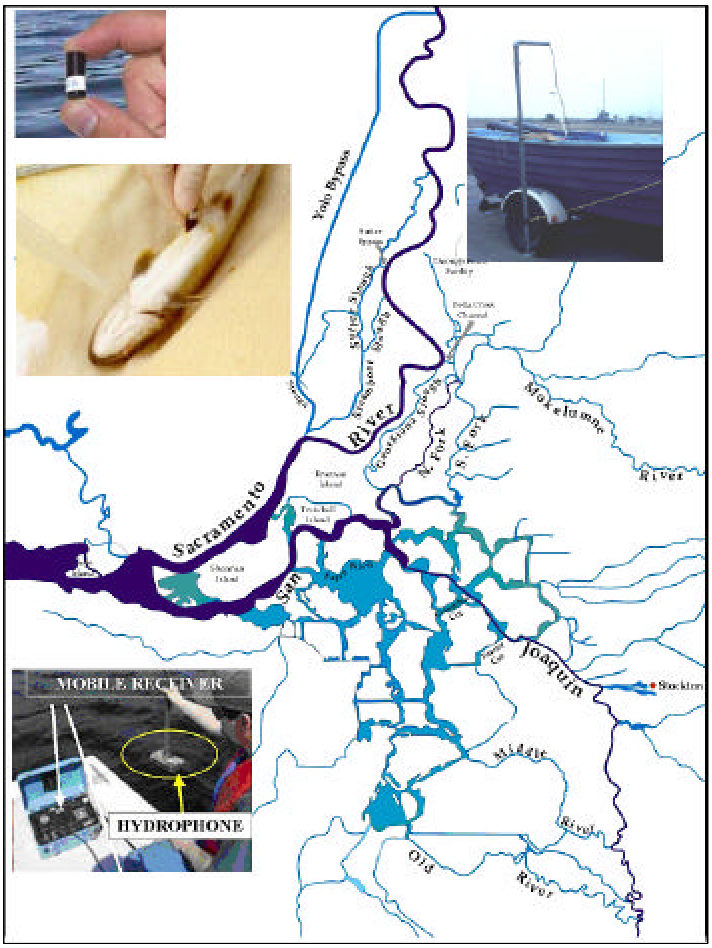
Acoustic Tracking Technology and Potential Applications for Salmonid Research within the San Francisco Bay and Sacramento-San Joaquin Delta



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EXECUTIVE SUMMARY

One of the most difficult water resource management problems facing California today is maintaining the quality and reliability of agricultural and municipal water supplies while restoring the San Francisco Bay/Sacramento-San Joaquin Delta (Delta) ecosystem. As human populations continue to grow and place increasing demands on water resources, it is crucial that resource managers understand the biology and behavior of fish species that live or migrate through the Delta in order to provide a balanced approach to water management that meets the needs of multiple natural resources and stakeholders. The objective of this paper is to present information regarding current state-of-the-art acoustic tracking technology and potential applications of acoustic research techniques for increasing our understanding of fishes, particularly salmonids, within the Delta.

The Delta is the largest estuary on the Pacific Coast and it consists of a maze of tributaries, sloughs, and islands that includes over 738,000 acres in five counties. The Sacramento and San Joaquin rivers and their tributaries feed the Delta, which then drains to the northeast end of San Francisco Bay. The Delta is vital to the health and economy of California, supplying drinking water for two-thirds of the California population and irrigating over 7 million acres of agricultural lands. In addition, the Delta is an important ecological resource that supports a diversity of fish and wildlife.

Several special status fish species (i.e., state and/or federally listed, proposed, or candidate species) utilize the Delta ecosystem during all, or portions, of their lifecycles including some that spawn and rear within the Delta, while others migrate through the Delta on their way to freshwater or marine spawning and rearing habitat (CALFED ERP 2000). Native resident fish, including Delta smelt and Sacramento splittail, spend most of their lives within the Delta while Chinook salmon (four races), steelhead, green sturgeon, white sturgeon, lamprey, striped bass, and American shad migrate through the Delta on their journey between the Pacific Ocean and Central Valley spawning rivers (CALFED ERP 2000).

While historic Delta environmental conditions are poorly understood, it is generally recognized that dramatic physical, chemical, and biological changes to the Delta have occurred since the arrival of European settlers and missionaries. These changes include, but are not limited to, the elimination of historic floodplain habitat resulting from levee construction, modification of flow regimes due to water management, degraded water quality attributable to pollution and water management, and native species displacement due to invasion of numerous exotic species (Yoshiyama et al. 1998; CALFED ERP 2000). Currently, the net effects of south Delta water

export operations, in conjunction with operations of other Delta facilities such as the Delta Cross Channel and Head of Old River Barrier, on fishery resources (particularly salmonids) are a source of significant debate.

Although salmonids use the Delta during both their upstream and downstream migrations, the migration of smolts from freshwater to the marine environment is considered to be a particularly critical period for the survival of salmon (Doubleday et al. 1979; Brown et al. 1982 as cited in Moore et al. 1995), and the timing of this movement has been suggested to be critical to the survival and return of adult fish (Larsson 1977; Cross and Piggins 1982; Hansen and Jonsson 1989 as cited in Moore et al. 1995).

According to CALFED (CALFED Strategic Plan 2000), scientific opinion varies regarding the suitability of habitat and extent of use of the Delta by rearing juvenile salmonids. Juvenile salmon emigrating from the Sacramento and San Joaquin basins pass through the Delta where they are subject to complex dynamics of river flows, tidal cycles, channel morphology, and the physiological transition from fresh to salt water. Juvenile mortality during this transition phase is believed to be significant, but actual mortality rates as well as the contribution of natural and anthropogenic components to mortality are unclear. In addition, the length of time that juvenile salmonids spend within the Delta is considered to be a double-edged sword relative to overall survival and fitness because greater time spent rearing in the area prior to ocean entry has both potential benefits and disadvantages; potential benefits leading to greater survival include an increased freshwater to saline transition phase and increased growth opportunities during the estuarine residence period, while potential disadvantages include an increased likelihood that fish will experience adverse conditions and reduced survival associated with Delta water management facilities.

Previously, there has been limited direct research conducted in the Delta regarding the effects of Delta water management operations on fish due to the difficulty associated with sampling and the types of sampling methods available. Most of our understanding regarding juvenile fish survival, distribution, migration, and habitat use within the Delta has come from anecdotal information or been inferred from monitoring projects using traditional sampling methods such as traps, seines, and trawls or fish salvage facilities at the Delta pumps. Based on available information from these sources, CALFED has identified freshwater inflow, water quality, water temperature, channel and flow hydraulics, and overall diversity of aquatic habitat, as the ecological factors having the greatest influence on Delta fish (CALFED ERP 2000). Additional information is needed about life history and species needs relative to habitat availability and environmental factors. The survival and growth of native fish and their linkage to the Delta ecosystem needs to be better understood to facilitate successful restoration actions and ensure the preservation of at-risk species.

Marks and tags are some of the most useful tools for fishery science and have a relatively long history. Marks and tags allow the identification of individual or groups of fish and are used for three general purposes (Guy et al. 1996): (1) labeling animals for specific handling, (2) identifying movement and migration patterns, and (3) collection of population statistics such as abundance, growth, and survival and harvest rates. Technology has been an important factor in the development of marks and tags and today there are many types to choose from, each with its own set of advantages and disadvantages. Generally, technical advances in mark and tag technology have been made to:

- Reduce the adverse effects associated with other marks or tags,
- Increase the number of unique codes available,
- Enable the marking or tagging of particular fish species or sizes (generally smaller),
- Reduce the costs of marking or tagging larger numbers of fish, and
- Increase the resolution of information obtained from marked or tagged fish.

Traditional tags and marks have greatly improved our knowledge of the relative distribution of different stocks and species in the freshwater, estuarine, and marine environments; however, these programs provided only glimpses of the environmental constraints that have shaped evolutionary biology of salmon and the environmental factors affecting their productivity (Welch 1997, as cited in National Marine Fisheries Service 1998). One of the major disadvantages to more traditional marks and tags relative to radio or acoustic tags is that individuals must be captured and handled at each mark and recapture event, which has the potential to adversely affect the survival, growth, or behavior of the captured individuals. In addition, no information is collected between the capture and recapture events. Any activities or experience with specific environmental conditions, or lack thereof, by marked or tagged individuals between mark and recapture events must be assumed or indirectly drawn from statistical correlations because the actual location of the fish between these events is imprecisely known. Improved knowledge of fish movements and habitat utilization during different life history stages is required to understand the role of the estuary and ocean on salmonid viability (National Research Council 1996).

Development of acoustic tags (or transmitters) for use with fish began in the late 1950s while radio tags, which were initially used for wildlife tracking, were used with fish beginning in the late 1960s (Winter 1996). The use of radio and acoustic tags is similar in many respects; each technique utilizes a transmitter attached to the fish, a hydrophone (acoustic) or antenna (radio) for signal detection, and a receiver for amplifying, filtering, and decoding signals. Tracking techniques are also similar: (1) tagged individuals within range of a remote station are logged with the time and code of the tags, (2) tagged individuals are followed continuously, generally from a boat, and (3) tagged individuals are located periodically from boats, airplanes (radio only), roadways (radio only), or on foot using various search strategies. Many tracking studies use a combination of these techniques. In addition to detecting fish location, radio and acoustic transmitters can be optionally outfitted with sensors to determine depth, temperature, light levels, or other parameters. The important feature that distinguishes radio or acoustic tags from traditional marks or tags is that the host fish is only captured and handled for tag attachment. After a tagged fish is released, the location of the fish can be ascertained numerous times or continuously without any additional captures or handling.

Until recently, most acoustic studies of salmon have been conducted with adults because tag sizes have been too large for smolts of most salmon species. A few studies were conducted during the late 1970s with relatively large Atlantic salmon smolts (Fried et al. 1978; Tytler et al. 1978; Thorpe et al. 1981) and the first smolt acoustic tracking study on Pacific salmon occurred in 1989 in Grays Harbor, Washington using Coho smolts that were 159 to 215 mm in length (Moser et al. 1991). Several radio and acoustic tracking studies on yearling or sub-yearling Pacific salmon or steelhead smolts have recently been conducted, or are in progress, at numerous Columbia River hydroelectric structures (USACE 2003; Timko et al. 2002; Steig 1999), the lower Columbia River and estuary (Shreck and Stahl 1996; McComas et al. 2001), the Columbia River plume (Welch 2003, personal communication), and Nehalem estuary (Clements and Schreck 2003). In combination, these recent studies suggest a groundswell of recent acoustic tracking activity for Pacific salmon smolts in the Pacific Northwest.

Nearly all yearling Chinook smolts found in the Delta are less than 200 mm and most are less than 150 mm (Brandes and McClain 2001). Recent advances in acoustic tag development have reduced tag sizes to less than 1 gram in water that can be used to track sub-yearling fish as small as 90 to 100 mm in size, but such tags have limited longevity (around 1 to 2 weeks) and are not suitable for use with remote hydrophone/receiver stations. However, these tags are suitable for short-term, continuous, mobile tracking studies that would allow tracking of small numbers of salmonid smolts. Slightly larger tags, approximately 2 grams in size, are available that last 2 to 4 weeks and are suitable for use with remote stations and larger numbers of fish near 150 mm in size. Based on limitations of battery technology, it is unlikely that transmitters will get much smaller in the foreseeable future. Overall, it appears that acoustic transmitters have become sufficiently small to conduct tracking studies on yearling and sub-yearling Chinook smolts in the Delta.

Attachment methods for transmitters include external placement, esophageal insertion, or surgical implantation procedures. There are advantages and disadvantages for each of these methods and choice depends on the type of tag, the species of interest, and the purpose of the research. External tagging is primarily used when handling large fish due to the fact that fish can easily and quickly be tagged without anesthetic. However, there is an increased opportunity for disease and loss of tags. External attachment is not recommended for salmonids. Esophageal insertion may be performed on either adults or juveniles; however, it is not recommended for medium to long-term studies of juveniles due to potential changes in feeding behavior (adults are not affected because they do not feed on their upstream migration). Esophageal insertion has several advantages including no need for surgery and associated anesthetic, reduced tag losses, and reduced changes in swimming behavior. Disadvantages include lower retention rates than surgical implantation due to increased regurgitation rates as a result of the nature of the procedure and altered behavior patterns. The disadvantages associated with external and esophageal insertion methods and the limited adverse affects associated with surgical implantation have led to surgical implantation becoming the preferred method for tagging juvenile salmonids. Anesthetics (clove oil or MS-222) should be used during tag attachment to smolts, but may be optional for adults.

There are four primary acoustic equipment manufacturers in North America: Lotek Wireless, Vemco, Sonotronics, and Hydroacoustic Technology, Inc. (HTI). With the exception of HTI, who has developed a niche product for work around structures such as dams, these manufacturers are highly competitive and are all active in research and development of acoustic technology. Each of the manufacturers produces slightly different equipment that is generally incompatible with equipment from other manufacturers. Recent innovations by manufacturers include reduced transmitter size, wireless remote hydrophone/receiver stations, tracking of fish within defined areas using simultaneous transmitter detections from multiple remote stations (including 3-D tracking), and code division multiple access (CDMA) transmitter coding, which increases the number of individual codes that can be detected on a single frequency. Choice of manufacturer for a particular study can be difficult because many factors can be involved including the average size of fish to be tracked (i.e., smallest available tag size), the number of fish to be released, the type of tracking to be performed (i.e., mobile, remote stations, near structures), the need for other sensors in the transmitter, compatibility with other studies in the area of concern, and of course, cost.

The field components of an acoustic tracking study include:

- Capture and selection of host fish,
- Transportation of experimental fish to release site,
- Transmitter attachment,
- Recovery from handling and transmitter attachment, and
- Release and tracking of tagged fish.

As in all types of fisheries monitoring studies where fish are captured, tagged, and released, researchers using acoustic technology typically assume that tagged fish behavior and physiological responses are not affected by the tag or tagging procedure. However, all types of fish tagging programs that involve procedures associated with capture, handling, and tagging have the potential to negatively affect the health and behavior of fish being studied.

