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Tagging, Telemetry, and Marking Measures for Monitoring Fish Populations






A compendium of new and recent science for use in informing technique and decision modalities

Pacific Northwest Aquatic Monitoring Partnership – Special Publication

Keith Wolf and Jennifer O'Neal, Eds.

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PNAMP Special Publication: Tagging, Telemetry and Marking Measures for Monitoring Fish Populations

A compendium of new and recent science for use in informing technique and decision modalities

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Dedication

This science compendium is dedicated to all professional natural resource practitioners who monitor the condition and health of our environment and the animal populations that depend upon it. You are doing the studies and research that have provided the content for this presentation of methods for tagging and telemetry, and your work has played a pivotal role in the current and future use of these methods for decisions and policies derived from improved science and the assessment of fish populations and their habitats.

The essential elements are intended to provide an approach where specific strategies integrate with real-world ecological restoration and protection challenges. The goal is to deliver precise, cost effective and science-based, information, coupled with an explicit process for decision makers and managers. Our objective is to assist them in implementing effective protection, restoration, conservation and enhancement actions and programs. And, finally, the expectation of this work is to ensure that future generations of humans use the best available knowledge, procedures and technology so that animals thrive and distribute naturally and subsist together with people in a healthy natural world.

Keith Wolf and Jennifer O'Neal – Winter 2009

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Chapter 1.—Introduction: Tagging, Telemetry, and Marking Compendium Project

Keith S. Wolf[1] and Stephen M. Waste[2]

Goal and Objectives of the Compendium

The goal of this compendium is to integrate profiles of on-going, individual, disparate efforts implementing the science of tagging, telemetry, and marking (TTM) into a compilation of experience to inform the development of fish population monitoring. This is accomplished by meeting the following objectives:

- Provide the region with information and peer reviewed analyses to facilitate optimization of the use of TTM technology and designs in a comparable and consistent manner.
- Provide findings that are organized, peer reviewed, and communicated widely.
- Increase the opportunity for data collection to provide more reliable information and result in improved analyses and higher confidence in data analyses for making informed and more relevant decisions.

Rationale for the Compendium

According to the American Fisheries Society (AFS), it has been more than 20 years since the last effort to provide a comprehensive compilation of the information available on advances in TTM techniques. Today, it is unclear which of the methods previously identified best measure performance benchmarks. The lack of an updated compendium confounds the efforts of scientists and management executives to evaluate actions and gauge the effects of regional recovery, mitigation, trust, and or enhancement programs. The June 2007 issue of *Fisheries* (v. 32, no. 6) provides a clear and convincing rational for the Pacific Northwest Aquatic Monitoring Partnership (PNAMP) and its contributing authors to act:

> *Measurement is the key technique in most investigations of fish and shellfish. The ability to identify individual and groups of fishes, as well as their habits, movements, and mortality, is crucial to effective fisheries science. The methods used must be appropriate, accurate, and repeatable. While uncertainty is an integral part of dealing with biological systems, as scientists it is crucial that we use methods that minimize uncertainty in order to improve the conservation and sustainability of fisheries and aquatic resources. In June 1988, over 400 fisheries and aquatic scientists gathered in Seattle, Washington, for the "International Symposium and Educational Workshop on Fish-Marking Techniques." This landmark event included presentations on virtually every fish tagging method in use at that time. The ultimate product was the 1990 publication Fish Marking Techniques, American Fisheries Society. In the nearly 20 years since that symposium, the world of fisheries science has changed dramatically; the technologies and analytical procedures available for marking and monitoring fisheries have evolved as well. Fish marking technologies on the cutting edge two decades ago are now commonplace, and new technologies are developed yearly. Clearly, the time has come to bring together again global expertise on fish tagging techniques and data analysis.*

Defining the Problem: Improving Comparability in Data Collection

Modern fishery management programs use various TTM techniques to track animals during rearing and migration life phases, but typically answer only individual or a limited number of questions using probability statistics or inferential information. Fishery managers throughout the Pacific Northwest, and beyond, generally rely on natural "intrinsic" or human-applied "extrinsic" identification methods to distinguish individual animals or groups of animals of interest. Meristic information such as body size, coloration, scale patterns, run-timing, and other factors make up the bulk of intrinsic methods, while the use of internal and or external tags, acoustic transmitters, or "marks" such as fin clipping represent extrinsic methods.

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The data gathered from all population and behavioral methods have important implications in many diverse biological and ecological science and policy forums. However, these approaches rely on the assumption that individual animals are representative of the population from which they originate and thus provide unbiased data within the study design. Yet, both intrinsic and extrinsic approaches to animal identification have pros and cons, and information may be improperly interpreted or applied resulting in bias or misinformed management actions. For all these reasons, the practitioners of fishery science need to make a concerted effort to ensure consistency in data collection within and between intrinsic and extrinsic approaches, in order to grow the basis for comparability of data and the relevance of the information derived from those data.

Setting the Stage for Adaptive Management

Why is comparability of data important? Adaptive management is dependent upon biological confirmation that planned and executed actions have had the intended effect and changes can be made to make a program more effective or data increasingly more reliable. To evaluate the effectiveness of actions, plans and performance measures require unbiased data. This provides the building blocks for developing initial and testable hypotheses and for examination of assumptions and a much stronger science-based approach. In order for adaptive management to work, it must be supported by data that have been consistently collected in an accurate and transparent fashion.

In light of public investment and the constraints of science and management, many in government and the public are rightfully insisting that organizations managing TTM programs coordinate efforts and use comparable data-collection techniques. At present (2010), Most project-scale monitoring efforts lack comparability, and therefore utility, in terms of supporting subsequent use at higher scales. Put simply, if monitoring within individual projects is unnecessary, duplicative, or deficient in design and application, then such efforts are not beneficial and resources should be allocated differently.

For example, most population monitoring programs are unable to provide regionally comparable or spatially relevant information that can result in data with intractable variability from year to year. Therefore, the objective of PNAMP's TTM project was to facilitate the development of comparable data by increasing consistency across individual and/or subregional stock information for regional, population, and or fishery management inferences using the most current technology, collaborations, designs, and methods.

To reinforce this point, several retrospective and contemporary analyses have indicated that there is little to no continuity in the application of monitoring in the large and expensive restoration programs at this time. These programs continue using methods or designs that have not been considered within the context of multiple high-level management questions identified by PNAMP and others, and have not provided robust datasets that focus on specific indicators. The resulting uncertainty, assumptions, and outdated methods do not provide satisfactory information to inform management needs regarding issues such as atypical mortality, pre-season forecasting, post-season run reconstruction, and smolt-to-adult estimates, and do not provide probable causes and corrective actions.

The fundamentals of producing comparable data with high confidence to assess viability, sustainability, spatial distribution, and/or genetics warrant further development. More specifically, research, monitoring, and evaluation (RME) programs conducted in isolation, with no set of common guiding management goals, objectives, consistent methods, adequate training, basic data management infrastructure, analytical consistency, or quality control introduce a very high level of risk to decision making. This makes it much more difficult, or even impossible, to implement resource management policies because the science itself suffers from poorly documented results. This point is a primary concern identified by professional scientists, policy and decisionmakers, funding entities, multiple stakeholders, Congress, and front-line managers. Another challenge is the lack of long term commitments to funding, which has handicapped much of the RME work in the region, e.g., intermittent or short-term funding and support for TTM programs.

These factors have contributed to a present-day situation that continues to enable: harvest levels set on questionable and imprecise data analysis; unanswered questions about the role and effects of artificial production; an inability to identify limiting factors; and actions that may in fact exacerbate the sustainability and long-term viability of species. As a result, science integrity and subsequent policy cannot be relied upon as "best science." Consequently, natural resource management and courts make questionable decisions based on variable interpretations of poorly documented or inadequate data. This has triggered a call for increased collaboration, objectivity, statistical confidence, and fiscal accountability.

Rationale for a Product-Based Approach

To determine whether work currently underway is sufficiently addressing the region's most pressing data and decision needs, PNAMP chose to deliberately compare new and emerging technologies with existing research designs and implementation techniques. This effort was led by various regional managers, science experts, and agency representatives through their participation in the Fish Population Monitoring Workgroup (FPM), the TTM Editorial and Review

Subcommittee (ERC), and the PNAMP Steering Committee (see Acknowledgments for more detail).

Another objective of the compendium is to provide the widest range of information possible and to organize it into logical categories of topics and techniques. This was important because the updated information on modern TTM was developed by an extensive and diverse group of scientists, professional societies, and policy leaders. The TTM techniques, technology, protocols, and methods in the compendium are used by more than 31 population monitoring divisions/subdivisions of State, Federal, Provincial, Tribal, and private agencies and organizations. The geographic scope of the TTM compilation includes all species of Pacific salmon and many marine and resident fishes in Washington, Oregon, Idaho, British Columbia, and northern California. In many cases, the TTM techniques, technology, protocols, and methods in the compendium also are relevant to the monitoring of wildlife species as well.

The compendium presents the most commonly used fish population monitoring tools that support contemporary management decisions. Designing studies to collect unbiased data is essential to the evaluation of the effectiveness of actions, plans, and performance measures. They provide the building blocks for developing testable hypotheses and intermittent confirmation of assumptions under standard designs. TTM acquired data can inform the activities listed in End Note 1.

Currently, the region is focused on identifying key indicators, milestones, protocols, and essential technical and logistical methods that will provide information addressing high-level management questions. This project will facilitate these efforts and improve coordination and collaboration. It is important to note that increased comparability will improve accountability.

Peer Review Process

In three calls for papers beginning in August 2007 at the AFS Annual Meeting in San Francisco, we sought out manuscripts on topical areas from new and existing information on:

- New Studies and Advancements in TTM Technology
- Methods, Techniques, and Designs
- Previous and Existing Approach Analysis
- Reviews of Ad-hoc Efforts and Programs
- Use of Technology for Analysis, Model Input, and Reporting
- Case Studies
- Adaptive Management Processes
- Previously Updated Documents
- Published Notes
- Need, Value, Approach, and Historical Perspectives

Authorship of the ten main Chapters and the five Special Sections came from 127 contributors representing about 39 State, Federal, Tribal and academic entities, as well as several non-governmental organizations. Once papers were received, the FPM WG and the editors initiated a workshop to establish the Editorial Review Committee (ERC). All ERC members are experts in natural resource monitoring, ecology, fish passage, tagging, marking, and/or telemetry. They conducted a team peer review of Chapters 2-9 to guide the publication's content, flow, and utility. Furthermore, all U.S. Geological Survey (USGS) contributions were subject to an internal review and an additional policy review by the agency. Finally, an additional five papers and all Special Session abstracts were previously published and/or subjected to AFS, university graduate work committee, and other review processes.

Team members reviewed one to three papers each, with each paper reviewed by at least two team members. They used an electronic review form to document questions, establish the validity of the paper, verify assumptions and the application of the techniques, and comment on overall quality and methods. The review included three parts: (1) a set of questions to evaluate the manuscript's content and accuracy; (2) a list of applicable management questions that were evaluated for how well the manuscript addressed them; and, (3) a section for providing two or three brief paragraphs summarizing the paper for possible future research or use in the region. Sample questions dealt with topics including: (1) an overall rating of the paper; (2) an assessment of the technical accuracy, clarity of presentation and how well the paper's topic was addressed; (3) whether the research questions were clearly stated; and (4) an assessment of the clarity of tables, figures, and charts. Each form was then provided to the second reviewer and the reviewers collaborated among themselves and the authors to complete the review.

The ERC confirmed that TTM data provides an information source that can be used to aid decision-making regarding policy and the management and monitoring of aquatic populations and their ecological attributes in the Pacific Northwest and other regions. The ERC also recognized that publication can help to inform and increase the robustness of research, monitoring, and evaluation tools. Many participants have commented that this product will serve important purposes at many levels as it is disseminated by the PNAMP Steering Committee and should therefore be used by regional leaders and managers.

PNAMP Sponsorship

In 2005, agencies and leaders of aquatic monitoring programs throughout five western states formed an alliance now known as the Pacific Northwest Aquatic Monitoring Partnership (PNAMP). This group is also supported by non-governmental organizations, expert consultancies, professional science societies, and the public (see End

Note 2). The rationale for this group's goals and objectives is that monitoring, data quality, and decision success will be improved if:

> …programs use more consistent monitoring approaches and protocols; follow a scientific foundation; support defined and harmonized monitoring policy and management objectives; and, collect and present information in a manner that can be shared.

The compendium is sponsored by the FPM, one of eight active PNAMP subcommittees, which is dedicated to advancing the science of monitoring and evaluation. This is done in several ways including broad collaboration, workshops, and communications such as reports, publications, and strategic plans. The FPM provides recommendations and contemporary research information for monitoring fish populations and the conditions of their biological and physical needs in the Pacific Northwest. The most recent FPM strategic plan identified as its top priority a comprehensive compilation of TTM techniques that would unify distinct and individual programs, projects, and research applications in a simple resource compendium. In response, the workgroup developed this document to provide the foundation for communicating information on TTM techniques for fish population monitoring. Thus, this compendium was developed through a high degree of collaboration from a variety of authors and authorship teams from State, Federal, and Tribal management agencies, experienced individuals, and private companies and institutions who contributed manuscripts and/or abstracts.

End Note 1. Set of Management Activities Affected by TTM

1. Status and Trend Fish Population Monitoring;
2. Run-Size Forecasting;
3. In-Season Harvest Monitoring;
4. Harvest Allocation;
5. Harvest Rates by Population;
6. International Harvest Allocation and Rates;
7. Delayed Mortality;
8. Hooking Mortality;
9. Predator Indexing, Standing Stock, and Juvenile Consumption Rates;
10. Post Season Evaluation;
11. Escapement;
12. Smolt-to-Adult Ratio (SAR) Calculations;
13. Adult and Juvenile Survival Studies for Viability and Sustainability;
14. Spatial Distribution;
15. Habitat Productivity;
16. Estuary Use and Survival;
17. In River Habitat and Microhabitat Use:
18. Ocean Use, Survival, and Productivity;
19. Migration Routes;
20. Run Timing;
21. Passage Routes, Mortality, and Survival;
22. Total Gas Saturation Monitoring;
23. Benchmarks and Performance for Mitigation and Recovery Actions;
24. Habitat Action Effectiveness Monitoring;
25. Watershed Condition Monitoring;
26. Genetic Stock Identification;
27. Otolith Microstructure and Microchemistry Techniques;
28. Hatchery Evaluation;
29. Supplementation Studies;
30. Stray Rates and Locations;
31. Research, Monitoring, and Design Evaluation; and
32. Validation Studies for Legally-Mandated, International Adjudicated, and/or Interlocal Agreement Monitoring.

End Note 2. The Pacific Northwest Aquatic Monitoring Partnership (PNAMP): Background

PNAMP:

- Provides a forum to coordinate monitoring activities and develop common monitoring approaches.
- Acknowledges different mandates, jurisdictions, issues, and questions of its partners.
- Focuses coordination effort on shared interests and needs.
- Coordinates programs and schedules to avoid duplication.
- Applies common guiding principles to provide significant support to policy and management with scientifically valid monitoring.
- Provides the framework for coordinated monitoring that each PNAMP partner may implement within its legal and jurisdictional boundaries.
- Allows its partners to decide their own individual management questions, which then guide development of PNAMP monitoring strategies.
- Requests that partners make reasonable efforts to incorporate PNAMP recommendations into their respective programs.
- Receives support from partners through allocation of staff time to participate in PNAMP and through contributed resources for administration of the effort, as appropriate.

Chapter 2.—Overview of the Coded Wire Tag Program in the Greater Pacific Region of North America

George F. Nandor[1], James R. Longwill[1], and Daniel L. Webb[1]

Abstract

The coded wire tag (CWT) was introduced in the greater Pacific region (Alaska, British Columbia, Washington, Idaho, Oregon, and California) in the late 1960s as an alternative to the fin clip and external tag for identification of anadromous salmonids—particularly hatchery origin fish. Coastwide use of the CWT quickly followed, and fisheries agencies in Alaska, British Columbia, Washington, Oregon, and California established ocean sampling and recovery programs. In 2009, 47 Federal, Provincial, State, Tribal, and private entities release more than 50 million salmonids with the CWT yearly. Regional coordination of these tagging programs is provided by the Regional Mark Processing Center (RMPC) operated by the Pacific States Marine Fisheries Commission (PSMFC). The center also maintains a centralized database for coastwide CWT releases and recoveries, as well as for associated catch and sample data. CWT data are provided to users through an interactive on-line data retrieval system.

An expert panel review of the CWT system in 2005 identified specific problems with the CWT system. In 2008, a CWT workgroup developed a response and an action plan to address those problems. Solutions included measures to increase the precision of the data through increased tagging and sampling, use of electronic tag detection methods, and more rigorous self review of agencies' procedures.

After 40 years, the CWT program in the greater Pacific region of North America continues to be the most important tool for salmonid research and management. The CWT system has served critical management and research needs for many years and remains the only stock identification tool that is Pacific coastwide in scope and provides unparalleled information about ocean distribution patterns, fishery impacts, and survival rates for Pacific salmon along the Pacific coast.

Introduction

The CWT is widely used by fisheries agencies on the West Coast of North America as a tool to collect information on natural and hatchery reared stocks of salmon and steelhead (*Oncorhynchus* spp.). Information from CWTs is used by these agencies to evaluate hatchery contributions to catch, smolt to adult survival rates, spawner abundance on spawning grounds, differential in-hatchery treatments, and other related studies that may be important for fisheries management and research.

The migratory nature of salmonids necessitated the development of a cooperative coastwide effort for using tag codes, sampling fisheries, tag recovery, data collection, and data exchange among all fisheries agencies in the U.S. and Canada. This paper presents an overview of the CWT system now in place and a brief history of its development.

History

The invention of minute CWTs (0.25 × 1.1 mm) that could be easily implanted in the tough nasal cartilage of juvenile salmonids (fig. 1) greatly changed marking studies because of this tag's numerous advantages over fin clipping. The first tags were developed in the 1960s (Jefferts et al., 1963; Bergman et al., 1968) and carried up to five longitudinal colored stripes. More than a dozen different colors provided approximately 5,000 different codes, compared to the 15–20 fin mark codes normally used to identify groups of fish.

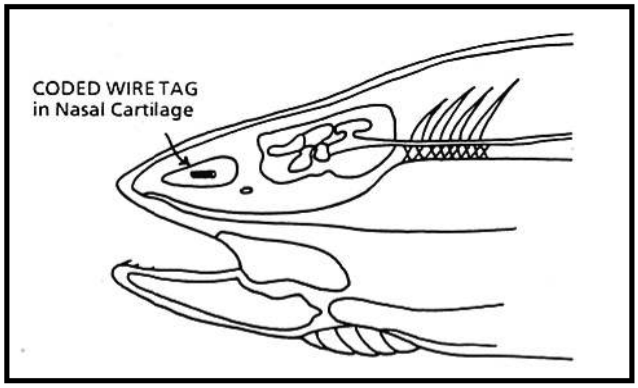

Figure 1. Longitudinal section through the head of a juvenile salmonid showing the correct placement of a CWT in the nasal cartilage. (After Koerner, 1977; extracted from Johnson, 2004.)

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Binary coded tags were introduced in 1971 by Northwest Marine Technology, Inc. (NMT). These new tags quickly replaced color coded tags because of their greatly improved readability and the enormous number of available codes per agency. In 1971, 250,000 unique codes were available on standard length binary tags (1.1 mm). The new tags provided unique codes for many years, and additional tens of thousands of binary codes were possible with a slight format change (such as adding alphabetic letters) on the wire (Johnson, 1990).

The large number of available binary codes, low cost per tag, ease of application, and high retention rates opened the way to large-scale experimentation by tagging agencies, including multiple experiments on any single stock of fish, because all experimental groups could be accurately identified regardless of recovery location or time. Another major advantage was that all experimental groups could be treated the same during the tagging process, thus reducing the variability in survival and behavior imparted by clipping different fins.

In 1985, a significant development was the introduction of sequentially coded wire tags (s-CWT), at that time using binary coding, and currently, using decimal codes. These allow identification of small batches of tags cut from the same spool, and even individual identification. Although for many large-scale projects, the standard coding system, where all tags cut from a spool are identical, is all that is required, the s-CWT made a wide range of smaller scale projects viable (Solomon, 2005).

The present decimal coding system was introduced in January 2000. More than 1 million different batch codes are available with this new decimal tag code system, providing capacity for many years to come (Solomon, 2005). Because the decimal system is much easier to read and decode, errors have decreased and data accuracy has been enhanced.

In 1977, the region agreed to reserve the adipose fin removal mark as an indicator flag of a tagged coho (*O. kisutch*), Chinook salmon (*O. tshawytscha*), or steelhead (*O. mykiss*) (Pacific Marine Fisheries Commission Memorandum, 1977). This was later expanded to include chum (*O. keta*), sockeye (*O. nerka*), and pink (*O. gorbuscha*) salmon (Pacific Marine Fisheries Commission Memorandum, 1978).

In 1996, the States of Oregon and Washington decided to adipose fin clip all hatchery reared coho smolts, not just the ones with CWTs, before release thereby implementing mass marking of hatchery reared coho. They did this to implement mark selective fisheries, manage hatchery broodstocks, and to determine the population composition and origin of natural spawners. Soon after, Canada also began mass marking hatchery reared coho that were released from their hatchery facilities in Southern British Columbia. Recently, most hatchery reared Chinook released into the Columbia River also have been mass marked and the practice is expanding to salmon releases up and down the Pacific Coast. In 2008, more than 37 million coho and more than 101 million Chinook were mass marked (Pacific Salmon Commission Selective Fisheries Evaluation Committee, 2008). In the past, fish were checked for a missing adipose fin to indicate that it had a CWT. Due to mass marking, it is necessary in many sampling areas to use electronic metal detectors to detect CWTs, such as handheld wands to pass over the salmon's snouts and tube detectors to pass the fish through.

Management Needs

Many State, Federal, Tribal, and private reporting agencies in the U.S. and Canada participate in a massive coastwide coded wire tagging effort to provide essential data for effective conservation and management of Pacific salmonid stocks. This information provides the basis for monitoring the fisheries, allocating harvest rights among competing domestic users, improving productivity of hatchery stocks, establishing escapement goals, and satisfying Tribal treaty obligations. These data also play a key role in the U.S. – Canada Salmon Treaty allocations and management of transboundary stocks. The data from CWTs are the primary management tool on the Pacific Coast used to allocate salmon catch in the various sport, commercial, and Tribal fisheries. Fishery management agencies rely on CWT data because the CWT program includes fully integrated tagging, sampling, and recovery operations along the entire West coast of North America. CWTs provide sufficient resolution for stock specific assessments, and coded wire tagging is the only stock identification technique for which a historical record back to the mid-1970s of stock specific assessments may be computed. No other practical mark-recovery system has yet been devised that is capable of providing such a high level of detail in a very timely fashion (Pacific Salmon Commission, 2008).

The historic success of the CWT program has been in no small part due to the high level of coordination and cooperation among the coastal U.S. and British Columbia and to the consistency of CWT tagging and recovery efforts across the many jurisdictions. Despite the emergence of other stock identification technologies, including various genetic methods and otolith thermal marking, the CWT recovery program remains the only method currently available for estimating and monitoring fishery impacts on individual stocks of coho and Chinook salmon when implementing fishing agreements under the Pacific Salmon Treaty (Hankin et al., 2005).

It is essential that the data from coded wire tagged salmon releases and their subsequent recovery is available to all fisheries management agencies and their analysts in order to make scientifically based decisions. The PSMFC hosts the RMPC. This office maintains the on-line Regional Mark Information System (RMIS) to facilitate exchange of CWT data among release agencies, sampling and recovery agencies, and other data users. The on-line query system is available at: http://www.rmpc.org. The RMPC also serves as the U.S. site for exchanging U.S. CWT data with Canada for Pacific Salmon Treaty purposes. Through this data exchange, both the U.S. and Canada house a complete copy of Pacific coastwide CWT datasets.

Tag Description and Tagging Methods

The CWT is a small length of stainless steel wire 0.25 mm in diameter and typically about 1.1 mm in length, although one-half, one and one-half, and double length tags also are used in some circumstances. The tag is coded with a series of factory-etched decimal numbers, which allow identification of the spool of wire (typically 10,000 tags) from which it was cut (standard format, see fig. 2), or the particular batch, or even the individual fish (sequential format). The tag is cut, magnetized, and implanted into suitable tissue with an injector; two types are widely used. The Mark IV is an electrically operated machine suitable for marking large numbers of fish, while the Handheld Multishot Injector is used where smaller numbers are involved. The usual target tissue in small salmonids is an area of muscle, connective tissue, and cartilage in the snout, but a number of other sites also are used, particularly in non-salmonids (Solomon, 2005).

Tags are injected into fish using a range of injectors, which are in widespread use. The Mark IV automatic tag injector is designed for large-scale projects tagging thousands or even millions of fish (see fig. 3). The handheld multiple shot tag injector is available for portability in the field and generally used for tagging hundreds or possibly thousands of fish. A single shot injector is available for laboratory trials and small-scale experiments tagging up to a few hundred fish. The newest system is the high capacity AutoFish system (see fig. 4), which is a self-contained system housed in a large trailer and can process 60,000 fish in 8 hours and is used to tag several million fish per year. It accomplishes adipose fin clipping and/or coded wire tagging without the fish being anesthetized or touched by humans (Solomon, 2005). The AutoFish system results in very high tag/mark retention rates. Retention rates ranged from 98.45 to 100% in California in 2008 (Pacific States Marine Fisheries Commission, 2008).

Figure 2. A magnified section of coded wire before it is cut and inserted as a tag (photograph by NMT).

Figure 3. Interior of a manual tagging trailer using Mark IV tag injectors (photograph by George Nandor).

CWTs have some advantages over other tag types or tag systems. They can be used on very small fish, down to 22 mm in length; they have minimal impacts on fish survival (Vander Haegen et al., 2005), growth, and behavior (Quinn and Groot, 1983); the tags have high retention rates over periods of years and with fish growth (Munro et al., 2003); coding capacity is almost unlimited; tags are inexpensive allowing for large numbers of fish to be tagged; and tags are easily identified and decoded if recovered anywhere in the world.

Figure 4. Interior view of an AutoFish trailer (photograph by George Nandor).

Coastwide Coordination

The coastwide CWT system—including the services of the RMPC—are coordinated through the activities of two principal organizations: (1) Regional Committee on Marking and Tagging (Mark Committee); and (2) Pacific Salmon Commission (PSC—established by the U.S.–Canada Pacific Salmon Treaty).

Regional Committee on Marking and Tagging (Mark Committee).—All tagging and recovery agencies on the Pacific coast are represented by the 14-member Mark Committee (appendix A, table A1). PSMFC's Regional Mark Coordinator serves as chair for the committee. Agency membership includes mark coordinators for the five member States of PSMFC (Alaska, Washington, Oregon, Idaho, and California), the National Marine Fisheries Service (NMFS), U.S. Fish and Wildlife Service (USFWS), Canada Department of Fisheries and Oceans (CDFO), British Columbia Ministry of Environment, Fish and Wildlife Branch, and the Metlakatla Indian Community in Southeast Alaska. In addition, the Northwest Indian Fisheries Commission (NWIFC) coordinates the tagging and fin marking activities of 20 Treaty Tribes in western Washington. The Columbia River Intertribal Fish Commission (CRITFC) serves the same role for four Tribes in the Columbia River basin (Regional Mark Committee, 2001). Private aquaculture, universities, and other nongovernmental organizations are coordinated through the respective State or Provincial coordinator.

The Mark Committee provides oversight and guidance to the RMPC. In addition, the Mark Committee meets each year in the spring to expedite coastwide coordination of fin marking and tagging activities. Regional agreements are reviewed and updated if necessary during this annual meeting.

Regional agreements and restrictions on fin marking and CWT usage are reached by committee consensus after thorough discussion of the issues. A 30-day review period follows publication of the Mark Meeting minutes to allow for agency reconsideration of an issue if necessary. If no objections are raised, the agreement stands as recorded in the minutes.

In those situations where unanimity cannot be achieved, the decision is reached by a two-thirds majority affirmative vote. All issues referred to a vote require a quorum of at least 75% of the committee members being present. Twelve votes are possible (appendix A, table A1). A single vote is assigned to the State/Province level or Federal agency level regardless of the respective number of coordinators serving on the committee (Regional Mark Committee, 2001).

The Mark Committee does not have any legal authority to enforce the regional agreements. Therefore, cooperation and compliance are voluntary. This has not been a serious weakness since all agencies mutually benefit from the cooperative environment. Implicit peer pressure among the agencies has supported the system because noncompliance can negatively affect studies of other agencies.

Pacific Salmon Commission U.S.–Canada Treaty.—PSC commissioners agreed in November 1987 that no unified U.S.–Canada CWT database would be established under the auspices of the commission. Instead, it was agreed that each country would maintain a single database, with parallel structure, to expedite exchange of CWT data between the two Nations.

The U.S. commissioners subsequently considered the site for the U.S. database and selected PSMFC's RMPC. This position was supported by the Working Group on Mark Recovery Databases. Advantages of the RMPC cited by the working group included long-term experience in CWT data administration, coastwide representation of all fisheries agencies, well-established coordination and reporting procedures, no start up costs to PSC, reduced time for implementation of the new formats, and lack of vested interest in any data interpretation or applications. The RMPC's primary role is to collect, validate, archive, and exchange U.S. data with Canada in the PSC data exchange formats (Pacific Salmon Commission Joint Technical Committee on Data Sharing, Joint Working Group on Mark Recovery Databases, 1989).

Role of PSMFC's RMPC

In 1970, Oregon's RMPC formally became the regional center when it was funded through the Anadromous Fish Act (Public Law 89 304) to establish and maintain a regional database for mark recoveries. In 1988, the RMPC was selected by the U.S. Section of the PSC to house and maintain the CWT database in the U.S. and to be the designated site for sharing data with Canada (Pacific Salmon Commission Joint Technical Committee on Data Sharing, Joint Working Group on Mark Recovery Databases, 1989).

In general, the RMPC supports and facilitates the ongoing CWT-related needs of: (1) the member States of the PSMFC; (2) the Regional Committee on Marking and Tagging (Mark Committee); and (3) the PSC.

Regional Coordination Role

The RMPC provides coordination for marking programs by: (1) establishing regional agreements for fin marking and use of CWTs with the assistance of agency coordinators; (2) recommending changes for upgrading the regional CWT database to meet expanding or changing user requirements; (3) assisting agencies to improve timeliness of reporting, with special emphasis on tag recovery data; and (4) developing recommendations for improving coordination and quality of CWT studies, with emphasis on experimental design, sampling design, estimation procedures, statistical problems, and documentation.

Data Management Role

The RMPC manages data by: (1) maintaining and upgrading a regional database for all CWT releases and recoveries, plus release data for fish groups given other types of marks; (2) ensuring that reported data meet established format standards and pass validation procedures; (3) developing and maintaining on-line computer applications for querying and reporting from the database—known collectively as the Regional Mark Information System (RMIS); (4) providing electronic copies of data sets upon request; and (5) implementing recommended changes in the regional database exchange formats to meet expanding requirements for new information.

The primary focus of the RMPC's data management activities since 1977 has been to serve as a clearinghouse for CWT release and recovery data, with special emphasis on timely reporting of data, standardization of data formats, and integrity of the data. Analysis of the politically sensitive recovery data, however, has remained the responsibility of the reporting agencies and other interested data users in order to maintain the RMPC's neutrality and the trust of all agencies submitting data.

Tagging and Release Programs

Scale of Tagging Effort and Cost

Coastwide, more than 50 million juvenile salmon and steelhead are now coded wire tagged annually by some 47 State, Federal, Tribal, and private entities in the U.S. and Canada (appendix A, table A2). Chinook salmon tagging levels are the highest (circa 40 million), followed by coho salmon (7–9 million), and steelhead at about 1.5 million. (Tagging of other species in recent years has been of minor importance—occurring at levels in the mere tens of thousands annually). This massive tagging effort involves approximately 1,100 new tag codes each year. Hundreds of separate studies are involved.

Total tagging cost exceeds US $9 million annually. The cost per individual fish ranges between 15 and 20 cents, depending on local labor costs, logistics of tagging, and number of tags purchased for a given code. (Individual tags range between 8.7 and 16.4 cents each, with price determined by order size and delivery time.)

There also are costs in recovering CWTs. These costs are associated with sampling the various fisheries, spawning ground surveys, sorting and enumerating returning adults at fish hatcheries, and finally dissecting the snouts and reading the tags in tag recovery laboratories. These costs are often difficult to define since they usually are part of larger fish management program budgets. The Alaska Department of Fish and Game estimated in 2004 that their sampling cost was approximately $20 per tag and their cost to dissect and decode the tag in the lab and make the data publicly available was another $18 per tag (Clark, 2004). Approximately 275,000 tags are recovered each year at a cost of $12–13 million annually (Hankin et al., 2005).

Current Uses of CWT Data

CWT data are used in hatchery management to evaluate rearing and release experiments, to estimate adult production, and to manage broodstocks, harvest, and natural populations (i.e., natural spawning population composition) (Independent Scientific Review Panel and Independent Scientific Advisory Board 2009).

Although there are many kinds of tagging studies, they can be divided into three basic types (Pacific Marine Fisheries Commission, 1982): experimental (e.g., multiple comparisons), stock assessment, and stock contribution. Contribution is defined as the number of fish of a defined group occurring in a specific fishery. Fishery, as used here, is defined in a broad sense to include harvest and escapement (fish that return to natal streams to spawn).

Experimental tagging studies in hatchery management are designed to compare the relative survival or contribution of two or more experimental groups to the fisheries. Studies in this category deal with diet comparisons, time or site of release, pond density factors, disease control, and genetics.

Stock assessment studies (from generally a hatchery viewpoint) have localized objectives and are designed to measure contributions and distributions of particular stocks among various fisheries, as well as escapement of those stocks. With this information, the success of a hatchery's production or of natural production can be evaluated. The data also may have value to fishery management if adequate numbers of fish are tagged.

Stock contribution studies also are done for stock assessment purposes; however, the focus is from the fishery management perspective. In this case, fishery managers seek information on the contribution rates of key stocks in a given fishery (by time and area strata) in order to better manage harvest rates for conservation of the resource. The major difference between stock assessment and stock contribution studies is in the number of fish tagged. Stock contribution studies require far more tagged fish to generate meaningful recovery rates on a regional basis.

Tagged Releases of Salmonids—Total Amounts Released

Tagging programs are carried out at more than 260 Federal, State, Tribal, and private hatcheries and rearing facilities on the West Coast. In addition, natural origin fish are trapped and tagged at numerous sites. The principal tagging facilities are presented by State and Province in appendix A. Unless otherwise noted in the legend, the facilities are operated by the State or Province. Sites for tagging naturally produced fish in streams are not plotted because they are too numerous. Coastwide totals for all fishes released known to contain a CWT are shown in appendix A, table A3.

Tagging agencies also may opt to use so-called "blank wire" tags to mark some hatchery stocks. In the past, blank tags literally were blank in that there was no code present. Northwest Marine Technology, Inc. has since replaced them with 'agency only' blank wire so that the responsible releasing agency can be identified. It differs in that the wire carries a single (2-digit) code for the agency. As such, the tag carries limited information on the origin of the tagged fish based on the agency code.

Blank wire tags and agency-only wire tags are not CWTs. They physically look like CWTs, are injected in the same manner as CWTs and have similar magnetic properties enabling them to trigger automatic diversion gates and electronic CWT detectors; however, blank wire and agency-only wire tags do not possess a specific etched binary or decimal code and, upon recovery, cannot be resolved to a specific tag code (Pacific Salmon Commission Data Standards Work Group, 2009).

Blank wire was used by various agencies in situations where stocks need to be marked for identification purposes only. For example, the Washington Department of Fish and Wildlife (WDFW) and NMFS operated a trap at Lower Granite Dam (lower Snake River) to selectively remove tagged fish while untagged fish were allowed to pass upstream.

The incentive for using blank wire is simply reduced cost over full CWTs. The current price for blank wire is $38 per 1,000 tags as compared to $92 per 1,000 tags for CWTs, depending on quantities purchased. By coastwide agreement, re-use of tag codes is not approved (Regional Mark Committee, 2001). In those cases when a tag code is re-used, whether by accident or intentionally, any subsequent recoveries may be regarded as unresolved discrepancies as determined by the agency reporting the tag recovery (Pacific Salmon Commission Data Standards Work Group, 2009). All coastwide releases known to contain blank or agency-only wire tags are shown in appendix A, table A4.

Tagged Releases of Salmonids – Releases by Location

See the figures and tables in appendix A for historical release numbers, maps, and facilities information regarding the greater regional geography of releases:

- Alaska State: Figures A1–A3, Tables A6–A7
- British Columbia Province: Figures A4–A6, Tables A8–A9
- Washington State: Figures A7–A9, Tables A10–A11
- Oregon State: Figures A10–A11, Table A12
- Idaho State: Figures A12–A13, Table A13
- California State: Figures A14–A15, Table A14

CWT Sampling, Recovery, and Abundance Estimation Procedures

Many agencies release tagged salmonids, but the burden of ocean tag recoveries falls on five agencies: Alaska Department of Fish and Game (ADFG), CDFO, WDFW, Oregon Department of Fish and Wildlife (ODFW), and California Department of Fish and Game (CDFG). In the lower Columbia River, ODFW and WDFW jointly share the primary responsibility for sampling the commercial, Tribal, and recreational fisheries. A sixth agency, Idaho Department of Fish and Game (IDFG), also samples its freshwater fisheries and hatchery returns for CWT-marked fish.

In addition, the 20 western Washington Treaty Tribes jointly carry out a sizable and important component of the coastwide sampling effort. Their Tribal fishery recovery information is combined with non-treaty recoveries and processed by WDFW. The Quinault Nation, Quileute Tribe, and Colville Tribe, however, maintain their own recovery and reporting programs.

Limited sampling is conducted by a few other agencies. In Alaska, NMFS and the Metlakatla Indian Community maintain sampling programs for their respective fisheries and escapement. In the upper Columbia River (Washington), the Yakama Tribe maintains a CWT sampling program. The Nez Perce Tribe likewise has a sampling program for the Snake River in Idaho. Their respective CWT recovery datasets are submitted to the RMPC. Lastly, USFWS maintains a sampling

program on the Klamath and Trinity Rivers system in northern California, as well as sampling programs at its various salmon and steelhead hatcheries in Washington, Oregon, Idaho, and California.

Sampling Design

The sampling programs of the participating agencies are comparable in overall design but differ in many specifics because of constraints imposed by local conditions and differing approaches to mark recovery. There are, however, common elements of the major recovery programs.

All major recovery programs sample landings of commercial marine and mainstem river fisheries for CWT-marked Chinook and coho salmon. Electronic tag detection equipment is used by Oregon, Idaho, and Washington to sample Chinook and coho salmon landings. In British Columbia, electronic sampling is limited to coho landings. In California and Alaska, visual sampling for adipose clips is the only method used to retrieve CWTs. Representative samples are randomly taken at ports throughout the State or Province at appropriate time intervals, ranging from days to weeks, to track changes in stock composition in the harvest and to also estimate survival rates for the intercepted stocks of interest.

An important component also is the sampling of recreational fisheries. The emphasis typically is focused on sampling day boats and charter boats in marine waters. Creel sampling also is carried out in some inland fisheries.

Another common element is the sampling of escapement. This includes both returns to the hatchery and surveys of the spawning grounds. Historically, spawning ground surveys have been the weakest component of the sampling coverage by nearly all recovery agencies in that they are infrequently sampled for tags. However, it has received ever increasing attention and importance with the implementation of the Pacific Salmon Treaty and recommendations from CWT program reviews.

