Fisheries Techniques Second Edition. American Fisheries Society, Bethesda, Maryland.

Zydlewski, G., G. Horton, T. Dubreuil et al. 2006. Remote monitoring of fish in small streams: a unified approach using pit tags. Marine Sciences Faculty Scholarship. Paper 104.

Table 1. Summary of advantages and disadvantages of three types of fish telemetry methods.

	Acoustic telemetry	Radio telemetry	PIT-tag technology
Advantages	-Internal, gastric, and external attachment -Deep water -High conductivity -Can provide high positioning resolution (sub-meter) - Presence/absence over wide range -Continuous monitoring	-Internal, gastric, and external attachments -Shallow water -Turbulent conditions -Aquatic vegetation -Ice - Presence/absence over wide range -Continuous monitoring	-Internal attachment -Permanent -Infrequent tag loss -No significant negative Impact -High read accuracy -Inexpensive tags, antennas, and readers - Presence/absence over wide range
Disadvantages	-Relatively short-lived -Equipment and data processing costly -Not as good in noisy or turbulent environments -Tag Errors (both false positives and false negatives) -Tag errors from possible tagged fish predation	-Relatively short-lived -Equipment costly -Tag Errors (both false positives and false negatives) -Tag errors from possible tagged fish predation	-Antennas vulnerable to river flood events -Low detection range -Tag collisions and reduced tag detection -Discontinuous monitoring -Intermittent monitoring -Tag errors from possible tagged fish predation