Factors that can influence the behavior of acoustically tagged fish include: the species, size, and lifestage of fish tagged; capture and handling methods; the location of the tag and attachment methods; the size, shape, and weight of the tag; the environmental conditions at the time of tagging; and the skill of the people applying the tags. The effect of capture, handling, and tagging on tagged fish can include damage to tissue, increased mortality (Nettles et al. 1983; Knights and Lasee 1996), decreased swimming mobility (McCleave and Stred 1975; Arnold and Holford 1978), reduced growth (Wrenn and Hackney 1979; Greenstreet and Morgan 1989), changes in social interaction, and tag expulsion (Moore et al. 1990; Chisholm and Hubert 1985; Marty and Summerfelt 1986; Jepsen et al. 2001). Scientists occasionally develop specific studies, often using dummy (or sham) transmitters that have a similar size and weight as real transmitters, to evaluate the hypothesis that tagged fish behave the same as untagged fish.

The following are conclusions and recommendations based upon the results of this white paper:

- Acoustic tagging studies can provide high-resolution data for better understanding the migratory behavior, survival, and habitat use of adult and juvenile salmon, as well as other fish species, in the Sacramento-San Joaquin Delta.
- New developments in acoustic tag miniaturization have produced transmitters sufficiently small to tag and detect fish as small as 90 to 100 mm, including sub-yearling Chinook salmon.
- Acoustic 3-D technology may be effective for examining smolt behavior near the Delta Cross Channel or South Delta pumping stations.
- Paired releases of acoustically tagged smolts may be an effective method for determining relative survival of smolts from the Sacramento River that utilize the Delta Cross Channel.
- A dummy tag experiment should be performed to examine the effects of different transmitter sizes and attachment methods on any special status fish species acoustically tagged in the Delta where limited data regarding tag attachment effects exists.
- A tracking experiment should be performed to observe differences in residence times and behavior between juvenile hatchery and wild fish migrating through the Delta.
- Fixed hydrophone arrays can be used to examine the travel routes and migration rates of adult and juvenile salmon through the Delta.
- Various combinations of continuous mobile tracking, mobile tracking with search strategies, and/or remote hydrophone/receiver arrays should be considered depending upon the specific goals of a study.
- A network of remote wireless hydrophone/receiver stations can be established to track multiple fish species within Central Valley tributaries, the Delta, and San Francisco Bay, as well as the coastal ocean.
- A biotelemetry workgroup for the region is crucial for coordinating biotelemetry studies, developing standardized fish tagging and handling protocols, and sharing results and experience gained from various studies; and may provide opportunities for developing coordinated research studies using shared equipment that would reduce costs and increase the overall coverage of areas being monitored.

1. PURPOSE AND BACKGROUND

Pacific salmonids have experienced dramatic declines in abundance during the past several decades (National Marine Fisheries Service 2000). Since 1991, the National Marine Fisheries Service has listed over 20 Evolutionarily Significant Units (ESUs) of West Coast salmon and steelhead as endangered or threatened species under the Endangered Species Act (ESA; National Marine Fisheries Service 1999). Given the complexity of salmonid life histories and the ecosystems where they reside, it is difficult to determine the contribution of any single factor on salmonid declines with precision (National Marine Fisheries Service 2000). Factors that confound our ability to identify causes for decline include high intra- and interannual variation in freshwater flows, operation of water management facilities (e.g., dams, diversions, and weirs), habitat degradation, hatchery practices, climate variability, and ocean conditions (National Research Council 1996). Human actions that depress population abundance have also caused salmonids to be more susceptible to natural environmental fluctuations such as poor ocean conditions and drought (National Marine Fisheries Service 1999). If declines in salmonid populations are to be reversed, it is critical that comprehensive, focused recovery efforts are implemented and accurate information regarding fish populations is needed. Conservation and restoration of fish species, particularly those with an anadromous life history, requires knowledge of their distribution, migratory patterns, habitat usage, and responses to environmental and anthropogenic variables throughout their entire lifecycle.

One of the most difficult water resource management problems facing California is maintaining the quality and reliability of water supplies while restoring the San Francisco Bay/Sacramento-San Joaquin Delta (Delta) ecosystem. Understanding the biology and behavior of fish species that live or migrate through the Delta is important for developing management policies that balance the needs of the many stakeholders concerned about Delta resources. The objective of this paper is to present information regarding current state-of-the-art acoustic tracking technology and potential applications of acoustic techniques for salmonid research within the Delta. This paper is designed to assist CUWA in determining whether recent acoustic telemetry advancements can provide new research opportunities to better understand the effects of water resource management in the Delta on special status species within the Central Valley, particularly Chinook salmon.

Due to the widespread use of historic and current acoustic tracking for investigating salmonid issues elsewhere, and the high priority placed on salmonid research within the Delta, this paper primarily presents information pertaining to these fish. However, acoustic technology can be applied to other species as long as they are sufficiently large to accommodate available acoustic tags during at least a portion of their lifecycle. In the Delta, this would include all special status species identified in the next section.

While there are many approaches to understanding the migratory behavior of anadromous fish as they travel between their freshwater and oceanic residences, recent advances in acoustic tracking technology have created systems that are powerful tools for investigating anadromous fishery resources due to their ability to collect information unavailable using other methods. The biggest advantage of acoustic tracking systems is their ability to track individual fish through both freshwater and saline environments, a factor which makes acoustic technology particularly suitable for addressing the hypotheses regarding salmonid populations being discussed by Central Valley scientists.

This paper documents the current status of Delta issues (Section 1); an introduction to acoustic fish tracking systems with a comparison to traditional tagging and marking techniques for fisheries research (Section 2); a detailed discussion of acoustic tracking system components including transmitters (tags), hydrophones, receivers, and data-recording systems (Section 3); a summary of products by major acoustic equipment manufacturers in North America (Section 4); a discussion of the application of acoustic tracking and potential adverse effects to fish health and behavior (Section 5); a summary of recent applications of acoustic technology related primarily to salmon (Section 6); and an overall discussion and conclusions (Section 7).

Background

The Delta is the largest estuary on the Pacific Coast. Draining to the northeast end of San Francisco Bay, it consists of a maze of tributaries, sloughs, and islands that includes over 738,000 acres in five counties, and supports over 750 plant and animal species (Figure 1). The Delta is fed by the Sacramento and San Joaquin rivers and their tributaries: the American, Feather, Mokelumne, Calaveras, Stanislaus, Tuolumne, and Merced rivers (Figure 2). In addition to being an important ecological resource, the Delta is vital to the health and economy of California, supplying drinking water for two-thirds of the California population and irrigating over 7 million acres of agricultural lands. These human water needs are met by California's two largest water distribution systems located within the south Delta: the Bureau of Reclamation's Central Valley Project (CVP) Tracy Export Facility and the Department of Water Resource's State Water Project (SWP) Banks Export Facility. Together, the CVP and SWP export facilities

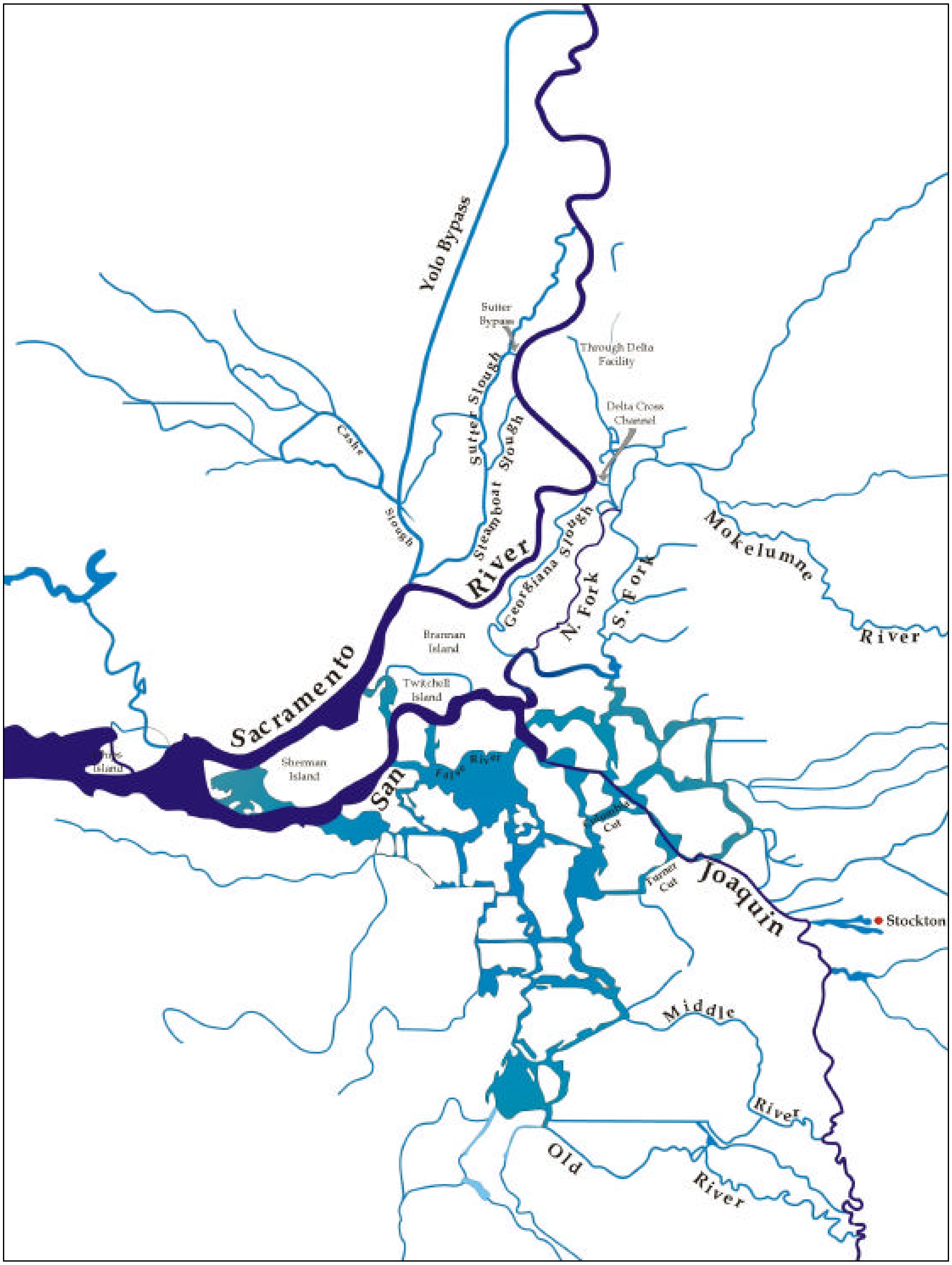

Figure 1. Sacramento-San Joaquin Delta. Source: Anadromous Fish Restoration Program USFWS and BOR, www.delta.dfq.ca.gov/afrp/watersheds.asp

Figure 2. Sacramento and San Joaquin River Systems.

can divert between 20 to 70 percent of the natural flow within the system, which has substantially changed ecosystem functions within the Delta and has led to the Delta becoming the epicenter of California water resource management issues.

In recent years, several factors have affected the ability of the CVP and SWP to meet their water quality and supply reliability objectives, such as droughts (e.g., 1987-1992); ongoing policy conflicts among stakeholders about water quality and supply, and fishery protection requirements, particularly for anadromous salmonids and Delta smelt populations. The effects of these factors on meeting water needs contributed to the recognition by agricultural, environmental, and urban stakeholders that a large-scale, cooperative management approach was necessary to manage multiple resources within the Delta. In response, state and federal agencies, working with these stakeholders, reached an agreement (known as the Bay-Delta Accord) on water quality standards and related provisions that would remain in effect for three years. During this period, while long-term solutions to problems in the Bay-Delta Estuary related to fish and wildlife, water supply reliability, natural disasters, and water quality were investigated through the CALFED-Bay Delta Program (CALFED Program). The Bay-Delta Accord was extended for several years while the CALFED Program developed “a long-term plan to restore ecosystem health and improve water management for beneficial uses of the Bay-Delta system” and completed a comprehensive programmatic environmental review process on August 28, 2000 under the National Environmental Policy Act and California Environmental Quality Act (CALFED 2000). As part of this process, considerable effort has been directed at identifying, documenting, and resolving the many complex issues surrounding resource management, particularly identifying stressors and restoration needs for special status fish populations and their habitat within the Delta and associated river systems. Unfortunately, even though unprecedented effort has been expended, resource managers still know little about the Delta’s contribution to promoting successful production of many fish resources.

In addition to the Delta serving as the hub for the largest water conveyance system in California, several special status fish species (i.e., state and/or federally listed, proposed, or candidate species; Table 1) utilize the Delta ecosystem during all, or portions, of their lifecycles including some that spawn and rear within the Delta, while others migrate through the Delta on their way to freshwater or marine spawning and rearing habitat (CALFED ERP 2000). Native resident fish including Delta smelt and Sacramento splittail spend most of their lives within the Delta while Chinook salmon (four races), steelhead, green sturgeon, white sturgeon, lamprey, striped bass, and American shad migrate through the Delta on their journey between the Pacific Ocean and Central Valley spawning rivers (CALFED ERP 2000). Although salmonids use the Delta primarily during their upstream and downstream migrations, the migration of smolts from fresh water to the marine environment is considered to be a particularly critical period for the survival of salmon (Doubleday et al. 1979; Brown et al. 1982 as cited in Moore et al. 1995), and the timing of this movement has been suggested to be critical to the survival and return as adult fish (Larsson 1977; Cross and Piggins 1982; Hansen and Jonsson 1989 as cited in Moore et al. 1995).

Table 1. Federal and State Listed Fish Species that Utilize the Delta During All, or a Portion of, their Life Cycle.

Species	**Status**
Sacramento River winter-run Chinook salmon	Federal and State endangered species
Central Valley spring-run Chinook salmon	Federal and State threatened species
Central Valley fall/late fall-run Chinook salmon	Federal candidate species
Central Valley steelhead	Federal threatened species; State species of concern
Delta smelt	Federal and State threatened species
Longfin smelt	Federal and State species of concern
Sacramento splittail	Federal threatened species; State species of concern
Pacific lamprey	Federal species of concern
River lamprey	Federal and State species of concern
Green sturgeon	Federal and State species of concern

Historic Delta environmental conditions and juvenile salmonid residence periods are poorly understood, but it is generally recognized that dramatic physical, chemical, and biological changes to the Delta have occurred since the arrival of European settlers and missionaries. These changes include, but are not limited to, the elimination of historic floodplain habitat resulting from levee construction, modification of flow regimes due to water management, degraded water quality attributable to pollution, and native species displacement due to invasion of numerous exotic species (Yoshiyama et al. 1998). The net effects of south Delta water export operations, in conjunction with operations of other Delta facilities such as the Delta Cross Channel and Head of Old River Barrier, on fishery resources are a source of significant debate. According to CALFED (CALFED Strategic Plan 2000), scientific opinion varies regarding the suitability of habitat and extent of use of the Delta by rearing juvenile salmonids. Juvenile salmon emigrating from the Sacramento and San Joaquin basins pass through the Delta where they are subject to complex dynamics of river flows, tidal cycles, channel morphology, and the physiological transition from fresh to salt water. Juvenile mortality during this transition phase is believed to be significant, but actual mortality rates as well as the contribution of natural and anthropogenic components to mortality are unclear.