All recovery agencies strive to randomly sample at least 20% of commercial and sport landings to have a statistically acceptable estimate of total tag recoveries for a given area-time stratum. Hatcheries generally are sampled at high rates, often at 100%. When sampled, spawning locations are sampled at levels up to 50% (Pacific Salmon Commission, 2008). In some cases, fisheries sampling coverage may exceed 50% if landing port coverage by samplers is high (Nandor et al., 2008).

Coastwide, CWT sampling coverage has some limitations. Chinook and coho salmon are the only species sampled in commercial and sport fisheries, both marine and freshwater, on a coastwide basis. Sampling and reporting is very well coordinated for Chinook and coho through various joint technical committees within the region. Some sampling does occur for chum, sockeye, pink salmon, and steelhead. In such cases, it typically involves agency-specific management objectives in marine terminal areas or limited freshwater areas.

Catch and Sampling Procedures (Visual and Electronic)

Field samplers typically work on the docks and sample commercial landings at buying stations. Recreational vessels also are sampled as they return to port. The basic sampling unit is the boatload of fish, not the individual fish. Samplers attempt to randomly sample vessels, whether they are day boats or trip boats. In the latter case, some of the larger vessels must be subsampled because of the size of the catch. Bins of fish then become the sampling units.

Sampled fish testing positive for the presence of a CWT (electronic sampling, see fig. 5) or missing the adipose fin (visual sampling) are set aside for removal of the head or snout. The sampler then records species, sex, and fork length of the fish on a small waterproof label and encloses it with the head in a plastic bag for later processing. Scale samples and weight information also may be collected.

Information on the sampled unit (boat load or bin) is recorded on a sample form. This typically includes catch location, catch period, gear type, processor, species, total fish sampled, total marks recovered, and sample date.

Figure 5. Electronic sampling of commercially caught Chinook salmon using a hand heldwand detector (photograph by George Nandor).

Processing and Tag Recovery

A simplified flowchart showing an example of CWT processing procedures is shown in figure 6. Heads removed from adipose clipped salmonids are transported frozen or preserved to the agency's CWT laboratory for tag removal and decoding. The tiny tags are recovered by dissection, aided by an electronic metal detector that indicates which portion of the snout the tag is in after each successive sectioning of the sample. If no tag is found, the sample is passed through a magnetic field to re-magnetize the tag (if present). The sample is then passed through a highly sensitive tubular tag detector to confirm the absence of a tag.

Following tag extraction, the tag is decoded under a low power microscope. After the initial reading, a second tag reader makes an independent reading for verification. Several agencies now use a small video camera to project the tag image on a screen, thereby making it easier to decode (see fig. 7).

Figure 7. A recovered CWT magnified and displayed on a monitor for easy reading (photograph provided by ODFW).

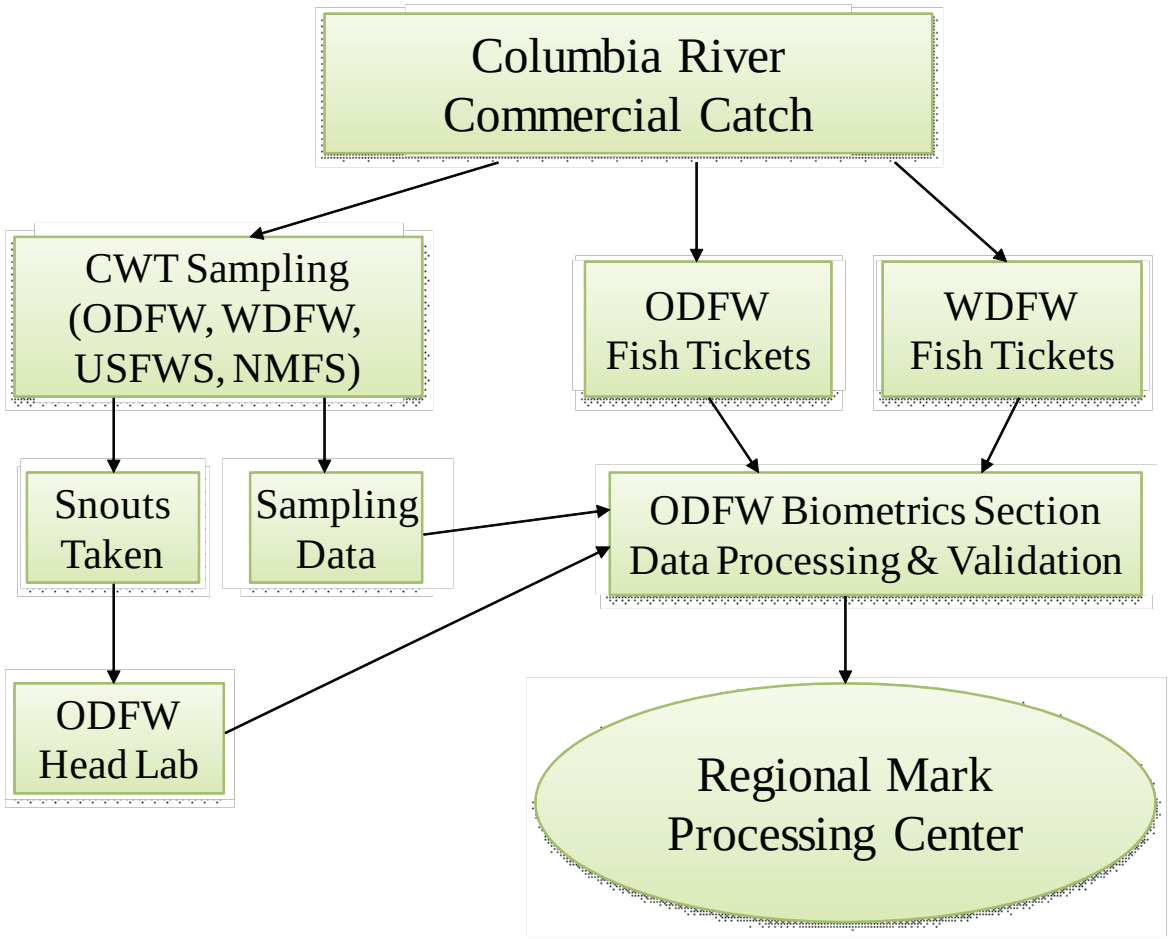

Figure 6. Flowchart showing program example: Columbia River CWT recovery system.

Once decoded, the tag code and associated sampling data are entered into a spreadsheet or database for further processing. Several error checks are run, including verification that the tag code is legitimate (i.e., was previously released) and that the species is correct. Questionable tag codes are re-read by dissection laboratory personnel, and pertinent supplementary data are checked to resolve other errors.

Upon validation, the "observed recoveries" are made available for use in preliminary reports. This includes expansion of the observed recoveries into "estimated recoveries" (see equations below) for the given area time stratum once the catch sample data are available.

Recovery Estimation

The total number of fish from a particular release group that are caught in a particular area (or landed at a particular port) during a particular time period can be estimated in a two-step process:

$$R_T = aR_O,$$

where

R_T is the estimataed total recoveries of tags bearing the release group's code,

R_O is the observed number of tags of the appropriate code, and

a is a sampling expansion factor: (total catch)/(sampled catch).

Equation 1.
Step 1: Estimate the number of tagged fish in the fishery sample for that area (or port) and time (Johnson, 2004).

$$C = bR_T,$$

where

C is the total estimated contribution of the release group to the fishery in that area at that time, and

b is a marking expansion factor: (total fish released)/(total fish marked).

Equation 2.
Step 2: Account for the fraction of the release group that was tagged (Johnson, 2004).

The contribution estimates then are summed over all relevant area (port) and time strata.

CWT Database and RMIS

Upon completion of the expansion process, the recovery agency submits the observed and estimated tag recovery data and associated catch and sample data via Internet transfer to the RMPC. The RMPC then checks the data for errors and works with the recovery agency to resolve discrepancies. Once validated, the data (incomplete or complete) are combined with those of other recovery agencies to document coastwide recoveries of any given tag code.

The data flow process of the RMPC is shown in figure 8. The CWT data are submitted to the RMPC where they are loaded and validated against an extensive set of checks. These checks are to verify the integrity and accuracy of the data elements. Two elements of critical importance are: (1) the number of fish released with the CWT for each tagged release group; and (2) the number of estimated recoveries for each reported observed tag recovery.

Once validated, the data are moved into a relational database and made accessible via the RMIS online. Likewise, validated datasets are posted to Canada (CDFO) on a regular basis as specified in the bilateral Pacific Salmon Treaty.

Types (Classes) of Data

Related to the processes described above, there are five main classes of CWT data in the database: Release, Catch/Sample, Recovery, Catch & Effort, and Location. In addition, the CWT database contains some descriptive metadata (e.g., Description data) referring to many rows of data among the main five data classes. This metadata is intended to help maintain a permanent centralized record of CWT program progress and special events that are reflected in the data values. The five classes of data are described as follows:

Release.—When a group of fish is released from a hatchery or other release site containing any number of coded wire tagged fish, the group is associated with a unique tag code. Any pertinent information from releasing agencies regarding the release group is submitted to the RMPC by the responsible State, Provincial, or Federal agencies. There are approximately 44,000 tagged release groups in the database dating back to 1968.

When groups of fish are released without coded wire tagged fish present, the release group is called an untagged/unassociated group. The release group is assigned a 12-character alpha-numeric identifier. This information is likewise submitted to the RMPC. There are approximately 95,000 untagged release groups in the database dating back to 1952.

Catch / Sample.—Tagged fish are sampled Pacific coastwide by sampling agencies from various commercial, recreational, Tribal, and escapement fisheries. These agencies usually record the sampling area, number caught, and percent of catch that was sampled and related information. This information is called Catch/Sample data and is collected by sampling agencies for submission to the RMPC on a yearly basis by specific reporting agencies. There are currently about 320,000 Catch/Sample records in the database.

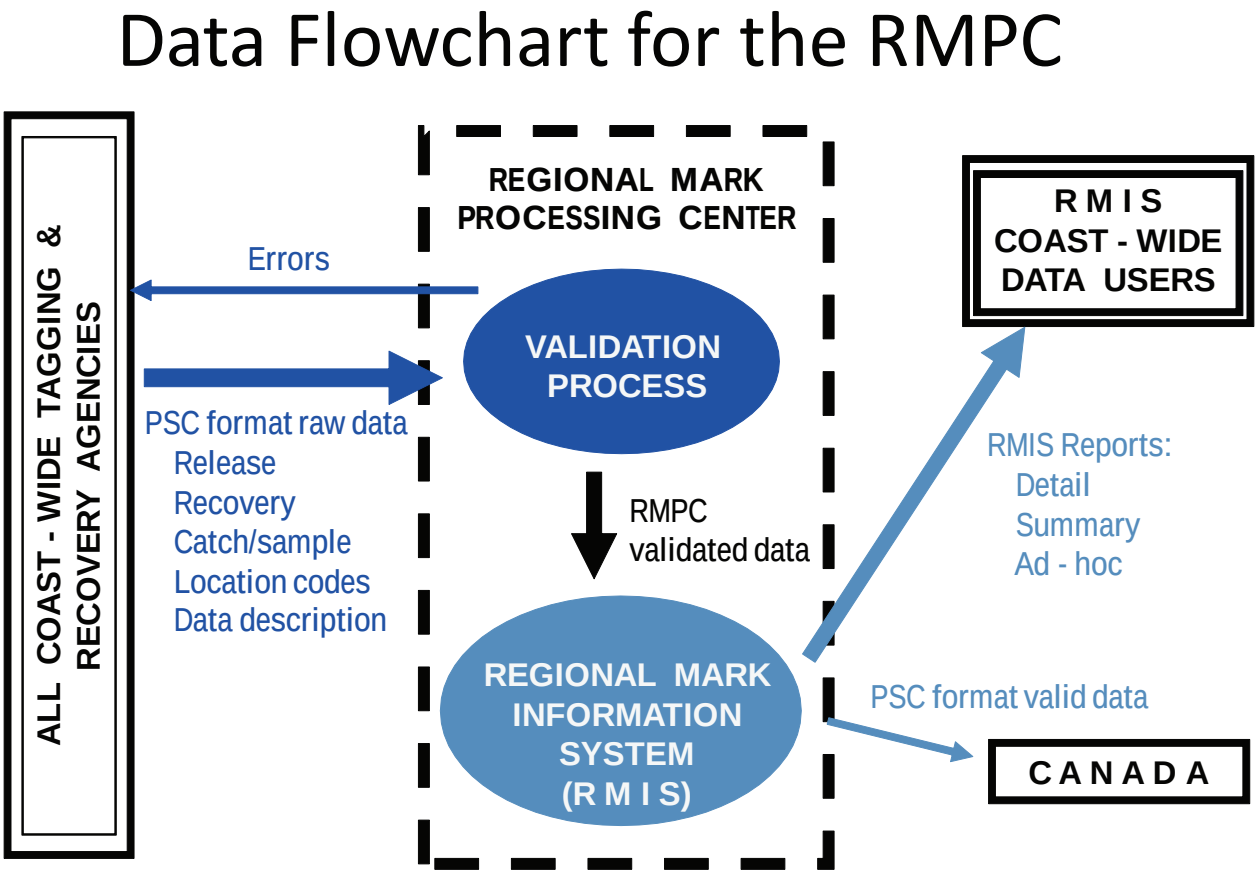

Figure 8. Flowchart showing flow of datasets through the PSMFC RMPC.

Recovery.—When tags are removed from fish and decoded, the tag is linked to the specific location of catch, date of catch, fishery, and other related biological data. Where possible, the ratio of the number of fish sampled to the total catch is multiplied by the total number of tags extracted to form the Estimated Number of fish. These data are collected by sampling agencies for submission to the RMPC on a yearly basis along with Catch/Sample data. Individual recovery records correspond to one observed (decoded) tag.

Each recovery record has an associated "Status of Tag." This status is coded as follows:

"1" Tag read OK
"2" No tag
"3" Tag lost before read
"4" Tag not readable
"7" Unresolved discrepancy
"8" Head not processed
"9" Pseudo tag, blank wire

In addition to passing rigorous validation tests, the status "1" recoveries must match by tag code with a tagged release group. There are currently about 5.5 million status "1" recovery records in the database. Recoveries with a status other than "1" are not included in most RMIS reports. There are currently about 1.3 million non-status "1" recoveries in the database.

Catch & Effort.—Catch effort is the amount of fish caught by a specified amount of effort. It also can be defined as the catch of fish, in numbers or in weight, taken by a defined unit of fishing effort. Typically, effort is a combination of gear type, gear size, and length of time gear is used. Catch per unit of effort is often used as a measurement of relative abundance for a particular fish. There are currently about 140,000 Catch & Effort records in the database.

Location.—The geographic locations of release, sample, and specific recovery of fish also are assembled by specific location reporting agencies. Collectively, these are called Location data and are submitted to the RMPC along with all other classes of data.

There are five types of locations. Within each type of location, the location record is uniquely identified coastwide by a 19-character Location Code. That code is associated with a textual description of the location and a geographical reference to the location. In 2009, there were approximately 14,000 locations in use in the database.

The five types of locations are described as follows:

1. **Recovery Site**: Indicates as closely as possible the actual geographic place where a tagged fish was caught. They usually are specified within larger Catch Areas in the sampling stratum. This type of location is found only in Recovery data.
2. **Catch Area**: Corresponds to geographic areas where sampling occurred for a given fishery. They may encompass several recovery sites. This type of location is found in Catch/Sample and Catch & Effort data.
3. **Hatchery**: Specifies the name of the hatchery or rearing facility for non-wild release groups. This type of location is found only in Release data.
4. **Release Site:** Specifies the geographic release location of the release group. It may differ from the hatchery. This type of location is found only in Release data.
5. **Stock:** Differs from all other locations in that they identify the brood stock or morphology of a release group rather than a geographic location. Stocks usually correspond to the name of a stream or if the stock was mixed, a composite of stream names. This type of location is found only in Release data.

Validation and Maintenance

Immediately after the reporting agency has transferred the recovery and catch/sample dataset to the RMPC (fig. 8), the RMPC then checks the data for errors and works with the reporting agency to resolve discrepancies. Once validated, the data (preliminary or final) are combined with those of other reporting agencies to document coastwide recoveries of any given tag code.

U.S.-Canada Data Exchange

The CWT system consists of several elements:

- There are separate U.S. and Canadian CWT reporting databases. The U.S. system (RMIS) is maintained by the RMPC of the PSMFC. The Canadian system (Mark Recovery Program, MRP) is maintained by the CDFO (fig. 9).
- Both countries acquire CWT data that originates within their country and provide access to information contained in their databases in a manner that satisfies users of their country.
- Reporting requirements and centralized responsibilities for data exchange between Canada and the U.S. are standardized to ensure both databases are identical.

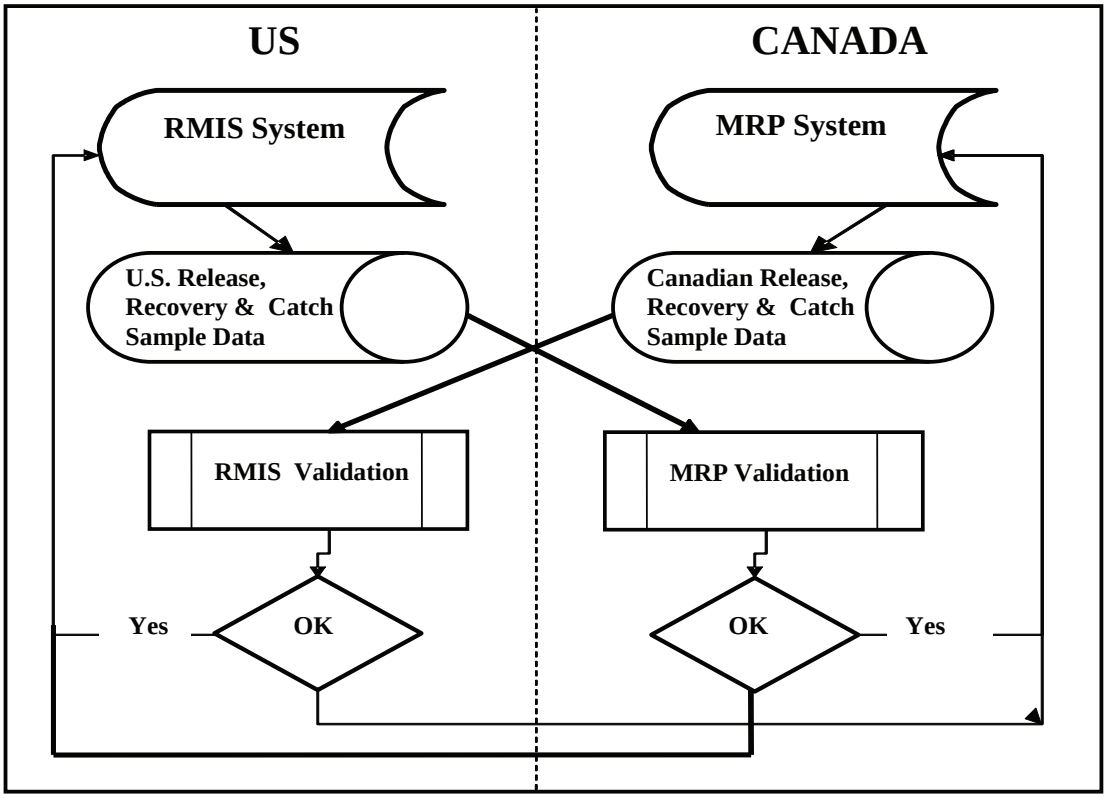

Figure 9. Main components of the data exchange protocols between the Canadian and U.S. CWT database systems (Pacific Salmon Commission (PSC), 2008).

- Cooperative development of standardized formats for reporting release, recovery, and catch sample data has been employed. The release system provides information on all releases coastwide, tagged and untagged. The recovery system encompasses the sampling and recovery information for all fisheries and escapement locations coastwide.
- There are inter-agency processes for review, coordination, and modification of CWT data.
- There are agreed upon rules for data validation and procedures for correction. The rules are specified in the PSC Data Standards Workgroup (DSWG) database specification report (Pacific Salmon Commission Data Standards Work Group, 2009), which may be found on the PSMFC web site. Validation rules indicate when columns must contain one of a set of allowed codes, such as for fishery type, gear type, species, agency code, or tag status. In addition, tag codes reported in a recovery file must match a tag code reported in a release file in the database. Information regarding species, sampling periods, and other data items in a catch/sample file must match the corresponding information in the recovery file. The location codes (for releases, recoveries and sampling sites) must follow certain rules such that the database operations can sort data by location. These are just some of the validation rules used. All reporting agencies are responsible for ensuring that complete and accurate data are reported (Pacific Salmon Commission, 2008).

RMIS Online Web-Accessible Data

RMIS is comprised of three principal Internet based reporting systems for public download of CWT and related datasets. They are: (1) RMIS Standard Reporting System; (2) RMIS Analysis Reporting System; and (3) RMIS Catch & Effort Data Reporting System. RMIS is located at the following address: http://www.rmpc.org.

The **RMIS Standard Reporting System** is an application that allows the user to build a query, select, and optionally preview the result set row by row, and then run a formatted report of their choice using the result set. The report may then be returned to the browser, or sent to their email address. Data retrieval includes selection by location or by tag code as well as many other data elements.

All classes of data are available in user-customizable raw data download format. In addition, RMIS Standard Reporting has the following report formats available in either textual summary (with page headers) or textual detail (one report row per line) levels:

- Release reports by tag code or release id: 5 reports (detail)
- Release reports by adipose clip: 1 report (summary).
- Recovery reports by tag code: 18 reports (summary and detail).
- Recovery reports by tag list: 2 reports (summary and detail).
- Recovery reports by hatchery of release: 7 reports (summary and detail)
- Catch / Sample reports: 1 report (detail)
- Location reports: 1 report (detail)

The **RMIS Analysis Reporting System** was developed to facilitate the analysis of coastwide salmon recovery information in terms of actual geographic areas used for management of the various fisheries. It refers to a version of the CWT database that is summarized by tag code, “management-fishery” units, and age class of returning fish. RMIS Analysis allows the user to auto-generate and maintain lists of tag codes based on various criteria—such as morphological characteristics of the fish releases. RMIS Analysis also provides a means of organizing (grouping) tag codes and/or management-fisheries by various user-identified criteria and using the group definitions as units for aggregation in report output.

RMIS Analysis Reporting has the following report formats available:

- CWT- based recovery reports: 9 reports (summary and detail).
- Management-fishery based recovery report: 1 report (summary).

The **RMIS Catch & Effort Reporting System** provides a means of selecting and downloading raw datasets of Catch & Effort data. There are no formatted reports available of Catch & Effort data.

The RMPC website also includes many other features such as:

- Status charts of all CWT metadata (“Descriptions”) selectable by data class and reporting agency which allow user tracking and review of data update activity.
- Status charts showing all current data processing information from the RMPC including load date and number of records loaded into the database.
- Running ticker of recent news developments regarding the RMPC computer system and the CWT database updates.
- Coastwide discussion forum for discussion of data management and related issues.
- Image gallery illustrating many aspects of coastwide CWT system and field processes.
- A set of numerous CWT related publications available for download.

Current Issues Impacting the CWT Program

The recent Report of the Expert Panel on the Future of the CWT Recovery Program for Pacific Salmon (Hankin et al. 2005) identified current issues and problems with the current CWT system and provided an extensive discussion of these issues. The issues include whether indicator stocks adequately represent natural populations, statistical uncertainty of CWT-based estimates, increasingly finer scales of fishery-time resolution to conserve individual populations of fish, mass marking, and selective fisheries. A review of California hatchery programs found that tagging levels were insufficient to calculate exploitation rates and escapement estimates of hatchery produced fish (Joint Hatchery Review Committee, 2001). The Columbia River Hatchery Reform Project also identified the need for increased tagging levels to better evaluate the success of hatchery rearing programs in the Columbia River Basin (Hatchery Scientific Reform Group, 2009). Additionally, coded wire tagging and subsequent fishery sampling efforts have been reduced due to budget constraints (ISRP/ISAB 2009-1).

Recommendations for improving the CWT program include reviewing indicator stocks to advance the understanding of the relationship between hatchery reared indicators stocks and their natural counterparts, increasing tagging rates of release groups and/or increasing sampling rates of fisheries to increase statistical precision, improving enforcement of sampling and CWT collection laws, increased use of electronic CWT detection methods, increased spawning ground surveys, and better reporting of all escapement data. More details of the recommendations are available in An Action Plan in Response to Coded Wire Tag (CWT) Expert Panel Recommendations (Pacific Salmon Commission, 2008).

The CWT system also has other limitations in that capital equipment costs are high; tags must be recovered from the fish for decoding, which is lethal for the fish; a sophisticated sampling and recovery program is needed for good statistical precision of the data; a tag recovery laboratory must be available; a computer data system is needed to record data and upload data to the central database (RMIS); and a trained staff is essential for success.

Future of the CWT Program

The 2008 bilateral agreement for the conservation and harvest sharing of Pacific salmon under the jurisdiction of the Pacific Salmon Treaty assures the continued use of CWTs as the primary data source for managing fisheries covered by the treaty. The governments of Canada and the U.S. agreed to invest $15 million ($7.5 million in each respective currency) to improve the coastwide CWT program. CWT technology also is expected to remain important for managing salmon populations and in salmon policy decision making in the Columbia River Basin (ISRP/ISAB 2009-1). Although tagging efforts have leveled off in most of the region, California has recently expanded to tagging 25% of all hatchery salmon released through the implementation of a Constant Fractional Marking Program ,which resulted in the tagging of about 8 million fall Chinook salmon in 2007 and 2008 (Pacific States Marine Fisheries Commission, 2008). Tagging and recovery efforts are funded by virtually all fisheries agencies in the region and by other entities that are responsible for funding fisheries mitigation programs. All this bodes well for the continued viability of the CWT program.

Improvements are needed, however. It is critically important for all fisheries agencies in the region to support the CWT program. This support not only includes funding but the commitment to exchange and share the data in a timely manner so that all agencies have equal access to the data. Agencies must implement the solutions provided by the CWT workgroup with reference to the priorities identified in An Action Plan in Response to Coded Wire Tag (CWT) Expert Panel Recommendations. The region also has to address the impact of mark selective fisheries on naturally produced (unmarked) fish through the increased use of double index tag groups of fish that act as surrogates for wild fish or through some other method, such as genetic stock identification. As stated above, tagging agencies must determine the proper number of tagged fish for the representative release groups and sampling agencies must implement robust sampling of fisheries and freshwater escapement areas, particularly spawning grounds, to increase precision of the statistical analyses. One of the keys for the program is the continued operation and maintenance of the RMIS and the CWT database by the PSMFCs's RMPC, which requires it to be adequately funded to facilitate the necessary data exchange that makes this regional CWT program a success.

Summary

After 40 years, the CWT program in the greater Pacific region of North America continues to be the most important tool for salmonid research and management. This paper has given an overview of the of the development of the CWT, how the tagging program meets management needs, current regional coordination procedures, the scale of tagging efforts and subsequent sampling and recovery procedures, data exchange through the centralized regional database, current issues impacting the CWT program, and the future of this program. It is important to note, however, that the various agencies' tagging, fish release, and recovery programs are considerably more complex than presented here. Additional specific information must be obtained directly from the agency tag coordinators (contact information available from the RMPC web site) and the RMPC for a complete understanding and assessment of specific tagging programs.

All tagging methods have their advantages and disadvantages, and the CWT is no exception. The implementation of electronic detection methods, increased tagging and sampling rates, and the use of statistical analysis to increase precision of data all help to increase the effectiveness of the program to meet management needs. The widespread use of these tags over a long period of time, along with the regional coordination among the tagging and sampling agencies, is unprecedented anywhere else in the world and is its greatest strength. In addition, CWTs are being used in conjunction with other marking and tagging methods (e.g., genetic markers, scale patterns, otolith banding, and PIT tags) to provide an enhanced analysis of Pacific salmon population dynamics.

More specific information about the Pacific coastwide CWT system also is available online at http://www.rmpc.org with links to other publications and resources pertaining to the program.

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Appendix A. Overview of the Coded Wire Tag Program in the Greater Pacific Region of North America.

Table A1. Votes (total, 12) assigned to the 14-member Mark Committee in the event there is no consensus on an issue involving fin marking or CWT use.

[Private and other nongovernmental organizations are represented by State or Provincial coordinators]

Jurisdiction	Committee Representatives (total) — U.S. and Canada	Number of members	Number of votes
Coordinating agency	Pacific States Marine Fisheries Commission (Chair – non-voting)	1	0
State agencies			
–Alaska	Alaska Department of Fish and Game	1	1
–Washington	Washington Department of Fish and of Wildlife	1	1
–Oregon	Oregon Department of Fish and Wildlife	1	1
–California	California Department of Fish and Game	1	1
–Idaho	Idaho Department of Fish and Game	1	1
Federal agencies			
–U.S. Fish and Wildlife Service	Region wide	1	1
–National Marine Fisheries Service	Alaska and Northwest regions and centers	2	1
Tribal groups			
–Annette Island (SE Alaska)	Metlakatla Indian Community, 1 tribe	1	1
–Western Washington	Northwest Indian Fisheries Commission, 20 tribes	1	1
–Columbia River basin	Columbia River Intertribal Fisheries Commission, 4 tribes	1	1
Canada			
–Federal level	Canada Department of Fisheries and Oceans	1	1
–Provincial level	British Columbia Ministry of Environment, Fish and Wildlife Branch	1	1

Table A2. Federal, State, Tribal, and private entities, and associated abbreviations (as used in RMIS), in the Pacific Northwest of North America that have formerly used or are currently using CWTs for salmonid fishes.

[Bolded abbreviations identify entities currently reporting releases of CWT-marked salmonids (2006–09)]

Agency	Agency name
AAC	American Aquaculture Corporation (AK)
AAI	Alaska Aquaculture, Inc
ADFG	**Alaska Department of Fish and Game**
AFSP	Aboriginal Fishery Strategy Program (BC)
AKI	**Armstrong Keta, Inc. (AK)**
ANAD	Anadromous Inc. (OR)
ASLC	**Alaska Sealife Center**
BCFW	British Columbia Fish and Wildlife
BHSR	Burnt Hill Salmon Ranch (now OPSR) (OR)
BURR	Burro Creek Hatchery
CDFG	**California Department of Fish and Game**
CDFG-KT	**California Dept. of Fish Game Klamath / Trinity**
CDFO	**Canada Department of Fisheries and Oceans**
CDFR	Canada Dept. of Fisheries and Oceans - Research
CDWR	**California Department of Water Resources**
CEDC	Clatsop Economic Development Council (OR)
CERA	Ceratodus Fisheries (OR)
CHEH	Chehalis Tribe (WA)
CIAA	**Cook Inlet Aquaculture Association (AK)**
COLV	Colville Tribe (WA)
COOP	**Washington Department of Fisheries – Cooperative**
CRFC	Columbia River Inter-Tribal Fish Commission
CTWS	Confederated Tribes of the Warm Springs of Oregon
DIPC	**Douglas Island Pink and Chum, Inc. (AK)**
DOMS	Domsea Farms, Inc. (OR-WA)
EBMD	**East Bay Municipal Utilities District (CA)**
EDUC	Educational Facility (excluding UW) (WA)
ELWA	**Lower Elwha Klallam Tribe (WA)**
ESRP	Eel River Salmon Restoration Project (CA)
FWS	**U.S. Fish and Wildlife Service**
H&H	Harris & Hugie Company (OR)
HECK	C.W. Heckard Company (OR)
HFAC	Humboldt Fish Action Council (CA)
HOH	**Hoh Tribe (WA)**
HSU	Humboldt State University (CA)
HVT	**Hoopa Valley Tribe (CA)**
IDFG	**Idaho Department of Fish and Game**
JAME	Jamestown Klallam Tribe (WA)
KAKE	**Kake Non-Profit Fisheries Corp. (AK)**
KETA	Keta Company (OR)
KRAA	**Kodiak Regional Aquaculture Association (AK)**

Agency	Agency name
KRHI	Klawock River Hatchery, Inc. (AK)
KRUK	Karuk Tribe (CA)
KTHC	**Ketchikan Tribal Hatchery Corporation (AK)**
LUMM	**Lummi Tribe (WA)**
MAKA	**Makah Tribe (WA)**
MIC	**Metlakatla Indian Community (AK)**
MTSG	Mattole Salmon Group (CA)
MUCK	**Muckleshoot Tribe (WA)**
NBS	National Biological Survey
NERK	Nerka Incorporated (AK)
NEZP	**Nez Perce Tribe (ID)**
NFA	**Nome Fishermen's Association**
NISQ	**Nisqually Tribe (WA)**
NLNS	Nehalem Land & Salmon (OR)
NMFS	**National Marine Fisheries Service (AK)**
NOOK	Nooksack Tribe (WA)
NSED	**Norton Sound Development Corp**
NSRA	**Northern SE Regional Aquaculture Assn. (AK)**
OAF	Oregon Aquafoods, Inc.
ODFW	**Oregon Department of Fish and Wildlife**
OPSR	Oregon-Pacific Salmon Ranch (formerly BHSR)
OSU	Oregon State University
PGAM	**Port Gamble S'Klallam Tribe (WA)**
PGHC	**Port Graham Hatchery Corporation (AK)**
PLCO	Pacific Lumber Company (CA)
PNPT	Point No Point Treaty Council (WA)
PPWR	Puget Power (WA)
PSE	Puget Sound Energy (WA)
PUYA	**Puyallup Tribe (WA)**
PWHA	**Prince of Wales Hatchery Association (AK)**
PWSA	**Prince William Sd Aquaculture Corporation (AK)**
QDNR	**Quinault Department of Natural Resources (WA)**
QUIL	**Quileute Tribe (WA)**
RMPC	Regional Mark Processing Center
ROWH	**Rowdy Cr. Hatchery (CA)**
SHOL	Shoalwater Tribe (WA)
SIUF	Siuslaw Fisheries (OR)
SJ	**Sheldon Jackson College (AK)**
SJRG	San Joaquin River Group (CA)
SKOK	**Skokomish Tribe (WA)**
SOF	Silverking Oceanic Farms (CA)

Table A2. Federal, State, Tribal, and private entities, and associated abbreviations (as used in RMIS), in the Pacific Northwest of North America that have formerly used or are currently using CWTs for salmonid fishes.—Continued

Agency	Agency name
SPOK	Spokane Tribe (WA)
SQAX	Squaxin Island Tribe (WA)
SRKC	Smith River Kiwanis Club
SSC	Skagit System Cooperative (WA)
SSLC	Seaward Sealife Center
SSRA	**Southern SE Regional Aquaculture Assn. (AK)**
STIL	**Stillaguamish Tribe (WA)**
SUQ	**Suquamish Tribe (WA)**
SYCL	South Yuba River Citizens League, CA
THCC	Tlingit-Haida Central Council (AK)
TULA	**Tulalip Tribe (WA)**

Agency	Agency name
TYEE	Tyee Foundation (CA)
UA	University of Alaska
UI	University of Idaho
UPSK	**Upper Skagit Tribe**
USFS	U.S. Forest Service
UW	**University of Washington**
VFDA	**Valdez Fisheries Development Association (AK)**
WDFW	**Washington Department of Fish and Wildlife**
WREG	Washington Regional Enhancement Groups
YAKA	**Yakama Tribe (WA)**

Table A3. Total CWT Releases by Species and State/Province since inception of CWT program in 1968 (Regional Mark Information System Database [online database]).

State / Province	Chinook	Coho	Steelhead	All Other	State/Province Total
Alaska	38,855,791	33,894,600	556,354	34,291,279	107,598,024
California	167,397,186	5,209,465	6,291,336	452,966	179,350,953
British Columbia	133,174,780	50,263,861	6,452,425	11,176,083	201,067,149
Idaho	55,838,627	1,447,878	24,584,157	448,676	82,319,338
Oregon	156,667,313	48,540,659	8,795,176	314,023	214,317,171
Washington	426,038,213	121,901,556	17,987,746	7,639,180	573,566,695
Species Total	977,971,910	261,258,019	64,667,194	54,322,207	1,358,219,330

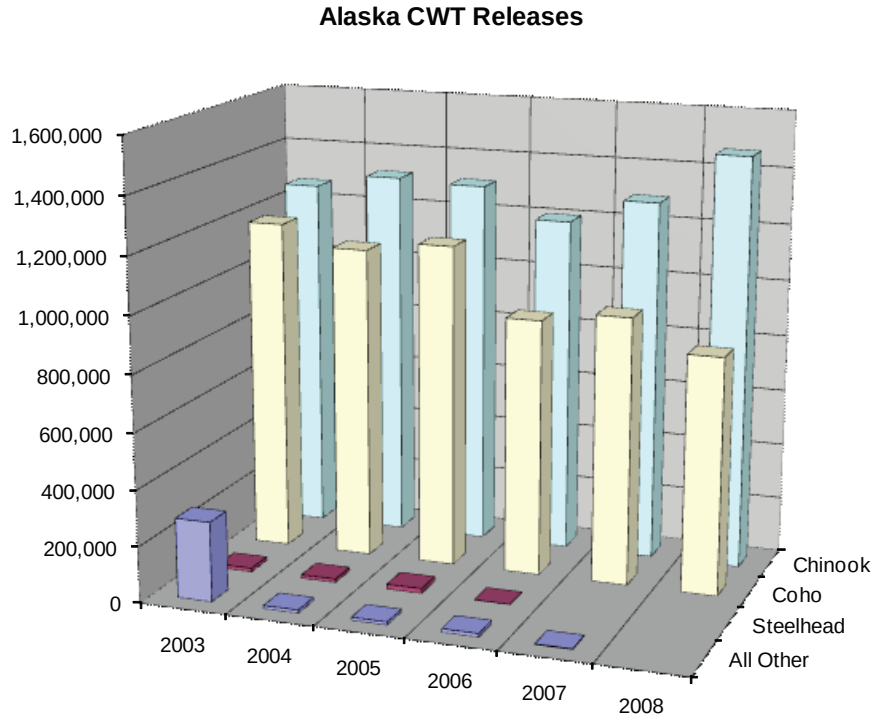
Table A4. All releases with blank or agency-only wire since inception of CWT program in 1968. (Regional Mark Information System Database [online database]).

State	Chinook	Coho	Steelhead	All Other	State Total
Alaska	0	2,412	0	15,362	17,774
Idaho	1,571,709	0	1,117,307	0	2,689,016
Oregon	19,134,773	282,651	447,683	0	19,865,107
Washington	18,131,576	147,654	3,615,582	0	21,894,812
Species Total	38,838,058	432,717	5,180,572	15,362	44,466,709

Table A5. Total CWT Recoveries by Species and Area recovered since inception of CWT program in 1968.

[Totals include all instances where a tag read was attempted at a tag recovery lab (i.e., where Tag Status is '1', '4', '7', or '9'; Regional Mark Information System Database [online database]). *By-catch recoveries from ocean fisheries targeting other non-salmonid species]

Area / State / Province	Chinook	Coho	Steelhead	All Other	Area Total
Alaska	318,018	445,356	1,118	172,822	937,314
California	277,758	20,031	5,194	0	302,983
British Columbia	331,832	787,455	7,778	26,508	1,153,573
High Seas*	6,236	453	264	26	6,979
Idaho	39,417	0	38,744	18	78,179
Oregon	523,178	547,084	44,142	709	1,115,113
Washington	677,529	1,247,034	42,261	5,397	1,972,221
Species Total	2,173,968	3,047,413	139,501	205,480	5,566,362



	2003	2004	2005	2006	2007	2008
All Other	283,918	11,514	10,614	12,652	2,460	
Steelhead	13,394	12,598	17,454	998		
Coho	1,185,311	1,114,923	1,151,119	915,307	952,008	842,718
Chinook	1,267,752	1,316,355	1,305,385	1,199,439	1,287,286	1,467,256

Figure A1. All CWT Releases in Alaska State by species and year from 2003 to 2008 (Regional Mark Information System Database [online database]).