The length of time that juvenile salmonids spend within the Delta is considered to be a double-edged sword relative to overall survival and fitness since greater time spent rearing in the area prior to ocean entry has both potential benefits and disadvantages; potential benefits leading to greater survival include an increased freshwater to saline transition phase and increased growth opportunities during the estuarine residence period, while potential disadvantages include an increased likelihood that fish will experience adverse conditions and reduced survival associated with Delta water management facilities. Healey (1982) noted substantial growth (e.g., 3.5 to 5.5 percent per day) of Chinook juveniles during estuarine residence in British Columbia, but also indicated that estuarine use could be highly variable among different salmon species and populations. He identified three criteria for evaluating the importance of an estuary: (1) the existence of alternate nursery habitats; (2) the proportion of the population that utilizes alternate habitats as opposed to estuarine habitats; and (3) the length of residence in estuarine habitats. The historic estuarine residence period of salmonids in the Delta is unknown, but recent studies suggest juvenile fall Chinook from the San Joaquin River migrate through the Delta in a median time of 11 days, but may take as long as 26 days (Baker and Morhardt 2001).

Juvenile salmonids that rear for extended periods within the Delta would increase their chances of experiencing adverse effects, as opposed to those migrating quickly through the Delta. Actual entrainment rates at the CVP and SWP export facilities are relatively low, but export facility and Delta Cross Channel operations may cause indirect mortality of juvenile salmon migrants as a result of effects on water flow, fish movement, and productivity patterns in the delta. The extent that these indirect and “other sources of Delta mortality affect fish populations has a bearing upon the relative importance of entrainment in the SWP and CVP pumps as a source of mortality” (CALFED Strategic Plan 2000). Juvenile Chinook directed into the central and south Delta due to water management operations are considered to experience higher mortality through reversed flow conditions, increased predation opportunities, reduced shallow water habitat for fry, higher water temperatures, salinity changes, and reduced river inflow during the spring, which decreases available nutrients, turbidity, and transport flows for migration.

Limited direct research has been conducted in the Delta regarding the effects of Delta water management operations on fish due to the difficulty associated with sampling and the types of sampling methods available. Most of our understanding regarding juvenile fish survival, distribution, migration, and habitat use within the Delta has come from anecdotal information or been inferred from monitoring projects using traditional sampling methods such as traps, seines, and trawls or fish salvage facilities at the Delta pumps. Based on available information from these sources, CALFED has identified freshwater inflow, water quality, water temperature, channel and flow hydraulics, and overall diversity of aquatic habitat, as the ecological factors having the greatest influence on Delta fish (CALFED ERP 2000). Additional information is needed about life history and species needs relative to habitat availability and environmental factors. The survival and growth of native fish and their linkage to the Delta ecosystem needs to be better understood to facilitate successful restoration actions and ensure the preservation of at-risk species. CALFED identified specific objectives to address questions regarding Delta effects on salmonids that include:

1) Clarifying the extent to which entrainment at the CVP and SWP pumping plants affects the population sizes, and
2) Clarifying the suitability and use of the Delta for rearing by juvenile salmon and steelhead (CALFED ERP 2000).

Scientists have also developed eight hypotheses specific to the effects of the Delta Cross Channel to fish, flows, and water quality (CALFED Bay-Delta Program 2001). Seven of the hypotheses are concerned with different behavioral aspects of adult or juvenile salmon migration and how they react to different ways of operating the Delta Cross Channel. These include a better understanding of when fish migrate (e.g., night or day, ebb or flood tidal flows), where they migrate (e.g., left bank or right bank, in the mainstem or through the cross channel), and migration speeds (e.g., quicker with tidal operation or with fully closed cross channel gates).

It is notable that many of the questions and hypotheses concerning juvenile and adult salmonid use of the Delta can be answered through a detailed understanding of the movements of individual fish. The questions being asked have relatively short time scales (e.g., hours to several weeks) and variable spatial scales that range from a few hundred meters to tens of kilometers. These are questions for which fish tracking studies are particularly suited because of the amount and type of detailed information that can be acquired from each study subject. Traditional sampling methods can provide important information, but falls short in many aspects.

2. INTRODUCTION TO ACOUSTIC FISH TRACKING SYSTEMS

This section provides an introduction to the development of acoustic tagging equipment and fish tracking methods. It includes a short history and discussion of traditional marks and tags to provide a context for the applicability of acoustic tracking.

Fish Marks and Tags

Marks and tags are some of the most useful tools for fishery science and have a relatively long history. Marks and tags allow the identification of individuals or groups and are used for three general purposes (Guy et al. 1996): (1) labeling animals for specific handling, (2) identifying movement and migration patterns, and (3) collection of population statistics such as abundance, growth, and survival and harvest rates. Although technological advances in recent decades have greatly expanded the variety of marks and tags available to the scientist, the idea of marking animals is anything but new. Because historical records are scarce, it is uncertain when fisheries managers first began applying marks to fish, and for what purpose. In 1653, Izaak Walton wrote in *The Compleat Angler* that private individuals marked Atlantic salmon with ribbons tied around their tail to demonstrate that salmon returned from sea to their natal rivers. The first recorded organized marking program for the purpose of research appears to have occurred on two occasions between 1851-1865 and 1870-1873, by the Experimental Committee of Tweed Commissioners (Delany 1978). The Commission marked Atlantic salmon (*Salmon Salar*) with wire to the tails and jaws, clipping fins, and attaching numbers to tails and opercles.

Technology has been an important factor in the development of marks and tags and today there are many types to choose from, each with its own set of advantages and disadvantages (Table 2). Generally, advances in mark and tag technology have occurred to:

- Reduce the adverse effects associated with other marks or tags,
- Increase the number of unique codes available,
- Enable the marking or tagging of particular fish species or sizes (generally smaller),
- Reduce the costs of marking or tagging larger numbers of fish, and
- Increase the resolution of information obtained from marked or tagged fish.

Due to the limited nature of the marks, early studies were primarily useful only to evaluate movements and identify stocks (McFarlane et al. 1990). As marking methods improved and research efforts evolved, marking studies provided additional detail, and beginning in the 1930s mark-recapture programs were used to estimate population size and mortality rates (Ricker 1956).

Table 2. Comparison of Marks and Tags including Mark or Tag Type, Information/Study Type, Groups or Individuals, Tag Recovery Handling, Smallest Organism Tagged, Advantages and Disadvantages.

	Information/ Study Type									
Mark or Tag Type	**Group History**[1]	**Population Abundance**	**Population Statistics**	**Migration Behavior**	**Groups**	**Individuals**	**Tag Recovery Handling**[2]	**Smallest Organism Size**[3]	**Advantages**	**Disadvantages**
Fin Clip, Fin Punch	**X**	**X**	**X**		**X**		**R**	**S**	Many fish can be marked with low level of effort.	Limited number of marks possible. Often difficult to distinguish after long period due to regrowth of clipped body part. May adversely affect swimming performance.
Brands/Pigment marks	**X**	**X**	**X**		**X**		**R; N**	**VS**	Many fish can be marked with low level of effort. Low mortality rate from tagging. Some marks can be distinguished with minimal handling of recaptured fish or via snorkeling or scuba.	Limited number of marks possible. Some marks types not visible for several days after marking. Marks eventually disappear.
Natural marks (parasites, morphometrics, meristics)	**X**		**X**		**X**	**X**	**S; R**	**VS**	Non-intrusive.	Often difficult to distinguish marks.
Otolith/Scale mark	**X**		**X**		**X**		**S; R**	**S**	Non-intrusive. High numbers of fish can be marked with low effort.	May need to sacrifice individual to recover tag. Specialized equipment and training needed to read tag.
Anchor tags		**X**	**X**	**X**	**X**	**X**	**R**	**S**	Tags relatively easy to attach. Tagged groups easy to distinguish visually.	Tag loss can be high.

Mark or Tag Type	Information/ Study Type: Group History[1]	Population Abundance	Population Statistics	Migration Behavior	Groups	Individuals	Tag Recovery Handling[2]	Smallest Organism Size[3]	Advantages	Disadvantages
Visible Implant tag		X	X	X	X	X	R	S	Tags are unobtrusive.	Variable retention. Mark needed to alert surveyor to presence of tag.
Transbody tag (Petersen Disc/Spaghetti)		X	X	X	X	X	R	S; M	Long retention.	Susceptible to snagging. Lengthy application time.
Coded Wire tag	X		X	X	X		S	VS	Long retention.	Individual must be sacrificed to recover tag. Mark needed to alert surveyor to presence of tag. Specialized equipment needed to recover and read tag. Specialized equipment needed to tag large numbers of fish.
Passive Integrated Transponder tag			X	X		X	R; N	VS	Individual codes can be recovered from live fish with minimal to no handling.	Individuals must be within range (less than 18 cm) of detection system.
Radio tag (position only)				X		X	N	S	Individuals can be located repeatedly without additional handling. Remote detection (airplanes, vehicles, etc.) possible because signals pass easily through air.	Signal attenuates with depth and salinity.

Mark or Tag Type	Information/ Study Type: Group History[1]	Population Abundance	Population Statistics	Migration Behavior	Groups	Individuals	Tag Recovery Handling[2]	Smallest Organism Size[3]	Advantages	Disadvantages
Acoustic tag (position only)				**X**		**X**	**N**	**S**	Individuals can be located repeatedly without additional handling. Signals can be transmitted through fresh and salt water.	Noise and air reduce signal detection. Requires in-water detection system (hydrophone). Signal bent at thermoclines.
Combined Acoustic and Radio tag/Position Plus tag[4]				**X**		**X**	**N**	**L**	Individuals can be located repeatedly without additional handling. CART tags combine the advantages of acoustic and radio tags.	Transmitters are large.
Archival tag				**X**		**X**	**R; S**	**L**	Allows collection of a variety of environmental data.	Transmitters are large. Tag must be recovered to collect data, which may include sacrifice of the individual.

1. Group History could include information such as stock source, specific group experimental manipulations; survey specific information, etc.

2. R = Recapture; S = Sacrifice; N = No Handling Needed.

3. VS = Very Small; S = Small; M = Medium; L = Large; VL = Very Large

4. A "Position Plus" also collects physical data such as depth, temperature, light, etc., or other biological data.

Most large-scale marking programs recognized by fisheries managers today have developed since 1945 (McFarlane et al. 1990). Between the mid-1940s through the 1960s fin clipping was the standard marking method for stock identification. In the 1970s, coded wire tags (CWT) were developed (Johnson 1990). CWTs are small and inexpensive to make, allow thousands of different codes, and are relatively easy to apply to a variety of fish species, including relatively small fish. The major disadvantage to CWTs is that the subject fish must be sacrificed to recover the tag and read its code. Consequently, it is well suited for many salmon studies where adult fish will be harvested, return to hatcheries, or will die following spawning. Currently, over 50 federal, provincial, state, Indian, and private entities release over 40 million salmonids with CWTs annually (Johnson 1990). The importance and magnitude of tagging programs to salmon and trout management have made salmonids the focus of many developments in tagging technology, such as the CWT (Bergman et al. 1968), the passive integrated transponder (PIT) tag (Prentice et al. 1990a), and the visible implant tag (Blankenship and Tipping 1993; Bonneau et al. 1995).

Traditional tags and marks have greatly improved our knowledge of the relative distribution of different stocks and species in the freshwater, estuarine, and marine environments; however, these programs provided only glimpses of the environmental constraints that have shaped evolutionary biology of salmon and the environmental factors affecting their productivity (Welch 1997; In National Marine Fisheries Service 1998). One of the major disadvantages to more traditional marks and tags relative to radio or acoustic tags is that individuals must be captured and handled at each mark and recapture event, which have a potential to adversely affect the survival, growth, or behavior of the captured individuals. In addition, no information is collected between the capture and recapture events. Any activities or experience with specific environmental conditions (or lack thereof) by marked or tagged individuals between mark and recapture events must be assumed or indirectly drawn from statistical correlations because the actual location of the fish between these events is imprecisely known.

Because fish are difficult to visually observe in the wild, biotelemetry provides researchers a unique and powerful tool to gather information on fish movements, activity, behavior, and habitat use that would otherwise be unattainable (Perry et al. 2001; Conners et al. 2002). Biotelemetry can fill in important details about the relationship of stock distribution and movement with oceanographic or other environmental factors on different time and space scales (National Marine Fisheries Service 1998). Although considerable research has been done on the habitat preferences of salmonids in freshwater systems, assessment of the importance of estuarine and ocean habitats on survival are largely inferred from catch and model data (Healy et al. 1990; Thomson et al. 1994; Welch et al. 1995; Beamish 1995) and the effects of estuarine and ocean environmental conditions on salmonid survival remains poorly known. Improved knowledge of fish movements and habitat utilization during different life history stages is required to understand the role of the estuary and ocean on salmonid viability (National Research Council 1996).

Development of acoustic tags (or transmitters) for use with fish began in the late 1950s while radio tags, which were initially used for wildlife tracking, were used with fish beginning in the late 1960s (Winter 1996). Use of radio and sonic tags is similar in many respects; each technique utilizes a transmitter attached to the fish, a hydrophone (acoustics) or antenna (radio) for signal detection, and a receiver for amplifying, filtering, and decoding signals. Many receivers currently available also allow for recording of information related to tag detection that can be downloaded to a computer. Tracking techniques are also similar: (1) tagged individuals within range of a remote station are logged with the time and code of tag; (2) tagged individuals are followed continuously, generally from a boat; (3) tagged individuals are located periodically from boats, airplanes (radio only), roadways (radio only), or on foot using various search strategies. Many tracking studies use a combination of these techniques. In addition to sensing location, radio and acoustic transmitters can be optionally outfitted with sensors to determine depth, temperature, light levels, or other parameters. The important feature that distinguishes radio or acoustic tags from traditional marks or tags is that the fish is only captured and handled for tag attachment. After a tagged fish is released, the location of the fish can be ascertained numerous times or continuously without any additional captures or handling.