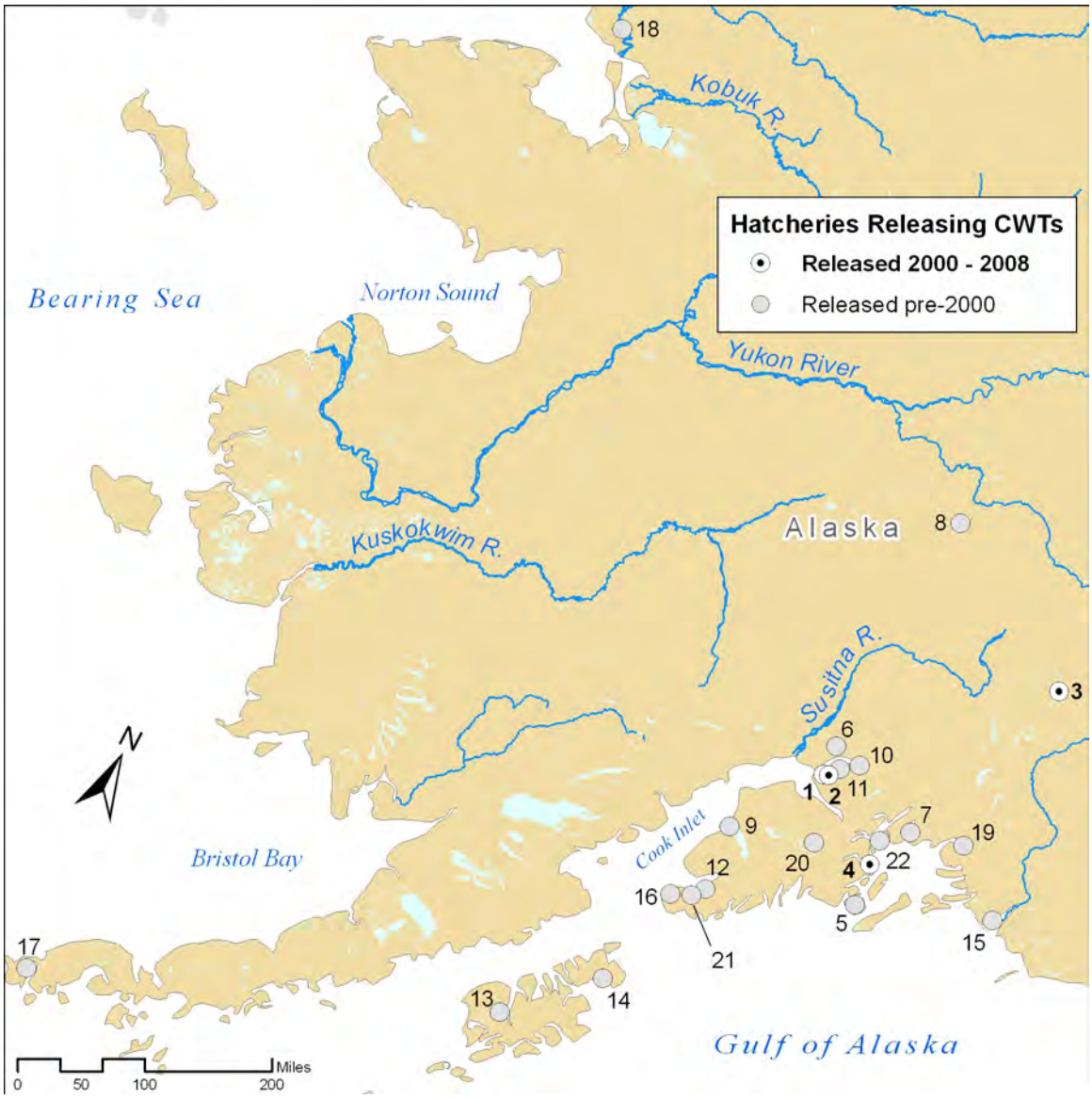


Figure A2. Hatcheries and rearing facilities in greater Alaska state (excluding Southeast area) that have released salmonids with CWTs (includes Federal, State, Tribal, other facilities).

Table A6. Legend: hatcheries and rearing facilities in greater Alaska state (excluding Southeast area) that have released salmonids with CWTs (includes Federal, State, Tribal, other facilities).

AK Facilities Releasing: 2000–2008		AK Facilities Releasing: pre–2000		AK Facilities Releasing: pre–2000	
1	Elmendorf	5	A F Koernig	13	Karluk
2	Fort Richardson	6	Big Lake	14	Kitoi Bay
3	Gulkana	7	Cannery Creek	15	Mile 25 Spawning Channel
4	Main Bay	8	Clear	16	Port Graham
		9	Crooked Creek	21	Tutka Bay
		10	Eklutna	22	Wally Noerenberg
		11	Fire Lake		
		12	Halibut Cove		

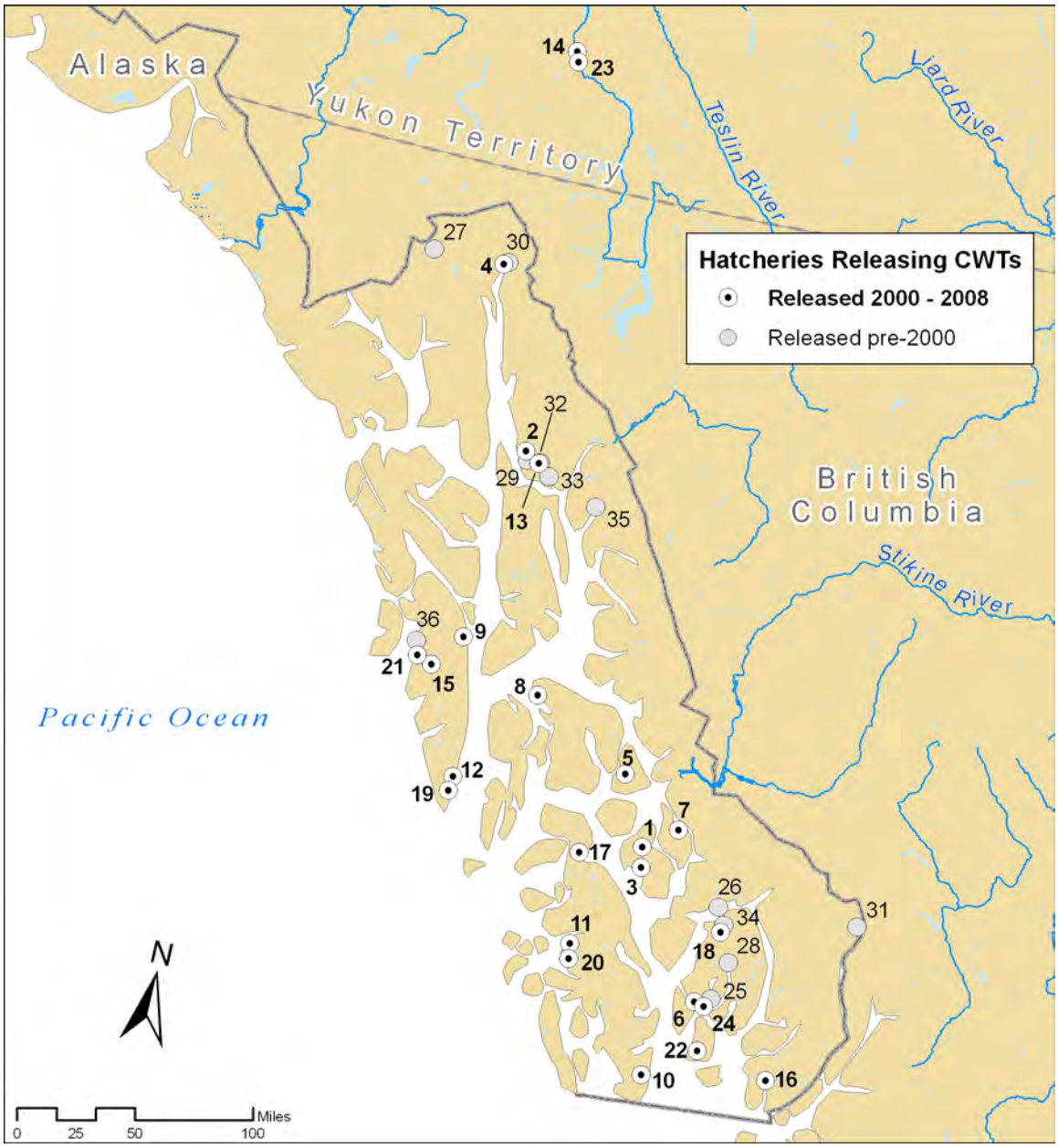
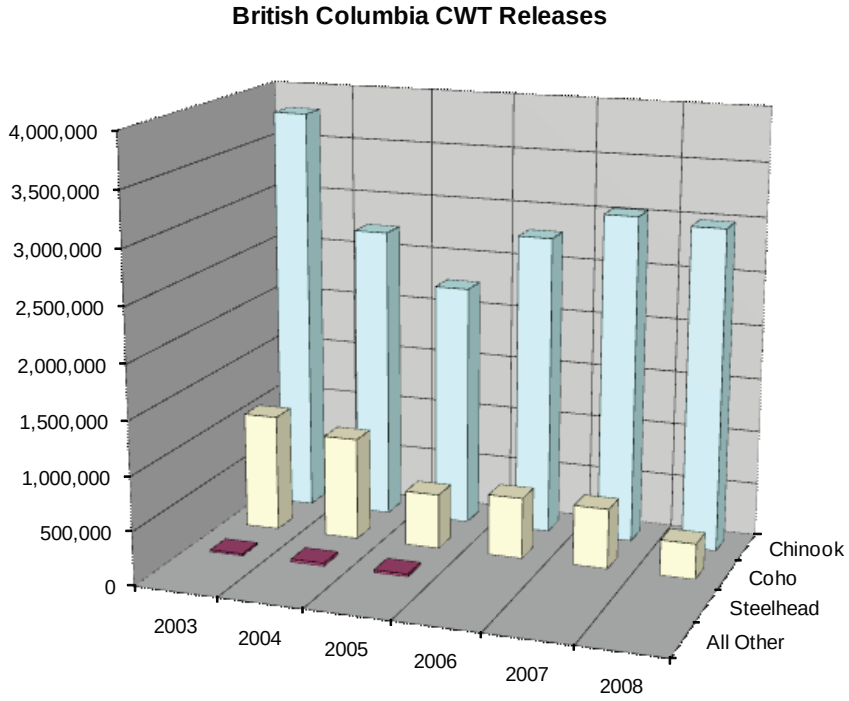


Figure A3. Hatcheries and rearing facilities in Alaska state, Southeast area, and the Yukon Territory in Canada that have released salmonids with CWTs (includes Federal, State, Tribal, other facilities).

Table A7. Legend: hatcheries and rearing facilities in Alaska state, Southeast area, and the Yukon Territory in Canada that have released salmonids with CWTs (includes Federal, State, Tribal, other facilities).

AK- Southeast Facilities Releasing: 2000–2008			AK- Southeast Facilities Releasing: 2000–2008	
1	Anita Bay		20	Port Saint Nicholas
2	Auke Creek		21	Sheldon Jackson
3	Burnett Inlet		22	Tamgas Creek
4	Burro Creek		23	Whitehorse (Canada/ Yukon T)
5	Crystal Lake		24	Whitman Lake
6	Deer Mountain			
7	Earl West Cove		**AK- Southeast Facilities Releasing: pre - 2000**	
8	Gunnuk Creek			
9	Hidden Falls		25	Beaver Falls
10	Kendrick Bay		26	Bell Island Net Pens
11	Klawock		27	Big Boulder Instream
12	Little Port Walter		28	Carroll Inlet
13	Macaulay		29	Fish Creek
14	McIntyre Creek (Canada/ Yukon T)		30	Jerry Myers
15	Medvejie		31	Marx Creek
16	Nakat Inlet		32	Salmon Creek
17	Neck Lake		33	Sheep Creek
18	Neets Bay		34	Shrimp Bay
19	Port Armstrong		35	Snettisham



	2003	2004	2005	2006	2007	2008
All Other						
Steelhead	17,902	27,507	24,500			
Coho	1,085,199	951,416	510,070	566,831	556,583	328,765
Chinook	3,792,128	2,725,567	2,252,355	2,784,773	3,038,841	2,984,434

Figure A4. All CWT Releases in British Columbia Province by species and year from 2003 to 2008 (Regional Mark Information System Database [online database]).

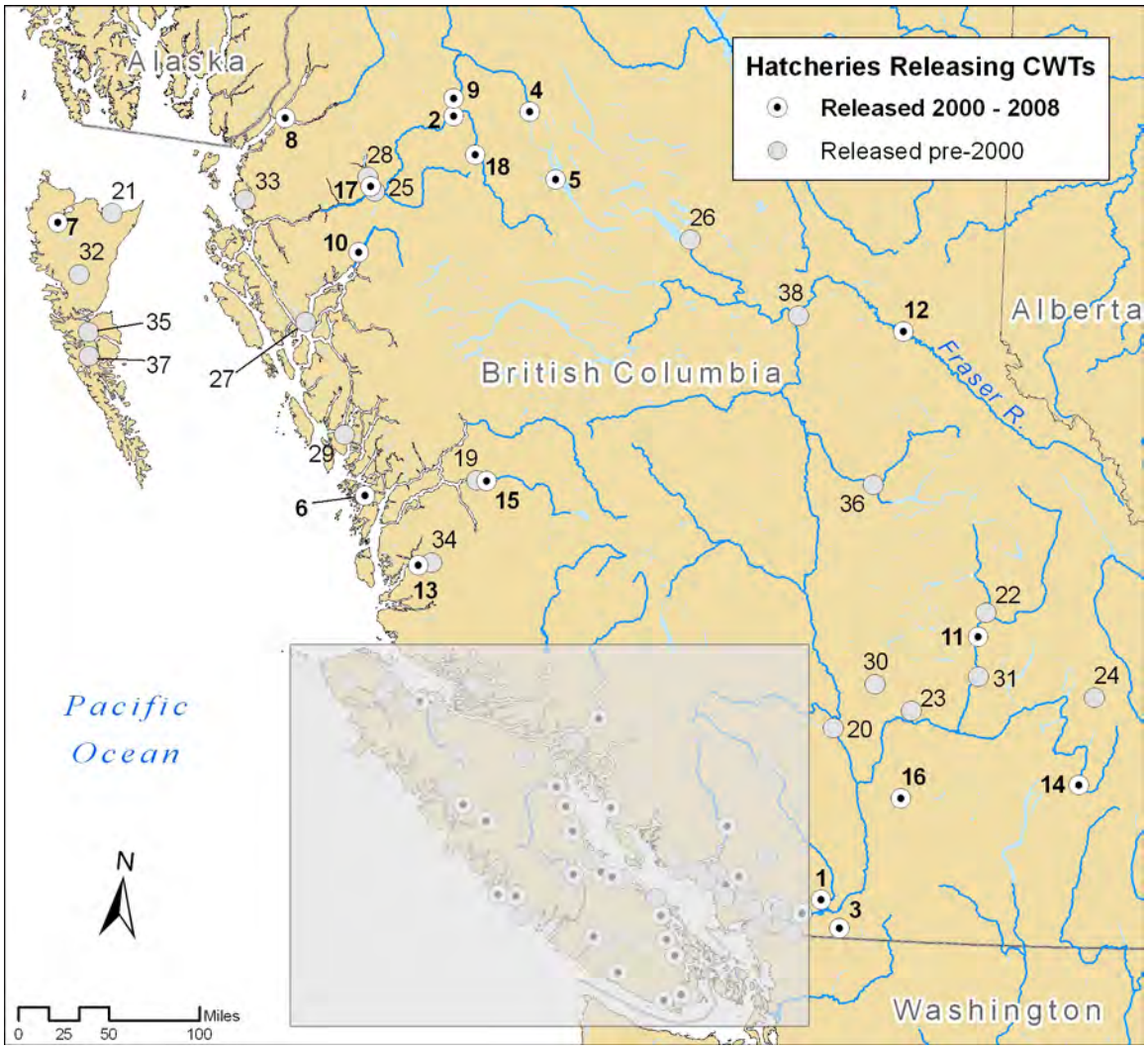


Figure A5. Hatcheries and rearing facilities in greater British Columbia Province (excluding Vancouver Island area) that have released salmonids with CWTs.

Table A8. Legend: hatcheries and rearing facilities in greater British Columbia Province (excluding Vancouver Island area) that have released salmonids with CWTs.

BC Facilities Releasing: 2000 - 2008		BC Facilities Releasing: pre - 2000	
1	Chehalis River	19	Bella Coola River
2	Chicago Creek	20	Bridge River
3	Chillwack River	21	Chown Brook
4	Fort Babine	22	Clearwater
5	Fulton River	23	Deadman River
6	Heiltsuk	24	Eagle River
7	Husby Forest Products	25	Eby Street
8	Kincolith River	26	Fort St. James
9	Kispiox River	27	Hartley Bay Creek
10	Kitimat River	28	Kitsumkalum
11	N. Thompson River	29	Klemtu Creek
12	Penny	30	Loon Creek
13	Shotbolt Bay	31	Louis Creek
14	Shuswap River	32	Masset
15	Snootli Creek	33	Oldfield Creek
16	Spius Creek	34	Oweekeno
17	Terrace	35	Pallant Creek
18	Toboggan Creek	36	Quesnel River
		37	Sewell Inlet
		38	Spruce City Wildlife Association

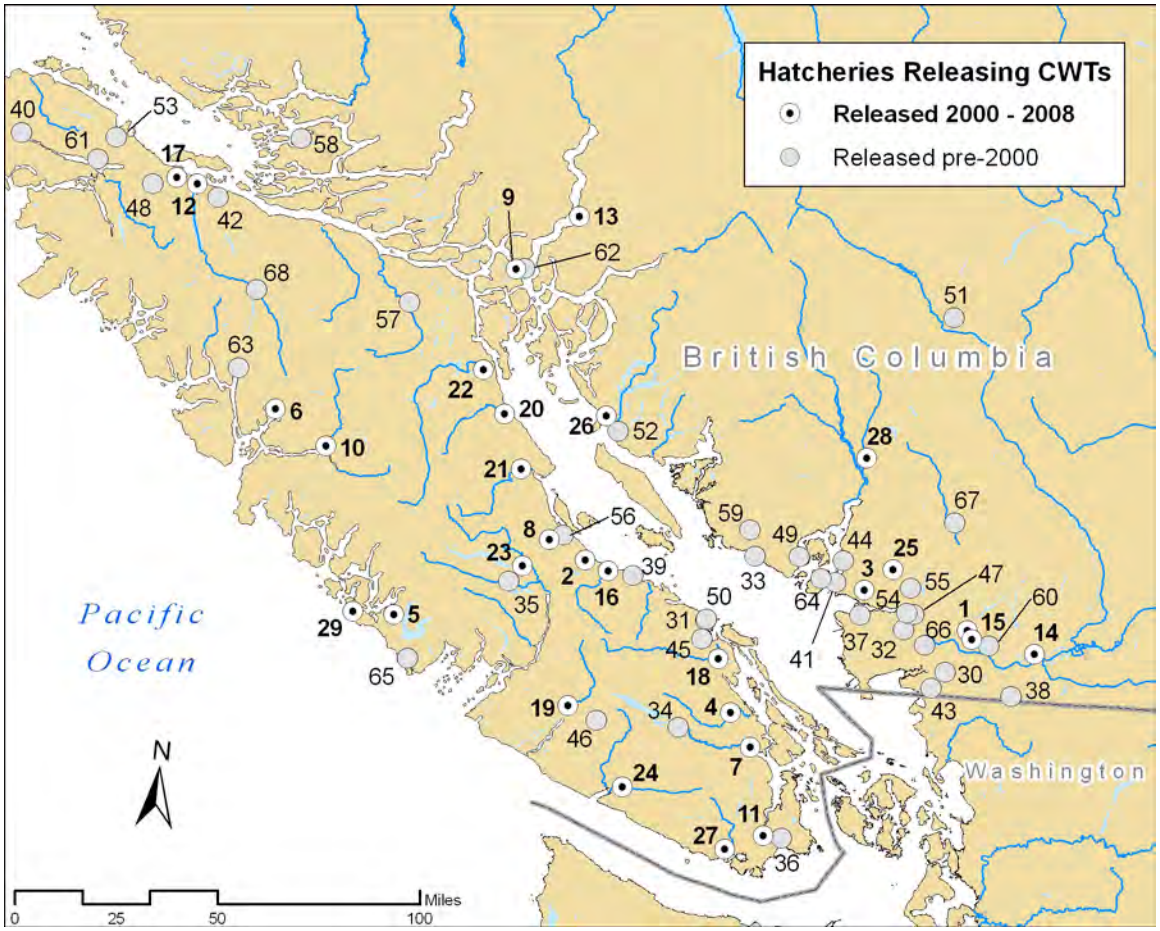
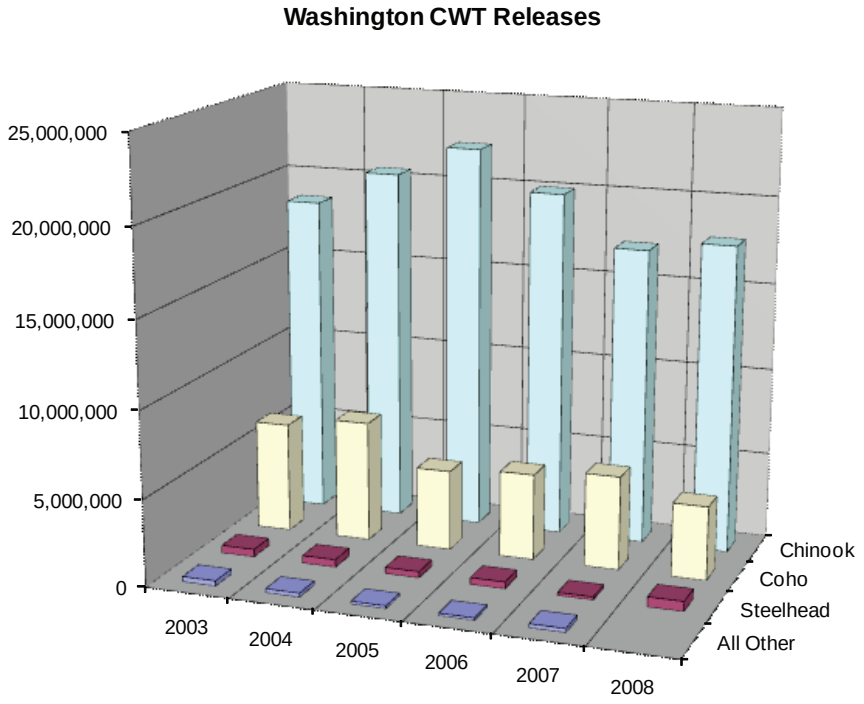


Figure A6. Hatcheries and rearing facilities in British Columbia Province, Vancouver Island area that have released salmonids with CWTs.

Table A9. Legend: hatcheries and rearing facilities in British Columbia Province, Vancouver Island area that have released salmonids with CWTs.

BC- Vancouver area Facilities Releasing: 2000 - 2008	
1	Alouette River
2	Big Qualicum River
3	Capilano River
4	Chemainus River
5	Clayoquot
6	Conuma River
7	Cowichan River
8	Fanny Bay
9	Gillard Pass
10	Gold River
11	Goldstream River
12	Gwa'ni
13	Homalco-Taggares
14	Inch Creek
15	Kanaka Creek
16	L. Qualicum River
17	Marble River
18	Nanaimo River
19	Nitinat River
20	Oyster River
21	Puntledge River
22	Quinsam River
23	Robertson Creek
24	San Juan River
25	Seymour River
26	Sliammon River
27	Sooke River
28	Tenderfoot Creek
29	Tofino
BC- Vancouver area Facilities Releasing: pre - 2000	
30	Anderson Creek Pen
31	Brandon Island
32	Brunette River
33	Chapman Creek

BC - Vancouver area Facilities Releasing: pre-2000	
34	Cowichan Lake
35	Englishman River
36	Esquimalt Harbor
37	False Creek
38	Fraser Valley
39	French Creek
40	Holberg Inlet
41	Horseshoe Bay
42	Kokish River
43	L. Campbell River
44	Lions Bay
45	Malaspina College
46	N. Vancouver Outdoor School
47	Noons Creek
48	O'Connor Lake
49	Ouillet Creek
50	Pacific Biological Station
51	Pemberton F&G
52	Powell River
53	Quatse River
54	Reed Pt.
55	Richards Creek
56	Rosewall Creek
57	Sayward F&G
58	Scott Cove Creek
59	Sechelt
60	Stave River
61	Stephen's Creek
62	Stuart Island
63	Tahsis River
64	Terminal Creek
65	Thornton Creek
66	Tynehead Hatchery
67	Upper Pitt River



	2003	2004	2005	2006	2007	2008
All Other	293,861	224,622	156,444	140,542	223,315	
Steelhead	439,161	442,338	358,738	389,673	176,535	572,397
Coho	6,366,174	6,969,286	4,639,626	4,978,300	5,404,630	4,246,960
Chinook	18,521,616	20,496,289	22,247,845	19,983,132	17,126,881	17,737,965

Figure A7. All CWT Releases in Washington State by species and year from 2003 to 2008 (Regional Mark Information System Database [online database]).

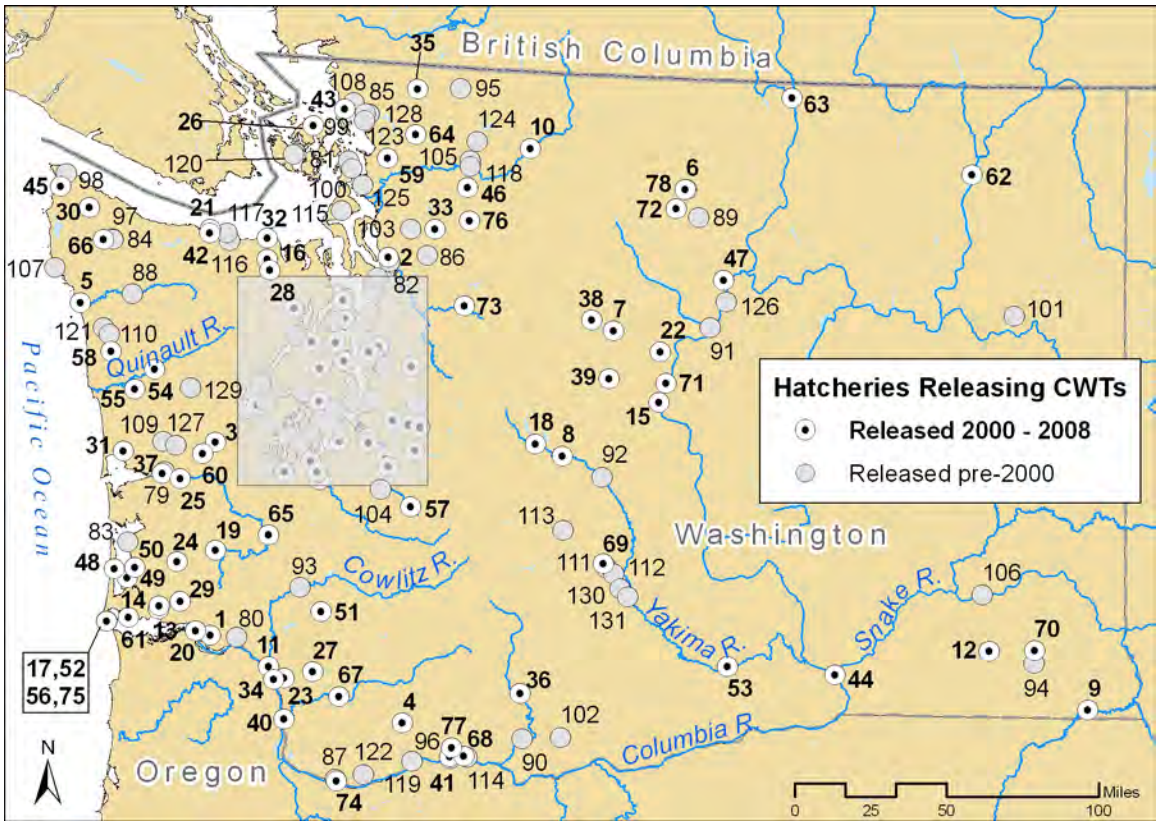


Figure A8. Hatcheries and rearing facilities in greater Washington State (excluding Puget Sound area) that have released salmonids with CWTs (includes federal, state, tribal, other facilities).

Table A10. Legend: hatcheries and rearing facilities in greater Washington State (excluding Puget Sound area) that have released salmonids with CWTs (includes Federal, State, Tribal, other facilities).

WA Facilities Releasing: 2000 - 2008		WA Facilities Releasing: pre - 2000	
1	Beaver Creek	79	Aberdeen Net Pens
2	Bernie Gobin	80	Abernathy
3	Bingham Creek	81	Anacortes Net Pens
4	Carson NFH	82	Battle Creek
5	Chalaat Creek	83	Bay Center Net Pens
6	Chewuch Rearing Pond	84	Bear Springs Rearing Pond 2
7	Chiwawa	85	Bellingham
8	Cle Elum	86	Brenner
9	Cottonwood Creek Pond	87	Camas Net Pens
10	County Line Ponds	88	Canyon Springs Pond
11	Cowlitz Salmon	89	Carlton Rearing Pond
12	Dayton Rearing Ponds	90	Champion Pond
13	Deep River Net Pens - Lower	91	Chelan
14	Deep River Net Pens - Upper	92	Clark Flat Pond
15	Dryden Pond	93	Cowlitz Trout
16	Dungeness	94	Curl Lake Rearing Ponds
17	Eastbank	95	Deadhorse Creek Pond
18	Easton Pond	96	Drano Lake Pens
19	Eight Creek Project	97	Eagle Creek
20	Elochoman	98	Educket Creek
21	Elwha	99	Fairhaven Net Pens
22	Entiat NFH	100	Fidalgo Bay Net Pens
23	Fallert Creek	101	Ford
24	Forks Creek	102	Goldendale
25	Friends Landing Net Pens	103	Harvey Creek
26	Glenwood Springs	104	Kapowsin Lake Net Pens
27	Gobar Pond	105	Lake Shannon Net Pens
28	Gray Wolf River Acclimation Pond	106	Little Goose Dam
29	Grays River	107	Lonesome Creek
30	Hoko Falls	108	Mamoya Pond
31	Humptulips	109	Mary Brothers Rearing Pond
32	Hurd Creek	110	Mule Pasture Pond
33	Jim Creek	111	Naches
34	Kalama Falls	112	Nelson Springs Ponds
35	Kendall Creek	113	Nile Springs Ponds
36	Klickitat	114	Northwestern Lake Pens
37	Lake Aberdeen	115	Oak Harbor Net Pens
38	Lake Wenatchee Net Pens	116	Peninsula College
39	Leavenworth NFH	117	Port Angeles Net Pen
40	Lewis River	118	Puget Sound Energy Spawning
41	Little White Salmon NFH	119	Rock Creek Net Pens
42	Lower Elwha	120	San Juan Net Pens

Table A10. Legend: hatcheries and rearing facilities in greater Washington State (excluding Puget Sound area) that have released salmonids with CWTs (includes Federal, State, Tribal, other facilities).—Continued

WA Facilities Releasing: 2000 - 2008		WA Facilities Releasing: pre - 2000	
43	Lummi Sea Ponds	121	Shale Creek
44	Lyons Ferry	122	Skamania Trout
45	Makah NFH	123	Squalicum Net Pens
46	Marblemount	124	Sulphur Springs
47	Methow	125	Swinomish Channel Rearing Ponds
48	Nahcotta Net Pens	126	Wells Dam Spawning Channel
49	Naselle	127	Weyco Pond
50	Nemah	128	Whatcom Creek
51	North Toutle	129	Wynoochee River Pens
52	Priest Rapids	130	Yakima
53	Prosser	131	Yakima Net Pens at Wapato Dam
54	Quinault Lake		
55	Quinault NFH		
56	Ringold Springs		
57	Rushingwater Acclimation Pond		
58	Salmon River Rearing Pond		
59	Samish		
60	Satsop Springs Rearing Ponds		
61	Sea Resources		
62	Sherman Creek		
63	Similkameen		
64	Skookum Creek		
65	Skookumchuck		
66	Solduc		
67	Speelyai		
68	Spring Creek NFH		
69	Stiles Pond		
70	Tucannon		
71	Turtle Rock		
72	Twisp Acclimation Pond		
73	Wallace River		
74	Washougal		
75	Wells		
76	Whitehorse Pond		
77	Willard NFH		
78	Winthrop NFH		

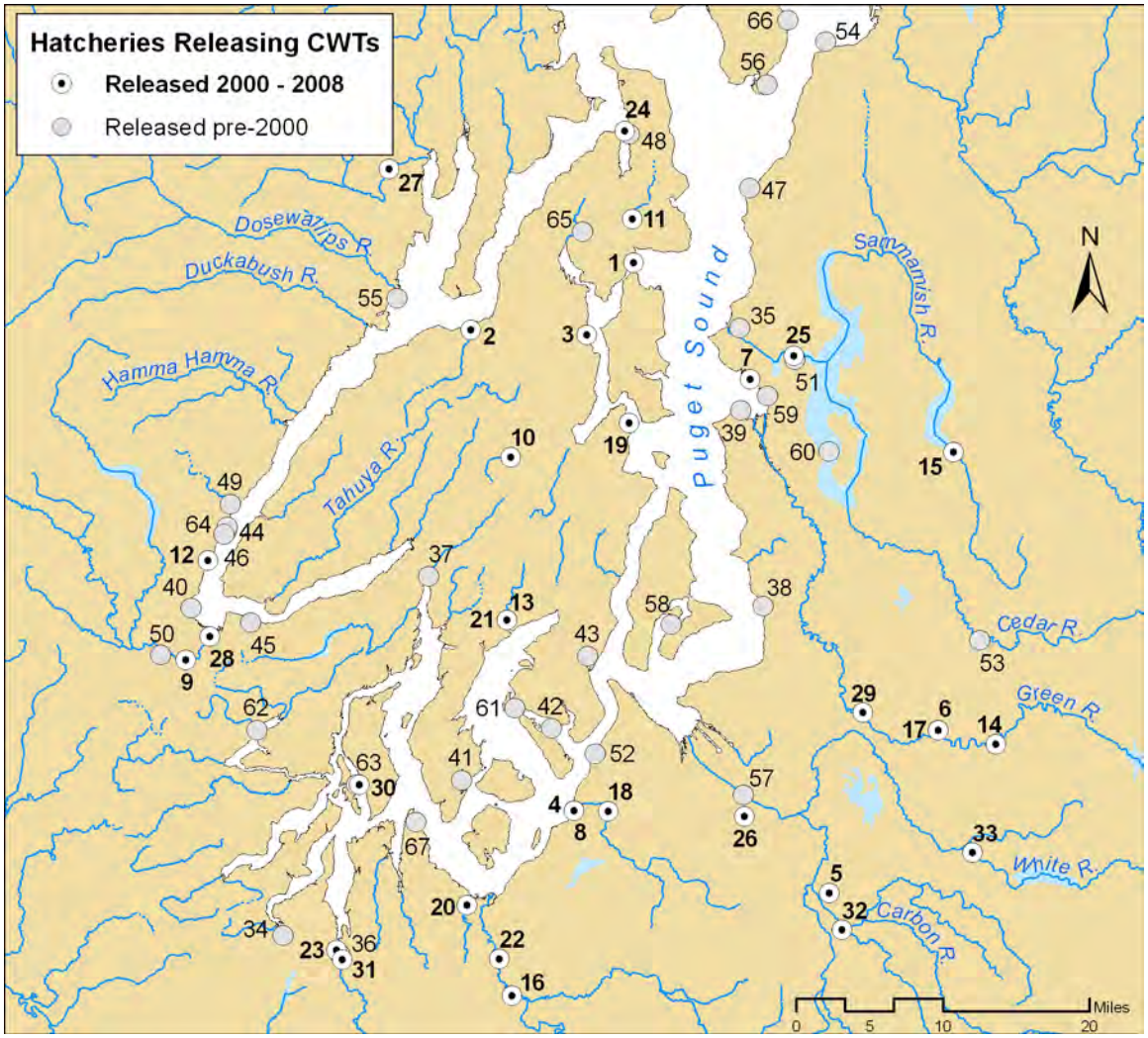
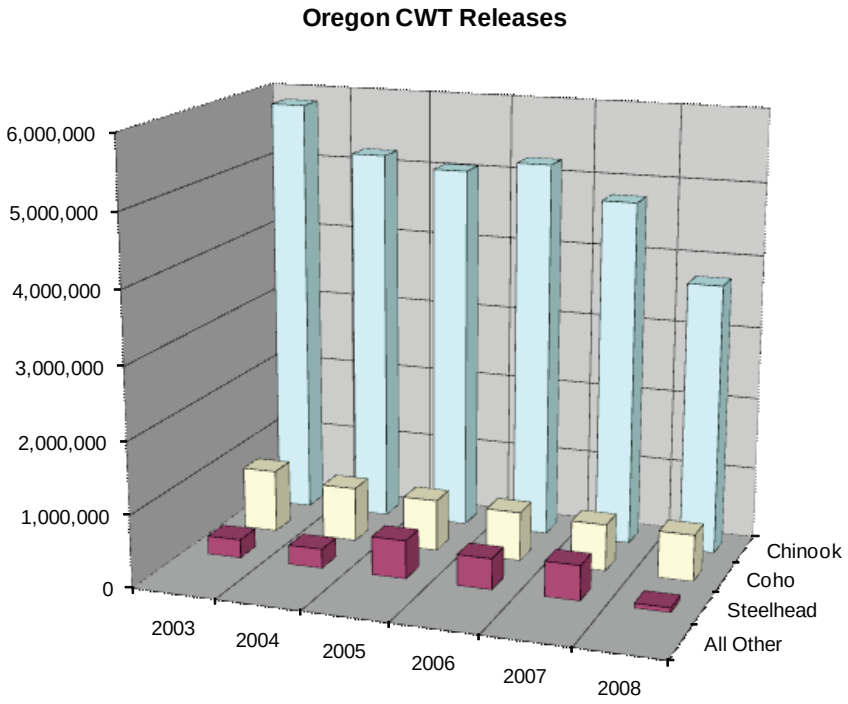


Figure A9. Hatcheries and rearing facilities in Washington State, Puget Sound area, that have released salmonids with CWTs (includes federal, state, tribal, other facilities).

Table A11. Hatcheries and rearing facilities in Washington State, Puget Sound area, that have released salmonids with CWTs (includes Federal, State, Tribal, other facilities).

	WA- Puget Sound area Facilities Releasing: 2000 - 2008		WA- Puget Sound area Facilities Releasing: pre - 2000
1	Agate Pass Sea Pens	34	Allison Springs
2	Big Beef Creek	35	Ballard Salmon Club
3	Brownsville Net Pens	36	Capitol Lake Rearing
4	Chambers Creek	37	Coulter Creek Rearing Pond
5	Clarks Creek	38	Des Moines Net Pens
6	Crisp Creek Rearing Pond	39	Elliott Bay Seapens
7	Elliott Bay Tribal Net Pens	40	Enetai
8	Garrison	41	Filucy Bay Net Pens
9	George Adams	42	Fox Island Net Pens
10	Gorst Creek Rearing Ponds	43	Gig Harbor Pens
11	Grovers Creek	44	Glen Ayr Net Pens
12	Hoodsport	45	Hood Canal Marina Net Pen
13	Hupp Springs Rearing	46	Hoodsport Marina Net Pens
14	Icy Creek	47	Leabugten Wharf Net Pens
15	Issaquah	48	Little Boston Creek
16	Kalama Creek	49	Long Live the Kings - Lilliwaup
17	Keta Creek	50	McKernan
18	Lakewood	51	Montlake
19	Manchester Fuel Depot	52	Narrows Marina Pens
20	McAllister	53	NWSSC - Cedar River
21	Minter Creek	54	NWSSC - Everett Net Pens
22	Nisqually	55	Pleasant Harbor Net Pens
23	Percival Cove Net Pens	56	Possession Bait Pond
24	Port Gamble Net Pens	57	Puyallup
25	Portage Bay	58	Quartermaster Harbor Net Pens
26	Puyallup Tribal	59	Seattle Aquarium
27	Quilcene NFH	60	Seward Park
28	Ricks Pond	61	Shaw Cove Net Pens
29	Soos Creek	62	Shelton
30	South Sound Net Pens	63	Squaxin Island Pens
31	Tumwater Falls	64	Sund Rock Net Pens
32	Voights Creek	65	Webster's
33	White River	66	Whidbey Island Net Pens
		67	Zittel's Marina Pens



	2003	2004	2005	2006	2007	2008
All Other						
Steelhead	255,405	267,531	529,766	427,459	483,527	63,661
Coho	867,756	751,448	710,592	678,468	645,243	643,512
Chinook	5,835,307	5,198,497	5,053,743	5,210,819	4,771,561	3,731,202

Figure A10. All CWT Releases in Oregon State by species and year from 2003 to 2008 (Regional Mark Information System Database [online database]).

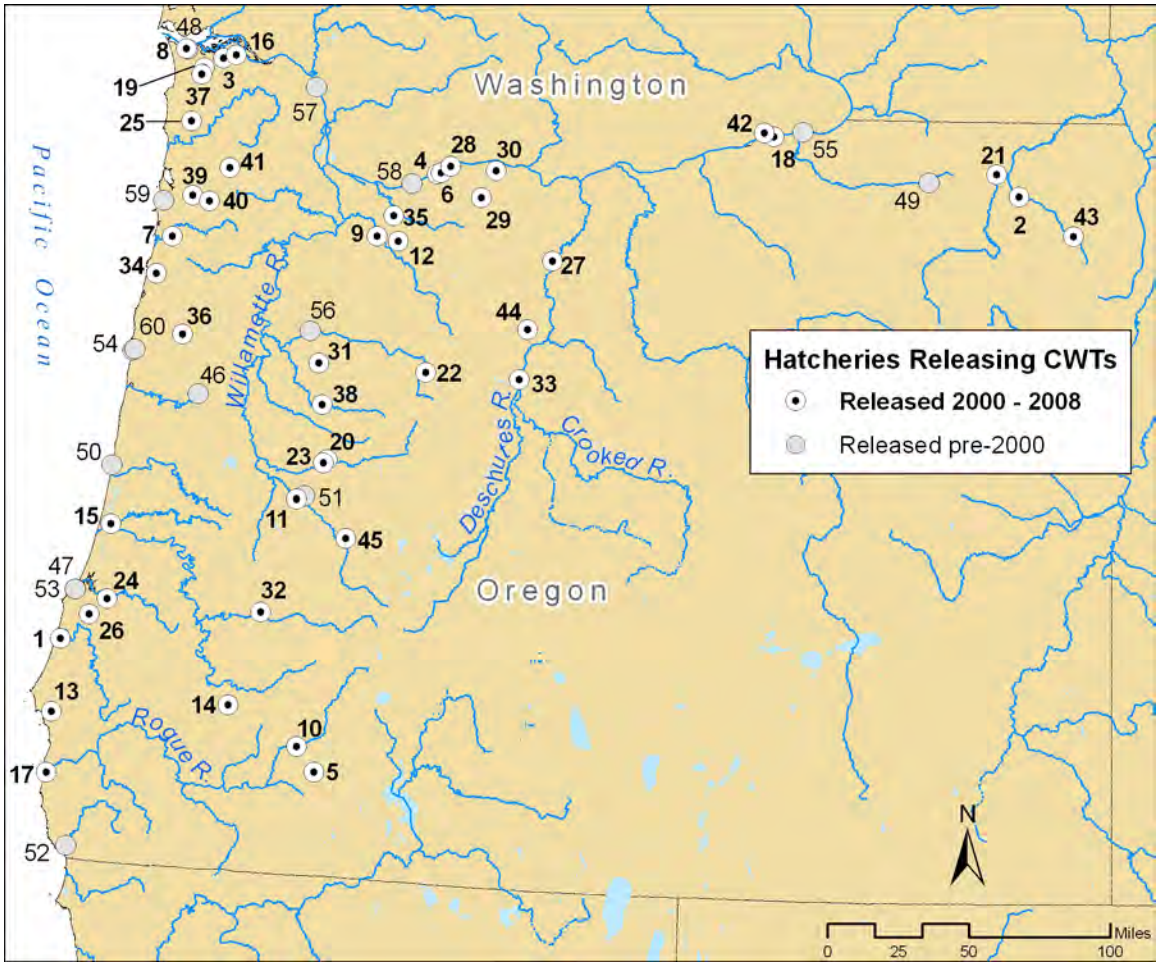
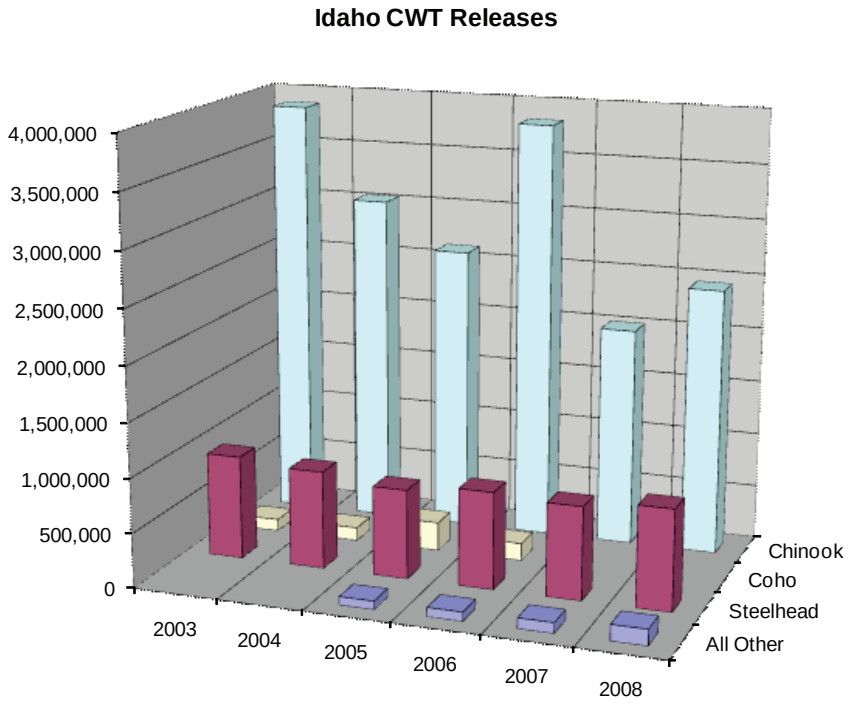


Figure A11. Hatcheries and rearing facilities in Oregon State that have released salmonids with CWTs (includes federal, state, tribal, other facilities).

Table A12. Legend: hatcheries and rearing facilities in Oregon State that have released salmonids with CWTs (includes Federal, State, Tribal, other facilities).

OR Facilities Releasing: 2000 - 2008		OR Facilities Releasing: 2000 - 2008	
1	Bandon	33	Round Butte
2	Big Canyon Pond	34	Salmon River
3	Big Creek	35	Sandy
4	Bonneville	36	Siletz
5	Butte Falls	37	South Fork. Klaskanine Pond
6	Cascade	38	South Santiam
7	Cedar Creek	39	Trask River
8	CEDC Youngs Bay Net Pens	40	Trask River Pond
9	Clackamas	41	Tuffy Creek Pond
10	Cole M. Rivers	42	Umatilla
11	Dexter Ponds	43	Wallowa
12	Eagle Creek NFH	44	Warm Springs NFH
13	Elk River	45	Willamette
14	Galesville Trap		
15	Gardiner Creek	OR Facilities Releasing: pre - 2000	
16	Gnat Creek		
17	Indian Creek Pond	46	Alsea
18	Irrigon	47	Anadromous Inc. - Coos Bay
19	Klaskanine	48	Astoria High School
20	Leaburg	49	Bonifer Pond
21	Lookingglass	50	Domsea Farms
22	Marion Forks	51	Fall Creek Trap
23	McKenzie	52	Jack Creek
24	Morgan Creek	53	Oregon Aqua Foods - Coos Bay
25	Nehalem	54	Oregon Aqua Foods - Yaquina Bay
26	Noble Creek	55	Social Security Pens
27	Oak Springs	56	Stayton Pond
28	Oxbow	57	Trojan Pond
29	Parkdale	58	Wahkeena Pond
30	Powerdale Dam Trap	59	Whiskey Creek
31	Roaring River	60	Yaquina Bay Salmon Ranch
32	Rock Creek		



	2003	2004	2005	2006	2007	2008
All Other			76,250	83,470	95,873	145,884
Steelhead	951,208	897,044	818,304	888,304	851,451	921,169
Coho	109,091	121,237	263,106	159,364		
Chinook	3,869,498	3,032,528	2,611,490	3,827,833	2,007,010	2,441,291

Figure A12. All CWT Releases in Idaho State by species and year from 2003 to 2008 (Regional Mark Information System Database [online database]).

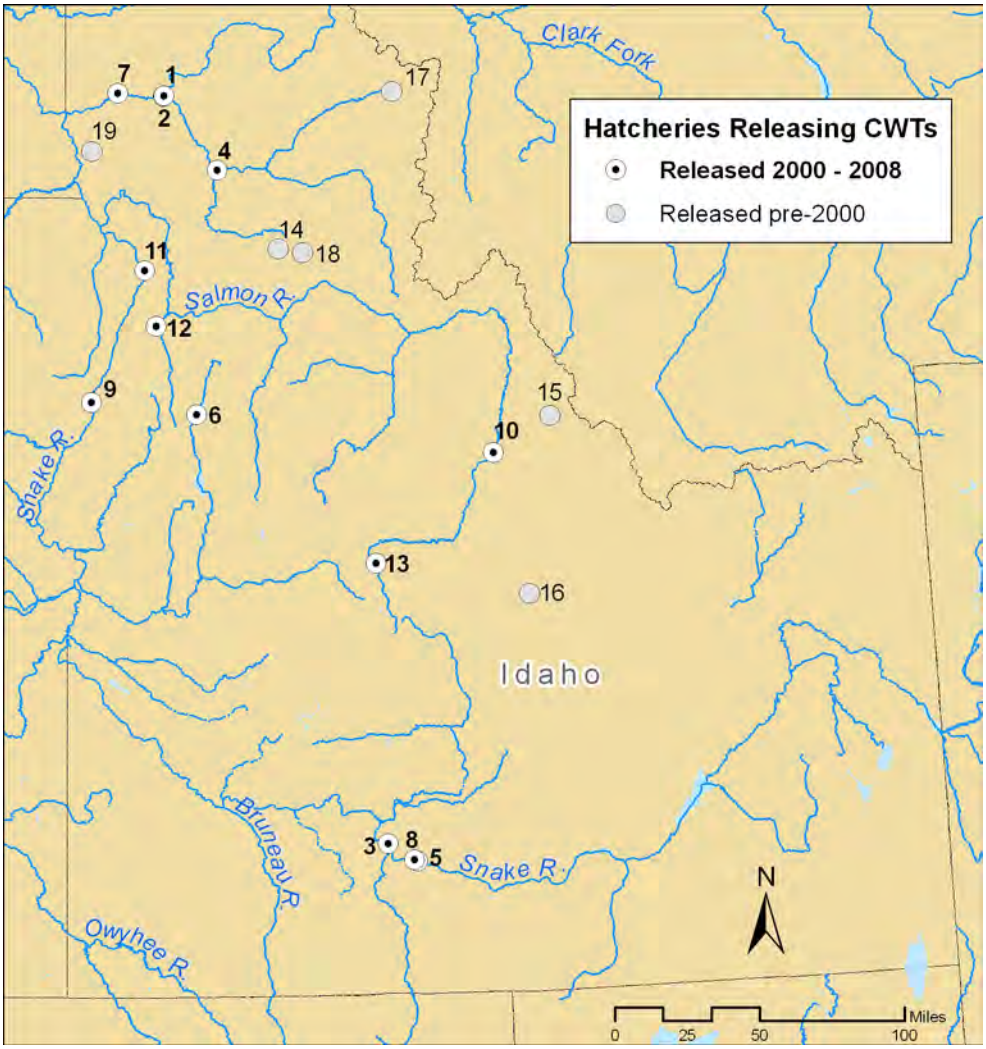
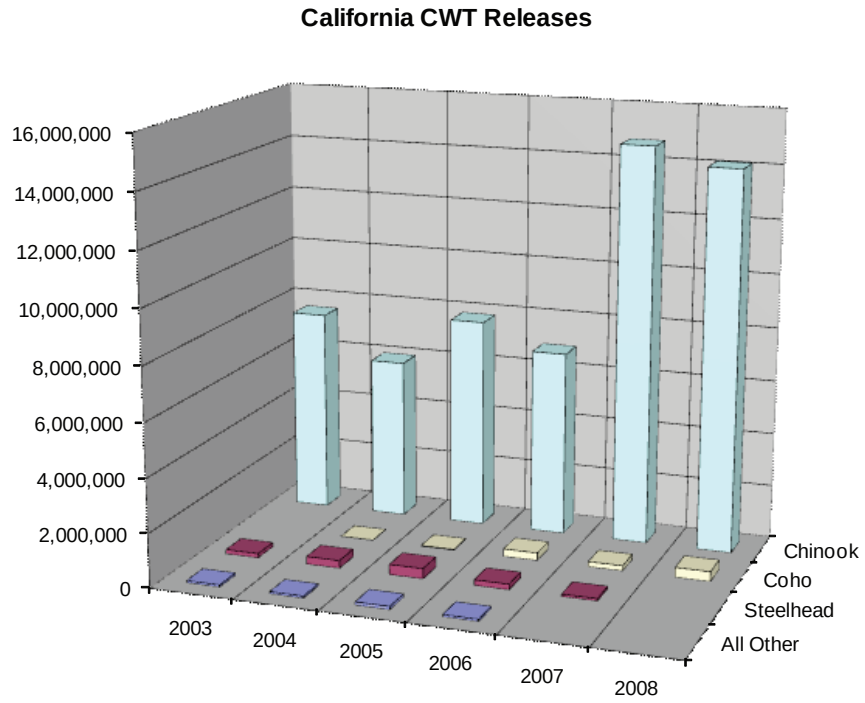


Figure A13. Hatcheries and rearing facilities in Idaho State that have released salmonids with CWTs (includes federal, state, tribal, other facilities).

Table 13. Legend: hatcheries and rearing facilities in Idaho State that have released salmonids with CWTs (includes Federal, State, Tribal, other facilities)

ID Facilities Releasing: 2000 - 2008		ID Facilities Releasing: 2000 - 2008	
1	Clearwater	12	Rapid River
2	Dworshak NFH	13	Sawtooth
3	Hagerman NFH		
4	Kooskia NFH	ID Facilities Releasing: pre - 2000	
5	Magic Valley	14	Crooked River Ponds
6	McCall	15	Hayden Creek
7	Nez Perce Tribal	16	Mackay
8	Niagara Springs	17	Powell Rearing Ponds
9	Oxbow	18	Red River Ponds
10	Pahsimeroi	19	Sweetwater
11	Pitt Landing		



	2003	2004	2005	2006	2007	2008
All Other	74,605	73,865	113,538	74,397		
Steelhead	159,207	284,959	380,730	205,819	85,842	
Coho		6,160	25,803	281,021	190,737	366,579
Chinook	7,566,562	5,975,524	7,824,466	6,892,055	14,756,567	14,129,051

Figure A14. All CWT Releases in California State by species and year from 2003 to 2008 (Regional Mark Information System Database [online database]).

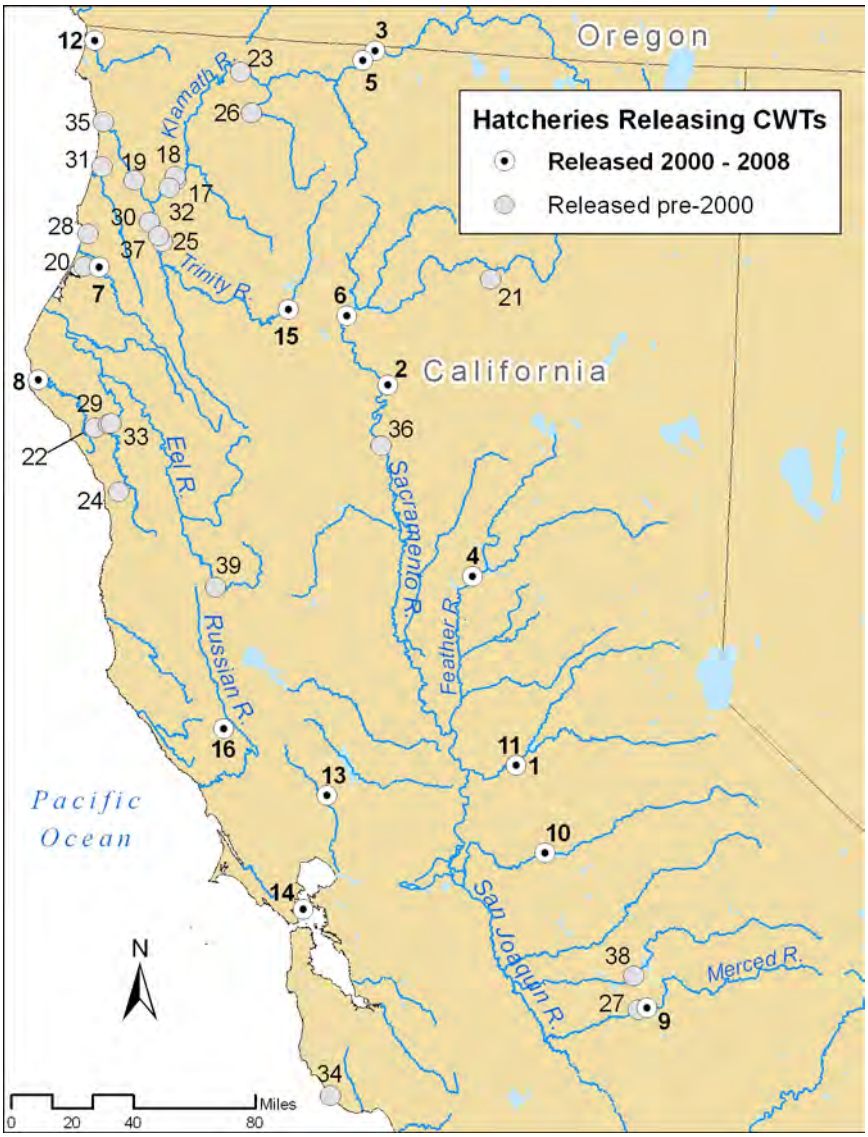


Figure A15. Hatcheries and rearing facilities in California State that have released salmonids with CWTs (includes Federal, State, Tribal, other facilities).

Table A14. Legend: hatcheries and rearing facilities in California State that have released salmonids with CWTs (includes Federal, State, Tribal, other facilities).

CA Facilities Releasing: 2000–2008		CA Facilities Releasing: pre–2000	
1	American River	17	Camp Creek
2	Coleman NFH	18	Camp Creek Enhancement Facility
3	Fall Creek Ponds	19	Cappel Creek Rearing Facility
4	Feather River	20	City of Arcata Ponds
5	Iron Gate	21	Crystal Lake
6	Livingston Stone NFH	22	Dinner Creek Ponds
7	Mad River	23	Grider Creek Ponds
8	Mattole Salmon Group	24	Hollow Tree Creek Ponds
9	Merced River Fish Facility	25	Horse-Linto
10	Mokelumne River	26	Kelsey Creek
11	Nimbus	27	La Grange Fish Facility
12	Rowdy Creek	28	Little River Pond
13	Silverado Fisheries Base	29	Marshall Creek Ponds
14	Tiburon Sea Pens	30	Mill Creek
15	Trinity River	31	Prairie Creek
16	Warm Springs	32	Red Cap Creek
		33	Redwood Creek Ponds
		34	Silverking Oceanic Farms
		35	Spruce Creek
		36	Tehama-Colusa Fish Facility
		37	Tish-Tang Rearing
		38	Tuolumne River Fish Facility
		39	Van Arsdale

Chapter 3.—Guidelines for Conducting Smolt Survival Studies in the Columbia River

Albert Giorgi[1], John Skalski[2], Chuck Peven[3], Mike Langeslay[4], Steve Smith[5],Tim Counihan[6], Russell Perry[6], Shane Bickford[7]

Abstract

For more than a decade, investigators from different research groups in the Pacific Northwest have been using electronic tags to estimate survival of salmonid smolts as they migrate seaward past hydroelectric dams and through impoundments on the Snake and Columbia Rivers. Over the years, they have refined both analytical and field methods associated with such studies. In this collaborative paper, they synthesize years of experience to formulate a set of guidelines that may assist others with the design and execution of survival studies involving smolts during their migratory phase.

Introduction

One of the most important issues facing the management of anadromous salmonids in the Columbia Basin is determining the survival rates of juvenile salmon and steelhead as they migrate seaward through the complex of hydroelectric dams on the Columbia and Snake Rivers. Smolt survival has become an important performance measure used by fish managers and hydroplant operators to evaluate the effectiveness of different management and recovery actions. These performance standards are typically expressed as survival probabilities in Biological Opinions, Habitat Conservation Plans, and hydro-relicensing agreements.

Increasingly, smolt survival monitoring is being adapted as a central performance measure reflecting the impacts of management actions in river systems throughout the western United States. Within the Columbia–Snake River hydroelectric system, fish managers are responsible for developing and implementing management actions to improve survival of outmigrating salmon and steelhead smolts. Similar requirements are found in other water systems with migrating populations. Survival studies are important because they permit a direct and immediate assessment of the effectiveness of management actions.

In the Columbia Basin, three types of electronic tags are currently used to generate assorted estimates of smolt survival. They are coded to uniquely identify individual tagged fish. All are miniaturized devices manufactured by a variety of vendors and include radio, acoustic, and passive integrated transponder (PIT) technologies. In a typical year, approximately 1 million PIT tags and 30,000–50,000 acoustic and/or radio tags are used to mark smolts in the Columbia-Snake River system. These numbers are in addition to nearly 10 million coded-wire-tagged (CWT) fish released from hatcheries each year. The detection distance of PIT tags is on the order of 1 meter or so, compared to a detection radius of the order of 0.5 km for active tags. This difference has a dramatic effect on how smolt survival studies are designed using the different tag technologies. The near-field requirements of PIT tags have until recently limited detection locations to turbine bypass systems and adult ladders at dams where fish can be concentrated. However, hydrophone and antenna arrays for detecting acoustic and radio tags can be deployed in a myriad of configurations in order to extract survival information at multiple geographic scales. Therefore, the tag type must be carefully paired with the spatial resolution of the study and the tag release-recapture model for the study to be effective.

The purpose of this document is to provide guidelines for planning, analyzing, executing, and effectively reporting results generated by survival studies involving juvenile salmonids. We rely on more than a decade and a half of experience to formulate the guidelines. We believe these guidelines are generic enough to have application anywhere evaluations of the effects of management actions on smolt survival are conducted.

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Analytical Methods

The cornerstone for designing a smolt survival study is the selection of an appropriate analytical framework. This takes the form of a release-recapture statistical model used to generate the survival estimates of interest. The selection of an appropriate analytical model is a function of the study objectives, the availability of recapture sites (i.e., detection sites in the case of electronic tags) with adequate recapture probabilities, and satisfactory fulfillment of key model assumptions. With respect to the last issue, it is not often possible to demonstrate that all assumptions are fully met. Even so, some release-recapture models are more robust to all or some model violations than others. For these reasons, the study design must take into account not only logistical concerns but perhaps, more importantly, the analytical foundation. In general, the more robust designs require more effort and more detailed information from the release-recapture process. Consequently, investigations need to balance the often conflicting demands of cost, feasibility, robustness, and precision.

The appropriate tagging model must also take into account the biology of the species and local geography. Specifically, most models assume the juvenile salmonids are active migrants. When this assumption is true, the estimated survival parameters are indeed quantifying survival. However, for fish stocks such as subyearling Chinook salmon or steelhead that might delay migration or residualize for a time, the estimated survival parameters are actually quantifying the joint probability of migrating and surviving, the complement of which is not mortality. Lowther and Skalski (1998) and Buchanan et al. (2009) have developed release-recapture models that differentiate mortality from residualization.

The Columbia-Snake River system has a relatively simple geographic layout where smolt outmigration is straight downriver and without options. In this case, the Cormack (1964) – Jolly (1965) – Seber (1965) model can be used to estimate reach survival, substituting the concept of spatial for temporal sampling. However, in complex river systems such as the Sacramento-San Joaquin River Delta of California, these models can be inadequate. Perry et al. (2009) illustrate the use of multi-State, mark-recapture (MSMR) models to estimate survival and transition probabilities through alternative migration corridors. In so doing, the tagging models more realistically describe the contribution of alternative routes to overall migration success.

There are basically two general approaches for estimating smolt survival through a river reach: the single release-recapture model (Skalski et al., 1998) and the paired release-recapture model (Burnham et al., 1987). The goals of both approaches are to estimate fish survival between two points in the river. These models can be used individually or in combination to estimate smolt survival through projects (i.e., dam plus reservoir), dams, reservoirs, and individual passage routes at dams. In addition, a third model ("quadruple release") can be used to partition survival at a dam into passage-route survival estimates (spillway, powerhouse, and bypass/sluice), while a fourth design ("virtual/paired release") can be used to isolate dam passage survival from pool passage survival. Details of these four release-recapture designs are presented below. Assumptions of the various release-recapture designs are discussed in appendix A.

Reach Survival

Single Release-Recapture Model (SRM) Design

The single release-recapture model (SRM) design consists of a single release of tagged fish with a minimum of two downstream recapture locations. The focus of this design is to estimate survival through extended reaches of river (fig. 1). At a minimum, the tags used for this model must be uniquely identifiable and at least a portion of the fish must be re-released at all locations except the last downstream site. In addition, the unique identities of each tagged fish must be accurately recorded at each recapture point.

In the case of radio-tag and acoustic-tag studies, the reaches are defined by the locations of the downstream antenna or hydrophone arrays. For PIT-tag studies in the Columbia River where detections occur at juvenile bypass systems, the reaches are defined by the mixing zone in the tailrace downstream of the dam, where bypassed and non-bypassed fish ultimately mix. Because the mixing zone is a process-based definition, exact specification of its location may not be possible. This non-specificity may be problematic if formal geographically based definitions of a reach are required (i.e., 500 m below tailrace).

Survival estimates generated by the SRM model reflect the effects of all sources of mortality within a river reach. Estimates of natural survival generated by the SRM may be negatively biased if there is post-release, delayed handling, or tagging mortality. Handling effects may persist from one to several reaches downstream of the initial release location; furthermore, the more intrusive the tagging procedure, the greater the probability for such an effect to occur. This potential bias may be of particular concern in the Columbia River basin where surgical implantation of radio or acoustic tags is used. A second source of bias could be post-release tag loss, which will negatively bias survival estimates. A third source of potential bias may be caused by post-detection bypass mortality. If PIT-tagged smolts die after detection in the juvenile bypass system at a dam but before mixing with the non-bypassed fish, reach survival estimates will be negatively biased. Radio- and acoustic-tag studies are not subject to this problem because the detected fish are never physically segregated from the non-detected fish crossing a detection array. Skalski et al. (1998) used the SRM to estimate project passage survival at Lower Granite Dam using PIT-tag releases. The parameter estimates are a special case of the Cormack-Jolly-Seber model.

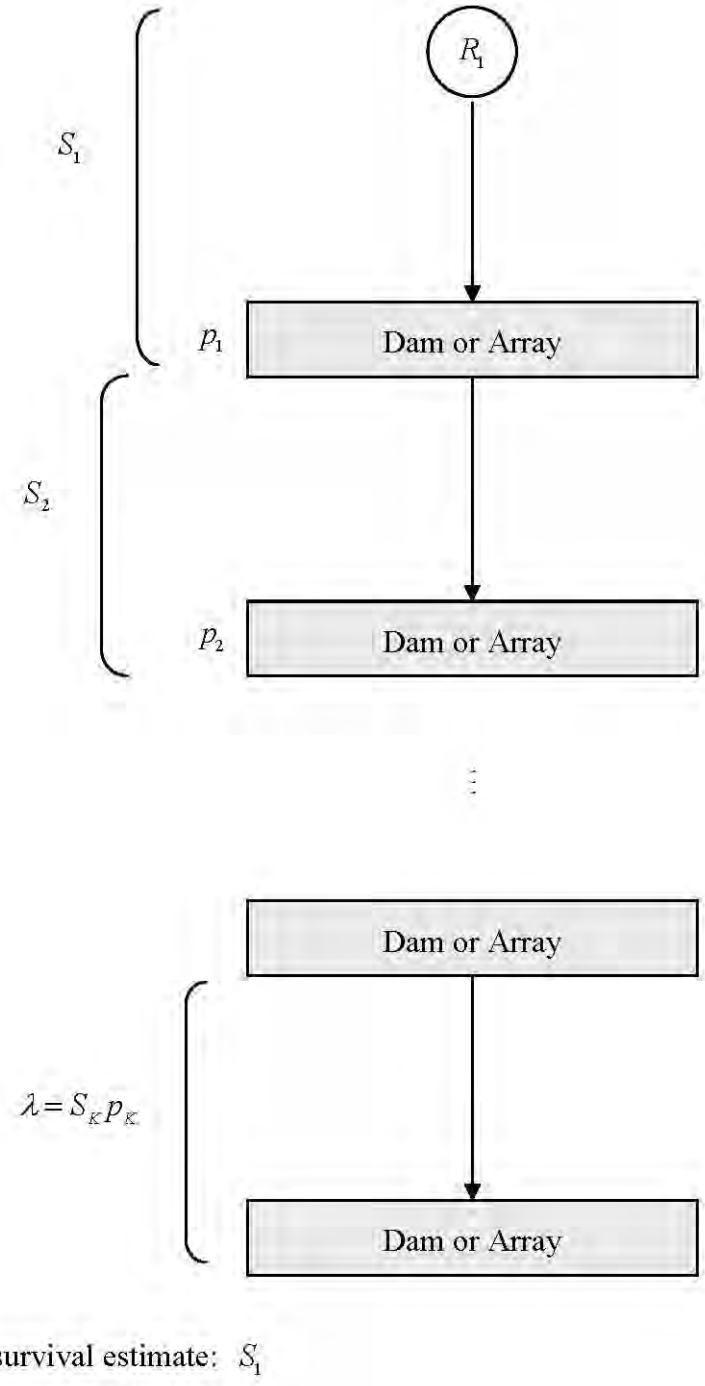


Figure 1. Schematic of a single release-recapture design with release location denoted R_1 along with estimable survival (S) and detection probability (p) parameters. In the last reach, only the joint probability of survival and detection is estimable (λ).

Unique detection/capture probabilities can be estimated at each detection site in an SRM design except the last. In the last reach, only the joint probability of survival to and being detected can be estimated (i.e., $\lambda=S_K p_K$). It is for this reason that the minimal study design must consist of at least two downstream detection locations. Assumptions of the SRM design are discussed in appendix A.

Paired Release-Recapture Model (PRM) Design

The paired release-recapture model (PRM) design consists of a minimum of two release locations (one upstream of and one downstream of the reach of inference) and two downstream recapture sites. With only a single downstream recapture site, the data are inadequate to distinguish differences in survival from differences in downstream recapture probabilities between release groups (fig. 2). The focus of the design is to estimate survival in the reach between the two release points (fig. 3). The ideal circumstance is what Burnham et al. (1987) describes as the "complete capture history model." In this situation, capture histories are recorded for all uniquely tagged fish at all detection sites.

The PRM requires the two releases to share common survival processes downstream of the second release site. To fulfill this requirement, release times are usually staggered so that the first release group arrives at the second release location as those fish are being released. The farther apart the release locations, the more difficult it is to achieve adequate mixing through the common migratory reach(es). The first difficulty is identifying the correct lag time for the releases; the second concern is the differential migration speed and dispersion of the experimental groups. Consequently, the greater the lag time and distance between releases, the more likely the arrival distributions will be different downriver for the two release groups.

The estimate of reach survival from the paired-release design (fig. 3) is the ratio of two independent SRM survival estimates. Capture processes can therefore differ between release groups without affecting valid estimation of reach survival. If mixing has not occurred, valid estimation of reach survival then depends on the assumption that survival processes were constant over the course of the study.

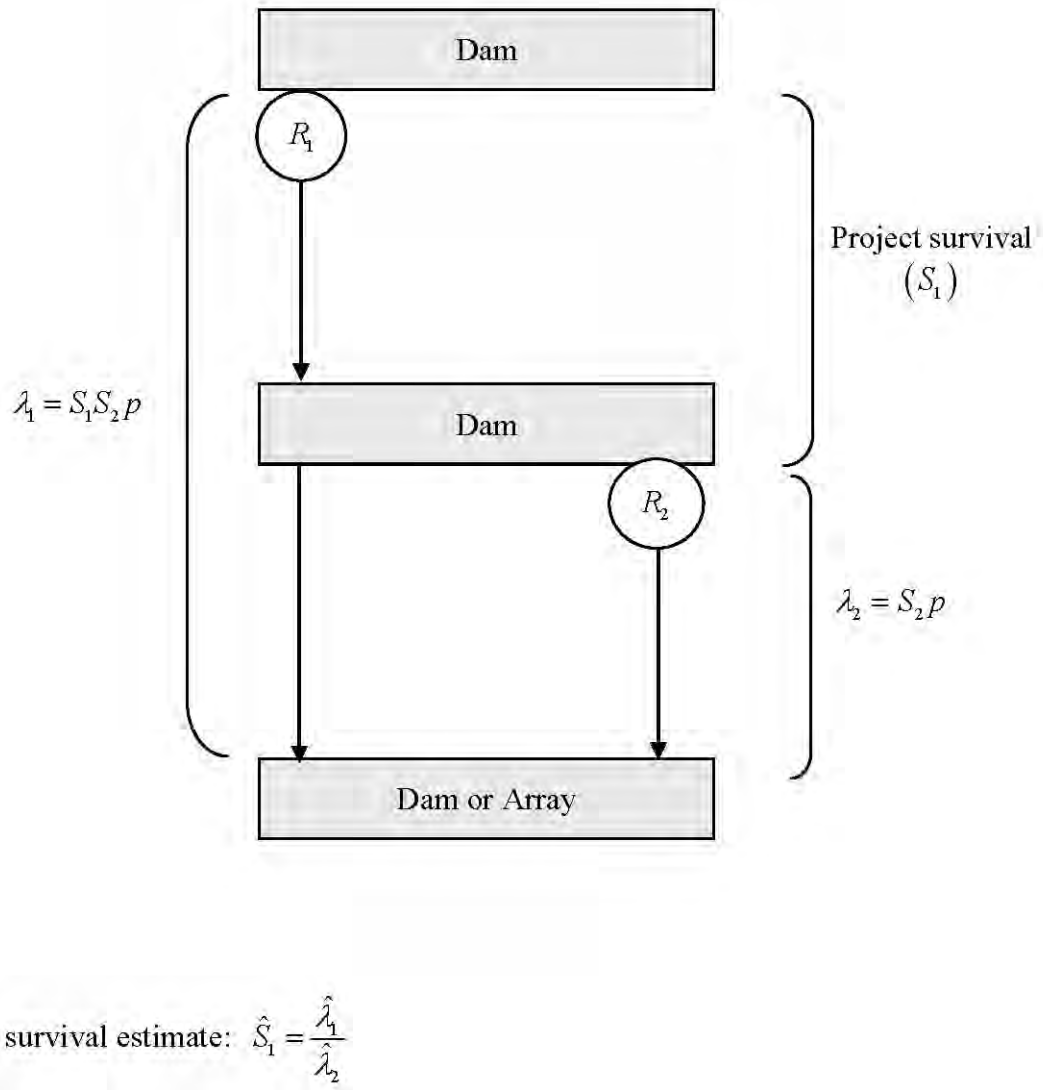


Figure 2. Schematic illustrating a minimal paired release-recapture design with two release sites (R_1 and R_2), one downstream detection site, and associated estimable parameters. Project survival (S_1) is estimated as a ratio of the recovery proportions (λs) for the two release groups.

To minimize any potential for bias, the study design needs to ensure that both release groups experience the same degree of handling effects. To accomplish this, the first downstream recapture site must be far enough downstream that the post-release handling mortality has been completely manifested in both release groups.

As an example, if both groups of PIT-tagged fish experience the same proportion of post-release tag loss, the effect of tag loss would be cancelled and the resultant PRM survival estimate would be unbiased. However, this may not be true in the case of radio tags or acoustic tags, where tag failure is time-dependent. If the upstream and downstream releases occur at different times, the time-dependent tag failure will necessarily be different between release groups. As such, separate corrections for tag failure may be necessary for the upstream and downstream releases in order to obtain an unbiased estimate of project survival (Townsend et al., 2006).

Dam Passage Survival

Partitioning project survival into dam and pool (i.e., reservoir) components requires additional tagging effort and design sophistication. Conducting a paired release in the forebay and tailrace of a dam is usually unsuccessful because the forebay release will not pass through the complex of passage routes at a dam the same way as run-of-river fish.