Winter (2000, based upon White and Garrott 1990) describes three types of tracking studies: descriptive, correlational, and manipulative. Descriptive studies merely describe the behavior of the tracked animals without attempting to demonstrate causative factors for that activity. Correlational studies attempt to determine why certain behaviors occur by the collection of environmental or other data that are presumed to provide cues and then correlating this data to observed behavior. Manipulative studies have a more traditional experimental approach that changes one or more factors and observes changes in behavior to test hypotheses. Winter (2000) recommends that descriptive studies be avoided except when little is known about a species and very basic biological information is needed. Most tracking studies investigating specific environmental resource management issues are correlational, but some attempt to manipulate specific factors of concern.

Acoustic tags were first developed for use in fisheries research because their low-frequency, long-wave acoustic signals travel well through water and are not substantially affected by conductivity, which allows them to be effective in estuarine and ocean environments (Murphy et al. 1996). In contrast, even relatively low conductivity levels and increasing depth attenuate radio signals. Consequently, radio tags are poorly suited for estuarine or ocean studies but have characteristics suitable for many shallow freshwater studies. This distinguishing characteristic makes acoustics the tag of choice for tracking studies in the Delta. Klimley and others (1998), O'Dor and Weber (1998), and Moore and others (1999) provide a thorough review of the advantages and disadvantages of different telemetry systems in marine environments.

The first acoustic tags were relatively large and therefore only large fish could be studied with this technique. One of the earliest attempts to use acoustic telemetry to track salmonids was in 1956 by the National Marine Fisheries Service (Trefethen 1956) with adult Chinook and Coho salmon. In 1957, similar studies were performed in the Columbia River Basin on upstream migrating steelhead, Coho, and Chinook salmon (Johnson 1960). Hallock, beginning in 1964, used the same equipment to evaluate adult fall-run Chinook salmon movements in the Sacramento-San Joaquin Delta and San Joaquin River (Hallock et al. 1970).

In the early 1960s, the development of smaller acoustic tags for tracking smaller fish was initiated at the University of Wisconsin (Hasler and Henderson 1963; Henderson et al. 1966, in Stasko et al. 1977). At that time, tags became small enough to track other ocean and estuarine species, but were still not small enough to use on most juvenile salmonids. Biotelemetry technology was advancing fast enough that by 1975 there were over 147 underwater biotelemetry (i.e., acoustic and radio tracking) publications and reports with 163 authors representing an estimated 56 research teams in seven countries (Stasko 1975). A total of 59 species were represented in published research, including 40 fishes, 10 mammals, 4 reptiles, and 5 invertebrates (Stasko and Pincock 1977).

Beginning in the 1980s, advances in acoustic technology including increased miniaturization of tags allowed researchers to begin tracking Atlantic salmonid smolts in the range of 300 mm. Although this allowed researchers to evaluate smolts for some salmon stocks, tags were still too large for widespread research applications with salmonids. Juvenile studies were conducted primarily on Atlantic salmon smolts because they are typically larger at outmigration than Pacific coast salmon. However, one study was conducted on relatively large (159 to 215 mm) Coho smolts in Grays Harbor, Washington, during the late 1980s (Moser et al. 1991).

Over the last decade, acoustic transmitters have gradually decreased in size such that fish as small as 90 to 100 mm can be tagged. The steady pace of electronic miniaturization has contributed to this decrease, but further miniaturization is primarily limited by battery size (the largest component to the transmitter), while waterproof packaging and other components also contribute to overall transmitter size. Substantial future decreases in transmitter size will likely require major advances in battery technology.

3. ACOUSTIC TRACKING COMPONENTS

As mentioned earlier, an acoustic tracking system consists of several components that function in unison to identify and track individual fish locations. Acoustic tracking is generally used in saline or semi-saline conditions where radio signals cannot be transmitted. Any acoustic tracking system, whether simple or complex, consists of three primary components: (1) a transmitter (also known as, acoustic transmitters, ultrasonic transmitters, acoustic tags, sonic tags, or pingers), (2) a hydrophone, and (3) a receiver (Figure 3). In addition, an automatic data-recorder is often integrated into the tracking system; however, manual data-recording options are available. The following discusses each of these components in more detail.

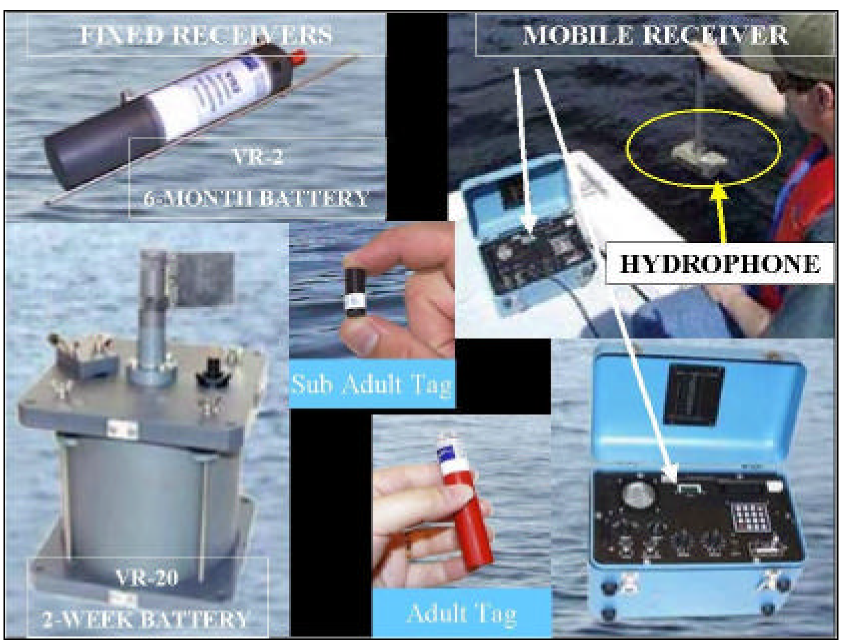

Figure 3. Typical Acoustic Tracking Equipment and Transmitters.
(Source: Vemco at http://www.vemco.com)

Transmitters

In general, an acoustic transmitter is attached to an individual fish and emits a detectible acoustic signal (i.e., sound wave) that is detected by either a stationary or mobile hydrophone with an associated receiver and is translated into an identification code. The individual code is recognized each time the transmitter is detected by the monitoring receiver, and, depending on the type of receiver, will either be recorded automatically into a data-recorder with a date and time stamp, or manually recorded by an investigator if manual tracking.

Transmitters, or tags, consist of four primary components: (1) transducer and amplifier, (2) battery, (3) electronics, and (4) some type of encapsulation coating (Stasko et al. 1977). Acoustic tags vary from company to company and are unique based upon their research application and performance capabilities. Performance between each manufacturer's tags is generally based upon the overall capabilities of the entire system.

The steady pace of electronic miniaturization has contributed to a steady decrease in the size of tags, but further miniaturization is probably limited by battery size, although waterproof packaging and other components contribute somewhat. Currently the smallest tag is only 0.5 g, but it has a short operational life of only 8 days and is not a crystal controlled tag, which means there will be frequency and pulse interval drift. Although the size is suited for tracking juvenile Chinook and other small fish, it is not conducive to fixed station tracking or tracking more than a few individuals. Two companies manufacture crystal-controlled tags that weigh 0.75 g and are suited for both manual and fixed station tracking, and larger numbers of individuals can be tracked simultaneously. Tags can range up to 39 g and last over 5 years.

Transmitter Operational Life, Frequency, Detection Range, and Pulse Interval

Tag lifetimes are a primary consideration when planning a study and can range from only a few days up to 5 years (depending on the size of the fish which, in turn, dictates the size of the tag and battery). Operational life is influenced by the tag's frequency, detection range, and pulse interval in relation to its size.

Acoustic tags emit pressure waves at ultrasonic frequencies that range from 20-300 kHz (although new tags under development are planned to operate at 400 kHz). As the tag frequency increases for a given size tag, the detection range decreases but tag operational life increases. For example, a 1.8-g tag at 76 KHz would have a 400-m detection range and maximum operational life of 20 days, but at 200 KHz would have a 150-m detection range and maximum operational life of 40 days. The pulse interval (i.e., the time spaced between each tag signal) can be increased to lengthen tag life or reduced to enhance detection rate. Long pulse intervals (e.g., 20 to 40 sec) decrease the chance that the tag's signal will be detected by the hydrophone, particularly at a stationary unit where fish are likely moving within detection range for only a brief period; however, long intervals can double the operational life of the tag. Additional stationary hydrophones may be used in order to compensate for the reduction in tag detection rate. The number of hydrophones required is dependant upon the anticipated speed a fish will pass through the hydrophone detection area with adult fish and actively migrating juveniles requiring a larger detection area versus juvenile fish rearing within a stream reach. The pulse interval can be adjusted in order to maximize tag life and still maintain a reasonable tag detection area.

Types of Transmitter Configurations

There are several types of coding methods designed to identify individual fish including pulsed tags, encoded acoustic signal transmitters, and CDMA coded transmitters. Factors to consider when deciding which transmitter is appropriate for the desired research include determining: (1) the maximum size of tag that can be used, which depends on fish size, (2) size of detection area, (3) type of telemetry monitoring system (manual, stationary, or both) that would best suit study plan requirements, (4) pulse rate of signals required to detect passing fish which depends on the expected fish speed past hydrophones and receivers, and (5) duration that individual fish need to be tracked to accomplish the study objectives (days, weeks, months, years).

(a) Pulsed tags

Conventional acoustic telemetry uses pulse-position coding and is generally available from all acoustic telemetry companies. This form of signal transmission embeds data (e.g., identification code and sensor information) within time intervals of a series of sonic pulses (Niezgoda et al. 2002). Basic acoustic tags can be identified by and can transmit data based on the pulse length ("on" time), pulse rate (number of pulses per minute), and pulse interval (time between pulses) (Murphy et al. 1996). The conventional system requires multiple tracking frequencies (e.g., usually 10 tags per frequency) be used when monitoring large numbers of tags which increases the receiver scan times and limits each tag's chance of detection. This condition limits the number of tags tracked at one time to a maximum of 256 tags. In addition, the need for high signal to noise ratios (e.g., generally 10:1) reduces reliable detections and hydrophone ranges.

Code collisions (i.e., overlap of acoustic signals when more than one tagged fish is near a hydrophone at one time) make hydrophones incapable of logging tags when multiple fish are within range and is the main factor limiting the number of tagged fish in an area. Small study areas further reduce the number of tags allowed in an area, because fish have a higher chance of interaction near hydrophones.

(b) Coded tags

Coded acoustic tags operate by transmitting a digitally encoded acoustic signal at specified intervals which results in numerous (over 200 to several thousand; number varies according to manufacturer) unique signals for individual frequencies. These tags utilize hundreds of unique aural codes which make each tag self-identifying; for example, “code 249 sounds 2 pulses, rest, 4 pulses, rest, 9 pulses, rest, and repeats” (Sonotronics 2003). Coded tags are useful for monitoring fish passage in marine and freshwater (Lacroix and McCurdy 1996; Voegeli et al. 1998). Coded tags offer the advantage that many individual fish can be tracked separately on a single frequency and that the information can be automatically recorded and downloaded to a PC. Coded tags increase the size of the sampling population that can be studied in a given area and increase data acquisition rates.

(c) CDMA coded tags

One of the acoustic tag manufacturers (Lotek Wireless, Inc.) have incorporated Code Division Multiple Access (CDMA) signaling to their acoustic tracking systems. In the past, CDMA technology was used to enhance GPS positioning and allow for high numbers of users in cellular communications (Dixon 1994). CDMA acoustics, or multiple access positioning (MAP) systems, are able to have high discrimination between each code. This means that what would have been only 10 tags on one frequency can now be hundreds to thousands per frequency. In addition, this technology has allowed improvements in the signal to noise ratio, allowing for higher resolution in acoustically noisy or shallow environments and at extreme hydrophone ranges (500m-700m in radius). Niezgoda et al. (2002) have conducted monitoring studies in water depths of as little as 0.5 meters. High code separation eliminates code collision further expanding transmitter numbers in small areas. Increased detection range reduces the number of hydrophones needed to accurately track a large area. The MAP system allows for expanded monitoring capabilities and increased accuracy and performance.

(d) Other Configurations

Tag manufacturers have incorporated a variety of environmental sensors or combined radio and acoustic transmitters into a single package. The types of sensors commonly added to transmitters include depth, light levels, and temperature. Combined Acoustic and Radio Tags (CART) tags are hybrids that combine the components of both radio and acoustic tags that offer the advantage of being able to track individuals between saline and freshwater environments (Solomon and Potter 1988). The CART tag contains a microprocessor and conductivity sensor that allows the tag to automatically modulate between acoustic transmission and radio transmission in response to changes in environmental salinity (Deary et al. 1998; Niezgoda et al. 1998). The smallest CART tag currently available is 25 grams and has an operating life of approximately 661 days which limits the utility of this tag to studies on adult anadromous fish (weighing at least 600 g) that are moving from saltwater to freshwater environments. The actual life of the CART tag varies based upon how often the tag is operating in radio versus acoustic modes.

Hydrophones, Receivers, and Data-Recorders

Acoustic tags send out a coded signal that is detected by a hydrophone (underwater microphone) that converts the acoustic signal into electrical impulses. These electrical impulses are relayed to a receiver unit which filters the input signal, amplifies it, and either converts it to an audible signal or processes and records it on an electronic signal detector known as a data-recorder (Murphy 1996). Both a hydrophone and receiver are necessary to detect and identify tagged fish, and are typically combined in newer “wireless” systems. Newer systems also typically contain an automatic data-recorder, so that units can be remotely deployed to automatically detect, record, and store information.

The hydrophone type (e.g., conventional wired or wireless) and receiver used for a particular study depends upon its desired application. Conventional, wired hydrophones (Figure 4) are composed of a small tapered shaft connected to a cable and can have a baffle placed on it, giving it a directional reading (used mainly for mobile tracking). Some manufacturers (e.g., Vemco) have designed directional hydrophones specifically for mobile tracking (Figure 5). The cable is physically linked to a receiver, which may be a mobile unit or stationed on land.