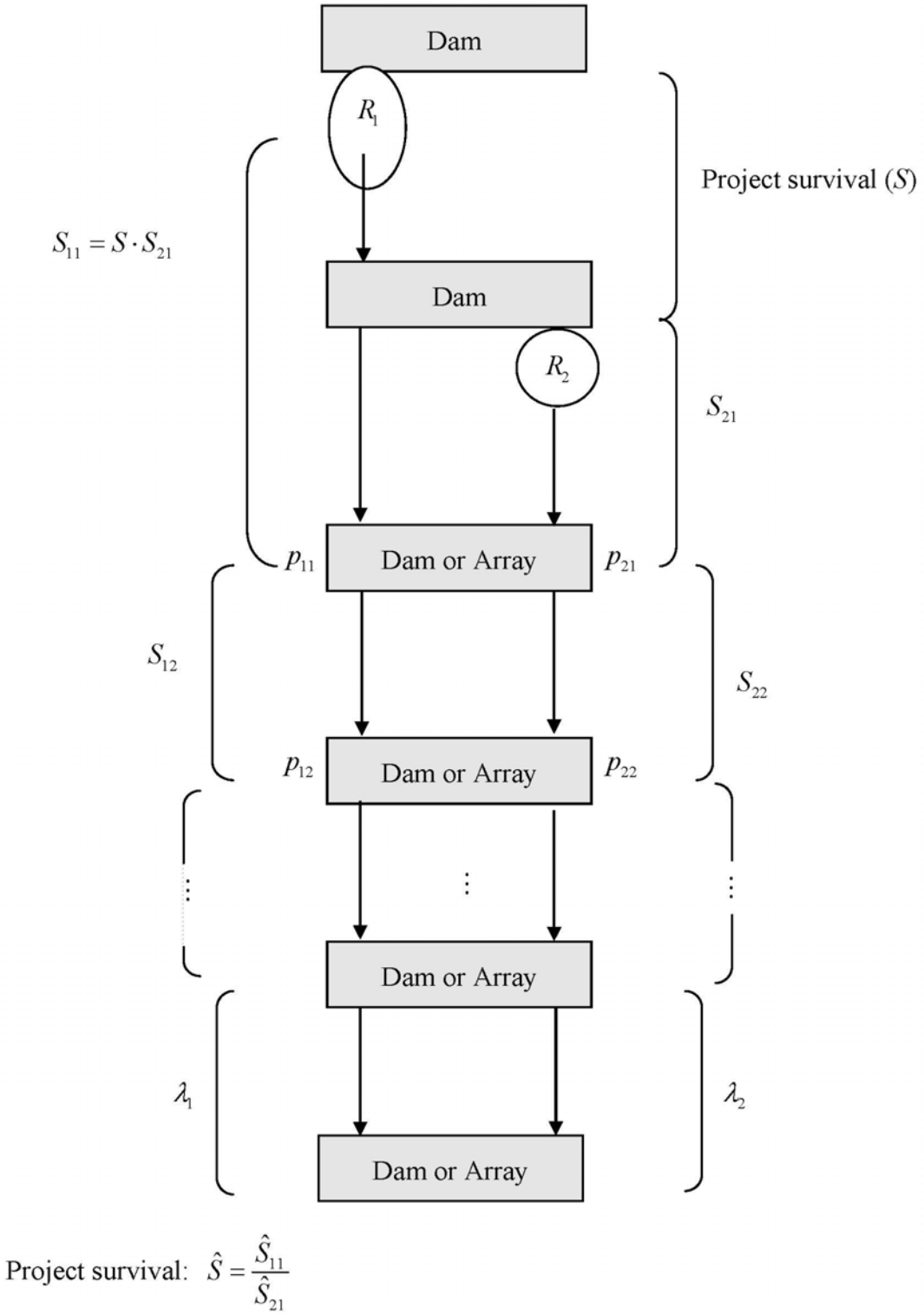


Figure 3. Schematic illustrating a paired release-recapture design with multiple downstream detection locations. Project survival (S) is estimated by the ratio of the reach survivals (S_{11}/S_{21}) to the first downstream detection site.

Conversely, pairing fish known to have arrived at the dam via telemetry with a fresh tailrace release can positively bias estimates of dam passage survival if the release locations are far enough apart to result in differential expression of handling effects. The reason is that the fish used in the virtual release may have had time to express handling effects before arriving at the dam, while the fresh fish release has not. Two approaches are used to overcome these problems and estimate dam passage survival.

Quadruple-Release Design

A quadruple-release design has been developed to overcome the difficulty of pairing inriver fish with newly released fish. This method starts with the traditional paired-release model to estimate project survival ($\hat{S}_{\text{Proj}}$) from the tailrace of one dam to the tailrace of the next (fig. 4; R_1 and R_2). This design is augmented with a double-detection array at each passage route in order to estimate route-specific passage proportions (P_i). Fish known to have passed through the various routes are then tracked downstream in order to estimate route-specific relative passage survivals. These relative survival estimates express the relative survival through an alternative passage route compared to the survival through a specific well-defined route, such as a juvenile bypass or sluiceway (e.g., $RS_{i/j}$, relative survival of route *i* to that of route *j*). The final component of the design is then a paired-release survival study through that specific route (i.e., S_j) in order to estimate absolute passage survival (fig. 4; R_3 and R_4). The absolute passage survival through route *j* times the relative survival of route *i* to route *j* then provides an estimate of absolute survival (e.g., $RS_{i/j} \bullet S_j = S_i$) through route *i*.

Dam passage survival is then reconstructed from the route-specific passage proportions and survival rates as follows

$$\hat{S}_{\text{Dam}} = \sum_{i=1}^{K} \hat{P}_i \widehat{RS}_{i/j} \hat{S}_j ,$$

where $RS_{j/j} \equiv 1$. In the case of figure 4, dam passage survival will be estimated as:

$$\hat{S}_{\text{Dam}} = \hat{P}_{SL} \cdot \hat{S}_{SL} + \hat{P}_{SP} \cdot RS_{SP/SL} \cdot \hat{S}_{SL} + \hat{P}_{PH} \cdot RS_{PH/SL} \cdot \hat{S}_{SL} ,$$

for a dam with sluiceway (SL), spillway (SP), and powerhouse (PH) routes. In this model, dam passage survival is defined from the front of the dam to the mixing zone in the tailrace where the tailrace releases were performed. Pool passage survival is estimated by the quotient

$$\hat{S}_{\text{Pool}} = \frac{\hat{S}_{\text{Proj}}}{\hat{S}_{\text{Dam}}} .$$

Precision of this model can be low because of the number of parameters that must be estimated. Precision also may be low if specific routes have very low passage numbers, since this increases the difficulty of precisely estimating survival through those routes.

Certain conditions need to be satisfied for this approach to provide valid estimation of dam passage survival. The first requirement is to obtain unbiased estimates of fish passage proportions through the various routes of a dam. Secondly, a valid Lincoln/Petersen estimate of tagged fish abundance through each route is needed.

The requirement that the product of a relative survival estimate for one route and the estimate of absolute passage survival for the well-defined route provide valid estimates of survival for the routes not directly measured is critical to this study design. Hence, survival through the selected route for absolute estimation must be representative of the conditions over which relative survival was estimated. All releases must be executed over the entire span of the study period, be it days, weeks, or months. Skalski et al. (2008a) describes the application of this model at Rocky Reach Dam on the Columbia River in estimating dam passage survival of sockeye salmon.

Virtual-Release/Paired-Release Design

Rather than reconstructing dam passage survival from route-specific information as done in the previous approach, this design attempts to estimate dam passage survival using traditional single- and paired-release methods. A detection array is located in the forebay to identify fish that have arrived at the dam (fig. 5). This virtual release group is used to estimate reach survival through the dam and downstream sufficiently far enough that false positive detections from dead tagged fish from dam passage are avoided (i.e.,). However, this reach includes not only the dam passage of interest but also part of the river downstream (fig. 5). In order to correct for the extraneous reservoir passage, a paired release is used to estimate survival from the tailrace to the end of the reach estimated by the virtual release group (fig. 5; S_2 and S_3). Dam passage survival is then estimated as the quotient of the single release to the paired release, where:

$$\hat{S}_{\text{Dam}} = \frac{\hat{S}_1}{\left(\frac{\hat{S}_2}{\hat{S}_3}\right)} = \frac{\hat{S}_1 \hat{S}_3}{\hat{S}_2}$$

This approach to estimating dam passage survival is more precise than the quadruple-release design—all things considered equal—because fewer parameters require estimation. However, the route-specific constituents that make up dam passage survival cannot be separately investigated by this approach.

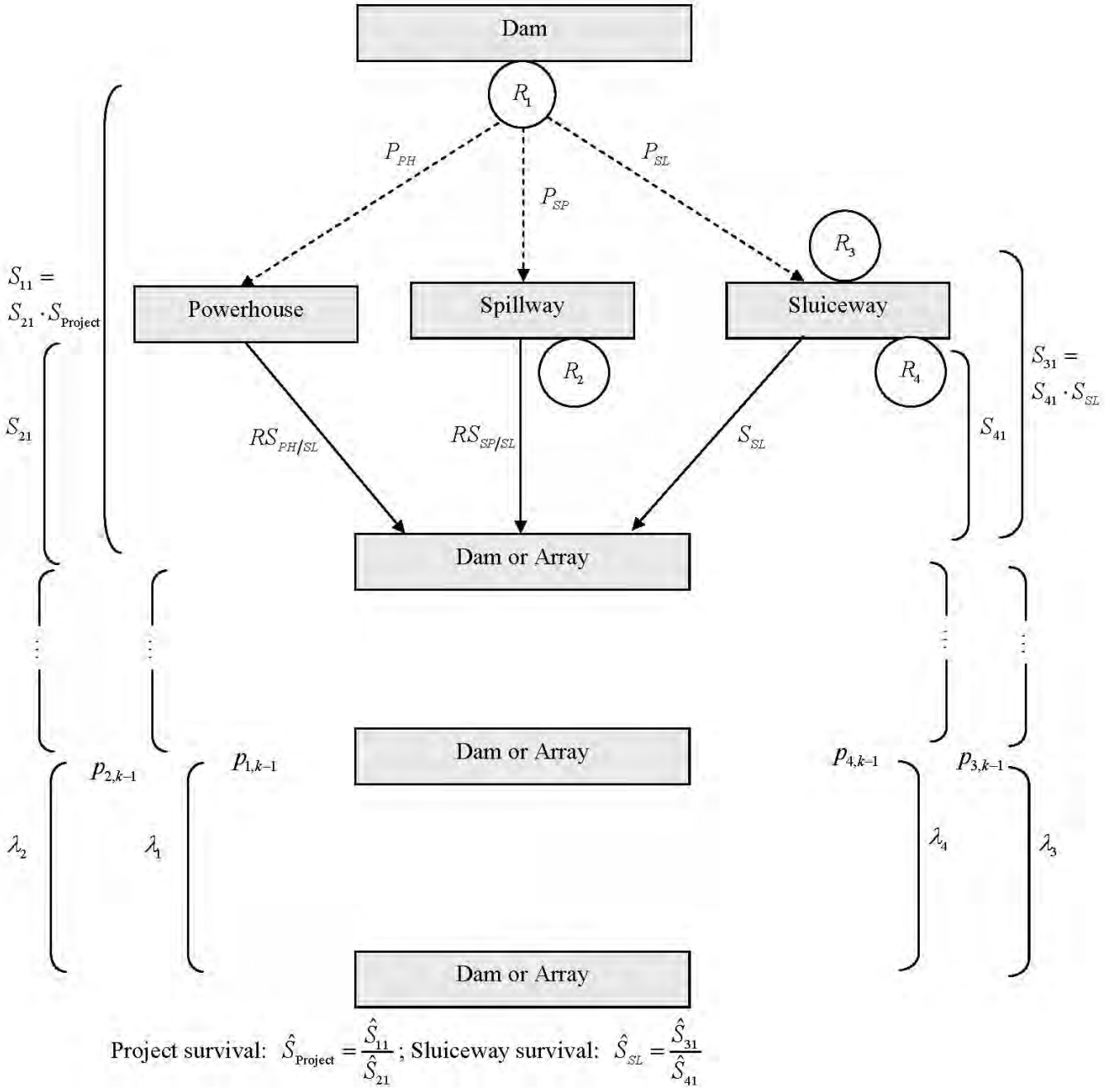
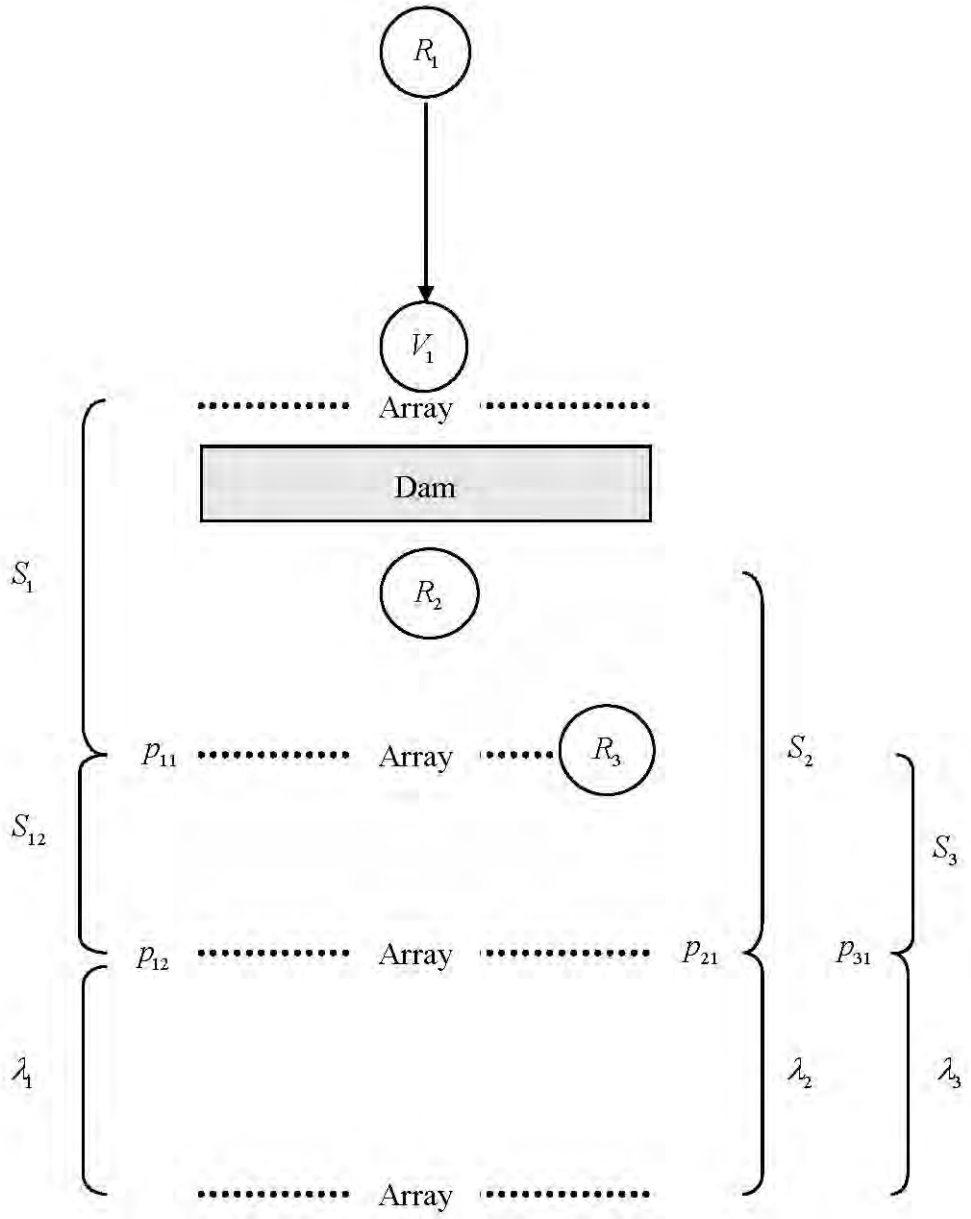


Figure 4. Schematic of quadruple-release design with releases R_1, R_2, R_3, R_4 and route-specific detection capabilities at the dam of interest. The estimate of dam passage survival is based on passage proportions (P), survival through a specific route (e.g., sluiceway, S_{SL}), and relative survival for the other routes (RS).



$$\text{Dam survival estimate: } \hat{S}_{\text{Dam}} = \frac{\hat{S}_1}{\left(\frac{\hat{S}_2}{\hat{S}_3}\right)} = \frac{\hat{S}_1 \cdot \hat{S}_3}{\hat{S}_2}$$

Figure 5. Schematic of the virtual-release/paired-release design with release R_1 that provides the fish for virtual release (V_1), releases R_2 and R_3, specific survival (S), and detection probabilities (p) of interest.

Timing of the virtual and paired releases is necessary for the model to correctly extract dam passage survival. In this design, dam passage survival is defined from the detection array in the forebay to the tailrace release location. The forebay detection array could be located either at the boat restriction zone (BRZ) or the directly in front of the dam, depending on the working definition of dam passage survival. Skalski et al. (2008b, 2009) applied this model using sockeye salmon at Rocky Reach Dam and found it to be approximately four times more efficient than the quadruple-release model for estimating dam passage survival.

Illustration of Sample Size Calculations

Release size (R_1) for a single release-recapture study was determined when estimating project survivals (fig. 6). The study design consisted of a single release and detection at three downstream detection sites. The objective was to estimate survival in the first reach (i.e., release to the tailrace of the first downstream dam). For simplicity, it was assumed each of the three projects had a survival rate of $S = 0.93$ and each detection site, a common detection rate of p (fig. 6). The anticipated precision (i.e., ε = half-width of a 95% confidence interval) is plotted as a function of the initial release size for various detection probabilities p. Each curve represents a different detection probability $p = 0.10, 0.20, \ldots, 0.90$ (fig. 6). As expected, as the detection probability increases, the required release size (R_1) decreases for a given level of precision ε. Conversely, as the desired level of precision (ε) becomes more stringent, release size (R) and/or detection probability (p) must increase.

Precision curves for single release-recapture designs similar to figure 6 can be generated using the free software, Program SampleSize 2.0 (http://www.cbr.washington.edu/paramest/samplesize/), as well as the paired-release design and the virtual/paired-release design. This sample size program provides a flexible platform to evaluate the precision of a variety of design configurations, including the number of detection sites, unique survival and detection probabilities per reach, censoring due to transport removal, and staggered entry. The instruction manual for Program SampleSize also can be obtained at the same web address.

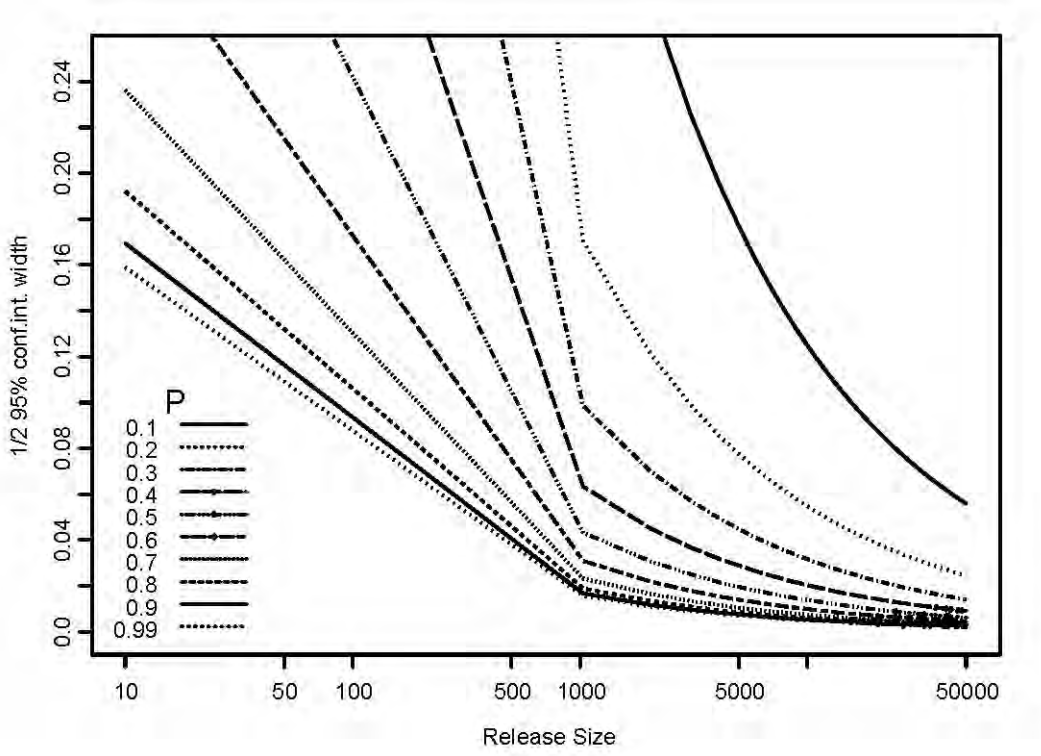


Figure 6. Precision curves for the single release-recapture design illustrated in figure 1. Precision (ε) is expressed as the anticipated half-width of a 95% confidence interval for a given release size (R) and a per-site detection probability (p).

Factors to Consider When Selecting Analytical Models and Tag Types

When designing a smolt survival study, there are a number of fundamental considerations that should be addressed to guide the selection of the proper tag type and analytical model. We briefly summarize six of these considerations below.

Size Distribution of the Run-of-River Population and Tagged Fish

Ideally, the size distribution of the tagged fish and the general population should be identical. Practically, this has been difficult to accomplish. In studies where active tags are used, larger size fish comprise the tagging groups, because they can more successfully accommodate the mass and volume of these devices. However, now that acoustic and radio tags are smaller than 0.5 g, broader size classes can be tagged. In fact, for some larger species like steelhead and yearling Chinook salmon, the tagged fish can often represent the entire size distribution of the run-of-river (ROR) population, whereas for smaller species like sockeye and subyearling Chinook salmon this may still not be possible given current tag sizes. When the size distribution of the ROR and tagged populations differ, investigators should be prepared to explain the implications of the size differential on survival inferences.

Passive Drift of Dead Fish Bearing Active Tags

Dead fish bearing active tags that are swept downstream after passage through a dam are a concern when acoustic or radio tags are used in a field study to estimate project or dam passage survival. Transmitters can continue to operate as these dead fish are swept downstream by the current to the next tag detection system. These false positive detections can result in positively biased survival estimates. To avoid false positive detections, field tests need to be conducted to ensure the downstream detection sites are located properly to avoid such tags. These tests involve intentionally releasing known dead fish bearing active tags into the tailrace and documenting any detections at the arrays situated downstream. Because drift distance will likely vary with river discharge, tests should be conducted multiple years and under high- and low-flow conditions.

Tag Life and Smolt Migration Rate

Ideally, all tagged fish should exit the entire study area prior to any tag expiration. This can be difficult to accomplish. Slow migrating species (e.g., some ocean-type Chinook salmon stocks), or the slower members of any species, can thwart the realization of this condition. It is possible to incorporate adjustments into the quantitative analysis, but certain information is required (Townsend et al., 2006). First, tag-life profile tests need to be performed using a random sample from each year's delivered allotment of tags. Fish travel time estimates between release sites and recapture sites also need to be documented. These can be depicted as cumulative fish arrival distributions and tag activity curves (e.g., Skalski et al., 2003). Tag-life corrections are helpful as long as maximum travel times are sufficiently shorter than maximum tag lives. Otherwise, bias correction will be incomplete. Tag-life adjustments must be made to both the point estimates and subsequent variance estimates.

Fish Availability Can Dictate Tag Selection

Survival estimates are supposed to represent the response of the population-at-large passing hydroelectric projects. Often times, the wild populations are of most concern, particularly if they are ESA-listed. Preferably, test fish would be randomly drawn from the migrating population in numbers sufficient to yield the desired precision. This rarely occurs. As an example, the collection of ESA-listed fish for experimental purposes is often discouraged or outright forbidden. Some stocks simply also cannot be easily collected from the river in sufficient quantities for use in PIT-tag-based investigations. The wild sockeye populations is one example of this in the mid-Columbia River basin.

A solution requires a decision, either to use tens of thousands of hatchery fish in PIT-tag-based studies, or hundreds of ROR or hatchery fish using active tags. This decision needs to be balanced against fish/tag size issues and the adequacy of hatchery fish as surrogates for wild fish. The bottom line is that any survival study will often be a compromise from the ideal evaluation that managers seek.

Tag-Recapture System Effectiveness Can Determine Sample Sizes

Recapturing, or more precisely, detecting, adequate numbers of tagged individuals determines if precision targets can be met. Tag recapture rates are in large part determined by the effectiveness of the tag detection system. Important features that contribute to the effectiveness of a detection system include density of hydrophones or antenna arrays, and the number of, and distance between, detection arrays over the migration route. An example may best illustrate the issue. For several years, studies have been underway at Rock Island Dam on the Columbia River to determine if project survival complies with specified standards. A multi-year study was conducted using both PIT and acoustic tags and yearling fall Chinook salmon to determine if both tags yield comparable

results. Acceptable precision levels (standard error [SE] = 0.025) for survival estimates were established by resource managers. In 2002, to achieve that precision, 90,003 smolts were PIT tagged, whereas only 800 smolts needed to be implanted with acoustic tags annually to achieve the same level of precision (Skalski et al., 2003).

The difference in sample sizes is dramatic and totally a function of the recapture rates realized by the two tag systems. For the PIT-tag system, the first recapture site is located well downstream on the Columbia River at McNary Dam, with additional detectors farther downstream. At these dams, only a portion of the population is interrogated for PIT tags (those fish guided by turbine screens). The longer distance from Rock Island to McNary (i.e., 162 miles) also permits the expression of more inriver mortality; thus, a lower number of fish arrive to be interrogated. In contrast, for the acoustic-tag system, the first recapture site is located at Crescent Bar, about 10 miles downstream of Rock Island, and the entire population arriving at the site is subject to interrogation.

Guidelines for Conducting Field Studies

Minimize Fish Injury and Stress during Collection and Tagging Process

Whether using fish from a hatchery or those collected from an inriver site, it is important to minimize direct contact with the fish when transferring fish to transport and holding containers. A water-to-water transfer is the preferred method; this limits contact of the fish with nets and containers, limiting scale loss and injuries. The use of “sanctuary” nets also can facilitate this.

Establish a Minimum Acclimation Time Prior to Surgery and a Minimum Recovery Time

Based on years of observations and experience with hundreds of thousands of surgically tagged fish, researchers in the Pacific Northwest have adopted a minimum pre-tagging holding period of 12–24 hours. Surgically implanting active tags too soon after capture can exacerbate post-tagging mortality. This guideline does not apply to PIT-tag implantation using a hypodermic syringe. Similarly, we recommend not liberating fish too soon following surgery. A recovery period of 24–48 hours is common, and we recommend this as a minimum. Fish are typically held in enclosures deployed inriver or in open-system tanks supplied with ambient river water at very low densities, often less than 15 g of fish per liter (L) of water. All of this is enacted to minimize stress and foster recovery of tagged fish.

Quantify the Effects of Tag Burden on Fish Survival and Performance

When determining the minimum fish size, researchers should select tags that minimize potential negative effects on fish while also attempting to represent a majority of the population. The most common index used to determine minimum fish size is the ratio of the weight of the tag (in air) relative to the weight of the fish. This is often referred to as the tag burden expressed as a percentage of fish weight. Laboratory investigations have been conducted to quantify tag effects on host fish. Indices of performance include monitoring swimming capability, buoyancy control, and, in some cases, predator avoidance. An early study recommended that the tag should be no more than 2% of the body weight of fish (Winter et al., 1996). However, more recent work supports higher tag-burden maximums of 6–12% (Brown et al., 1999). We recommend a tag-burden maximum between 5 and 6.5% based on the laboratory tests conducted by Adams et al. (1998a, 1998b), Prentice et al. (1990, 1993), and Anglea et al. (2004). For example, Adams et al. (1998) found that swimming performance of juvenile Chinook salmon was compromised relative to controls when the tag ratio exceeded about 5%. For tag ratios <5%, the authors suggested that gastrically implanted tags were more suitable for short-term studies (days), whereas surgically implanted tags were best suited to longer term studies (weeks).

Laboratory tests similar to those conducted by U.S. Geological Survey (Adams et al., 1998a, 1998b), National Marine Fisheries Service (Prentice et al., 1990, 1993a, 1993b) and Battelle Pacific Northwest National Laboratory (Anglea et al., 2004) are needed to establish the lower size limit for each tag type. Each species needs to be tested as well, because some species (e.g., sockeye salmon) are more sensitive to handling than others. Although the tag weight ratio has been the most commonly used index for determining the minimum size of fish to tag, researchers also should consider other factors, such as the tag’s weight in water, its volume, and whether or not it has an antenna. The volume of the tag controls the amount of water displaced, and, thus, the weight of the tag in water. The weight of a tag in water represents the additional mass that a fish must carry, so this measure is just as important to consider as the tag’s weight in air. Perry et al. (2001) showed that fish filled their bladder by the amount needed to offset the tag’s weight in water, not in air. The implication here is that two tags may weigh the same in air, but if their volumes differ, the tag with lower volume (higher density) will weigh more in water and have a larger effect on fish. Complicating this assessment, tags with larger volume can restrict air bladder inflation, thereby compromising the ability to regulate buoyancy. This can have an unintended effect on behavior and perhaps survival. Lastly, radio tags with antennas may affect swimming behavior due to increased drag caused by the protruding antenna (Anglea et al., 2004). In contrast, acoustic tags have no external antenna. Researchers may therefore

choose to tag slightly smaller fish for use with acoustic tags than they would with a radio tag of similar weight. The lesson here is that each device should undergo a thorough laboratory investigation of lethal and sub-lethal effects on host fish.

Monitor and Record Key Environmental and Biological Parameters from Collection through Liberation

When analyzing survival data, it is not uncommon to observe that certain replicates or experimental treatments produce unexpected results. To resolve these inconsistencies, it is beneficial to have a detailed history describing the characteristics of the experimental animals, how they were handled, and what environmental conditions they were exposed to from the time of collection through liberation. This information can be critical in establishing a rationale for eliminating a particular group as an outlier, and is a critical step in the QA/QC process. Biological information required is basic and includes fish weight, length, presence of injuries, and level of descaling. Common abiotic information includes water temperature and dissolved oxygen levels, which should be monitored in all containers that hold fish.

Adhere to Accepted Protocols and Procedures for Surgical and Gastric Implantation of Tags

The internal implantation of electronic tags in fish requires some basic level of technical expertise. The act of surgery, and even gastric implantation, is physically traumatic to the host. Establishing a standard set of implantation protocols for application in all tagging studies would be beneficial. However, getting researchers to adopt a standard set of protocols is a difficult step. In the Columbia River basin, we are still trying to establish this after more than a decade of application. Even so, certain protocols are emerging as standards for Columbia River smolt survival studies. Currently, we recommend a combination of methods described by Adams et al. (1998a, 1998b) and Skalski et al. (2003). Because tags that are attached externally can have a large effect on swimming behavior of small fish (McCleave and Stred, 1975), that approach is not deemed acceptable for salmonid smolt survival studies.

Conduct a Tag-Life Performance Test during the Course of Every Survival Study

As a critical quality-assurance measure and source of bias correction, a tag-life study should always be conducted in conjunction with a survival study using active transmitters. A major assumption of survival studies is that no marks or tags are lost during the study. Survival estimates may be negatively biased if the transmitters fail (thereby losing the mark) prior to fish exiting the study area. Transmitters may expire prematurely because of malfunction or due to long migration times of certain fish during certain conditions. Importantly, information provided by a tag-life study can be used to adjust survival estimates for the premature failure of tags (Cowan and Schwarz, 2003). Absent this information, there is no recourse for adjusting potentially biased survival estimates caused by tag failure. Results must be considered unreliable with respect to accuracy.

We recommend conducting the tag-life study concurrent with the survival study and under ambient conditions at the study site. Select a minimum of 50 tags randomly from the entire production lot used in the study. Battery life is sensitive to temperature; thus, we recommend submerging tags in ambient river water and monitoring the codes until all tags have expired. Transmitter life may vary across years or among production batches. Therefore, *post hoc* initiation of a tag-life study after problems have been identified in the survival study may not yield an accurate representation of the failure of transmitters used in the survival study.

The objective of a tag-life study is to develop a failure-time curve for the radio tags (proportion of tags active over time) and fit a survival function to the tag-life data (e.g., Cowan and Schwarz [2003] used a Kaplan-Meier survival function, whereas Skalski et al. [2000, 2005] used Gompertz and Weibull functions).

Examination of Tagger Effects

A common assumption is that treatment and control groups are similar in all respects, other than the treatment condition. Investigators go to great lengths to ensure this. The studies discussed here can be quite complex, involving the tagging of thousands of fish that are released over broad geographic distances (scores of kilometers). Executing these studies often involves the use of several tagging teams. We have clear evidence from quality-assurance monitoring that even under the strictest protocols, individual taggers can have an effect on fish survival. This should not be surprising, given the precise surgical procedures involved on these small fish. Thus, it is imperative that the tagger effect is homogenous across experimental groups. This is most easily accomplished if all fish are tagged at one central location. This is not always possible. In those cases, care must be taken to rotate taggers among tagging locations to ensure homogeneous effort by taggers across all experimental groups.

Nevertheless, there is growing evidence that balancing tagger effects across all experimental groups may be insufficient. In a number of cases, tagger effects appear to have been time dependent and not eliminated by traditional paired release-recapture designs. A fixed proportion of the fish is not seemingly affected; instead, the proportion of fish that are affected continues to increase the longer the fish are inriver. The differential time inriver for paired upstream–downstream releases results in negatively biased survival

estimates. The only available recourse is to eliminate the tag groups by the offending taggers, and the only way to identify the problem is to compare survival estimates for the fish tagged by different individuals. Major differences can be identified in these comparisons, but slight effects may go undetected. Balancing the tagger effort should help to minimize the remaining problems. Examination of tagger effects should be a standard component of all survival analyses.

Formalize Tagger Training

The training we refer to here pertains to the proper implantation of internal tags (PIT, radio, acoustic). Standardized protocols for tagging fish with PIT tags are well established and documented (e.g., "PIT tag marking procedures manual" at http://www.fpc.org/). However, standard procedures for acoustic- and radio-tag implantation have not been formally adopted. General guidelines have been established by individual research groups, but no broad-based regional standards have been adopted. Many research agencies conduct annual review sessions to train new and refresh accomplished surgeons. It would be advantageous to establish regional standards, and we encourage funding agencies to pursue this. Some research groups monitor the fates of fish tagged during training sessions for weeks thereafter to identify subtle effects that would otherwise go unnoticed. Post-season analysis of the fates of inriver fish by tagger should be an integral component of the quality assurance process of all tagging studies.

Guidelines for Conveying Information

Standardize Terminology

Variations in terminology among survival studies can lead to confusion and difficulties in interpretation and comparison of results. The Columbia River basin salmon survival literature is replete with a dizzying array of terms used as descriptors. This is particularly evident for terms used to classify types of survival estimates. Often times, these terms are confusing or poorly defined. A sampling includes the terms direct survival, indirect survival, delayed mortality, extra mortality, project survival, dam survival, system survival, combined survival, etc.

Definitions of these terms can differ among investigators. The various definitions can confuse both investigators and managers who seek clear "apples-to-apples" comparisons. Resource managers have suggested that standardization of terminology could improve this situation. We concur and offer a provisional glossary of preferred definitions for use in the Columbia River basin (appendix B). Absent that standardization, an explicit description of the geographic bounds and nature of the effects embraced by the reported survival estimate needs to be prominently stated in proposals and reports.

Standardize Data Management Procedures

Often the lack of data transparency and unavailability of access to recapture data associated with active tags have been problematic. The regionally supported PIT-tag data system stands alone as an accepted and entirely functional model for archiving data from electronic tags. For other active tags, establishing a common database system remains challenging. Investigators have argued that the size and complexity involved in detection systems (frequently, scores of antennas, hydrophones, and receivers at a single site) complicates this greatly for studies using active tags, as does the multi-step process of identifying valid tag codes. They suggest that reporting raw tag detections, as does the PIT-tag system, is neither practical nor instructive. At this juncture, we concur. Although absent a standardized central database for active tags, we recommend that each investigation report the following to provide some basic level of transparency:

- State criteria for identifying valid tag recaptures for your particular study. These will vary by tag type (acoustic or radio) and can vary among investigators. Examples of criteria include the number of coded signals detected at a locale per unit time, power strength of the signal, etc.
- Describe the data reduction process in a stepwise manner, preferably using a flowchart.
- Provide the recapture history matrix used to calculate the survival estimates as an appendix.

Quality Assurance/Quality Check

We suggest that the guidelines identified thus far for executing smolt survival studies form the basis for a sound set of quality assurance/quality check (QA/QC) elements. Even so, to these we recommend adding the following:

- Confirm tag operation and codes at the time of release. This will ensure no tag loss has occurred prior to initiation of the experiment. Given our recommended 24–48 hour recovery time for surgical implants, we feel this is a mandatory step.
- Validate tag codes recorded by automated processing software. This can simply amount to processing subsets of tag detections manually, then comparing results with the auto-processed data.

Conclusions

More than ever, successful tagging studies require the successful melding of biology, electronics, and statistics, and this trend is not likely to change. Few individuals are trained in all the necessary disciplines to conduct a successful survival investigation. Instead, interdisciplinary research teams will be the only recourse to achieving defensible and reliable results. As electronic tags continue to decrease in size and cost and increase in power and longevity, the questions they will be asked to address will become increasingly complex, providing greater insights into the biology of salmonids and the consequences of anthropogenic effects. For tagging studies to meet growing expectations, careful attention to detail will be required. This paper presents as a minimum some of the more important considerations in designing, conducting, and analyzing release-recapture studies.

The standardization of protocols is more than simply developing a set of rules. The protocols should represent the best available information we have on how to successfully address alternative research goals. As goals and technologies advance, and our experience with methods increases, the protocols must also continue to advance and adjust. More importantly, study protocols should provide a common ground for scientists, fish managers, and policy makers to come together to understand what was done and what should have been done to help assure reliable survival results. Only through mutual understanding of basic methodologies and rigorous testing will the results of expensive tag investigations be accepted in resource management decisions.

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Appendix A. Model Assumptions

Single Release-Recapture Model (SRM) Design

The assumptions of the single release-recapture model (SRM) are the following:

A1. Individuals marked for the study are a representative sample from the population of interest.

A2. Survival and capture probabilities are not affected by tagging or sampling. That is, tagged animals have the same probabilities as untagged animals.

A3. All sampling events are "instantaneous." That is, sampling occurs over a negligible distance relative to the length of the intervals between sampling events.

A4. The fate of each tagged individual is independent of the fate of all others.

A5. All tagged individuals alive at a sampling location have the same probability of surviving until the end of that event.

A6. All tagged individuals alive at a sampling location have the same probability of being detected on that event.

A7. All tags are correctly identified and the status of smolt (i.e., alive or dead), correctly assessed.

The first assumption (A1) concerns making inferences from the sample to the target population. For example, if inferences are sought to Chinook salmon smolts, then the sample of tagged fish should be drawn from that class of fish. Otherwise, nonstatistical inferences are necessary to justify the similarity between the target population and the representative sample. These assumptions could also be violated if smolts selected for tagging were on the average larger than the population of smolts in general.

Assumption (A2) again relates to making inferences to the population of interest (i.e., untagged fish). If tagging has a detrimental effect on survival, then survival estimates from the single release-recapture design will tend to be negatively biased (i.e., underestimated).

The third assumption (A3) specifies that mortality is negligible immediately in the vicinity of the sampling stations, so that the estimated mortality is related to the river reaches in question and not during the sampling event. In the case of outmigrating smolts, the time they spend in the vicinity of detection equipment is brief and small, relative to the size of the river reaches in question. This assumption is for sake of mathematical convenience and should be fulfilled by the nature of the outmigration dynamics and deployment of the hydrophone or antenna array in the case of active tags.

The assumption of independence (A4) implies that the survival or death of one smolt has no effect on the fates of others. In the larger river system with tens of thousands of smolts, this is likely true. Furthermore, this assumption is common to all tag analyses with little or no evidence collected to suggest it is not generally true. Nevertheless, violations of assumption (A4) have little effect on the point estimate but might bias the variance estimate with precision being less than calculated.

Assumption (A5) specifies that a smolt's prior detection history has no effect on subsequent survival. This could be violated if some smolts were self-trained to repeatedly go through turbine or spill routes or alternatively, avoid routes because of prior experience. The problem could also arise if route-specific passage at a dam is influenced by the size of the smolt (Zabel et al. 2005). This occurrence is unlikely and can be assessed from the detection histories of the individual smolts. The lack of handling following initial release of acoustic-tagged or radio-tagged smolts further minimizes the risk that subsequent detections influence survival. Similarly, assumption (A6) could be violated if downstream detections were influenced by passage routes taken by the smolts at an upstream site. Violation of this assumption is minimized by placing hydrophone or acoustic arrays across the breadth of the river or below the mixing zones for smolts following different passages at the dam.

Assumption (A7) implies that the smolts do not lose their tags and are subsequently misidentified as dead or not captured, nor are dead fish falsely recorded as alive at detection locations. Tag loss and tag failure would tend to result in a negative bias (i.e., underestimation) of smolt survival rates. The possibility of a radio- or acoustic-tag failure will depend on travel time relative to battery life. Dead fish drifting downstream could result in a false-positive detections and upwardly bias survival estimates. Tailrace hydrophone and antenna arrays are therefore not recommended because of this reason.

Burnham et al. (1987) Tests 2 and 3 can be used to assess overall goodness-of-fit to single release-recapture assumptions. In particular, these tests can determine whether upstream capture histories affect downstream histories of occurrence.

Discussion of Bias

The distinct advantage of the SRM is that only a single release group of fish is necessary in order to estimate survival. In the case of PIT-tags, radio-tags, and acoustic-tags, the fish also do not need to be physically rehandled to record detections downstream. The model also is generic enough that unique survival and capture parameters can be estimated for all reaches but the last. One potential limitation, however, is the need for a minimum of two detection sites downstream of the release point.

In the case of radio-tag and acoustic-tag studies, the reaches are defined by the locations of the downstream antenna or hydrophone arrays. For PIT-tag studies, the reaches are defined by the mixing zone in the tailrace below the dam, where bypassed and nonbypassed fish ultimately mix. Because the mixing zone is a process-based definition of an area, exact specification of its location is not possible. This nonspecificity may be problematic if formal geographically based definitions of a reach are required (i.e., 500 m below tailrace).

The reach survival estimates from the SRM may be negatively biased in three different ways. If there is post-release delayed handling mortality, that mortality would be incorporated in the first one or two reaches below the initial release location. Consequently, survival S_1 (fig. 1) may be most susceptible to handling bias. The more invasive the tagging process (i.e., radio-tag, acoustic-tag), the more likely the chance for bias to be present. Post-release tag loss will also negatively bias survival estimates. The third source of bias is caused by post-detection bypass mortality. If PIT-tagged smolts die after detection but before mixing with the non-bypassed fish, reach survival estimates will be negatively biased. Radio-tag and acoustic-tag studies are oblivious to this problem of post-detection bypass mortality because the detected fish are never physically segregated from the nondetected fish crossing a detection array.

Paired Release-Recapture Model (PRM) Design

The paired-release model shares the assumptions A1–A7 with the single-release model. However, it was two additional assumptions:

A8. Survival in the lower river segment of the first reach is conditionally independent of survival in the upper river segment (i.e., $S_{11} = S \bullet S_{21}$).

A9. Releases R_1 and R_2 experience the same survival probabilities in the lower river segment of the first reach they share in common (i.e., S_{21}).

Assumption (A8) implies there is no synergistic relationship between survival processes in the two river segments of the first reach. In other words, smolts that survive the first river segment are no more or less susceptible to mortality in the second river segment than smolts released in the second river segment. Assumption (A9) is satisfied by the inriver mixing of the release groups but also can be satisfied if the survival processes are stable over the course of smolt passage by the releases. A stable survival process might well be expected for 1 to a few days under similar flow and spill conditions.

Burnham et al. (1987) Tests 2 and 3 can be used to assess overall goodness-of-fit to single release-recapture assumptions—in particular, whether upstream capture histories affect downstream histories of occurrence. Chi-square R × C contingency table tests can be used to assess whether the two release groups are mixed upon arrival at downstream sites. Alternatively, Kolmogorov–Smirnov tests of equal distribution can be used to test for mixing and homogeneous arrival distributions at downstream sites (Conover, 1980, p. 369-373).

Discussion of Bias

Mixing of the two release groups can assure the two releases share common survival processes in the first reach. The farther apart the release locations, then the more difficult is the task of assuring downstream mixing. Release times may need to be offset to accommodate for travel time of the first release group to the location of the second release. Even then, the arrival pattern of the upstream release group may be spread out over time when matched with the point release of the downstream control group.

The simple paired-release design of figure 2 does not permit the differentiation between effects on survival and capture probabilities when the relative recovery rates (i.e., λ_1, λ_2) are used to estimate absolute survival (S_1). However, when there are two or more downstream detection sites, survival and capture probabilities can be differentiated and estimated separately for each release group. As such, the estimate of reach survival for the paired-release design of figure 3 is the ratio of two independent estimates of absolute survival (i.e., $\hat{S}_{11} / \hat{S}_{21}$). Capture processes can therefore differ between release groups without affecting valid estimation of reach survival. If mixing has not occurred, valid estimation of reach survival then depends on the assumption that survival processes were constant over the course of the passage of the two smolt release groups through the first reach of interest.

Care also is needed to assure both release groups experience the same degrees of handling and transportation mortality. In which case, if post-release handling mortality occurs, it will be comparable in both groups. By taking the ratio of the survival estimates (i.e., $\hat{S}_{11}$ and $\hat{S}_{21}$, handling effects may cancel, yielding an unbiased estimate of reach survival. However, in order for the cancellation to occur, the first downstream detection site must be sufficiently far so that the post-release handling mortality has been totally manifested in both release groups.

The same also holds for the loss of PIT-tags post-release. If both groups experience the same tag-loss rate, the effect is cancelled in taking the ratio of the survival estimates. However, this may not be true in the case of radio tags or acoustic tags, where tag failure is time dependent. If the upstream and downstream releases occur at different times, the time-dependent tag failure will necessarily be different between release groups. As such, separate corrections for tag failure will be necessary for the upstream and downstream releases in order to obtain an unbiased estimate of project survival.

Route-Specific Model

This approach to estimating dam passage survival uses the same assumptions A1–A9 as the paired-release method. However, it has specific assumptions unique to its estimation goals:

A10. Releases R_1, R_2, and route-specific (R_{PH}, R_{SP}, R_{SL}) experience the same survival probabilities in the lower river segment of the first reach they share in common.

A11. Fish are identified correctly according to their route of passage at the dam.

A12. The dual-detection arrays within a passage route provide independent probabilities of detection.

Assumption (A10) is analogous to assumption (A8) discussed under the paired-release design. Classification of a fish to an incorrect passage route (A11) will bias the estimate of dam passage (i.e., P_{PH}, P_{SL}, etc.), as well as the subsequent estimate of route-specific survival probabilities (i.e., S_{PH}, S_{SL}, etc.). Such bias can be minimized or completely avoided by using stringent detection criteria when assigning a detected fish to a particular passage route.

To obtain unbiased estimates of arrival distribution at the dam (i.e., P_{PH}, P_{SL}, etc.), valid estimates of route-specific, tagged fish abundance are required. The Lincoln/Petersen estimator is very sensitive to nonindependence between the first and second detection events. At a hydroproject, this translates into placing antenna or hydrophone arrays in such a manner that detection in one array has no effect on fish detections in the second array. There is no empirical way to detect violations of assumption (A12). Instead, the detection arrays need to be physically located such that a fish detected in the first array has no more or less chance of being detected in the second array than a fish not detected in the first array.

In using the quadruple-release approach, a well-confined passage route such as a sluiceway or juvenile bypass is recommended. With such routes, there is limited discretion about where to release the downstream and in-route release groups. This is not true of the powerhouse or spillways with multiple intakes.

Discussion of Bias

Although this estimation approach is reasonably robust, there are minimal requirements. Foremost is the necessity to obtain unbiased estimates of fish proportions through the various routes of a dam. Valid Lincoln/Petersen estimates and proper detection-array deployment are therefore essential. The double arrays used to estimate passage abundance of the tagged fish must be independent. Otherwise, passage estimates will be biased.

Pivotal to this study design is the requirement that the product of the relative survival estimate of one route to another (i.e., $R_{SP/SL}$) and estimate of absolute passage survival (S_{SL}), e.g.,

$$\hat{R}_{SP/SL} \cdot \hat{S}_{SL} = \hat{S}_{SP}$$

provides a valid estimate of survival for the routes not directly measured (i.e., S_{SP}). Hence, survival through the selected route for absolute estimation must be representative of the conditions over which relative survival was estimated. If relative passage survival was estimated over days, weeks, or months, then so must the absolute passage survival. If the estimate of absolute passage survival is not comparable to the estimate of relative survival, bias of dam passage survival will occur, either high or low.

Virtual-Release/Paired-Release Design

The assumptions A1–A7 apply to this design as they do to all other designs discussed. In addition, the virtual/paired-release design includes the following assumptions:

A13. Survival in the lower river segment of the first reach is conditionally independent of survival in the upper river segment.

A14. Releases V_1, R_1, and R_2 experience the same survival probabilities in the lower river segments they share in common.

A15. The virtual release group is constructed of tagged fish known to have passed through the dam.

A16. All fish arriving at the dam have an equal probability of inclusion in the virtual release group, independent of passage route through the dam.

Assumption (A13) implies there is no synergistic relationship between survival processes in the two river segments of the first reach. In other words, smolts that survive dam passage are no more or less susceptible to mortality downriver than smolts released downriver (i.e., R_2 and R_3). This is the reason the virtual-release groups are not simply paired with tailrace release groups. Such a paired design

would match in-river tag groups with a new release. While the fish in the virtual-release group would have time to express any post-release handling mortality, the fresh release group would not. The resulting discrepancy could bias estimates of dam passage survival upward. Instead, the virtual/paired-release design matches fresh releases (R_2 and R_3; fig. 5) in order for handling effects to be cancelled before adjusting the reach survival of the virtual-release group. In addition, all three release groups (i.e., V_1, R_2, and R_3; fig. 5) will pass through the two downstream reaches formed by the three below-dam hydrophone arrays. Comparison of the survival estimates through these reaches for the three release groups can therefore be used to help assess the validity of assumption (A13).

Assumption (A14) is satisfied by the in-river mixing of the release groups and can further be satisfied if the survival processes prove stable over the course of the study. Release times for the release groups will be intentionally staggered during the survival study to help facilitate the in-river mixing. Arrival times will later be examined to determine the degree of temporal mixing of release groups.

Assumptions (A15) and (A16) refer to constructing a representative sample of fish that pass through the dam. By placing the hydrophone arrays used in constructing the virtual-release groups directly at the dam face, the prospects that only live fish are included is improved. Should identified fish for the virtual release die due to predation prior to dam passage, the estimates of dam passage survival will be negatively biased. Detection rates of the forebay array need to be uniform across the dam face to insure fish passage is representatively sampled with respect to all passage routes. A double-detection array in the forebay increases detection probabilities close to 1.0 and will be used to test for homogeneous detection rates.

Discussion of Bias

This model relies on the well-established single- and paired-release models and their assumptions. Mixing of the virtual and two fresh releases is essential or the survival process must be static over the course of the study in order for dam passage survival to be extracted from the quotient. Burnham et al. (1987) tests of goodness-of-fit, chi-square tests of mixing, and models using AIC and/or likelihood ratio tests can be used to determine the validity of the assumptions and find the most parsimonious model for parameter estimation.

Appendix B. Glossary of Terms

Absolute survival: The actual proportion of smolts surviving through the zone of inference.

Dam survival: The survival of the fish going through the combined passage routes of the dam, as defined by the forebay to the tailrace. For example, in the Habitat Conservation Plans (HCPs), this area is defined as 500 feet upstream of the dam to 1,000 feet downstream.

Delayed mortality: Indirect mortality expressed beyond the zone of inference. Evidence for the existence of such effects can only be ascertained by sampling the tagged fish later in the life history, most commonly upon return as adults. Because delayed mortality studies require the measurement of adult returns, delayed mortality is outside the scope of a guidance document for juvenile survival studies.

Direct survival/mortality: Direct mortality occurs in close proximity in time and space to the causative mechanism (i.e., direct effects are localized and immediate—the impact causes mortality directly). Direct mortality is typically studied for fish passing a specific passage route (e.g., turbine or sluiceway) at a dam[1].

Effect zone: That segment of the hydroelectric system where fish encounter the mortality agents under study (an effect zone can be as small as a bypass outfall, or as large as the entire Federal Columbia River Power System [FCRPS].)

Indirect survival/mortality: Indirect mortality is mortality that occurs as a consequence of the causative mechanism, but not in close proximity in time and space to the causative mechanism. For example, fish passing through a turbine may be disoriented and become more susceptible to predation for some distance downstream. Resulting increased predation, then, would be mortality that occurred indirectly because of turbine passage.

Project survival: Survival passing through a dam and the reservoir it impounds. The effect zone typically extends from the tailrace of the upper dam (or head of the reservoir) to the tailrace of the next dam.

Reach survival: Survival of fish passing through a segment of river that may include free-flowing sections or one or more projects.

Relative survival estimates: The ratio of the absolute survival of two groups (i.e., S_1/S_2). For example, the ratio through two different passage routes at a dam.

Reservoir survival: The survival of the fish going through the reservoir, defined by the tailrace of one dam to the forebay of the dam downstream. For example, in the HCPs, this area is defined as 1,000 feet downstream (of the upstream dam), to 500 feet upstream of the next dam downstream.

Route-specific survival: Survival of fish going through a known passage route at the dam (e.g., spillway, sluice, turbines, etc.).

Survival estimate: An estimate of absolute survival through a particular zone of inference.

Total survival: Reflects the combination of both direct and indirect effects.

Zone of inference: That segment of the hydroelectric system through which passage survival is estimated. This zone is defined by the particular release and recapture[2] locations of the study.

[1]Estimates of direct mortality are typically obtained using paired-release protocols, wherein treatment and control (reference) release sites bound the effect zone of interest. The study zone is also typically compact, with tagged fish recaptured shortly (minutes) after liberation and as close to the downstream end of the impact zone as practical.

[2]We use the term “recapture” throughout this document to denote detection of a tagged fish without handling.

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Chapter 4.—Surgical Implantation of Acoustic Tags: Influence of Tag Loss and Tag-Induced Mortality on Free-Ranging and Hatchery-Held Spring Chinook Salmon (*Oncorhynchus tshawytscha)* Smolts

Erin L. Rechisky[1] and David W. Welch[2]

Abstract

Medium to long-term acoustic monitoring (>1 month) of salmon smolts in the ocean requires that telemetry tags have minimal impact on growth and survival. In 2006 and 2008, we implanted acoustic transmitters into the abdominal cavity of spring Chinook salmon smolts (*Oncorhynchus tshawytscha*) from two populations within the Columbia River basin and tracked them to north of the Alaskan panhandle—a 2,500 km, 3-month long journey. Concurrently, we conducted captive tag effects studies to compare survival, tag retention, and growth of smolts (from the two populations) implanted with dummy acoustic transmitters (DATS) to a control group implanted with passive integrated transponder (PIT) tags, which weigh only 0.1 gram. The acoustic tags used in field studies in 2006 weighed 2.6–11.5% of the weight of the fish (in air) and were implanted into smolts ≥140 mm fork length (FL). DATs used in captive studies had identical dimensions as live acoustic tags, weighed 5.2–10.4 % of the weight of the fish, and were implanted into smolts ≥140 mm FL. The acoustic tags and DATs used in 2008 were slightly smaller and were implanted into smolts ≥130 mm FL. Acoustic tags used in field studies weighed 2.9–7.3% of fish weight. DATs used in captive studies were identical to live transmitters and weighed 2.8–7.6% of the weight of the fish.

Overall, short-term (<1 month) tag loss and tag related mortality of captive smolts were negligible for both tag types and both populations. Beyond 1 month, significant acoustic tag loss and tag mortality occurred in one of the two populations (which may be attributed to the sutures). In both years and in both populations, surgery and/or tag implantation caused an initial period of slower growth (compared to PIT tagged fish), followed by growth rates comparable to their PIT tagged counterparts.

We used the captive data to calculate the proportion of migrating fish available for detection (tagged live fish) at two detection sites in the ocean, and then we adjusted survival estimates for migrating smolts to account for tag loss and mortality. The proportion of fish available for detection was >98% at the first ocean detection site 40 km north of the Columbia River mouth, therefore the adjustment to survival was minor (2%). The proportion of fish available for detection at the more distant site (525 km north of the river mouth) was 85% for one population; however, relative to the mortality incurred during migration, the adjustment was relatively minor and the adjusted values fell well within the 95% confidence intervals of the unadjusted survival estimates.

We also compared statistical survival models for migrating smolts to determine if survival was a function of fish fork length at tagging, and we compared our survival estimates to independent PIT tag estimates for the same population in the same year. Survival models indicated that survival was not a function of size at tagging, and independent PIT tag survival estimates were similar to our acoustic tag estimates.

We conclude that short-term acoustic tag loss and tag related mortality were minimal for the size of smolts and transmitters that were used in our studies, and that tag loss that occurred over the longer term was minor when compared to high rates of natural mortality occurring in migrating smolts. Conversely, growth rates of acoustic tagged smolts were affected in the short term but were comparable to PIT tagged fish in the longer term.

Introduction

Pacific salmon researchers have acknowledged for decades that most of the mortality experienced by salmon occurs during the first several months at sea (see Quinn, 2005); however, tracking juvenile salmon through rivers and into the ocean has only recently been accomplished (Lacroix et al., 2004a; Melnychuk et al., 2007; Chittenden et al., 2008; Welch et al., 2008; Rechisky et al., 2009) due to the development of stationary acoustic receivers and the miniaturization of acoustic transmitters (see review by Voegeli et al., 1998; Heupel et al., 2006). Thus, it is possible to measure survival of individually identifiable fish and to test hypotheses regarding ocean survival during the critical months after ocean entry.

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To measure survival with acoustic tags it is necessary to surgically implant the transmitter into the abdominal cavity of a fish, as external methods of attachment are unlikely to be successful, and tag loss will confound estimates of survival (i.e., tag loss is assumed to be mortality). The surgical procedure or the tag itself, however, may potentially alter behavior, growth, or survival if the size of the tag exceeds biological limits (Lacroix et al., 2004b; Welch et al., 2007; Chittenden et al., 2009). If transmitters cause mortality or are expelled by the animal, then the results may not be representative of the untagged population. It is thus important to quantify the effects of tag implantation on growth and survival.

Tag effect studies have been conducted on numerous species and with several internal tag types (coded wire tags, passive integrated transponder [PIT] tags, radio transmitters, acoustic transmitters). The results obtained from these studies is dependent on the specifics of transmitter size and fish size (often expressed as percent body weight or tag burden), and morphology of the study species, as well as the study duration. For example, Lacroix et al. (2004b) specifically recommended that transmitter weight not exceed 8% of body weight for Atlantic salmon (*Salmo salar*) measuring 14–15 cm and tagged for several months. However, these specifications may not be applicable to other species and thus it is important to quantify tag effects for individual tagging studies particularly if the study focuses on survival.

Pacific salmon from the Columbia River basin (northwestern U.S.) are often the subject of tag effects studies due to their conservation status (13 of 16 *Oncorhynchus* spp. from the Columbia River basin are listed under the U.S. Endangered Species Act), and thus extensive research on salmon survival takes place within the basin (Independent Scientific Review Panel/Independent Scientific Advisory Board, 2009). PIT tags are the primary method of measuring survival in the Columbia River Basin (Faulkner et al., 2007) because they are small, light, and inexpensive, and have little or negligible effect on survival (Prentice et al., 1987); however, the use of radio transmitters (Adams et al., 1998a, 1998b; Martinelli et al., 1998; Hockersmith et al., 2003), and acoustic transmitters have become more common with the advent of smaller transmitters (Anglea et al., 2004; Brown et al., 2006).

Tag effects studies generally are conducted in controlled environments where predation or prey capture is not a factor and fish are held in artificial conditions and fed to satiation every day. Although captive studies do not incorporate stresses encountered by fish in the wild, they are the most practical method currently available for measuring changes in growth, and for monitoring survival and tag retention. If a captive study and a field study are conducted concurrently (on the same population within the same year) then the specific results from the captive study can then be extrapolated to help assess the potential negative impact of tag implantation on the release group used in field studies. If the captive tag study yields no tag effects or tag loss, then the field study may be impacted minimally by tag implantation effects; however, if captive studies reveal significant mortality or tag loss, then field study results may be severely compromised and at a minimum should be adjusted for negative tag effects (e.g., field estimates of survival could be corrected upwards to compensate for tag loss). The adjustments based on captive studies may, however, underestimate mortality and tag loss in the wild, as migrating smolts must contend with predation, prey acquisition, and other stressors such as dam passage.

Short-term tag effects may be measured in the river by using a paired release strategy to compare migration behavior or survival of a tagged group to a control group. Hockersmith et al. (2003) used this strategy in the Columbia River to compare survival and migration rate of radio transmitter tagged and PIT tagged yearling Chinook salmon (*Oncorhynchus tshawytscha*) and found no initial differences between treatments, although they did detect a decrease in survival for transmitter tagged fish tracked to more distant sites in the river. This reduced survival, however, may have been influenced by the presence of the radio tag antenna trailing behind the fish, which could become entangled, biofouled, or infected (Adams et al., 1998b; Jepsen et al., 2002). Martinelli et al. (1998) compared different methods of implantation of radio transmitters in subyearling Chinook salmon and also found no difference in migration time for fish tracked for fewer than 5 days.

To date, medium- and long-term tag effects studies are completely lacking for the ocean phase of the life history due to logistical difficulties. To address this issue we: (1) conducted captive studies to quantify tag effects in two populations of juvenile spring Chinook salmon from the Columbia River basin implanted with dummy acoustic transmitters (DATs); to do so, we measured and compared growth, survival, and tag loss of DAT tagged fish to a control group tagged with PIT tags (which is the generally accepted method for analyzing in-river survival of juvenile salmon); (2) concurrently, we released spring Chinook salmon from these two populations tagged with live acoustic transmitters and estimated their survival during the out-migration (Rechisky et al., 2009; Rechisky, 2010); to examine size effects on fish survival, we compared survival by size class and statistical survival models to determine if survival is positively associated with size at tagging; (3) we then adjusted estimated survival probabilities of migrating smolts for tag loss and tag mortality that was quantified in captivity; and (4) additionally, we compared our acoustic tag survival estimates of migrating smolts to PIT tags survival estimates estimated independently for both populations in both years of the study.

For the study, we used two different size acoustic transmitters; in 2006 smolts were tagged with 9 mm DATs and live transmitters, and in 2008 smaller 7 mm DATs and live transmitters were used.

Methods

In 2006 and 2008, we conducted captive tagging studies with two populations of hatchery spring Chinook salmon to quantify acoustic tag retention and the effect of transmitter implantation on survival and growth (table 1). Additionally, we released acoustic tagged smolts from both populations in both years (table 2) and estimated river and early ocean survival using the Pacific Ocean Shelf Tracking (POST) array (Welch et al., 2002). Smolts originated from Dworshak National Fish Hatchery (NFH; Ahsahka, ID) on the Clearwater River (a tributary of the Snake River) and Cle Elum Supplementation and Research Facility (CESRF; Cle Elum, WA) on the Yakima River (a tributary of the Columbia River).

Study/Release Sites.—For logistical reasons, all Dworshak hatchery spring Chinook salmon were tagged at Kooskia NFH. Smolts were transferred from Dworshak NFH to Kooskia NFH in early March 2006 and in February/March 2008. In 2006, captive tag effects studies were conducted at Kooskia NFH; however, in 2008, smolts were transferred back to Dworshak NFH (1 week after tagging) for tag effect studies (the transfer back to Dworshak NFH was necessary because of limited availability of tanks at Kooskia NFH). In both years, run of river (ROR) fish used in field studies were released from Kooskia NFH (60 km upstream of Dworshak NFH; fig. 1).

Table 1. Tagging summary for captive spring Chinook salmon smolts tagged with 9 mm dummy acoustic transmitters (DATs) in 2006, and 7 mm DATs in 2008.

[Dworshak smolts were transferred and tagged at Kooskia National Fish Hatchery (NFH). In 2006, the tag study was conducted at Kooskia NFH; however, in 2008, the smolts were transferred back to Dworshak NFH for the remainder of the tag study. Cle Elum smolts were captured at the Chandler Juvenile Monitoring Facility and held at Prosser Hatchery. FL, fork length; g, gram; mm, millimeter]

Tributary (hatchery)	Study site	Tag type	Number of tagged	Mean size at tagging (mm FL; range)	Mean weight at tagging (g; range)
9 mm					
Snake (Dworshak)	Kooskia NFH	DAT	100	154.5 (142–169)	41.7 (31.0–57.5)
Snake (Dworshak)	Kooskia NFH	PIT tag	100	154.8 (140–168)	41.9 (28.4–60.2)
Yakima (Cle Elum)	Prosser Hatchery	DAT	100	154.8 (143–174)	41.4 (29.9–59.6)
Yakima (Cle Elum)	Prosser Hatchery	PIT tag	92	154.4 (139–170)	40.7 (23.7–60.4)
7 mm					
Snake (Dworshak)	Dworshak NFH	DAT	100	148.2 (135–159)	39.1 (25.8–57.1)
Snake (Dworshak)	Dworshak NFH	PIT tag	100	148.1 (135–159)	38.2 (25.5–58.0)
Yakima (Cle Elum)	Prosser Hatchery	DAT	97	139.9 (132–149)	27.3 (21.1–34.4)
Yakima (Cle Elum)	Prosser Hatchery	PIT tag	100	140.2 (131–154)	27.3 (20.5–35.4)

Table 2. Tagging summary for run of river spring Chinook salmon smolts tagged with 9 mm acoustic transmitters in 2006 and 7 mm transmitters in 2008.

[Dworshak smolts were transferred to and then tagged and released at Kooskia National Fish Hatchery (NFH) (60 km upstream of Dworshak NFH). Cle Elum smolts were captured and released at Chandler Juvenile Monitoring Facility (CJMF). FL, fork length; g, gram; mm, millimeter]

Tributary (Hatchery)	Release date	Number of tagged	Mean size at tagging (mm FL; range)	Mean weight at tagging (g; range)	Release site
9 mm					
Snake (Dworshak)	May 1	198	146.9 (140–208)	35.2 (26.9–117.5)	Kooskia NFH
Snake (Dworshak)	May 8	198	145.6 (140–192)	34.0 (27.4–83.7)	Kooskia NFH
Yakima (Cle Elum)	May 30	199	154.5 (140–173)	43.2 (30.0–64.2)	CJMF
Yakima (Cle Elum)	June 6	199	154.5 (140–168)	41.9 (28.8–59.2)	CJMF
7 mm					
Snake (Dworshak)	Apr 25	197	146.2 (130–159)	37.5 (23.3–55.5)	Kooskia NFH
Snake (Dworshak)	May 2	198	146.3 (131–159)	37.3 (23.9–52.7)	Kooskia NFH
Yakima (Cle Elum)	May 15	189	140.3 (129–158)	28.1 (22.0–10.9)	CJMF
Yakima (Cle Elum)	May 21	189	140.4 (131–157)	28.1 (22.1–37.2)	CJMF

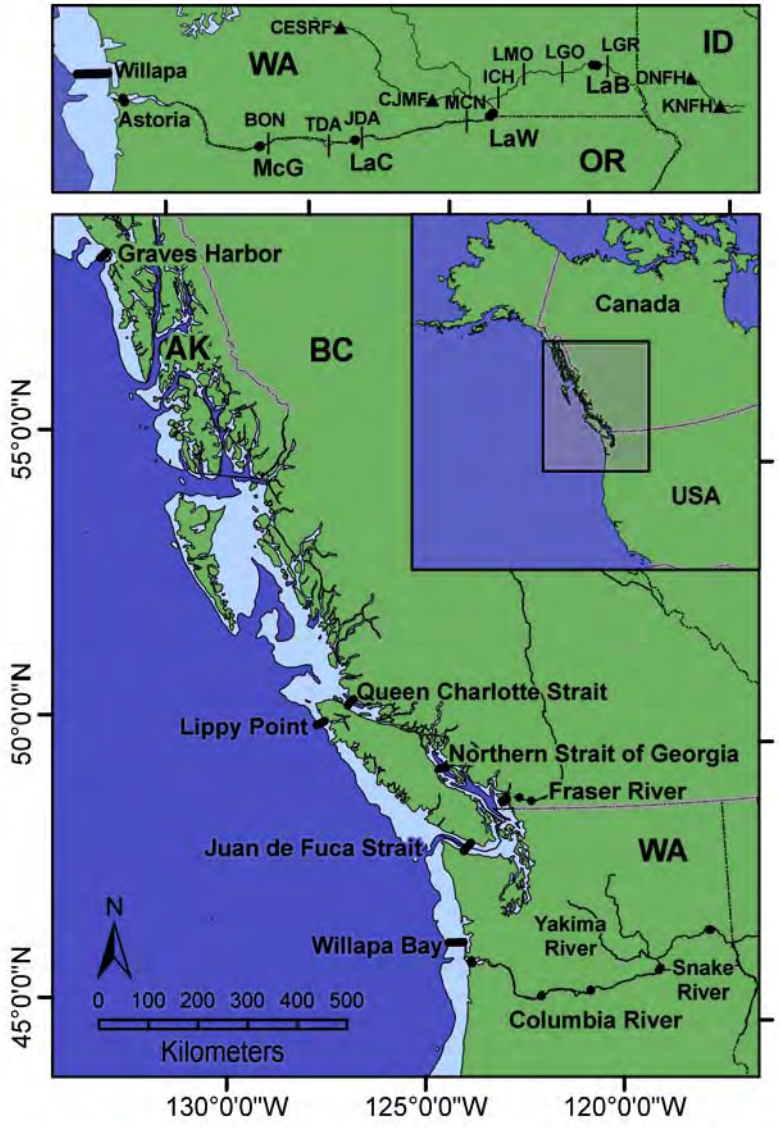

Figure 1. Pacific Ocean Shelf Tracking (POST) acoustic array. Acoustic tagged smolts were detected in the Columbia River basin and at ocean sites at Willapa Bay, Lippy Point, and Graves Harbor. Inset shows the location of the hatcheries (DNFH, Dworshak National Fish Hatchery; CESRF, Cle Elum Supplementation and Research Facility), release sites (CJMF, Chandler Juvenile Monitoring Facility; KNFH, Kooskia National Fish Hatchery), acoustic detection sites (McG, McGowan's Channel, 10 km downstream of Bonneville Dam; LaC, Lake Celilo, 7 km downstream of John Day Dam; LaW, Lake Wallula, 10 km downstream of the confluence of the Snake and Columbia Rivers; LaB, Lake Bryan,14 km downstream of Lower Granite Dam); and dams (BON, Bonneville; TDA, The Dalles; JDA, John Day; MCN, McNary; ICH, Ice Harbor; LMO, Lower Monumental; LGO, Little Goose; LGR, Lower Granite) within the Yakima, lower Snake, and Columbia Rivers. The continental shelf (depths <200 m) is shaded.

In 2006 and 2008, spring Chinook salmon released from CESRF acclimation sites in the upper Yakima River were recaptured in the lower river at the Chandler Juvenile Monitoring Facility (CJMF) downstream of Prosser Dam and used in our captive and field studies. We chose to recapture fish downstream at CJMF because fish mortality from the acclimation sites to CJMF (approximately 200 km) was as high as 80% in recent years (Yakama Nation, 2008). All tagging and captive tag studies took place at Prosser Hatchery, Prosser, WA, which is directly adjacent to CJMF. In both years, ROR fish used in field studies were released into the Yakima River from the CJMF (fig. 1).

Tags and tagging.—We used Vemco (Halifax, Nova Scotia) V9-6L acoustic transmitters (9 mm × 21 mm, 3.1 g in air, 69 kHz) and V7-2L transmitters (7 × 20 mm, 1.6 g in air, 69 kHz) to estimate survival of migrating fish in 2006 and 2008, respectively (table 2). The larger, more powerful V9 transmitter has a detection radius ≤400 m, and the smaller V7 tag has a detection radius ≤300 m; however, detection range is location and time-dependent, and may vary with freshwater/estuarine/ocean conditions, local topography, river flow, and weather conditions. Each transmitter was uniquely coded so that individual fish were identified when detected by river and ocean receivers along their migration route. For captive tag effects studies, we used DATs that were identical in volume, weight, and shape to live transmitters used in respective years. DATs also were embedded with a PIT tag (12.5 × 2.07 mm, 0.1 g) at our request by the manufacturer, and all control fish were implanted with a PIT tag; therefore, each individual could be identified throughout the tag effects study (unless a tag was lost). DAT tagged fish and control fish were held in the same tank. We did not include a non-tagged group because it was necessary to identify all individuals for growth analyses.

We specified a minimum size limit of 140 mm fork length (FL) for smolts implanted with a 9 mm acoustic or dummy tag, and a minimum size of 130 mm FL for the 7 mm tag. The mean tag to body weight ratio for Yakima smolts implanted with live 9 mm transmitters was similar to the ratio of smolts implanted with DATs (7.4 and 7.7%, respectively, table 3); however, Dworshak smolts implanted with live 9 mm transmitters and released, were slightly smaller on average than the hatchery-held DAT tagged smolts, and the mean tag to body weight ratio was thus slightly higher for ROR smolts (ROR=9.3%, captive smolts=7.6%; table 3). Although the mean tag to body weight ratio was higher for ROR smolts,

Table 3. Tag burden (%) of spring Chinook salmon smolts implanted with 9 mm and 7 mm dummy acoustic transmitters (DAT) used in captive tag effects studies, and 9 mm and 7 mm live transmitters used to estimate run of river (ROR) survival estimates; mean (range).

Tag group	Tag weight : Body weight	Tag length : Fork length	Tag weight : Body weight	Tag length : Fork length
	9 mm		7 mm	
Dworshak DAT	7.6 (5.4–10.0)	13.6 (12.4–14.8)	4.2 (2.8–6.2)	13.5 (12.6–14.8)
Yakima DAT	7.7 (5.2–10.4)	13.6 (12.1–14.7)	5.9 (4.7–7.6)	14.3 (13.4–15.2)
Dworshak ROR	9.3 (2.6–11.5)	14.4 (10.1–15.0)	4.5 (2.9–6.9)	13.7 (12.6–15.4)
Yakima ROR	7.4 (4.8–10.8)	13.6 (12.1–15.0)	5.8 (3.9–7.3)	14.3 (12.7–15.5)

there were DAT tagged representatives within each size class (fig. 2). The mean tag weight to body weight ratio for fish implanted with live 7 mm transmitters was similar to the ratio for smolts implanted with DATs for both Yakima (5.8 and 5.9%, respectively) and Dworshak populations (4.5 and 4.2%, respectively; table 3).

Surgical procedures used to implant acoustic transmitters were reviewed annually by institutional animal care committees and met or exceeded the Canadian Council on Animal Care standards (www.ccac.ca). The same surgical protocol was used in 2006 and 2008 for fish tagged with live and dummy acoustic transmitters and PIT tags. Portable self-sustaining surgical units are assembled on site, and fish surgery was carried out by highly experienced, veterinarian-trained staff. Fish were not fed for 24 h prior to surgery. Fish were dip netted from their holding tank and lightly anesthetized, or sedated, with a low dose (20 ppm) of Tricaine Methane Sulphonate (MS-222) to reduce stress from handling. A mucous protectant (Vidalife) was added to all water baths and contact surfaces, and surgeons wore latex or nitril gloves while handling fish to reduce scale and mucous loss. All water baths were aerated, and dissolved oxygen (DO) and temperature were monitored approximately every 3 minutes. Fish were taken from the sedation bath once there was slight loss of equilibrium and were anesthetized one at a time in 70 ppm of MS-222. Induction time to total loss of equilibrium, loss of reflex reactivity, and slow and irregular opercular motion was <5 min. Each individual was removed from the induction bath, fork length was measured to the nearest millimeter and weight was measured to the nearest tenth of a gram. The fish was then placed ventral side up into a v-shaped trough and a maintenance dose of anesthetic (50 ppm) was pumped through the fish's mouth and over the gills. Tags were disinfected in an iodine solution (Ovadine) and rinsed in distilled water. An incision was made at the ventral midline midway between the pelvic and pectoral fins with a #12 curved blade on #3 scalpel and the tag was gently inserted through the incision into the peritoneal cavity. The transmitter was set in place directly below the incision with the tip of the scalpel blade. For ROR fish used in field studies, a PIT tag was inserted through the incision prior to transmitter insertion. This was to ensure that ROR fish were not collected at Snake and Columbia River dams for transport to the lower Columbia River. Two surgical-grade stainless steel cutting needle drivers and sterile, absorbable Monocryl 4-0 violet sutures with a swaged on reverse cutting needle (14 mm) were then used to set and tie sutures using a surgeon's knot covered by a square knot. Sutures were carefully tied to achieve edge apposition (i.e., no overlap of the incision edges). For a 9 mm live or dummy transmitter, the incision was 10–12 mm in length and was closed with two interrupted sutures; for a 7 mm live or dummy transmitter, the incision was 7–8 mm and was closed with one suture; for PIT tagged control fish in the captive, tag effects study, a 2 mm incision was made and no sutures were used. Two sets of instruments were rotated during surgeries so that one set soaked in the disinfectant solution (Ovadine and distilled water) during surgery. Instruments were rinsed with distilled water before use. Surgery time was <2 min for a 9 mm tag and about 1 min for a 7 mm tag. Immediately following surgery, fish were placed into a recovery bath and monitored. Within minutes fish regained equilibrium and reactivity; after several more minutes of recovery, fish were transferred into either the captive study holding tank or one of the field study tanks. At both hatcheries, captive fish were held in partially shaded outdoor tanks. Well water at Prosser Hatchery ranged from 13 to 16 °C, recirculated well water at Kooskia NFH was 11°C, and river water from the North Fork of the Clearwater River at Dworshak NFH increased from 4°C to 10°C as the captive study progressed.

To reduce bias during tagging (i.e., to reduce the chance that a surgeon might take more care in tagging a fish bound for the tagging study) DAT tagged fish were randomly tagged during the tagging of acoustic tagged fish intended for release. The surgeon was aware of the fate of the fish because transmitter identification must be verified before insertion (i.e., we could not conduct a truly blind study); however, intermingling dummy tagging with live acoustic tagging was intended to reduce any involuntary bias. Within each year, the same surgeons tagged all treatment groups at both hatcheries.