Wireless hydrophones are relatively new and are completely self-contained with an integrated receiver/data-recorder that allows data to be stored internally. The wireless feature allows for the hydrophone and integrated receiver/data-recorder to be placed in areas where a land-based receiver is not feasible, such as underwater where equipment is visually undetectable, which reduces vandalism. Currently, uploading the data is done manually by connecting a notebook computer directly to the hydrophone. Although land-based units are capable of transmitting data to a database via satellite and cell phone technology, currently the submersible integrated units still have to be manually downloaded. Manufacturers have stated that the lack of availability of this feature is due to market demand at the present time, not technology limitations. As with conventional hydrophone systems, data is downloaded every two to three weeks, but is capable of operating for months. However, biweekly downloading is recommended to ensure the system is operating properly.

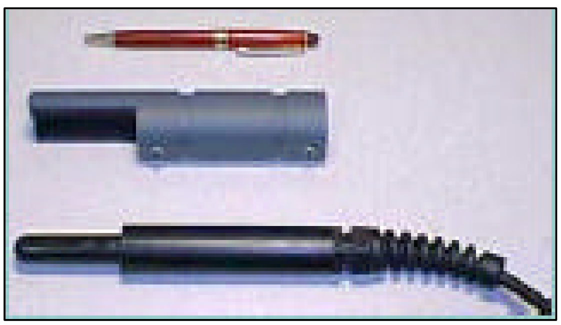

Figure 4. Omnidirectional and Directional Baffle.

Figure 5. Boat Rigged for Mobile Tracking with Directional Hydrophone

Research programs are generally designed to ensure that tagged fish will be successfully detected, either by placing stationary receivers in strategic land-based locations, or by using portable receivers for mobile tracking. Acoustic tracking systems typically consist of fixed arrays of hydrophones that provide continuous tag detection within a specified area to investigate individual fish passage. Any number of automated, stationary receiving stations can be placed within an acoustic monitoring system. The range of detection and performance of the telemetry system being used establish the number of receivers. However, mobile tracking can also be implemented to cost effectively increase the area monitored by reducing the amount of monitoring stations needed. Standard hydrophone detection ranges can vary from 250m to 500m in radius (Voegeli et al. 1998). Factors affecting detection range are water depth and environmental noise. Shallow water (e.g., less than 1.5 m) and high noise levels (e.g., water pumps, riffles, etc.) will decrease the range of detection. High noise environments can create spurious signals (random unusable data), which can compound data analysis. An ideal aquatic environment would consist of a laminar flow with water depth over 2 meters. However, newer technology, such as CDMA signaling has enabled researchers to consistently track fish in water depths of 0.5 m, and detection ranges up to 700 m.

Satellite Technology

An exciting development in biotelemetry in the last decade is the ability to monitor animal movements by satellite (Taillade 1992). Tags that communicate information directly to satellites are large and their use is limited to animals such as whales, sea turtles, and dolphins. Currently, the smallest satellite tags weigh between 60-150 g, and are powered by lithium batteries or solar cells (Murphy and Willis 1996). The position accuracy of the tags ranges from ± 150 m to several kilometers, depending on environmental conditions and animal behavior (Murphy and Willis 1996).

Although tags that communicate directly to satellites cannot be used to track salmonids, radio tags have been used to send signals to a fixed recording station, which then relays the information via satellite to a main global receiving center. Eiler (1995) demonstrated the feasibility of using a remote satellite-linked ATS tracking system for studying Pacific salmon in Alaska with radio tags in rivers where conditions make airplane tracking too difficult. In this study, Coho and Chinook salmon were tagged with pulse-coded radio tags and remote station receivers automatically collected, processed, and transferred tag signal data via a computer-controlled receiver to a satellite. A satellite uplink was then used to retrieve the data for within-season analysis. Even though this system used radio tracking and was located on-shore, it required 12-volt battery equipment with a solar recharging system; similar remote systems for acoustic tracking that can be located in aquatic environments are expected to be available within the next 1 to 2 years. This will enable researchers to deploy buoy-type monitoring stations that will transmit environmental and fish tracking data, via satellite or cell phone signal directly to a computer database. In addition to providing researchers significant savings in labor costs, and allow monitoring of aquatic environments on an even larger scale, it will also allow for real-time tracking of fish movements.

4. ACOUSTIC EQUIPMENT MANUFACTURERS

There are four primary acoustic equipment manufacturers in North America: Lotek Wireless, Vemco, Sonotronics, and Hydroacoustic Technology, Inc (HTI). With the exception of HTI, which has developed a niche product for work around structures such as dams, these manufacturers are highly competitive; active in research and development of acoustic technology; often willing to develop custom transmitters, hydrophones, and receiver equipment; and may provide bulk discounts. Each of the manufacturers produces slightly different equipment that is generally incompatible with equipment from other manufacturers. Choice of manufacturer for a particular study can be difficult because many factors can be involved including the average size of fish to be tracked (i.e., smallest available tag size), the number of fish to be released, the type of tracking to be performed (mobile, remote stations, near structures), the need for other sensors in the transmitter, compatibility with other studies in the area of concern, and of course, cost.

Most of the manufacturers produce conventional location-only pingers, hydrophones, and receiver/data loggers needed for a complete tracking system. The following provides a short synopsis of the types of equipment that distinguishes each manufacturer from the others. Included are the URLs to access these manufacturers' websites. We have not included any discussion of costs because comparison between manufacturers can be difficult for anything but the most basic systems provided by each manufacturer, which may not be representative of the cost for a system actually used for a specific study.

Lotek Wireless

Lotek Wireless (www.lotek.com) produces a wide range of acoustic, radio, and archival tags and related equipment. They produce transmitters as small as 2 grams in size with a lifespan of about 35 days. In addition to traditional receiver systems with cabled hydrophones, Lotek also produces a wireless hydrophone that retransmits signals by radio to a receiver. Their standard receiver/datalogger can be used for both radio and acoustic telemetry work and can be operated remotely using radio, cell phone modem, or satellite.

The multiple access positioning (MAP) series is a unique system only produced through Lotek that uses advanced spread spectrum signal processing methods along with code division multiple access (CDMA) signaling, a technology more widely utilized in the cell phone industry. The MAP system performs provides sub-meter resolution along with hydrophone ranges (averaging 500m-700m), that are somewhat larger than the industry norm (up to 500m). The CDMA technology allows for the receivers to operate in shallow, high noise environments and still maintain elevated hydrophone ranges. One advantage of the CDMA coded MAP tags is that they do not suffer code collision. This means that multiple tagged fish can be located simultaneously within a hydrophone detection range and still have all of the individual tags be detected. The broad frequency spectrum also allows for a large amount of fish to be tagged and tracked at once in a small area. Tag capacities are estimated in the ranges of tens of thousands all on one single frequency. Code filters allow manual tracking of a single fish, a selected group, or all fish at the same time. The MAP system is capable of both wired and wireless monitoring. The smallest MAP system transmitter has a lifespan of approximately 60 days.

Lotek also produces a combined acoustic and radio transmitter (CART) tag and archival tags. The CART tag is able to switch between acoustic and radio-tracking modes through an external conductivity sensor and provides the advantages of both an acoustic and radio transmitter. The CART tag allows researchers to seamlessly monitor anadromous fish from fresh water to saltwater environments and allows for a variety of tracking methods (automated monitoring, mobile boat tracking, fly over land/water tracking). However, CART tags are relatively large, with the smallest available tag weighing approximately 13.5 grams in water. Consequently, the CART tags are only suitable for adult salmonids. Archival tags can record pressure (depth), temperature, and light levels (used for geolocation). Their smallest archival tag weighs 2 grams in water and has 128 kilobytes of memory, but does not include geolocation.

Vemco

Vemco (www.Vemco.com) has a strong background in field research by its lead research and development scientists (F.A. Voegeli and G.L. Lacroix). Recently, Amirix Corporation purchased Vemco. This merger is expected to provide Vemco with opportunities to expand their product line. Vemco has produced a reliable field-tested acoustic telemetry system for over 20 years. Vemco has tagged and successfully tracked salmonid smolts as small as 105 mm (Welch et al., in press). Their smallest transmitter weighs about 2 grams in water and has a tag life of 32 to 229 days, depending upon the pulse delay interval. Larger transmitters, suitable for adult salmonids, can include temperature or depth sensors.

Vemco has the widest suite of hydrophones available relative to other manufacturers. Vemco has developed directional hydrophones specifically for mobile tracking of individual fish, handheld underwater hydrophone/receivers for use by scuba divers, a VFIN hydrophone mount that allows for towing of an omnidirectional hydrophone at a desired depth, and multiple element hydrophones that allow the relative location of a transmitter to be determined without rotating a directional hydrophone. Their directional hydrophones have characteristics that allow tracking from a boat while under power at low speeds and a horizontal beam width between 18 and 30 degrees depending upon operating frequency. An important innovation from Vemco is development of a submersible combination hydrophone, receiver, and datalogger that can be stationed using anchors and buoys. These remote stations can be recovered and then downloaded, or can include a transponder for wireless download of logged data. For animals tracked within a small area, their VRAP system utilizes three anchored hydrophone/receivers, which sends real-time information to a base station by radio. Triangulation from three hydrophone/receivers allows calculation of fish locations within the three buoys.

Sonotronics

Sonotronics (www.sonotronics.com) has produced acoustic tracking equipment since 1971. They produce a wide variety of conventional and coded transmitters, receivers, and hydrophones. Sonotronics has developed miniature transmitters as small as 0.5 grams that last approximately 8 days, but are only suitable for continuous tracking. Their 0.75-gram tag with a 12-day lifespan is crystal-controlled and consequently more suitable for tracking using remote receiver stations. They also produce transmitters that can telemeter depth and temperature data. One of the innovations from Sonotronics is a combination archival tag and pinger. The transmitter collects and archives temperature and depth information while the pinger allows for tracking of the fish and a higher likelihood of retrieving the transmitter. However, the transmitter must be returned to the manufacturer to recover the archived data. Sonotronics has also developed underwater receivers for tracking fish using scuba.

Hydroacoustic Technology Inc.

HTI (www.htisonar.com) is primarily a developer of hydroacoustic equipment and consultant for hydroacoustic surveys. Acoustic telemetry is a relatively new field for HTI and they are specialized in 3-D monitoring and tracking, especially near structures such as hydroelectric dams. They use a conventional acoustic transmitter system with a hydrophone array that allows signal detection simultaneously from several locations. This system allows locating tagged fish in three dimensions and depiction of fish paths utilizing a custom graphical computer program.

HTI offers one of the smallest acoustic tags on the market, weighing 0.8 g in air with an average tag life about 12-14 days.

5. APPLICATION OF ACOUSTIC TRACKING AND POTENTIAL ADVERSE EFFECTS TO FISH HEALTH AND BEHAVIOR

An understanding of acoustic equipment and technology is only part of what is needed to conduct a successful acoustic tracking study. Proper application of the technology in the field is also important. The field components to an acoustic tracking study include:

- Capture and selection of host fish,
- Transportation of experimental fish to release site,
- Transmitter attachment,
- Recovery from handling and tag effects, and
- Release and tracking of tagged fish.

As in all types of fisheries monitoring studies where fish are captured, tagged, and released, researchers using acoustic technology typically assume that tagged fish behavior and physiological responses are not affected by the tag or tagging procedure and, therefore, correspond to untagged fish. However, all types of fish tagging programs involve procedures associated with capture, handling, and tagging that have the potential to negatively affect the health and behavior of fish being studied. Scientists occasionally develop specific studies, often using dummy (or sham) tags that have a similar size and weight as real transmitters, to evaluate the hypothesis that tagged fish behave the same as untagged fish.

The results of these experiments are valuable for understanding the potential biases in an acoustic tracking study. Although some authors have found no difference between tagged and untagged fish in terms of behavior, growth, or physiology (Hinch et al. 1996), other studies have documented adverse effects. Factors that can influence the behavior of tagged fish include: the species, size, and lifestage of fish tagged; capture and handling methods; the location of the tag and attachment methods; the size, shape, and weight of the tag; the environmental conditions at the time of tagging; and the skill of the people applying the tags. The effect of capture, handling, and tagging on tagged fish can include damage to tissue, increased mortality (Nettles et al. 1983; Knights and Lasee 1996), decreased swimming mobility (McCleave and Stred 1975; Arnold and Holford 1978), reduced growth (Wrenn and Hackney 1979; Greenstreet and Morgan 1989), changes in social interaction, and tag expulsion (Moore et al. 1990; Chisholm and Hubert 1985; Marty and Summerfelt 1986; Jepsen et al. 2001). Although all variables associated with the effects of tagging cannot always be quantified for every research project, considerable field and laboratory studies have been conducted to help researchers minimize and account for the effects of handling and tagging. The following discusses each of these stages.

Effects Associated with Host Capture and Selection

The types of capture and handling methods chosen for acoustic tagging studies are important to ensure that fish being studied are not unduly stressed or damaged and that they behave similar to untagged fish during tracking experiments. Assorted capture and handling methods inflict varied damages and stressors on different species since species have different tolerances for capture and handling. In addition, vulnerability to handling may vary during different life stages within the same species. For example, salmonids vary greatly in their stress response to handling during their lifespan and lifestages of interest in the Delta would include returning adults and outmigrating smolts.

Adult salmonids migrating into freshwater have been captured worldwide by a variety of methods. In the Delta, adult salmon have been captured most recently via sampling gear such as fyke traps. Most methods used for capturing adults are relatively harmless. In addition, salmon are typically more resistant to handling at this stage in their life history due to physiological changes to skin and mucus that occur in conjunction with maturation.

The results of tracking studies can be influenced by the source and condition of the subject fish. In the case of salmon smolts, many experimenters have used hatchery fish because they are readily available and more likely to be sufficiently large to tag. However, the behavior and physiological condition of hatchery fish may be different from actively migrating wild smolts. Smolts from wild stocks have been tagged where they were large enough to use the smallest available electronic tags. However, selection of the largest smolts to avoid tag effects may result in biased data that do not represent the full range of the population. For example, larger fish can swim faster than smaller fish and result in an underestimate of transit times across an area of interest.

Past acoustic studies of wild smolts used fish traps (Tytler et al. 1978; Holm et al. 1982) and fyke nets to capture fish (Moore and Potter 1994; Moore et al. 1990b, 1990c, 1992, 1995). Other techniques available to capture wild smolts include electrofishing and beach seining. However, fish traps and fyke nets are often preferred since they are more likely to capture actively migrating smolts and require less handling than the other methods. Host fish captured from an outmigrant trap are generally presumed to be more fully developed as smolts, but does not guarantee active movement. Moser et al. (1991) observed that 3 of 16 Coho smolts moved upstream into a tributary following release and 4 smolts held position within 1.5 kilometers of the release site; none of these 7 smolts continued downstream movement prior to tag failure from drained batteries.