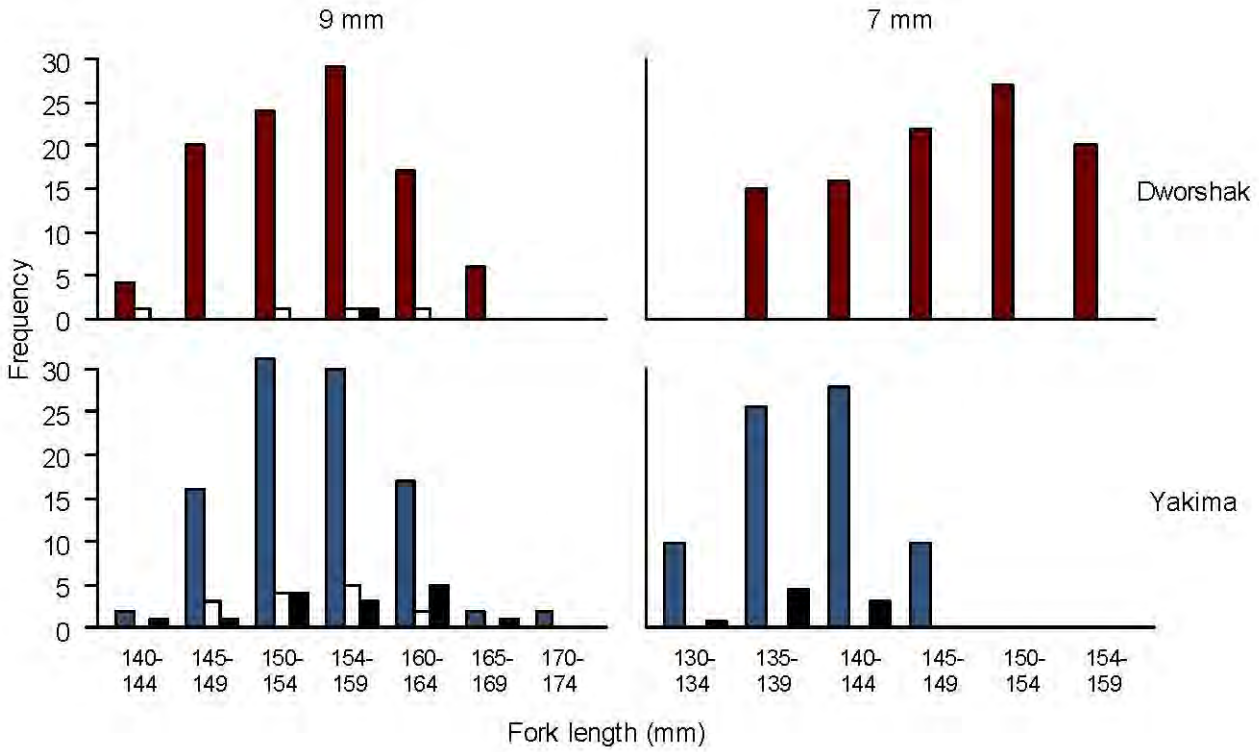

Figure 2. Size distribution of Dworshak (red bars) and Yakima (blue bars) spring Chinook salmon tagged with 9 mm and 7 mm dummy acoustic transmitters (2006 and 2008, respectively), initial size of smolts that expelled tags (white bars) and initial size of fish that died during the tag study (black bars). (Dworshak mortalities exclude deaths due to "ich" (a freshwater parasite) in 2006 and precocial male maturation in 2008). There was no tag loss in 2008.

Captive Study

Tanks were monitored daily for dead fish or expelled tags, and fork length and weight were recorded 1-3 times post-surgery (depending on the length of the study). All weights were adjusted by subtracting the average weight of the dummy tags. Tag retention was calculated each day as:

$$\frac{\text{N tags intact}}{\text{N tags implanted} - \text{N mortalities of tagged fish}},$$

and survival was calculated as:

$$\frac{\text{N live fish}}{\text{N fish initially tagged}}.$$

The percent of tags available for detection (K, i.e., live fish with tags) was calculated as:

$$\frac{\text{N tags implanted} - \text{N mortalities of tagged fish} - \text{N tags expelled}}{\text{N tags implanted}}.$$

Sample size.—Approximately 100 DAT tagged fish and 100 PIT tagged fish were tagged at each hatchery in each year. Mean fork lengths and mean weights were similar for both treatments (table 1).

Duration.—In 2006, the Dworshak captive tag study took place at Kooskia NFH from May 31 to Nov 17 (24 weeks) and fish were measured at weeks 5, 11, and 24. The study was terminated and fish were euthanized with a lethal dose of MS-222 after the final measurement during week 24. In 2008, the captive tag study took place from April 22 to Oct 3, 2008 (23 weeks). Approximately 1 week after tagging, the fish were transferred from Kooskia NFH back to Dworshak NFH for the duration of the study; mortality after transfer was zero. Fish were measured at weeks 7 and 23. During week 23, a dead DAT fish was found with fresh water fungus *Saprolignia* spp. In the following days, four PIT tagged and four DAT tagged smolts succumbed to the fungus, therefore we took final measurements and terminated the study before the fungus spread to all of the captive fish.

The Yakima captive tag study in 2006 took place at Prosser Hatchery from May 27 to August 21 (12 weeks) and fish were measured at weeks 6 and 12. In early September, a major mortality event occurred due to a disease outbreak at the hatchery, which killed approximately 60% of the study fish and therefore the tag study was effectively terminated after measurements were taken on August 21, 2006. In 2008, the tag study took place from May 7 to June 13 (5 weeks) and fish were measured at week 5. The study was inadvertently terminated during week 5 after nearly all of the fish died (DAT and PIT tagged) the day after we obtained growth measurements. Several of the fish that died just prior to this major mortality event were examined by a fish pathologist (Eric Pelton, U.S. Fish and Wildlife Service) because there had been a decline in survival of both DAT and PIT tagged fish during week 5 (prior to week 5 survival was 98% for DAT tagged fish and 100% for PIT tagged fish). There was no indication of disease or stress, however, and therefore we do not know the cause of the mass mortality that subsequently occurred the day after our growth measurements were collected.

Field Study

Sample size.—In each year, at each hatchery, approximately 400 fish were tagged with live acoustic transmitters and were released into their respective rivers as the ROR groups (table 2). We attempted to match mean sizes between both hatcheries; however, we were somewhat limited in size availability because we were collecting Yakima smolts at CJMF as they migrated through. Therefore the mean FL of Dworshak smolts was approximately 10 mm smaller than the mean FL of Yakima smolts in 2006 and 6 mm larger in 2008.

Release timing.—Dworshak smolts were released in the Snake River basin 349 km upstream of the confluence of the Snake and Columbia Rivers (RKM 522). We released Yakima smolts into the Yakima River, 76 km upstream of the confluence to the Columbia River (RKM 539), several weeks after the Dworshak smolts were released in order to have both populations arrive at the Columbia River mouth simultaneously so that they encountered similar ocean conditions.

Array Location.—The POST array is composed of individual Vemco omni-directional acoustic receivers (VR2s or VR3s) anchored to the river or ocean floor to form a component line or an "acoustic curtain" at each sub-array (Welch et al., 2002) and extends approximately 2,300 km from the Snake River to southeast Alaska (fig. 1). Each receiver records the date, time, and identification of uniquely coded acoustic tags passing near it. Oceanic receivers of the POST array at Willapa Bay (southern WA), Lippy Point (northwest Vancouver Island, BC), and Graves Harbor (southeast AK) were deployed approximately every 800 m and extend from near-shore to the edge of the continental shelf, a distance of up to 30 km.

Component sub-arrays relative to this study were deployed within the Columbia River at McGowan's Channel (10 km downstream of Bonneville Dam), in Lake Celilo (7 km downstream of John Day Dam in 2006, and upstream and downstream of John Day Dam in 2008), and in Lake Wallula (21 km downstream of the confluence of the upper Columbia and Snake Rivers). In the Snake River, receivers were installed in Lake Bryan (14 km downstream Lower Granite Dam; total distance from the ocean was 681 km). At each of these locations, receivers were deployed across the river as paired lines to evaluate the detection probability for each of the pairs, and to provide a survival measurement downstream of four of the major hydroelectric dams. In river receivers were deployed every 100–200 m to ensure high transmitter detection rates in the fast flowing rivers. In 2007, an additional line of receivers was deployed at the Astoria Bridge, 22 km from the mouth of the Columbia River. Therefore, survival was estimated to an additional point near the river mouth in 2008, but not in 2006.

Data Analyses

Captive Studies.—All data analyses for captive studies were performed in the statistical programming language R (R Development Core Team, 2008). We used chi-squared tests of homogeneity to test the null hypothesis that survival of PIT tagged fish is equal to survival of DAT tagged fish. This null hypothesis was tested for each population at those times when growth was measured. For example, in 2006, we compared the survival of each treatment group (PIT and DAT) of the Dworshak population at weeks 5, 11, and 24, and for the Yakima population, we compared survival at weeks 6 and 12. In 2008, it was only necessary to make a statistical comparison for Yakima smolts (at week 5), as no mortality occurred in DAT tagged Dworshak smolts. In the case where the expected cell count was less than five, we estimated the p-value using a Monte Carlo simulation. This simulation is based on 2,000 replicates, and as a result the degrees of freedom are reported as NA. We repeated this procedure with the tag retention data using the null hypothesis that tag retention of PIT tagged fish was equal to tag retention of DAT tagged fish; however, we only tested the 2006 data as there was no PIT tag or DAT tag loss in either population in 2008.

To determine whether DAT tag loss or mortality was a function of FL, we used logistic regression analyses with tag retention or survival as the dichotomous response variable (1= tag retained/survived, 0=tag lost/died) and fork length at tagging as the continuous independent variable. As mortality was low or zero for Dworshak smolts implanted with either 9 mm or 7 mm DATs, respectively, and tag loss was zero for 7 mm DATs for both populations, we only conducted three logistic regression analyses for Yakima smolts: (1) survival (with 9 mm DAT intact at death) as a function of FL; (2) retention of 9 mm DATs as a function of FL; and (3) survival with 7 mm DATs as a function of FL. A Wald X^2 test was used to assess significance of the FL coefficient.

We used t-tests to compare fork length and weight of PIT tagged to DAT tagged smolts after each measurement was obtained. ANCOVA analyses were used to compare specific growth rate. Specific growth rate (SGR, % weight/week) of PIT tagged and DAT tagged fish was calculated for each interval: from initial tagging to the second measurement, from the second measurement to the third measurement, etc. SGR in weight was calculated as SGR=100 $[(\ln(W_2)–\ln(W_1))/(t_2–t_1)]$, where W_2 is the weight at time t_2 and W_1 is the weight at time t_1. For the first interval, we compared SGR of the two treatment groups with initial fork length as the covariate; for subsequent intervals, we used the fork length from the previous measurement as the covariate.

In 2008, it was obvious at week 23 that a small percentage of the Dworshak smolts had become sexually mature males (13% DAT, 5% PIT). These precocious males were noticeably smaller, were olive green in color (not silvery smolts) and were swollen with milt. These fish were excluded from the 2008 growth analyses as they were not representative of a typical spring Chinook salmon smolt, and were unmistakable outliers in the study.

Field Studies.—Estimates of smolt survival (Φ) and detection probability (p) for each recapture occasion, i.e., acoustic detection line, in 2006 and 2008 were calculated using the Cormack-Jolly-Seber (CJS) model for live recaptured animals implemented in Program MARK (White and Burnham, 1999). This model jointly estimates survival and detection within a likelihood framework. Survival probabilities in both years were estimated to detection sites within the Columbia River and to an ocean detection site adjacent to Willapa Bay (Rechisky et al., 2009; Rechisky, 2010). Smolts were detected north of Willapa Bay at Lippy Point (both populations) and in Alaska (Dworshak only, in both years); however, it was not possible to estimate survival to Lippy Point with the CJS model due to small sample size on the Alaska detection line. Therefore, in order to examine medium-term tag effects, we present the percent of fish detected at Lippy Point, which represents the minimum survival of migrating fish and likely underestimates survival to this site.

For in-river lines, we recognized basic CJS model assumptions (equal survival probability, equal recapture probability, no tag loss, and instantaneous sampling); however, for oceanic lines that are not bounded on the offshore end (continental slope), we required two additional assumptions: (1) as fish migrate, they cross over the acoustic detection lines that span the length of the continental shelf; and (2) most fish departing the Columbia River swim north. These assumptions are supported by evidence from numerous ocean sampling programs (e.g., Fisher and Pearcy, 1995; Brodeur et al., 2004; Bi et al., 2007).

To estimate overdispersion in the data, we used a median $\hat{c}$ procedure (White and Burnham, 1999) to test the goodness of fit (GOF) of our global model ($\Phi_{\text{population*line}}\, p_{\text{population*line,}}$ where line = acoustic detection site) and then corrected for this overdispersion across all candidate models. Because of the low number of fish detected at Vancouver Island and Alaska, we included in our models two additional treatment groups (each N=100) of spring Chinook salmon smolts from Dworshak NFH, tagged with the same acoustic tag, that were released downstream of Bonneville Dam during the spring out-migration, in order to better quantify the detection probability of the Willapa Bay detection line. (These two treatment groups were used in our transportation survival study, which is not reported here.) The survival estimate of this group was modeled in the same way across models (Φ_{line}) and did not influence survival estimates for ROR smolts. Recapture parameters were modeled to vary with population and line except at Willapa Bay where all populations were pooled.

To test the hypothesis that smaller fish have lower survival due to tag burden, we followed a similar procedure as described above, accept we modeled each population separately and then compared the global CJS survival model ($\Phi_{\text{line}}\, p_{\text{line}}$) to an additive model that included fork length as a covariate ($\Phi_{\text{line + FL}}\, p_{\text{line),}}$ as well as a model that included the interaction between acoustic detection site and FL ($\Phi_{\text{line * FL}}\, p_{\text{line}}$). We used Akaike's Information Criterion (AIC) values to rank the performance of the models. In general, the model with the lowest AIC value (which accounts for the number of model parameters, n_{pars}) has more support in the data, and if the ΔAIC of the other candidate models is greater than 2, then these models (i.e., hypotheses) have little or no support. If the additive model has more support given the data (i.e., ΔAIC >2) then there is evidence that FL had a constant additive effect on survival at each detection site. If the interaction model has more support, then the effect of FL varies at each detection site.

Comparison with PIT Tag studies.—We obtained PIT tag survival estimates for out-migrating Dworshak [Steve Smith, National Oceanic and Atmospheric Administration (NOAA), personal commun.; Faulkner et al., 2008] and Yakima (David Lind, Yakama Nation, personal commun.) spring Chinook salmon to compare with our estimates of ROR survival using 9 mm and 7 mm acoustic tags in 2006 and 2008, respectively. PIT tagged Dworshak smolts were released at Dworshak NFH and survival was estimated to several dams in the lower Snake and Columbia Rivers to as far as Bonneville Dam (577 km). Acoustic tagged smolts were released at Kooskia NFH and survival was estimated to four (2006) or five (2008) detection sites in the lower Snake and Columbia Rivers and to coastal Washington (adjacent to Willapa Bay, 911 km). PIT

tagged Yakima smolts were released from acclimation sites in the upper Yakima River; however, survival estimates were calculated only for those fish that were recaptured and released at CJMF. Survival was estimated to two dams in the lower Columbia River—McNary Dam and John Day Dam (268 km). Survival estimates for acoustic tagged Yakima smolts were from release at CJMF to three (2006) or four (2008) river detection sites and to Willapa Bay (655 km).

To statistically compare survival rates (S/km) we regressed the log-transformed cumulative survival estimates at the j-th detection site, $\ln\left(S_{i,j}\right) = bd_{i,j}$, for each of the i-th populations against migration distance from the respective release sites, $d_{i,j}$, resulting in a survival rate per kilometer, b_i. To estimate the uncertainty in the estimated regression coefficients (b_i), we used a Monte Carlo procedure to randomly generate 10,000 individual survival estimates at each of the detection sites for each population *i* (in each year) using the estimated survival proportions, $S_{i,j}$, and associated estimated variances that define the parameters of the binomial distribution. We then took the 10,000 sets of generated survival estimates with distance for each population, and calculated the log-transformed regression estimates to empirically define the distribution of survival rates, b_i, for each population. The null hypothesis that the survival rate of acoustic tagged smolts is equal to that of the PIT tagged smolts is equivalent to assuming that on average the difference in the regression coefficients, $b_{DAT} - b_{PIT}$, is zero. We tested this null hypothesis by evaluating whether the central 95% of the 10,000 survival rate differences included zero.

Survival estimates of ROR spring Chinook salmon corrected for tag loss in captive studies.—To correct for tag loss and mortality, we calculated the percent of tagged animals available for detection on day *i*, K_i, from the proportion of fish that were alive and retaining tags in captivity. We then used K_i to provide an estimate of survival in free-ranging smolts adjusted to account for tag loss and mortality due to surgical implantation of tags:

$$S_K(t,j) = \frac{\text{estimated survival to detection site j}}{\text{K for the median day of arrival, t, to detection site J}}.$$

For example, the median time to arrival at Willapa Bay for ROR Dworshak smolts in 2006 was 24 days, and so we calculated K on day 24 of the captive survival study and divided the ROR survival estimate at Willapa Bay by $K_{t=24}$ to obtain S_K.

Results

Tag Effects–Captive Studies

Tag Retention

9 mm DATs.—For the duration of the tag study in 2006 (24 weeks, fig. 3, table 4a), 100% of PIT tagged and 95% of DAT tagged Dworshak fish retained their tags. At weeks 5 and 11, there were no significant differences in tag retention of PIT tagged and DAT tagged smolts; however, at week 24, DAT tag loss was significantly greater than PIT tag loss (table 4a). The initial fork lengths of the four fish that expelled tags were distributed across the size range of DAT tagged fish (fig. 2); too few tags were expelled to warrant a significance test of whether some size classes had greater tag expulsion.

For the duration of the study (12 weeks; fig. 3), 100% of PIT tagged and 83% of DAT tagged Yakima fish retained their tags. Tag loss was significantly greater for DAT tagged smolts at week 6 and week 12 (table 4a). We believe that tag loss was greater in DAT tagged Yakima smolts because the sutures (most of which were present after 86 days) were observed tearing through the skin and muscle toward the incision (figs. 5b, 5c); Dworshak smolts also retained their sutures for several months; however, tearing was not observed (fig. 5a). The sutures, when completely ripped out, left a large open wound where the tag could be expelled. Often times the incision itself was well healed or completely healed but the sutures prevented complete recovery from the surgery. In some cases, the sutures were observed to have ripped toward the incision and completely out of the body but the DAT tag was still intact. Tag retention was not a function of initial FL (Wald $X^2 = 0.603$, df = 99, $p = 0.547$), therefore tag loss was not limited to smaller individuals (fig. 2).

7 mm DATs.—Retention of PIT tags and 7 mm DATs was 100% for the duration of the study for both Dworshak (23 weeks) and Yakima smolts (5 weeks; fig. 4).

Captive Survival

9 mm DATs.—Approximately 1 month into the Dworshak tag study, fish were treated with chloramine-T due to an *Ichthyophthirius* spp. (“ich”) outbreak at Kooskia NFH. The death of 12 DAT tagged fish and eight PIT tagged fish was attributed to ich and/or treatment. Following the ich outbreak only one DAT tagged fish and two PIT tagged fish died during the remainder of the study (a total of 170 days). Total survival of DAT tagged fish was 87%, and survival excluding the mortalities associated with chloramine-T treatment was 99%.

Table 4. Summary of statistical analyses used in the captive tag study.

[Significant *p*-values are represented by **bold** type. Degrees of freedom (d.f.) for the X^2 tests for tag retention and survival are not available because *p*-values were estimated with a Monte Carlo simulation when some cells contained fewer than five data points. Significance tests were not applicable (NA) when tag retention or survival was 1. DAT=dummy acoustic tag, PIT=passive integrated transponder tag. (* excludes precocial males)]

a. Tag retention	Tag size	Population	Time since tagging	Proportion of tags retained		X^2	d.f.	*p*
				DAT	PIT			
	9 mm	Dworshak	week 5	0.98	1	2.1	–	0.25
			week 11	0.97	1	3.2	–	0.13
			week 24	0.95	1	5.3	–	**0.03**
		Yakima	week 6	0.91	1	7.5	–	**0.007**
			week 12	0.83	1	9	–	**0.002**
	7 mm	Dworshak	week 7	1	1	NA	NA	NA
			week 23	1	1	NA	NA	NA
		Yakima	week 5	1	1	NA	NA	NA
b. Survival	**Tag size**	**Population**	**Time since tagging**	**Proportion of surviving fish**		X^2	**d.f.**	***p***
				DAT	PIT			
	9 mm	Dworshak	week 5	0.88	0.93	1.5	–	0.35
			week 11	0.88	0.91	0.48	–	0.64
			week 24	0.87	0.90	0.44	–	0.65
		Yakima	week 6	0.93	0.99	4.2	–	**0.07**
			week 12	0.84	0.96	8.8	–	**0.005**
	7 mm	Dworshak	week 7	1	1	NA	NA	NA
			week 23	1	1	NA	NA	NA
		Yakima	week 5	0.89	0.96	3.8	–	0.06
c. Fork length (mm)	**Tag size**	**Population**	**Time since tagging**	**DAT mean (SD)**	**PIT mean (SD)**	***t***	**d.f.**	***p***
	9 mm	Dworshak	week 0	155.3 (6.5)	155.2 (5.6)	0.07	158	0.94
			week 5	167.6 (8.8)	173.8 (7.8)	4.8	159	**<0.001**
			week 11	182.1 (11.4)	189.6 (9.9)	4.6	157	**<0.001**
			week 24	202.8 (17.9)	212.9 (14.7)	3.9	153	**<0.001**
		Yakima	week 0	154.6 (5.9)	154.2 (5.9)	0.41	147	0.68
			week 6	163.5 (7.5)	166 (7.6)	2.2	148	**0.03**
			week 12	174.2 (7.8)	178.8 (7.7)	3.7	148	**<0.001**
	7 mm	Dworshak	week 0	148.3 (5.8)	147.9 (6.9)	0.33	195	0.74
			week 7	165.1 (6.3)	166.6 (5.6)	1.7	192	0.08
			week 23*	215.9 (9.5)	217.3 (8.9)	0.9	165	0.35
			week 0	139.9 (4.5)	139.9 (4.7)	0.03	177	0.98
		Yakima	week 5	150.5 (5.1)	151.2 (5.3)	0.9	177	0.36
d. Weight (g)	**Tag size**	**Population**	**Time since tagging**	**DAT mean (SD)**	**PIT mean (SD)**	***t***	**d.f.**	***p***
	9 mm	Dworshak	week 0	42.2 (6.4)	42.3 (5.8)	0.1	161	0.91
			week 5	59.7 (13.2)	67.6 (12.1)	4.1	161	**<0.001**
			week 11	72.6 (15.4)	81.2 (14.2)	3.7	161	**<0.001**
			week 24	93.6 (23.9)	107.2 (21.4)	3.8	160	**<0.001**
		Yakima	week 0	41.2 (6.1)	40.5 (5.9)	0.72	140	0.47
			week 6	51.1 (8.8)	54.4 (8.0)	2.3	137	**0.02**
			week 12	68.7 (11.8)	75.2 (11.1)	3.4	139	**<0.001**
	7 mm	Dworshak	week 0	39.2 (6.6)	38.1 (6.8)	1.15	195	0.25
			week 7	55.1 (8.2)	55.6 (8.3)	0.48	195	0.63
			week 23*	114 (18.4)	115.3 (16.2)	0.53	165	0.59
		Yakima	week 0	27.4 (2.9)	27.2 (3.3)	0.52	178	0.60
			week 5	37.6 (4.6)	38.2 (5.2)	0.84	178	0.40

Table 4. Summary of statistical analyses used in the captive tag study.—Continued

[Significant *p*-values are represented by bold type. Degrees of freedom (d.f.) for the X^2 tests for tag retention and survival are not available (NA) because *p*-values were estimated with a Monte Carlo simulation when some cells contained fewer than 5 data points. DAT=dummy acoustic tag, PIT=passive integrated transponder tag. (* excludes precocial males)]

e. Specific growth rate (% g/week)	Tag size	Population	Time	DAT mean (SD)	PIT mean (SD)	*F*	d.f.	*p*
	9 mm	Dworshak	week 0 to week 5	5.84 (2.6)	8.12 (2.2)	37.5	165	**<0.001**
			week 5 to week 11	3.28 (1.7)	3.09 (1.7)	0.19	165	0.65
			week 11 to week 24	1.85 (1.2)	2.13 (0.74)	0.028	165	0.86
		Yakima	week 0 to week 6	3.33 (0.91)	4.61 (1.06)	62.3	144	**<0.001**
			week 6 to week 12	4.99 (2.02)	5.48 (1.62)	3.73	144	0.055
	7 mm	Dworshak	week 0 to week 7	4.87 (1.2)	5.45 (1.2)	13.19	169	<0.001
			week 7 to week 23*	4.59 (0.91)	4.57 (0.88)	0.16	169	0.69
		Yakima	week 0 to week 5	6.16 (1.3)	6.65 (1.6)	4.81	178	**0.029**

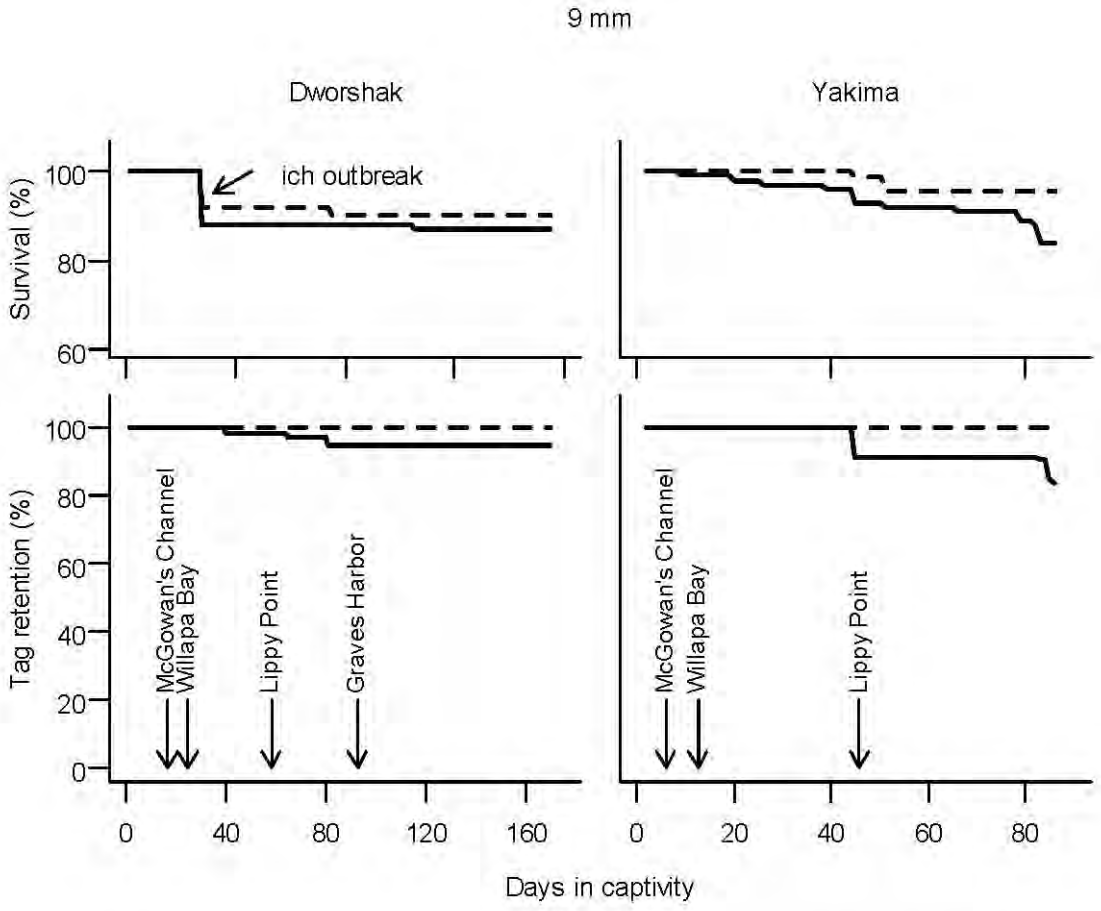

Figure 3. Tag retention and survival for Dworshak and Yakima spring Chinook salmon tagged with 9 mm dummy acoustic transmitters (solid lines) and passive integrated transponder tags (dashed lines) in 2006. The arrows on the tag retention plots are reference points that indicate the mean day of arrival of in-river migrants to each of the acoustic detection lines. Yakima smolts were not detected at Graves Harbor. Note the y-axis scale on the survival plot does not go to zero.

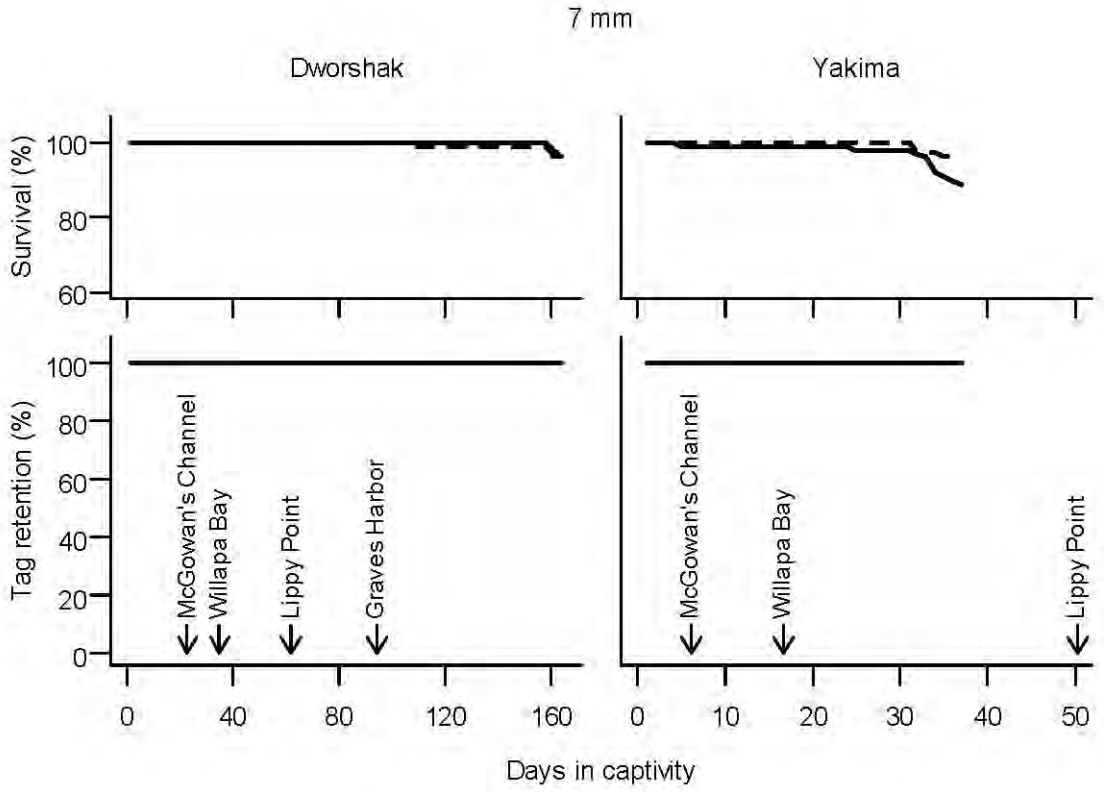

Figure 4. Tag retention and survival for Dworshak and Yakima spring Chinook salmon tagged with 7 mm dummy acoustic transmitters (solid lines) and passive integrated transponder tags (dashed lines) in 2008. The arrows on the tag retention plots are reference points that indicate the mean day of arrival of in-river migrants to each of the acoustic detection lines. Yakima smolts were not detected at Graves Harbor.Note the y-axis scale on the survival plot does not go to zero.

Survival of PIT tagged fish was similar; total survival was 90% and survival excluding chloramine-T mortalities was 98%. Because the ich parasite cannot survive in seawater and in-river migrants were released from the hatchery before the outbreak, it is likely that in-river migrants were not affected. At weeks 5, 11, and 24 there were no significant differences in survival of PIT tagged and DAT tagged smolts (table 4b; fig. 3). As only 1 fish died after the ich outbreak, a significance test for survival as a function of FL was not warranted.

Survival to day 86 (the final day of the study) was 84% for DAT tagged and 96% for PIT tagged fish. At week 6, there was no significant difference in survival of PIT tagged and DAT tagged smolts; however, at week 12 survival of PIT tag smolt was significantly greater than DAT tagged smolts (table 4b; fig. 3). As mortality was not limited to smaller individuals, survival was not a function of initial FL (Wald X^2= -0.309, df = 99, p = 0.757, fig. 2). Mortality of some DAT tagged fish may be attributed to the suture wound.

7 mm DATs.—Survival of PIT tagged and DAT tagged Dworshak smolts was 100% up to day 108 of the study. On day 108, one PIT tagged fish was found dead with no obvious cause of mortality. On day 159, a dead DAT tagged fish was found with fresh water fungus *Saprolignia* spp. In the following days, four PIT tagged and four DAT tagged smolts succumbed to the fungus. At that point, we terminated the tag study as it was obvious that the fungus was spreading throughout the fish in the tank and the tag study results would be compromised. Prior to the occurrence of the fungus (day 159), survival was 100% for DAT tagged fish and 99% for PIT tagged fish. If these fish had the opportunity to migrate, they would have reached the ocean in several weeks (median day of arrival of ROR smolts to the ocean was 35 days), and thus would likely not have been affected by this freshwater pathogen.

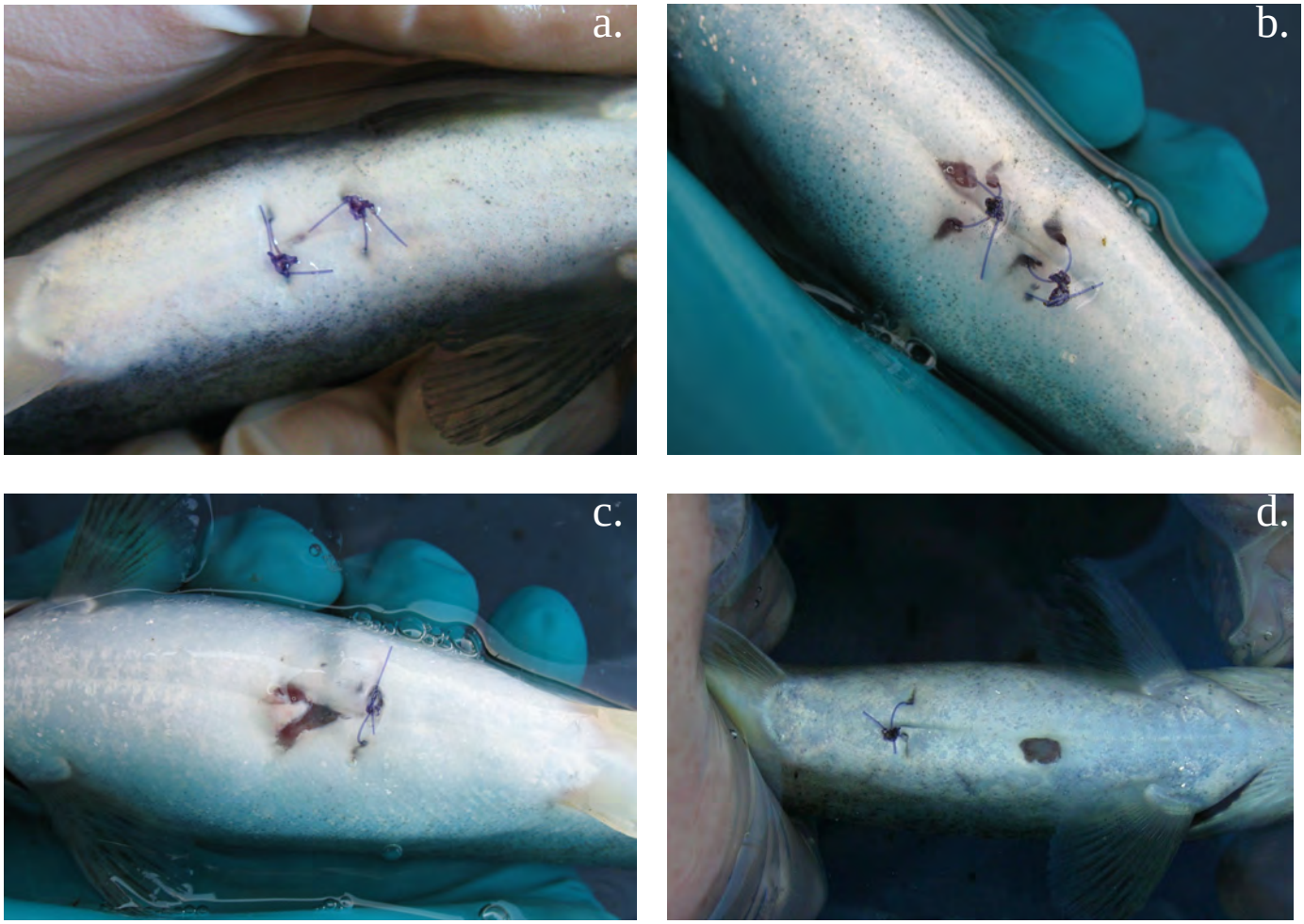

Figure 5. a. Typical Dworshak spring Chinook salmon smolt 11 weeks post-surgery with healed incision and 9 mm dummy acoustic transmitter (DAT) and sutures still intact. b. After 12 weeks in captivity, Yakima Chinook salmon implanted with a 9 mm DAT have a completely healed incision, although sutures have not dissolved and are tearing through the skin of some fish. c. Yakima spring Chinook salmon 12 weeks post-surgery with sutures torn to incision leaving wound for 9 mm transmitter to exit. The relatively delicate skin of Yakima Chinook may be an intrinsic trait; however, suture tearing also may plausibly be attributed to warmer water temperatures experienced at Prosser Hatchery. As run of river Yakima smolts migrated into the ocean only days after release, they would have experience cooler water temperatures within weeks of surgery. As well, it is likely that tag loss would have been minimal during the time when fish migrated over the array (see fig. 3). d. Yakima spring Chinook salmon implanted with a 7 mm DAT 5 weeks post-surgery; this fish is forming a pore anterior of the surgery site from which the transmitter might potentially be expelled. (Suture tearing and tag expulsion did not occur in Dworshak fish.)

Survival of Yakima smolts to day 31 was 98% for DAT tagged and 100% for PIT tagged fish. From day 32 to day 37, nine DAT tagged and four PIT tagged fish died. Although more DAT tagged fish died during the final week, the difference was not significant (table 4b). Because the study was inadvertently terminated on day 38 (see section "Methods"), we were not able to monitor fish in captivity beyond 5 weeks. Survival was not a function of initial fork length (Wald $X^2 = 1.075$, df = 99, $p = 0.283$; fig. 2), therefore mortality was not limited to smaller individuals.

Growth

9 mm DATs.—The initial mean fork length (mm) and weight (g) of PIT tagged and 9 mm DAT tagged Dworshak smolts were not significantly different (table 4c,d, fig. 6). At 5 weeks post-surgery, the mean fork length and mean weight of PIT tagged smolts were significantly greater than DAT tagged fish. At 11 and 24 weeks post-surgery, the mean fork length and weight of PIT tagged smolts remained significantly greater than DAT tagged fish.

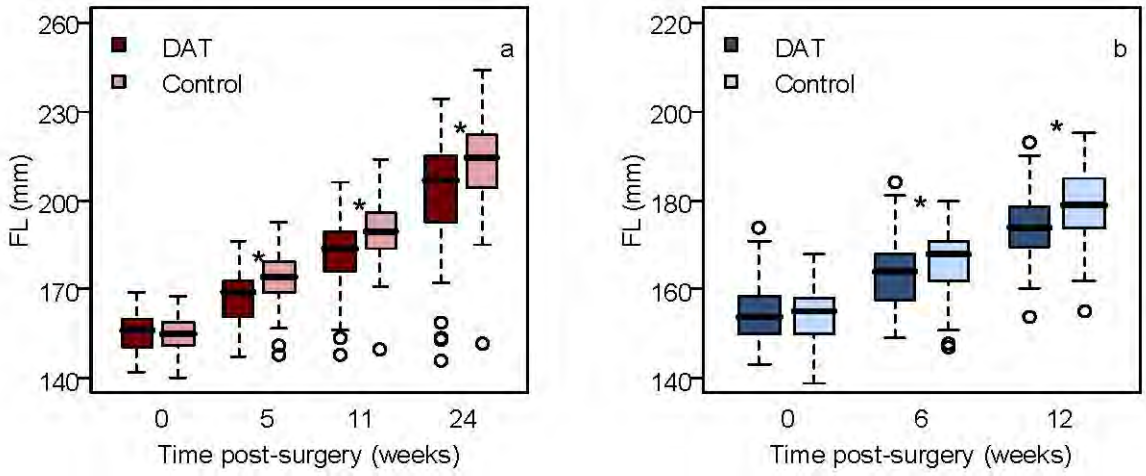

Figure 6. Boxplots (median, quartiles, and 95% confidence interval) of fork length (FL) for Dworshak (a) and Yakima (b) spring Chinook salmon tagged with 9 mm dummy acoustic transmitters (DAT) and passive integrated transponder tags (control) in 2006. Asterisks indicate a difference at a 0.05 level of significance. Open circles represent precocious fish that were not included in the analysis. Boxplots of weight are not shown, but see table 4d.