McCleave and Stred (1975), Moore and others (1990a), Moser et al. (1990), and Lacroix and McCurdy (1996), among others, have investigated the effects of tagging and handling on salmonids and determined that fish recovered quickly from the handling process. However, once the fish has been released it is difficult to assess potential delayed impacts of capture, handling, and tagging procedures.

Transportation and Handling

Frequently, a study will require the transportation of host fish to a release site and maintenance during the transmitter attachment and recovery procedure. The surrounding environmental conditions are important to monitor when attempting to reduce overall stress levels and behavioral alterations. Excessively cold or warm water can both have negative effects on individuals. Furthermore, extreme temperatures will compound the effects of handling when both are combined. Warm water has also shown to increase the chance of infection after surgery (Knights and Lasee 1996; Walsh et al. 2000). In addition to water temperature, pH, turbidity and dissolved oxygen levels are all crucial to monitor and maintain in order to successfully tag, acclimate and release the fish (Jepsen 2002).

A variety of handling methods have been applied during the tagging procedure, ranging from use of blindfolding in calming fish (Arnold et al. 1994; Thorsteinsson 1995; Sparkman 2003) to full anesthesia. It is well known that anesthetics can cause physiological effects that can be measured as changes in levels of corticosteroid and other parameters (Bell 1987), which in turn may lead to changes in fish behavior for a varying time after sedation. On the other hand, anesthesia reduces handling stress and decreases tagging time so the potential for damaging fish is reduced. The benefits of anesthesia must be weighed against potential detrimental effects on the physiology and behavior of the fish.

Fish are often anesthetized with diluted clove oil (Bridger 2001; Jepsen 2002; Connors 2002) or tricaine methane sulphonate, trade name MS 222 (Niezgoda 1998; Voegeli et al. 1998), to calm or render fish unconscious during surgical implantation to reduce handling stress, and may be used during other tagging methods for the same reason. Both forms of anesthesia are proven to work well and are generally selected based upon local regulatory policies and restrictions. MS-222 is probably the most widely used fish anesthetic worldwide. However, clove oil is used in field studies where immediate release of the fish into the food chain is required (Thorsteinsson 1995) because it is regarded as a GRAS ('generally recognized as safe') substance by the U.S. Federal Drug Administration.

Tag Effects

Tag effects are generally related to transmitter size and weight relative to the host and the method of tag attachment.

Tag Size and Weight

There is considerable speculation surrounding the acceptable fish to tag weight ratio. For many years researchers were reluctant to exceed the 2 percent rule-of-thumb, which presumed that any behavioral or physiological effects of tags were minimal, and therefore acceptable, if the ratio of tag weight in water to fish weight did not exceed 2 percent. Problems that may arise from excessive tag weight include negative buoyancy, poor equilibrium, diminished swimming performance, reduced feeding, and the tendency to expel tags (Jepsen 2002; Figure 6). As more laboratory work is being done, there is growing evidence that the 2 percent rule can be exceeded, but that researchers must take adequate precautions to ensure that there are no negative and unknown effects caused by the tags.

One of the confounding variables in trying to develop rules of thumb, such as tags should not exceed 2 percent of a fishes body weight, is that many other variables also influence the successful outcome of the tagging procedure. For instance, handling and recovery time are important variables in successful tagging procedures. Excessively long handling or recovery times will stress the fish and may lead to high mortality rates. Past research has shown that some species, particularly salmonids, are more prone to high stress levels while being handled (Strange et al. 1977; Jepsen et al. 2001). Therefore, the most successful tagging methodologies are those that are quick, sterile, and least invasive.

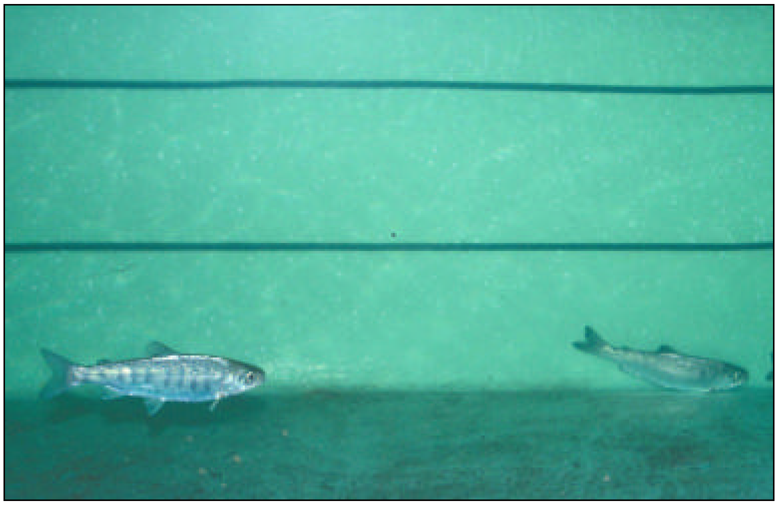

Figure 6. Control and Experimental Coho Juveniles during a Tag Effects Study. Note the Swimming Position of a Recently Tagged Fish on the Right.

Tag Attachment

There are three ways a tag may be attached: (1) externally attached either directly to the body or tethered to the dorsal or pectoral fins; (2) placed in the stomach through esophageal insertion; or (3) by surgical implantation into the peritoneal cavity. Typically, some form of sedation or anesthetic is used during surgical implantation but is often not necessary during implementation of other tagging methods. There are advantages and disadvantages for each of these methods and choice depends on the type of tag, the type of fish and its lifestyle, and the purpose of the research.

(1) External attachment

External tagging is primarily used when handling large fish due to the fact that fish can easily and quickly be tagged without anesthetic. Some external tags are sutured directly to the fish and one of the most common positions for these directly attached tags is alongside the base of the dorsal fin. However, most external tags are attached with fine wires or nylon cords that are passed through either a fin or body muscle, and subsequently are attached to plastic discs or plates on the other side of the fish. Trailing tags are typically attached dorsally, both anterior and posterior; but may also be attached dorso-laterally; and ventrally. These trailing external tags are easier and quicker to use than most internal tagging procedures, avoid the need for surgery and anesthesia, and may also shorten the recovery period allowing fish to be released within minutes of tagging. However, these trailing tags have a higher probability to be snagged on surrounding impediments that may increase infection and mortality rates and reduces the overall tag retention rate, but these are considered small trade-offs when handling large species.

Other problems that can occur associated with externally attached tags include chafing, abrasion, and creation of ulcerated wounds; changes in behavior; and delayed mortality. Fish with externally attached and surgically-implanted tags may develop infections at the attachment point or incision site. Fungus infections can become problems for all external attachment types at higher temperatures, especially for salmonids (Lucas 1989; Kaseloo et al. 1992; Adams et al. 1998), possibly as a consequence of handling (Solomon and Storeton-West 1983). The potential for infections increases with the presence of permanent foreign bodies (Roberts et al. 1973) such as the threads of externally attached tags.

Although few studies have been carried out to assess the impact of simple external tags on the behavior of fish (Lewis and Muntz 1984; McFarlane and Beamish 1990), they may affect various aspects of the behavior and physiology of swimming animals, particularly if they have not been designed for minimal drag. Changes in behavior may cause fish to be more susceptible to predation than untagged fish and the shape and color of the tag may influence the risk of predation.

Mortality of externally tagged fish rarely takes place within the first days or weeks. Instead, external tag attachment may involve progressive or chronic lesions to occur which are slow to heal (Roberts et al. 1973; Birtles et al. 1995; Knights and Lasee 1996). Adverse effects thus accumulate over time and can be exacerbated by exposure to increased water velocity, which increases the drag on the tag.

(2) Esophageal insertion

Although esophageal insertion is more commonly used with radio tags than acoustic tags, this method of internal tagging has several advantages including the fact that it does not require surgery and associated anesthesia; reduces tag losses that are associated with external tags; and it places the tag near the center of gravity for fish which reduces changes in swimming behavior. Disadvantages include lower retention rates than surgical implantation that are due to increased regurgitation rates as a result of the nature of the procedure, altered behavior, and decreased propensity to eat (Adams 1997). Due to these disadvantages, esophageal insertion has since been proven to be a less preferred method of tag attachment for medium to long-term studies of juvenile salmon or trout.

In a gastric insertion, the tag can be inserted into a special probe, which is used to push the tag through the esophagus and into the stomach. Following insertion, the probe is withdrawn leaving the transmitter in the stomach (FAO 2003). Forced insertion is possible with small fish; however, it is better suitable for larger fish with enough stomach space to accommodate the tag without damaging internal organs or reducing the fish's ability to feed.

Stomach-inserted acoustic tags are less prone to cause the death of fish, compared with externally attached or surgically inserted tags. However, stomach-inserted acoustic tags may be lost through regurgitation (vomiting) or egestion (defecation). Regurgitation rates and delays between insertion and regurgitation vary greatly, depending on the fish species, lifestage, and the relative size of the tag (Moser et al. 1990; Nielsen 1992). Regurgitation rates generally increase as relative tag size increases (Nielsen 1992). Small tags, in contrast, may be lost through egestion (Baras 1992). Some species are known to regurgitate tags more frequently than others; for example, rainbow trout are likely to regurgitate tags while Chinook salmon typically do not (Nielsen 1992).

(3) Surgical implantation

Surgical implantation (Figure 7) has become the most broadly used method of acoustic tag attachment due to a number of reasons, including higher tag retention than external tagging and esophageal insertions, and reduced abrasion. Surgical implantation of tags into the peritoneum has been conducted successfully over the last couple of decades with a number of marine and freshwater species, both with and without the use of anesthetics. Surgical insertion often involves making only a very a small incision in the body wall and the entire surgical procedure can often be completed in less than three minutes by well-trained field technicians. Since surgery is a relatively invasive procedure, technicians should be trained to ensure that tagged fish are minimally affected by implantation, which reduces or eliminates changes in fish behavior due to tagging.

The internal implantation procedure is composed of creating a small incision, typically near the mid-ventral surface of the fish body, which exposes the peritoneal cavity. Incisions are made as small as possible to minimize adverse effects to fish and are determined by the dimensions of the tag and the body wall/skin type (rigid or flexible body wall and thin or thick skin) of the species being tagged. Once the incision is made, the tag is gently inserted and the incision may be sutured closed with monofilament or glued with acrylic adhesives.

Tag expulsion does occur on occasion but is not common and is usually due to a combination of factors. Tag implants may exit in three ways: through the incision, through an intact part of the body wall, or through the intestine (Jepsen 2002). Generally, tags are shed within one day of the procedure or after five to six months. Proper tagging procedures can help to reduce or eliminate implant shedding.

Figure 7. Attaching a Tag using Surgery.

Researchers have developed methods to minimize impacts of surgery during transmitter attachment. Moore and others (1990b) have created the most broadly accepted surgical implantation method. The majority of monitoring projects have used this methodology with consistent results depicting no or acceptable signs of altered behavior (Moore et al. 1992; Moore and Picket 1994; Lacroix and McCurdy 1996; Russel et al. 1998). A detailed listing of products and procedures can be found within past research (Lacroix and McCurdy 1996; Moore et al. 1990b).

Other Potential Adverse Tag Effects

Although a basic assumption in most field telemetry studies is that fish act normally after release (Winter 1993), Swanberg and Geist (1997) noted that little research (Young et al. 1972; Mellas and Haynes 1985) has been conducted on the effects of tags on social interactions, and no research has quantified the effects of tag on aggression. They postured that lower rank among test fish could change habitat use or movement patterns and bias telemetry studies. Swanberg and Geist (1997) tested the assumption that surgically implanted tags may decrease aggression, resulting in a decreased ability to compete in a dominance hierarchy. They concluded that dominant fish implanted with dummy tags retained their rank and showed no signs of significant differences from control fish in amounts of agonism and interaction time with subdominant fish (Swanberg and Geist 1997).

In a recent study conducted by Battelle (Anglea et al. 2003), the effects of surgically implanted transmitters on swimming performance, predator avoidance, and buoyancy compensation of juvenile fall-run Chinook salmon were examined. They found no measurable differences between tagged and untagged fish, however, trends for all three factors indicated that tagged fish consistently performed slightly worse than untagged fish. Based on their results, they concluded that tagged fish behaved similarly to the population at large but that subtle differences exist in the behavior of tagged fish.

Studies of tagged fish swimming performance have found that fish swimming behavior may be adversely affected (Adams et al. 1998b) or not affected at all (Brown et al. 1999; Moser et al. 1990; Anglea et al. 2003), and demonstrates that effects vary considerably depending on tag placement, and the species, as well as lifestage considered. Swimming performance may be affected by the presence of a tag, which is especially important to consider when dealing with migratory species, such as salmonids. Swimming performance seems least affected when tag size and volume are as small as possible in proportion to fish size.

Drag resistance created by externally attached tags is an obvious cause of reduced swimming capacity and varies depending on tag bulk and shape. Position of external tags is often outside the center of gravity, which may cause disequilibrium and irregular swimming either permanently or temporarily (Thorp et al. 1981; Mellas and Haynes 1985; Beaumont et al. 1996). In addition, large internal tags may inhibit swimming movements by reducing fish health and/or increasing the energy required to swim.

Juvenile versus adult salmonid swimming abilities were found to be affected differently by external and surgically implanted tags; juveniles were affected by externally placed tags but not by surgically implanted tags (Mellas and Haynes 1985; Lewis and Muntz 1984; McCleave and

Stred 1975; Moore et al. 1990a) while adult salmonids were just the opposite (i.e., not affected by external tags but were affected by surgically-implanted tags; Haynes and Gray 1979).

Recovery and Release of Host Fish

Host fish usually require a period of recovery following transmitter attachment prior to release. Although it may seem intuitive that fish need long periods to acclimatize with the tag before release, researchers have actually found long acclimation periods can further stress the fish, especially wild caught individuals (Schreck 2000; Jepsen et al. 1998; Voegeli et al. 1998). Factors that could influence the minimum recovery period include the size of fish, the size of the transmitter, the attachment method, and whether anesthetic was used. For adult fish tagged through esophageal insertion without anesthetic, the needed recovery period could be less than an hour (Russel et al. 1998). For smolts, various researchers have utilized recovery and holding periods of around 5 hours (Clements and Schreck 2003) and up to 3 days (Moser et al. 1991; Voegeli 1998), but some of this period could be for tracking convenience or logistics rather than for actual fish recovery. Clements and Schreck (2003) suggested that extended periods of holding (not defined) could result in a stress response from tagged fish. Moser et al. (1990) recommended that smolts carrying tags up to 5 percent of their body weight be allowed a minimum recovery period of 4 hours and those with tags exceeding 9 percent of body weight a minimum of 36 hours of recovery time. Moser et al. (1990) concurred with Fried et al. (1976) that salmonids must be allowed access to the water surface in order to gulp air, inflate their swim bladder, and recover their buoyancy. Furthermore, it was recommended that recovery occur in shallow, small-meshed enclosures located in slow moving water.

Selection of release site is an important consideration and can be dependant upon the study objectives. Under most circumstances release near or at the capture and/or tag attachment site is preferred in order to reduce the amount of handling that is required. Release sites should also be selected so that released fish are not immediately at risk of predation. Survival studies at Columbia River hydroelectric projects often use paired releases: one at the head of the reservoir and another at the tailrace of project (USACE 2003). Comparison of tag detections at a downstream location provides the estimate of survival. It was noted in USACE (2003) that the timing of release and condition and host size of control and treatment groups in paired releases should be similar to obtain reliable survival estimates. It was also recommended in USACE (2003) that release sites be far enough upstream (about 4 km) of the specific area of interest to avoid dead drift into the project area and to allow sufficient time for the host to choose a route. Battery failure rates must be taken into account and transmitter lifespan should be sufficiently long for all fish to transverse the study area; otherwise survival would be underestimated.

6. APPLICATIONS OF ACOUSTIC TECHNOLOGY

Recent studies demonstrate how new acoustic technology is being used to track increasingly smaller fish and to answer increasingly complicated questions surrounding juvenile salmonid migration and behavior. In addition to tracking smaller fish, new technology allows researchers to monitor individual fish movements over a much broader scale than in the past. Large-scale projects studying smolt migration through estuaries, bays, and/or in coastal waters are either ongoing or planned on the Atlantic and Pacific coasts. In many ways, the examples described below attempt to address similar questions being faced within the Delta, namely: What habitats do salmonids use? What behavior patterns are expressed when salmon use, or travel to and from, these habitats? And, how does management of environmental resources affect this habitat use and behavior?

United States-Atlantic Coast

Although reports concerning the use of acoustic tags with juvenile Pacific salmon are rare, several recent studies have investigated the use of acoustic tags with juvenile Atlantic salmon smolts. Prior to 1996, most smolt tracking studies involved following fish with mobile systems (Fried et al. 1978; Tytler et al. 1978; LaBar 1978; Greenstreet 1992). In 1996, Lacroix and McCurdy developed and used strategically placed fixed monitoring stations (i.e., sonar buoys); these sonar boys were similar to those used by others to track movements through smaller estuaries (Potter 1988; Solomon and Potter 1988; Moore et al. 1990a and 1995). However, the system used by Lacroix and McCurdy (1996) was “wireless” meaning it did not require any receivers or other equipment on shore. This wireless feature greatly improved the flexibility of the system, and allowed for much larger scale tracking. Fifty to 100 percent of the codes transmitted by each tag were usually detected within 400 m of the receivers (Lacroix and Voegeli 1996).

By 1998 and 1999, additional advancements in technology enabled researchers to track juvenile Atlantic salmon as small as 130 mm for several months. Further, the new tags were coded, which enabled a larger number of individual tags to be tracked at one time, potentially increasing the number of tags available for use in any one experiment from around one hundred to thousands. In addition to tracking smolts as small as 130 mm, tests demonstrated that smolts could be tracked for several months over a large area with considerable tidal influence by wireless receivers.

United States-Pacific Coast

From 1964 to 1967, Hallock and others (1970) tracked adult fall-run Chinook salmon through the Delta to evaluate migration relative to low dissolved oxygen levels and reverse flows. During the four years of tracking, a total of 316 adult salmon were captured, tagged, and released. Large acoustic tags were externally attached above the back and forward of the dorsal fin. Hallock and others (1970) determined that acoustic tracking of adult salmon was successful at detecting and tracking fish from fixed and mobile stations over a wide range of flow and environmental conditions.

Several acoustic tagging studies on homing adult sockeye salmon (Quinn 1988; Quinn et al. 1989), steelhead (Ruggerone et al. 1990), and Chinook salmon (Olson and Quinn 1992) have been conducted in the Pacific Northwest. Each of these studies utilized mobile tracking techniques to continuously follow homing adults in nearshore (sockeye and steelhead) or estuarine waters (Chinook). These studies collected both horizontal and vertical positions of the tagged fish and related their movements to environmental factors such as tidal flows, temperature and salinity stratification, and time of day (Figure 8). These correlational studies were primarily interested in investigating factors that guide migration behavior and comparing observed behaviors patterns to those expected based upon homing migration theories.

As indicated previously, few acoustic studies have been conducted on Pacific salmon juveniles because of the available tag sizes. The first study (Moser et al. 1991) tracked Coho smolts in the Chehalis River and Grays Harbor, Washington, using a combination of radio and acoustic tagged fish. In addition to documenting travel routes and speed, the study attempted to identify general behavior patterns and the environmental cues most important to smolt orientation. Coho smolts in the upper Grays Harbor estuary were observed to exhibit strong positive rheotaxis (i.e., swim against currents) when they encountered swift currents, but moved both with and against slow currents. This behavior resulted in increasing the residence time of smolts in the estuary. It is important to note that this study utilized relatively large smolts (159 to 215 mm) because the available tags were not sufficiently small to use on average-sized smolts. However, fish size did not appear to noticeably affect fish behavior over the range of sizes used.

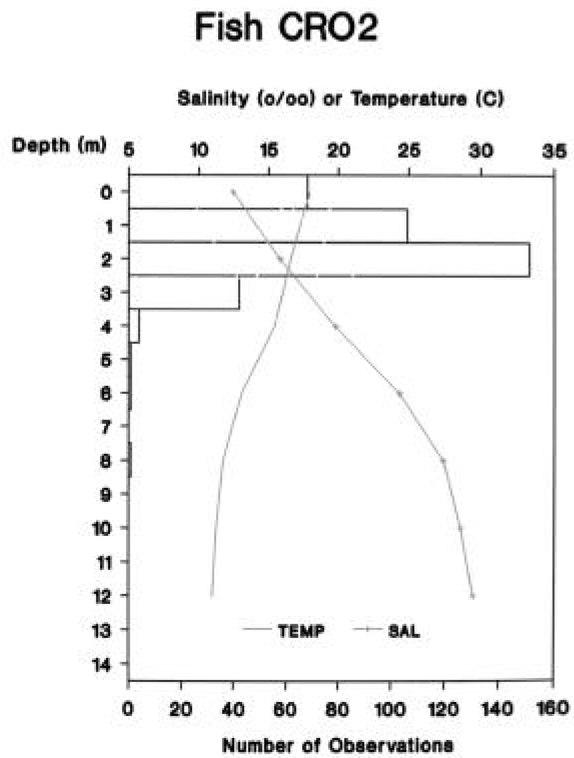

Figure 8. Fish Depth, Water Temperature, and Salinity for an Adult Chinook Salmon Tracked in the Columbia River Estuary (Source: Olson and Quinn 1992).

Studies utilizing PIT, radio, and acoustic tags have been conducted over the past several years to examine smolt survival and behavior through Columbia River reservoirs and their associated hydroelectric dams (USACE 2003). PIT tags have been used since 1993 to evaluate juvenile fish passage survival through the federal Columbia River power system. PIT tags require host fish to be within 18 cm of detectors, which can be accomplished at a powerhouse or bypass system, but a proportion of the tagged population can be missed because of guidance efficiency and the availability of alternate routes. In contrast, radio or acoustic system can sample the entire experimental population.

These studies have been designed to compare project level and route-specific survival estimates from the different tagging methods and have utilized paired releases (experimental and control groups) (USACE 2003). Under a paired release, experimental groups are released at the head of a reservoir and control groups are released at the tailrace of the dam. Survival is based upon detections at a location further downstream. Results suggest that paired release strategies appear to be a useful method to obtain unbiased survival estimates. One modification to the paired releases is the virtual release design, where fish included in the experimental group are only those detected just upstream of the area of interest (i.e., dam forebay), rather than all of the tagged fish released. The virtual release design has been abandoned because survival estimates were drastically different than those from other methods. Route-specific dam passage survival estimates have been made using tagged fish released at an upstream location and allowed to distribute naturally or by targeted releases via a hose. The natural distribution method has resulted in lower precision survival estimates because of variable sample sizes for the different routes, but is useful for obtaining total project survival estimates. Most route-specific survival estimates have utilized a balloon tag, which is a radio transmitter combined with a timed released colored balloon that allows recapture of the tagged fish following passage.

In 2001 and 2002, wild steelhead smolts and hatchery Coho and steelhead smolts were tagged with acoustic or radio transmitters and tracked in the Newhalem watershed and estuary, Oregon, to determine survival rates and observe fish behavior (Clements and Schreck 2003). Bird predation was suspected of being an important source of mortality in the estuary. Locations of tagged fish occurred by mobile tracking techniques and a system of 13 wireless remote hydrophone/receivers located along lines just outside of the estuary or at strategic constrictions in the estuary. Tagged fish were found to remain stationary during flood tides and moved seaward during ebbing tides. Residence times within the 11-mile long estuary were up to 11 days for individual with significant differences among the tagged groups. Wild steelhead spent less than a day in the estuary while hatchery steelhead spent up to 4 days and hatchery Coho spent about 8 days. Birds ate about two-thirds of tagged hatchery steelhead and Coho, but less than a third of wild steelhead were consumed.

More recently, acoustic tags were made small enough to use on 80-90 mm smolts and have proven to be a very valuable tool for studying smolt behavior as they approach hydro-electric dams in the Columbia and Snake rivers (Ehrenberg and Steig 2002). During fall 1997, Steig (1999) used acoustic tags and hydrophone arrays to track juvenile salmon smolts (size unreported) in the forebay of Rocky Reach Dam on the Columbia River. The experiment was designed to determine the optimal tag transmitting frequency to operate in the acoustically noisy forebay of the dam. Prior to this time, an often-cited disadvantage of acoustic tags was their inability to function in acoustically "noisy" environments. The study determined that 5 fish could be tracked in the coverage area at a time (up to 20 theoretically) and that sub-meter position accuracy could be achieved. This innovative technology also used a computer display system that provided a three-dimensional background showing a representation of the coverage area and the fish tracks. The researchers concluded that the technique is feasible for documenting the behavior of fish approaching hydroelectric projects and other types of structures and that these tools are capable of providing managers with new insights in entrainment, predation, and decision-making processes (Ehrenberg and Steig 2002).

Three studies are now in progress to examine salmon smolt behavior in the Columbia River estuary and the Columbia River plume using acoustic tags. The first study is being conducted by NOAA fisheries and Battelle's Pacific Northwest National laboratory (PNNL) and includes the development of a micro-acoustic tag to implant in juvenile salmonids as small as 92 mm (fork length) and of a tag detection array to be located in the Columbia River estuary (McComas et al. 2001). A prototype tag design operating at 400 kHz for use in the estuary is being finalized and has undergone preliminary evaluation for biological compatibility and detection testing during 2002 and 2003. Partial deployment of the detection array system within the Columbia estuary and concomitant tag detection testing will be conducted in 2004 followed by full deployment in 2005. Although the tag prototype continues to be refined, it is currently close to meeting all size and operating goals with the ability to run for at least 30 days and has a capacity for approximately 65,000 codes (John Ferguson, pers. comm. 2003).

The second study is an expansion of radio tracking studies between Bonneville Dam and the estuary that is being conducted by the Oregon State University Fish and Wildlife Coop. Under the expanded scope of work smolts will be tagged with acoustic tags and trucked through the estuary to the nearshore environment.

The third study is a pilot project for the Pacific Ocean Salmon Tracking Project (POST), which desires to use existing and developing technology to track the ocean movements of salmon for months or years at a time (Welch et al., in press). The development of this technology and the identification of the need to increase our understanding of ocean migration habits led to the development of the POST project in 2002. The POST project was initiated to develop an acoustic receiver array for tracking movements of Pacific salmon during the shelf-resident phase of their life history, and use archival tags to delineate their open ocean migration pathways off the continental shelf (Welch et al., in press). A similar program, the Atlantic Salmon Marine Acoustic-tagging Program (*Salar* MAP), has been in place for several years. The program is a collaborative effort between the Atlantic Salmon Federation and the Canadian Department of

Fisheries and Oceans to implement new technologies and strategies for tagging and tracking small salmon at sea.

In other ongoing studies, the California Department of Fish and Game (CDFG) has conducted acoustic telemetry studies with adult Chinook salmon in the Delta. The studies have included evaluation of salinity control gates in Suisun Marsh, and general migration behavior in response to flow and Delta Cross Channel (DCC) operations in the lower Sacramento and San Joaquin rivers. In addition, the U.S. Geological Survey has developed complimentary evaluations for tracking adults through the north Delta. In 2003/2004, the different research projects are being coordinated such that the equipment from the same manufacturer (i.e., Vemco) will be used throughout the Delta and lower Sacramento and San Joaquin rivers. The new monitoring stations will consist of new wireless integrated hydrophone/receiver/data-recorder units.

The USGS, in coordination with the U.S. Bureau of Reclamation, is also conducting pilot studies at Georgiana Slough in 2003 to test the effectiveness of new 3-D monitoring equipment developed by HTI for detecting juvenile movement in relation to local hydraulic conditions. In 2004, they plan to use the 3-D acoustic system to monitor juveniles at several different junction points including the DCC and Sutter, Steamboat, and Georgiana Sloughs.

United States-Inland

While radio tags have typically been used in riverine habitats, acoustic tags are sometimes used in deep lakes and reservoirs because radio telemetry is only effective in freshwater environments within 10 m of the surface (Ehrenberg and Steig 2002). Acoustic tags were first utilized to observe cutthroat homing behavior in Yellowstone Lake in the early 1970s (McCleave and LaBar 1972). Other species that have been tracked in lentic environments with acoustic tags include adult steelhead (Monan et al. 1976; Monan et al. 1970), adult chinook (Monan and Johnson 1974), rainbow trout, bream (Schulz and Berg 1972), walleye, smallmouth bass, lake sturgeon, yellow perch, muskellunge, and others. Recently, Baldwin and others (2002) tracked the diel movements and distribution of cutthroat trout (*O. clarki utah*) in Strawberry Reservoir, Utah, in relation to vertical environmental gradients and prey distribution. Surgically implanted acoustic tags provided the depth and general location of the fish, while differentially corrected Global Positioning System recorded boat positions that were overlaid on a bathymetric map to determine temporal and spatial habitat use patterns (Baldwin et al. 2002).

Outside United States

One of the earliest acoustic tagging studies on Atlantic salmon smolts, 125 to 250 mm in length, occurred in 1977 in Scotland (Tytler et al. 1978) and observed outmigration in two estuaries. Hatchery reared smolts tracked in the lower River Eden migrated through the estuary in within a single tidal cycle while smolts tracked in the North Esk required up to 4.5 days. Tytler et al. (1978) suggested that differences in behavior were attributable to physical differences between the two estuaries and the conditions under which the tagged fish were released.

In 1992 and 1993, Moore and others (1995) tagged wild Atlantic salmon smolts with miniature acoustic tag in the River Conwy, North Wales, to evaluate the freshwater and estuarine patterns of migration. Thirty-two wild smolts (mean length 201 mm) were captured and surgically implanted with tags measuring 17 mm x 8 mm and weighing 1.3 g. Moore and others (1995) determined that migration was primarily nocturnal, although there was a seasonal change with later fish migrating both during the day and night. Additionally, smolts tagged earlier in the study spent significantly longer in the river before migrating into coastal waters. All of the smolts migrated towards the ocean on ebb tide close to the surface and with the fastest moving section of the water column (Moore et al. 1995).

In 2000, Lembo and others (2002) used a wireless communication system near the Island of Ustica, Italy, to evaluate grouper site fidelity. The system was based on five wireless hydrophones distributed approximately 200 meters apart, each monitoring acoustic signals from tags within a reception cell. The hydrophones retransmitted signals as a radio signal to their associated land-based receiver and data-recorder. Because the WHS units were acoustic to radio repeaters, the hydrophone element had to be positioned in water to detect the acoustic signals and the radio antenna positioned in air to transmit the radio signals. This configuration was accomplished by suspending the WHS unit in the water column from a float at the surface, which also supported a tuned radio antenna above the water surface. Unique identifiers for each hydrophone permitted the identification of which detection cell contained the tagged fish. The wireless hydrophones had partly overlapping detection ranges, dividing the study area into more than five cells. The average detection range was 232 m, but coverage varied from site to site depending on ambient noise, wave action, and signal strength of the tags. The study determined that automated systems are a feasible and powerful technique for studying site fidelity in fish, because they provide continuous monitoring (24 hours/day, 7 days/per week) while saving labor costs.

7. DISCUSSION

In the Delta, a better understanding of hydrology, water chemistry, and biological requirements of fish species is necessary to achieve the objectives of the CALFED-Bay Delta Program, which include long-term reliable water supplies, high water quality, and restoration of the Delta ecosystem. Currently, our understanding of salmonid migratory behavior and habitat utilization of the Delta is limited and major data gaps continue to exist even though traditional sampling and tagging methods and modeling efforts have increased understanding of these issues over the last 5 to 10 years (Brown 2001). Due to the need for high-resolution fisheries data that is currently unavailable through traditional methods and the need to minimize handling and tagging stress of ESA-listed species during research studies, biotelemetry is fast becoming an important tool and can increase our knowledge regarding special status fish species in the Delta so that more effective fishery management and restoration actions can be conducted.

Acoustic technology manufacturers have made tremendous advances in tag miniaturization and wireless networking receiving and data-recording stations within the last few years that have made this technology an attractive choice for researchers investigating anadromous fish behavior throughout their lifecycle. New batteries, and smaller, more powerful and more efficient tags, have overcome many of the earlier problems of longevity and reliability. Data can now be recorded for hundreds to thousands of individual fish in both fresh and saline water environments and can be recorded inexpensively and remotely, which increases the feasibility of large-scale monitoring programs.

As additional advances continue to be made, acoustic tags are likely to play a major role in fisheries research in the upcoming years and are expected to provide information that can be used to answer questions and develop solutions to complex resource issues. Ongoing acoustic tracking studies on juvenile and adult Pacific salmon and trout are occurring throughout the west coast from California to British Columbia. In addition, pilot projects are underway to study movements of these fish along the continental shelf (the POST project; Welch, in progress). Typical information acquired from these studies includes travel routes and speed. Most studies also collect information regarding the environmental conditions experienced by fish including water temperature, salinity, water flow, tidal current and direction, time of day, and habitat features (water depth and other characteristics).

Currently, there are four dominant manufacturers of acoustic tracking systems in North America (see Section 4). However, at this time it is difficult to point to any one acoustic tracking system as being the best choice under all circumstances, due to the relationship between system performance and the many environmental and biological variables that must be taken into account. Further, the technology is advancing so rapidly, with each manufacturer and non-commercial research agencies having somewhat different research and development projects, that it is difficult to keep informed regarding new capabilities. The major similarity among the different manufacturers is the development of smaller tags that can be effectively used on smaller fish. Research studies are typically not published until a few years following significant technological, and laboratory studies of fish behavior or physiology associated with the new technology are typically even further behind. In addition, research studies that are conducted to document new system performances often can provide only general rule-of-thumbs regarding performance or accuracy due to the specific particularities associated with the study site, and species or lifestage studied that limit the applicability to future studies.

Until recently, most acoustic studies of salmon have occurred with adults because tag sizes have been too large for smolts of most salmon species. A few studies were conducted during the late-1970s with Atlantic salmon smolts (Fried et al. 1978; Tytler et al. 1978; Thorpe et al. 1981). At the time, dummy tag studies demonstrated that fish about 200 mm in length, or larger, could accommodate the 4 to 5 gram commercially available tags at the time (McCleave and Stred 1975; Fried et al. 1976). Thorpe et al. (1981) utilized custom built acoustic tags to fit smaller Atlantic smolts around 120 mm or larger. The first smolt acoustic tracking study on Pacific salmon occurred in 1989 using tags weighing 2.5 grams in water on Coho smolts 159 to 215 mm in length in Grays Harbor, Washington (Moser et al. 1991). Several radio and acoustic tracking studies on yearling or sub-yearling Pacific salmon or steelhead smolts have recently been conducted, or are in progress, at numerous Columbia River hydroelectric structures (Timko et al. 2002; Steig 1999), the lower Columbia River and estuary (Shreck and Stahl 1996; McComas et al. 2001), the Columbia River plume (Welch personal communication), and Nehalem estuary, (Clements and Schreck 2003). In combination, these recent studies suggest a groundswell of acoustic tracking activity for Pacific salmon smolts in the Pacific Northwest.

Nearly all yearling Chinook smolts found in the Delta are less than 200 mm and most are less than 150 mm (Brandes and McClain 2001). Recent advances in acoustic tag development have reduced tag sizes to less than 1 gram in water that can be used to track sub-yearling fish as small as 90 to 100 mm in size, but such tags have limited longevity (around 1 to 2 weeks) and are not suitable for use with remote hydrophone/receiver stations. However, these tags are suitable for short-term, continuous, mobile tracking studies that would allow tracking of small numbers of salmonid smolts. Slightly larger tags, approximately 2 grams in size, are available that last 2 to 4 weeks and are suitable for use with remote stations and larger numbers of fish near 150 mm in size. Based on limitations of battery technology, it is unlikely that transmitters will get much smaller in the foreseeable future. Overall, it appears that acoustic transmitters have become sufficiently small to conduct tracking studies on yearling and sub-yearling Chinook smolts in the Delta. However, dummy tag experiments would be beneficial to assess the hypothesis that tags, and the associated handling attachment procedures, do not have an appreciable adverse effect on fish behavior.

Attachment methods for transmitters include external placement, esophageal insertion, or surgical implantation procedures. There are advantages and disadvantages for each of these methods and choice depends on the type of tag, the species of fish, and the purpose of the research. External tagging is primarily used when handling large fish due to the fact that fish can easily and quickly be tagged without anesthetic. However, there is an increased opportunity for disease and loss of tags. Esophageal insertion may be performed on either adults or juveniles, however, it is not recommended for medium to long-term studies on juveniles due to potential changes in feeding behavior (adults are not affected because they do not feed on their upstream migration). Esophageal insertion has several advantages including less invasive than surgery and associated anesthetic, reduced tag losses compared to external attachment, and reduced changes in swimming behavior. Disadvantages include lower retention rates than surgical implantation due to regurgitation. The disadvantages associated with external and esophageal insertion methods and the limited adverse affects associated with surgical implantation have led to surgical implantation becoming the preferred method for tagging for most juvenile tracking studies. Anesthetics (clove oil or MS-222) should be used during tag attachment to smolts, but may be optional for adults. Tests of attachment method effects on salmonids can be incorporated into dummy tag experiments designed to test tag size effects on smolts.

Various combinations of continuous mobile tracking, mobile tracking with search strategies, and/or remote hydrophone/receiver arrays should be considered depending upon the specific goals of a study. Continuous mobile tracking can be useful for observing behavior during short-term events such as tidal flow reversal events or opening or closing of the Delta Cross Channel. This method can also be useful for discerning adult salmonid homing guidance mechanisms and upstream migration routes through the various channels in the Delta. The disadvantage to continuous mobile tracking is that it is labor intensive and can result in low numbers of individuals tracked. However, it can provide information that cannot be provided from other tracking methods. Mobile tracking with search strategies provides intermediate benefits between continuous mobile tracking and remote stations by providing more information on intermediate fish locations than remote stations, but at a lower resolution than continuous tracking. This method can be labor intensive and may require some level of luck to locate dispersed fish over an area the size of the Delta. However, it can be used effectively if conducted on a frequent basis or with additional knowledge such as a recent detection at a nearby remote station. Remote hydrophone/receiver stations can allow calculation of overall rates of movement and survival across the Delta and can help in discerning travel routes if adequate numbers of stations are deployed. If logged data is downloaded frequently, it can then be used to help locate fish for mobile tracking with specific search strategies. Remote stations allow the collection of data on relatively large numbers of fish with lower labor costs.

Technology currently exists to develop a network of remote wireless hydrophone/receiver stations to track multiple fish species within Central Valley tributaries, the Delta, and San Francisco Bay, as well as the coastal ocean. New, relatively inexpensive, buoy-type monitoring stations with integrated hydrophones, receivers, and data recorders are a significant advancement in the technology, and greatly increase the ability to effectively track fish over a very large environment. Whereas previously researchers were saddled with high labor costs, land access challenges, and the threat of theft or vandalism, wireless systems offer never-before flexibility and expandability. It is also technologically possible to develop a system that could relay information from field monitoring stations located throughout the Central Valley directly to a computer database via satellite, cell phone, or radio technology.

In the near future, a regional workgroup dedicated to biotelemetry studies will become necessary for acoustic research coordination within the Central Valley. As the number of acoustic tracking studies increase in the region, coordination of these studies will become more important to ensure that conflicts over transmitter frequencies and pulse rates are minimized or that uniquely coded tags are utilized. A regional workgroup can provide a forum for exchanging experiences regarding different manufactures and equipment, analytical tools, and the results of studies; and for developing standardized fish capture, handling, and tagging procedures. Also, a workgroup may provide opportunities for developing coordinated research studies that could use shared remote station equipment, which would reduce project costs and increase overall coverage of monitored areas, as well as provide more readily available backup systems in case of equipment failures. Nevertheless, substantive differences in the acoustic technologies of the different manufacturers may prevent consensus on equipment choice because some studies may require products that can only be provided by one manufacturer.

Advancements in other technological fields should be considered when designing acoustic tracking studies. Six technologies of particular importance include sonar, Doppler current meters, Global Positioning Systems (GPS), Geographic Information Systems (GIS) mapping software, and 3-D mapping systems. Sonar is not a particularly new technology, but low-resolution sonar equipment is now relatively inexpensive and can provide real-time depth information during tracking. Doppler current meters are relatively new devices that allow real-time collection of water column velocity profiles. Although relatively expensive, they should be considered for projects where tidal currents are hypothesized to be an important component to migration behavior. GPS is now commonplace equipment and provides relatively precise locations of remote tracking stations and tracking boats that are presumed to be representative of tagged fish locations. In addition, GPS data can be downloaded directly into GIS software to allow real-time plotting of tracking boat movements. GIS mapping tools are useful for depicting fish movements relative to structures of interest (islands, shipping channels, etc) and overlaying other information such as depth data, current maps, shoreline vegetation, etc. 3-D mapping is a new innovation that has allowed a visual representation of fish movements near dams and bypass structures within the Columbia River and could be useful for studies near the Delta Cross channel or South Delta pumping stations.

Conclusions and Recommendations

The following is a list of conclusions and recommendations:

- Acoustic tagging studies can provide high-resolution data for better understanding the migratory behavior, survival, and habitat use of adult and juvenile salmon, as well as other fish species, in the Sacramento-San Joaquin Delta.
- New developments in acoustic tag miniaturization have produced transmitters sufficiently small to tag and detect fish as small as 90 to 100 mm including sub-yearling Chinook salmon.
- Acoustic 3-D technology may be effective for examining smolt behavior near the Delta Cross Channel or South Delta pumping stations.
- Paired releases of acoustically tagged smolts may be an effective method for determining relative survival of smolts from the Sacramento River that utilize the Delta Cross Channel.
- A dummy tag experiment should be performed to examine the effects of different transmitter sizes and attachment methods on any special status fish species acoustically tagged in the Delta where limited data regarding tag attachment effects exists.

- A tracking experiment should be performed to observe differences in residence times and behavior between juvenile hatchery and wild fish migrating through the Delta.
- Fixed hydrophone arrays can be used to examine the travel routes and migration rates of adult and juvenile salmon through the Delta.
- Various combinations of continuous mobile tracking, mobile tracking with search strategies, and/or remote hydrophone/receiver arrays should be considered depending upon the specific goals of a study.
- A network of remote wireless hydrophone/receiver stations can be established to track multiple fish species within Central Valley tributaries, the Delta, and San Francisco Bay, as well as the coastal ocean.
- A biotelemetry workgroup for the region is crucial for coordinating biotelemetry studies, developing standardized fish tagging and handling protocols, and sharing results and experience gained from various studies; and may provide opportunities for developing coordinated research studies using shared equipment that would reduce costs and increase overall research coverage.

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