The specific growth rates (% weight/week) of PIT tagged smolts were significantly greater than DAT tagged smolts from week 0 to week 5 when we accounted for initial fork length (table 4e). During this initial 5 week period, PIT tagged fish grew 2.2% /week more than DAT tagged fish. From week 5 to the final week of the study (week 24), however, specific growth rate was not statistically distinguishable for the two treatments, demonstrating that DAT tagged smolts grew at the same rate as PIT tagged smolts and that recovery from an initial set back in growth (due to the DAT or the surgery, or the cumulative effects of both) occurred within 5 weeks post-surgery.

The initial mean fork length and weight of PIT tagged and DAT tagged Yakima smolts were not significantly different; however, by week 6, PIT tagged fish were significantly larger than DAT tagged fish (table 4c-d, fig. 6). At week 12, this difference was still significant.

The specific growth rates of PIT tagged smolts were significantly greater than DAT tagged smolts from week 0 to week 6 when we accounted for initial fork length (table 4e). During this initial 6-week period, PIT tagged fish grew 1.3%/week more than DAT tagged fish. From week 6 to the final week of the study (week 12), PIT tagged fish grew 0.58%/week more than the DAT tagged fish; however, this was not a significant difference for the two treatment groups. Therefore, Dworshak and Yakima fish tagged with a 9 mm DAT suffered an initial growth set back due either to the DAT or the surgery, or the cumulative effects of both, but this effect did not persist beyond the first growth measurements at weeks 5 and 6, respectively.

7 mm DATs.—The initial mean fork length and weight of PIT tagged and 7 mm DAT tagged Dworshak smolts were not significantly different (table 4c,d, fig. 7). The mean fork length and weight of PIT tagged smolts 7 and 23 weeks post-surgery also were not significantly greater than DAT tagged fish (table 4c, d). Therefore, the 7 mm DAT did not have an initial impact on fork length or weight, as was observed for the 9 mm tag (which was implanted into slightly larger fish).

The specific growth rate analyses indicated that PIT tagged Dworshak fish grew 0.52%/week more than DAT tagged fish during the first 7 weeks, which was significantly greater (table 4e), despite the non-significant finding for the fork length and weight comparisons during the same time interval. From week 7 to week 23, however, specific growth rates were not statistically distinguishable for the two treatments, and both groups grew at approximately the same rate; thus recovery from the initial set back in growth occurred in less than 7 weeks post-surgery.

The initial mean fork length and weight of PIT tagged and DAT tagged Yakima smolts were not significantly different (table 4c-d, fig. 7). The mean fork length and weight of PIT tagged smolts 5 weeks post surgery also were not significantly greater than DAT tagged fish.

The specific growth rate analyses indicated that PIT tagged Yakima fish grew 0.48%/week more than DAT tagged fish during the first 5 weeks, which was significantly greater, despite the non-significant finding for the fork length and weight comparison during the same time interval (table 4e). As the study ran for only 5 weeks, we were unable to monitor growth for a second interval. However, compared to the 9 mm tag, the initial set back in growth rate was not as large for the 7 mm tag (1.3% vs. 0.48%).

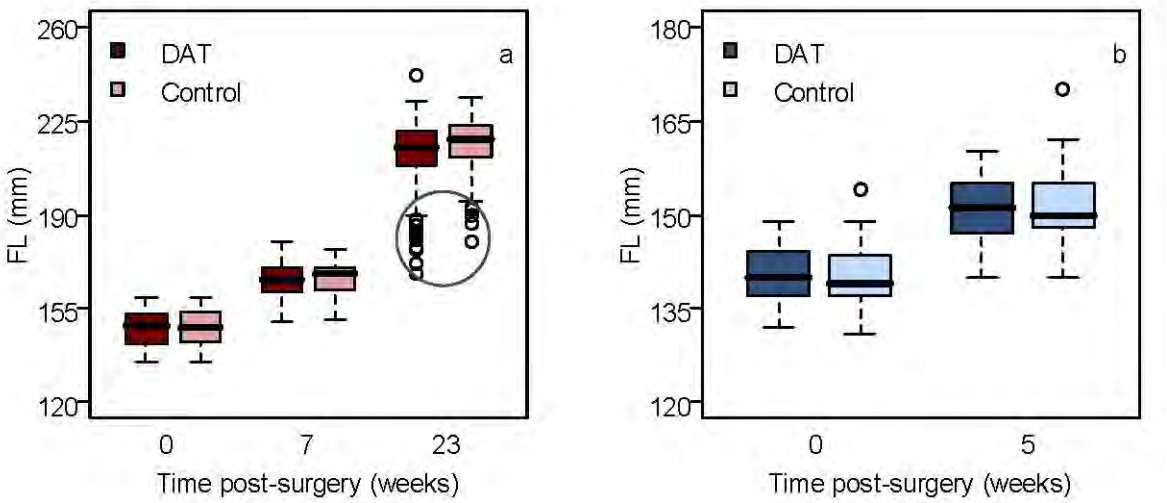

Figure 7. Boxplots (median, quartiles, and 95% confidence interval) of fork length (FL) for Dworshak (a) and Yakima (b) spring Chinook salmon tagged with 7 mm dummy acoustic transmitters (DAT) and passive integrated transponder tags (control) in 2008. There was no significant difference in FL of DAT and control groups for either population during the study. The circle in (a) shows the FL's of precocial males which were excluded from the significance test. Open circles represent precocious fish that were not included in the analysis. Boxplots of weight are not shown, but see table 4d.

Tag Effects–Field Study

In 2006 and 2008, Columbia River basin spring Chinook salmon smolts were tagged with 9 mm (minimum size 140 mm FL) and 7 mm (minimum size 130 mm FL) acoustic tags, respectively, released into the river, and tracked as far north as Alaska. Although smolts were detected on the Vancouver Island line (at Lippy Point), survivorship for these ROR groups was estimated to coastal Washington (the Willapa Bay detection site, fig. 8). To determine if tags may have affected survival we: (1) plotted the estimated survival of 5 mm size classes at each detection site for each population in each year for a visual comparison of survival by size; (2) used initial fork length as an individual covariate within a linear model framework in Program MARK to statistically test the hypothesis that smaller fish have lower survival due to tag burden; and (3) compared our in-river survival estimates obtained with acoustic tags to other studies that obtained survival estimates with PIT tags.

Survival by Size Class

9 mm transmitter.—Survival of Dworshak ROR smolts tagged with 9 mm transmitters was variable across all size classes at each detection site, and smaller size classes did not appear to have lower survival (fig. 9). Similarly, survival of Yakima ROR smolts was variable across all size classes at each detection site as well (fig. 9). The smallest Yakima size class had the lowest survival; however, it was made up of only six fish. It is possible that fish at the lower limit of our size requirements of 140 mm may have suffered from tag induced mortality (Welch et al., 2007); however, it is difficult to draw conclusions about this size class because of the low sample size. If smaller fish had reduced survival then we would have expected survival to increase with increasing body size, however, the largest groups did not have the highest survival. Thus, the 9 mm acoustic transmitter did not appear to differentially affect survival over the size range tested.

7 mm transmitter.—Survival of Dworshak ROR smolts tagged with 7 mm transmitters was variable across all size classes at each detection site (i.e., there was no general trend in survival), with the exception that the largest size class (155–159 mm) appeared to have consistently higher survival than all other size classes (fig. 10). Survival of Yakima ROR smolts was variable across all size classes at each detection site; however, the largest Yakima size class had the lowest survival, in contrast to Dworshak (fig. 10). The sample size of the largest Yakima size class was low, however, and therefore it is difficult to draw conclusions about this size class. In general, survival did not increase with increasing body size, and thus the 7 mm acoustic transmitter did not appear to differentially affect survival across the size range tested.

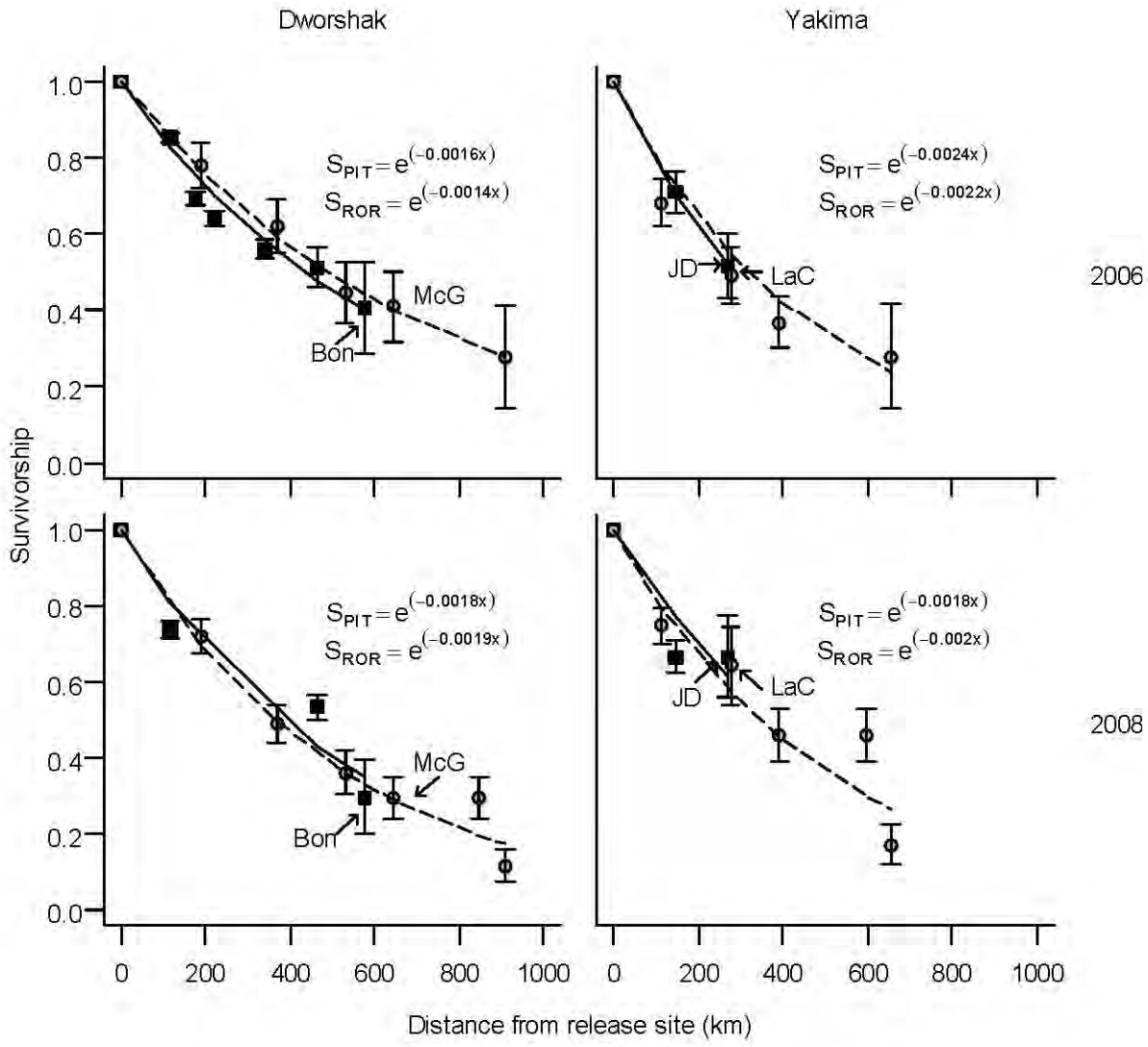

Figure 8. Survivorship of Dworshak and Yakima spring Chinook salmon in 2006 and 2008. Survivorship of acoustic tagged smolts (grey circles, dashed line) was estimated to coastal Washington (Willapa Bay). Survivorship of passive integrated transponder (PIT) tagged smolts (black squares, solid line) was estimated to Bonneville Dam (Bon) and John Day (JD) for Dworshak and Yakima smolts, respectively. Survivorship curves are calculated by fitting the log-transformed regression $S(x)=e^{-bx}$, where x is distance from release site. (PIT tag survival estimates for Dworshak are from Steve Smith at NOAA/National Marine Fisheries Service/Northwest Fisheries Science Center and Faulkner et al., 2008, and Yakima PIT tag estimates are from David Lind at Yakama Fisheries). ROR =run of river treatment groups presented in this study, McG=McGowan's Channel (10 km downstream of Bon), LaC=Lake Celilo (7 km downstream of JD). Error bars are 95% confidence intervals.

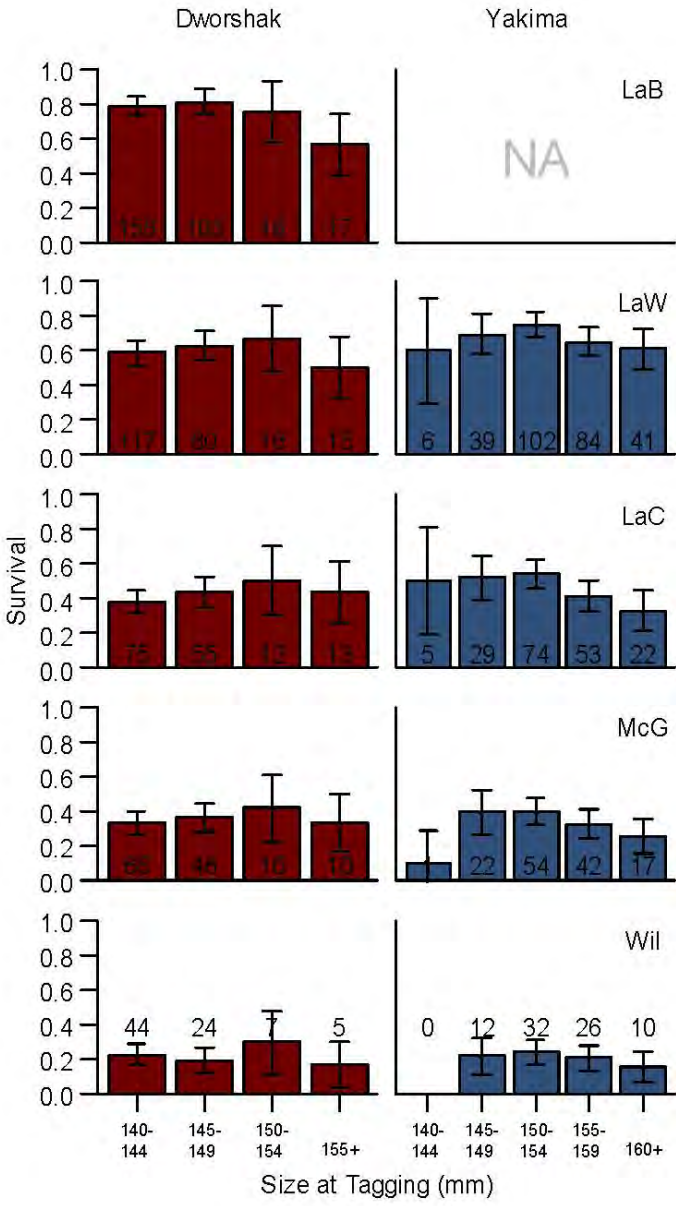

Figure 9. Survival in 2006 by size class (fork length) of migrating Dworshak (red) and Yakima (blue) spring Chinook salmon tagged with 9 mm acoustic transmitters. The numbers on or above the bars indicate the estimated number of fish detected within each size class at each detection site. LaB=Lake Bryan, LaW=Lake Wallula, LaC=Lake Celilo, McG=McGowan's Channel, Wil=Willapa Bay. Error bars are 95% confidence intervals.

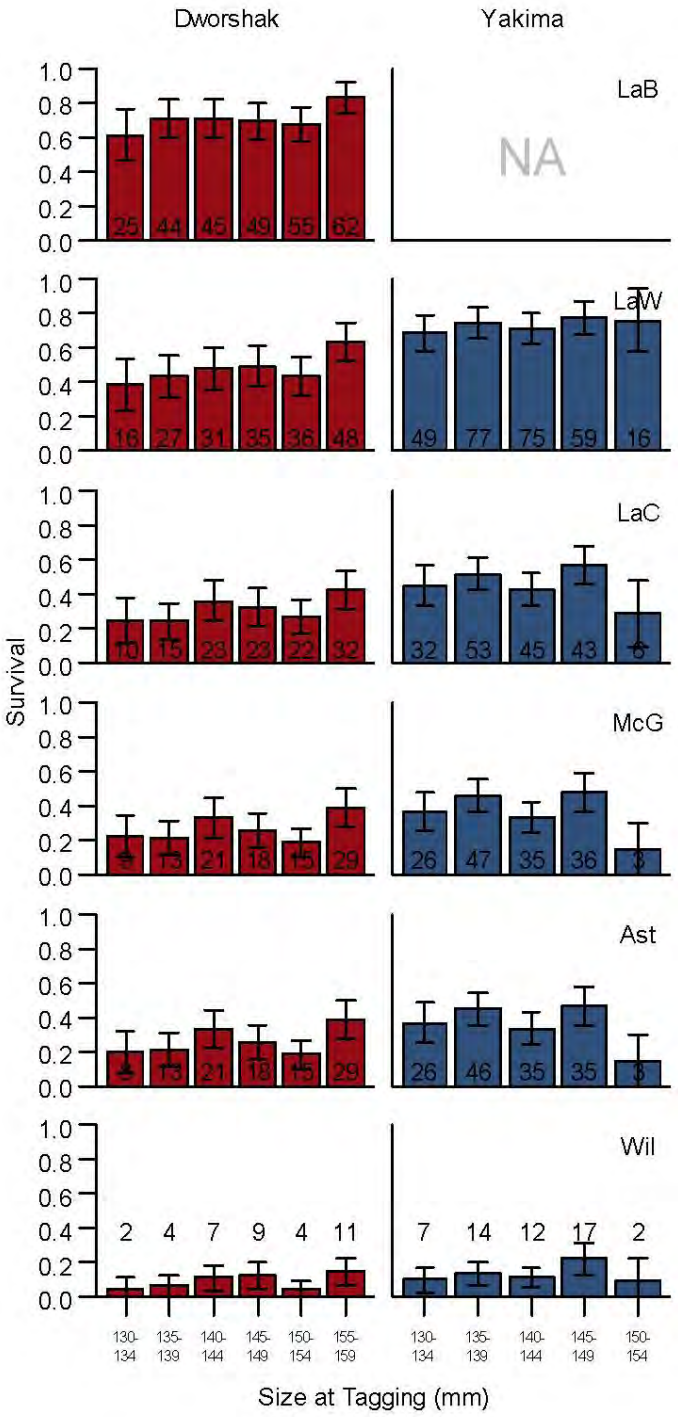

Figure 10. Survival in 2008 by size class (fork length) of migrating Dworshak (red) and Yakima (blue) spring Chinook salmon tagged with 7 mm acoustic transmitters. The numbers on or above the bars indicate the estimated number of fish detected within each size class at each detection site. LaB=Lake Bryan, LaW=Lake Wallula, LaC=Lake Celilo, McG=McGowan's Channel, Ast=Astoria Bridge, Wil=Willapa Bay. Error bars are 95% confidence intervals.

Fork Length as a Covariate in Survival Models

To test the hypothesis that smaller ROR fish have lower survival due to tag burden, we used an information theoretic approach to compare the fully time-varying CJS survival models to additive and interaction models that included fork length as a covariate.

9 mm transmitters.—For Dworshak ROR smolts, the most parsimonious survival model was the fully time (i.e., line) varying CJS model (table 5). The ΔAIC of the additive model with fork length as a covariate was approximately 2, and the deviances of the models were nearly identical, which implies that there was no difference in the models. For Yakima ROR smolts, there was some support for the additive survival model with fork length as a covariate (ΔAIC=0.83); however, the most parsimonious model was the fully time varying CJS model (table 5). Therefore, there is no support that smaller smolts suffered higher mortality.

7 mm transmitters.—For Dworshak smolts implanted with 7 mm transmitters, the most parsimonious survival model was the additive model with fork length as a covariate, which provided support that as fork length increased survival increased; however, figure 10 demonstrates that the largest size class had consistently higher survival, and therefore we re-ran the analysis and excluded smolts that were 155–159 mm FL to determine if size was a factor across all other sizes (from 130–154 mm FL). When we excluded the largest size class, the fully time varying CJS model was the most parsimonious model (table 5). The AIC of the additive model with fork length as a covariate was <2, and the deviances of the models were nearly identical, which implies that there was no additional support for a model with FL as a covariate.

For Yakima ROR smolts, there was little support for the additive model with fork length as a covariate; the most parsimonious model was the fully time varying CJS model (table 5). There is no statistical support that smolts suffered higher mortality.

Table 5. Model selection for fork length (FL) analyses using Akaike's Information Criterion (AIC).

[QAICc=quasi-AIC corrected for overdispersion and effective sample size. Φ = survival probability, line = acoustic detection site. Recapture parameters were held constant for all models ($p_{population*line}$)]

	Model	QAICc	ΔQAICc	Num. Par	QDeviance
2006					
Snake	Φ_{line}	592.37	0	11	570.14
	$\Phi_{line + FL}$	594.35	1.98	12	570.08
	$\Phi_{line * FL}$	600.97	6.62	17	566.44
Yakima	Φ_{line}	1,281.24	0	9	1,263.06
	$\Phi_{line + FL}$	1,282.07	0.83	10	1,261.85
	$\Phi_{line * FL}$	1,282.71	0.65	14	1,254.30
2008					
Snake	$\Phi_{line + FL}$	1,765.71	0	14	1,737.31
	Φ_{line}	1,769.53	3.82	13	1,743.18
	$\Phi_{line * FL}$	1,775.38	5.86	20	1,734.59
Snake (FL=130–154)	Φ_{line}	1,381.77	0	13	1,355.32
	$\Phi_{line + FL}$	1,383.56	1.79	14	1,355.05
	$\Phi_{line * FL}$	1,388.66	5.10	20	1,347.62
Yakima	Φ_{line}	1,683.99	0	11	1,661.70
	$\Phi_{line + FL}$	1,685.12	1.13	12	1,660.78
	$\Phi_{line * FL}$	1,687.51	2.39	17	1,652.84

Comparative Survival of In-River Migrants Using Acoustic Tags and PIT Tags

9 mm transmitter.—Survival of acoustic tagged smolts was similar to PIT tagged smolt survival (fig. 8). We compared our Dworshak spring Chinook salmon acoustic survival rate (S/km) to the Pacific Ocean with NOAA's PIT tag survival rate from Dworshak NFH to Bonneville Dam in 2006. We chose to compare survival rate rather than survivorship estimates because distances to detection sites for each tag type vary, but we present the estimates of apparent survivorship in parentheses to inform the interpretation. We found no difference in estimated survival rate (p>0.05; fig. 8) between acoustically tagged smolts to the Pacific Ocean (survivorship to Willapa Bay, 911 km from the release site, was 27.5%, SE=6.9%) and PIT tagged smolts to Bonneville Dam (survivorship from release, a distance of 577 km, was 40.8%, SE=6.1%). Due to tag limitations, we could only tag smolts >140 mm FL (i.e., we could not tag the entire size range) and our release dates were during the latter part of the spring Chinook migration. Further, we released Dworshak smolts from Kooskia Hatchery 60 km upstream (purely for logistical reasons); however, comparing results from the two studies provided a second approach to assessing the reasonableness of our survival estimates by assessing whether our acoustically tagged smolts had lower survival than smolts tagged with PIT tags, a much smaller tag.

PIT tag survival estimates of Yakima spring Chinook salmon released from Cle Elum Hatchery and recaptured at CJFM in Prosser, WA, were available to McNary Dam and John Day Dam in the lower Columbia River. Although survival of PIT tagged fish could only be estimated to as far as John Day Dam (survivorship to John Day, 268 km from the release site, was 51.8%, SE= 4.3%), the estimated survival rate calculated from acoustic tag estimates for the entire lower Columbia River and into the ocean (survivorship to Willapa Bay, 655 km from release, was 27.9%, SE=7.0%) is consistent with the estimated PIT tag survival rate to John Day Dam (p>0.05; fig. 8).

7 mm transmitter.—We compared our Dworshak spring Chinook salmon acoustic survival estimates to the river mouth and to Willapa Bay (survivorship to Willapa Bay was 11.8%, SE=2.1%) to NOAA's PIT tag survival estimates in the river to as far as Bonneville Dam (survivorship to Bonneville Dam was 29.7%, SE=5.0%) in 2008 and found no difference in estimated survival rate (p>0.05; fig. 8). Because we used the smaller 7 mm tag, we were able to tag smolts as small as 130 mm FL, and we were able to tag and release fish approximately 1 week earlier than in 2006. Therefore, our release dates coincided with the peak of the Snake River spring Chinook salmon run but were still several weeks after NOAA PIT tagged smolts were released from Dworshak NFH.

PIT tag survival estimates for Yakima spring Chinook salmon were available to McNary Dam and John Day Dam in 2008. The estimated survival rate from release to John Day Dam (survivorship was 66.7%, SE=5.5%) was not significantly different than the estimated survival rate of acoustic tagged Yakima spring Chinook salmon smolts from release to Willapa Bay (survivorship of acoustic tagged smolts to Willapa Bay was 17.3%, SE= 2.6%; p>0.05; fig. 8).

Survival Estimates of ROR Spring Chinook Salmon Corrected for Tag Loss in Captive Studies

How much does tag loss and mortality due to the surgical procedure affect survival estimates for ROR smolts? All estimates of K (live, tagged animals in the captive study) were >98% at the time when migrating ROR smolts would have passed the Willapa Bay detection line. K was greater than >97% when Dworshak smolts migrated passed Lippy Point (in 2006 and 2008), and 85% when Yakima smolts passed Lippy Point in 2006 (in 2008 the Yakima tag study was only held for 5 weeks, which was insufficient time to estimates K to Lippy Point). Figure 11 shows ROR estimated survival and S_K. In general, the difference between adjusted and unadjusted survival estimates is negligible and well within the 95% confidence interval of the unadjusted survival estimates for both populations in both years. Dworshak smolts had zero mortality and tag loss in captivity within the first month in 2006 and 2008, and thus the survivorship estimates to Willapa Bay are not altered (28.5% in 2006, 11.8% in 2008). Beyond 1 month, there was minor tag loss and mortality of captive Dworshak smolts in 2006 and therefore, minimum survival of migrating smolts would increase 2%, from 1.49 to 1.52% at the Lippy Point detections site. In 2008, there was no tag loss or mortality in captive smolts at the time when migrating smolts were passing Lippy Point and no adjustment is necessary (minimum survival to Lippy Point was 3.1%).

For Yakima smolts in 2006 and 2008, the percent of fish available for detection based on captive studies was 99% at Willapa Bay. If we account for this slight reduction in detectability, survivorship would increase from 27.9 to 28.1% at Willapa Bay in 2006, and from 17.4 to 17.6% in 2008. Although combined tag loss and mortality was 15% after 45 days in captivity for Yakima smolts in 2006, the minimum survival of free ranging smolts to Lippy Point would only increase from 0.7 to 0.8% (we could not assess medium-term tag loss for Yakima smolts in 2008).

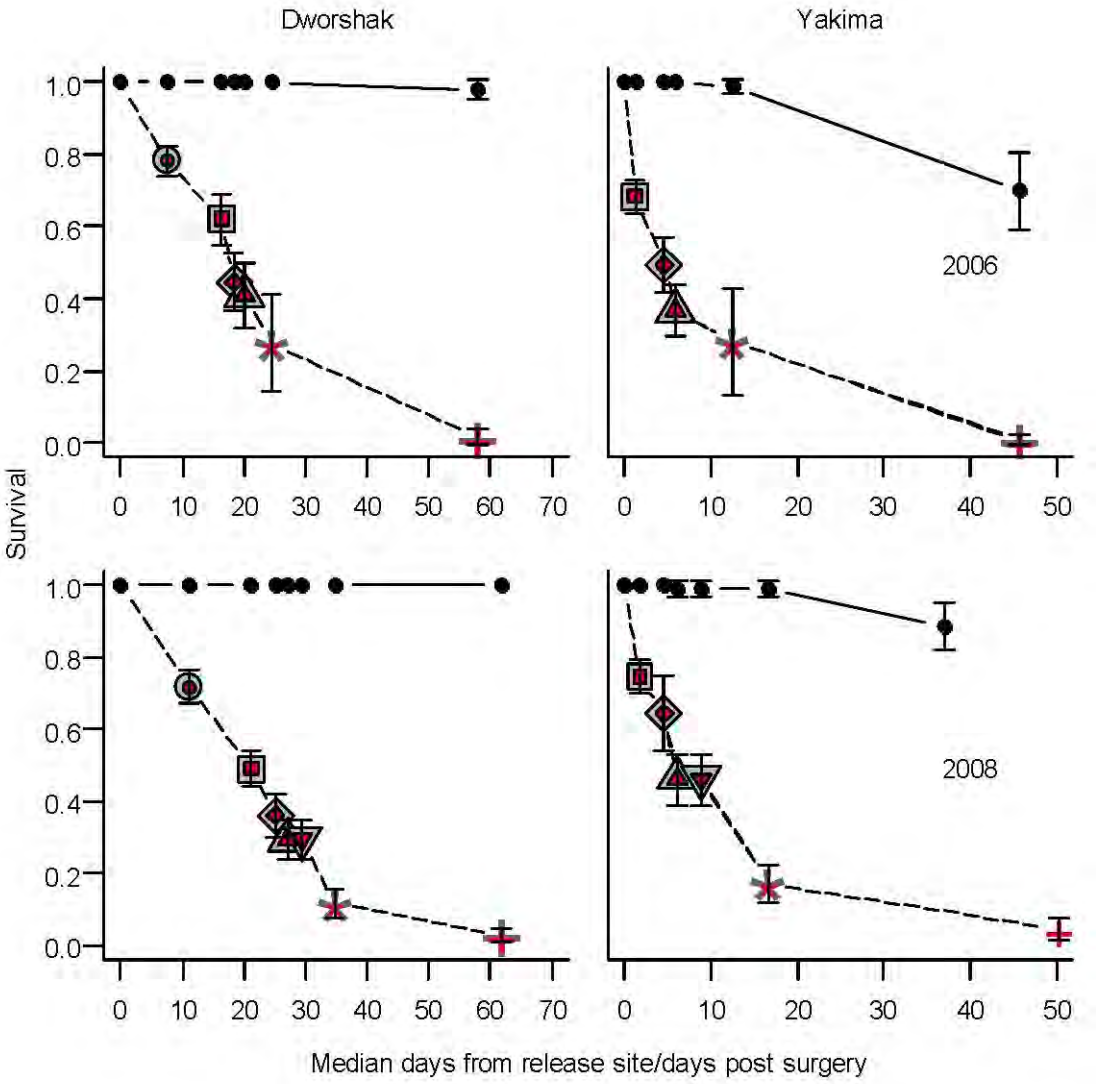

Figure 11. Proportion of tagged animals available for detection from the captive tag study (K; black circles), estimated in river survival with 95% confidence intervals (red symbols), and estimated ROR survival corrected for tag effects (S_K, larger, grey symbols). The correction for potential mortality and tag loss as a result of surgical implantation had no material effect on the measured survival of free-ranging smolts. Note that the corrected survival falls almost perfectly on top of the survival estimates. ○ = Lake Bryan, □ = Lake Wallula, ◊ = Lake Celilo, Δ = McGowan's Channel, ∇ = Astoria Bridge, * = Willapa Bay, + = Lippy Point.

Discussion

Overall, short term (<1 month) mortality and tag loss following surgical implantation was minimal for 9 mm dummy acoustic transmitters implanted into smolts ≥140 mm FL and weighing 5.2–10.4% of the body weight. The short-term effects of the smaller 7 mm transmitter on tag retention and mortality were negligible for smolts ≥130 mm FL implanted with 7 mm dummy transmitters, and weighing 2.8–7.6% of the weight of the fish. Therefore, estimates of survival of migrating smolts over long distances and up to 1 month are reasonable within these size limitations.

Medium-term (30–90 d) mortality and tag loss was minimal for Dworshak smolts tagged with both transmitter sizes. Yakima smolts tagged with 9 mm transmitters were more susceptible to medium-term tag loss, but nearly 3 months post-implantation 84% of the tags were still retained. We believe that the 16% tag loss may have been due to the sutures tearing through the skin, leaving a large open wound through which the transmitter could escape. While conducting surgeries, we noticed that the skin and musculature of the body wall of Yakima smolts was much thinner and more delicate than what we observed in the more robust Dworshak population, and this may have made fish more susceptible to chafing by the sutures. Further, we noted that 60% of the Yakima DAT tagged fish had one suture that had either ripped out or was visibly ripping through the skin 86 days post-surgery. Tag loss and mortality, however, were not a function of size (i.e., smaller fish no more susceptible than larger fish), and damage did not appear to be caused by the transmitter pushing against sutures (see fig. 5b-c).

Water temperature may contribute to the more fragile skin of the Yakima smolts, as Dworshak smolts were held in colder water than Yakima smolts and showed only minor medium-term effects from the 9 mm tag. Both populations were, however, held at water temperatures that were comparable to their respective river temperatures; therefore, it is possible that the Yakima population has inherently more delicate skin. It has been demonstrated that fish implanted with transmitters have significantly higher occurrence of tag loss at higher temperatures (Knights and Lasee, 1996; Bunnell and Isely, 1999). In bluegills (*Lepotnis macrochirus*), transmitters were expelled through necrotic muscle tissue for fish held at 20°C (Knights and Lasee, 1996), and in rainbow trout (*O. mykiss*) held at the same temperature, transmitters were expelled through the incision (Bunnell and Isely, 1999). There is, however, contrasting evidence that fish held in warmer water heal faster after injury (Anderson and Roberts, 1975). As we observed transmitter expulsion at the torn suture site, it is difficult to discern whether warmer temperatures caused the musculature to become more delicate and susceptible to chafing by sutures.

Ideally, the use of a more rapidly dissolving suture would likely address this issue, but commercially available absorbable sutures are designed for use in mammals. In mammals, these sutures rapidly lose their strength; however, the sutures do not readily degrade in fish held in cold water. If the sutures degraded as desired, the tearing we observed in Yakima fish would likely not have occurred and tag loss would have been lower. This does not appear to be a common problem among researchers that use surgical implantation as a method of transmitter attachment (Wagner and Cooke, 2005). We suspect that the wound caused by the sutures may have also contributed to mortalities, as we witnessed several fish with the pyloric caeca or liver protruding through the wound. We also witnessed several live fish that had lost transmitters and had well healed wounds where the transmitter exited; therefore, transmitter expulsion did not always kill the fish.

We were unable to assess medium- or long-term tag effects of the 7 mm transmitter on Yakima smolts, as the tag study was inadvertently terminated on day 37. Although survival and tag retention was >98% for the first month of the study, nine DAT and four PIT tagged fish died during the last week. Because PIT tagged fish also died in the final days of the study, we hesitate to attribute the death of DAT tagged fish (in the last 5 days) to the transmitters or the surgical procedure. On the final day of the study, we also observed potential tag expulsion. Unlike the 9 mm DAT, tag expulsion of the 7 mm DAT in Yakima smolts was beginning to occur at a location away from the incision site (a pore had started to form in the body wall). This mechanism of tag expulsion has previously been reported by Lucas (1989), Moore et al. (1990), Welch et al. (2007), and others (see Jepsen et al., 2002). We were unable to quantify tag loss through the body wall in 2008 to compare to the 2006 tag study results.

Although we were not able to observe medium- and long-term tag effects, there is support that 7 mm transmitters had less of an effect on the Yakima population than 9 mm transmitters. For example, the mean FL of PIT tagged and 9 mm DAT tagged fish differed significantly after 6 weeks, whereas mean FL 5 weeks post-implantation with the 7 mm tag was not significantly different. Further evidence that 7 mm transmitters had less of an effect is reflected in the growth rates; during the first interval after tagging, PIT tagged smolts grew 1.3% per week more than 9 mm DAT tagged smolts and only 0.48% per week more than 7 mm DAT tagged fish.

In Dworshak smolts tagged with both tag types, growth rate rebounded for DAT tagged fish after an initial period of slower growth following surgery. An initial period of impaired growth followed by growth at the same rate as control fish was also observed in fall Chinook salmon smolts implanted with radio transmitters that weighed up to 5.5% of the body weight of the fish (Adams et al., 1998a). Tag loss may thus have the potential to have some relatively small effects on long-term tracking studies (>3 months), when we consider only tag

effects in captivity. It is possible that tag loss and mortality are higher in the wild, but the contribution of this source of error needs to be put in perspective relative to the size of the survival decline being measured in free-ranging smolts. Our results indicate that short- or medium-term studies would be minimally affected by tag loss or tag induced mortality even for Yakima smolts tagged with 9 mm transmitters.

Survival by Size of Migrating Smolts

We found no strong evidence for a relationship between size and survival for ROR smolts. Survival by 5 mm size class was variable for both transmitter types and for both populations and there was little support for survival models that incorporated body length as a covariate. There was only one exception to this general observation that did show some evidence for larger tagged smolts surviving better: in Dworshak smolts implanted with 7 mm tags in 2008, the largest size class (155–159 mm FL) had higher survival than all other size classes. The survival model results were consistent with this finding: when we included body size as a covariate and used all size classes tagged, this model had more support; however, when we excluded fish in the 155–159 mm FL size range, there was little support for the fork length model. This indicates that size did not affect survival of fish between 130 and 154 mm FL.

This survival difference (the largest size class with the highest survival) appeared to develop in the first migration interval between the release site and Lake Bryan (downstream of Lower Granite Dam) and persisted as fish migrated downstream. It is possible that larger fish escaped post-release predation or migrated more quickly resulting in higher survival; however, we did not see this trend in 2006 with the 9 mm tag where the largest smolts had the lowest survival in the same migration segment. In summary, only one of four comparisons showed evidence for larger fish having improved survival, and this result was restricted to the largest size class tagged. We thus have little evidence that the surgically implanted tags of the size we used were imposing a substantial burden on smolts above our specified size thresholds.

Effect of Tag Loss and Tag-Induced Mortality on ROR Survival Estimates

Although captive fish do not encounter the stressors that ROR fish must contend with in the wild, captive studies are the most practical method available for quantifying tag loss and mortality following surgical implantation of a transmitter. We used captive data to infer tag loss and tag mortality in actively migrating smolts and found that survival estimates of ROR smolts to Willapa Bay (40 km north of the Columbia River mouth) were unlikely to be affected by tag loss or tag mortality because tag retention and survival of captive groups was near 100% during the first month. Nearly all (96% in 2006 and 92% in 2008) of the Yakima smolts had migrated rapidly down the river and across the Willapa Bay line by day 30. Dworshak fish had farther to travel to reach the Willapa Bay line; however, by day 45, most fish had passed Willapa Bay (97% in 2006 and 88% in 2008).

In 2006 by day 60, all Dworshak fish had passed Lippy Point on northern Vancouver Island. The proportion of live, tagged, captive fish was 95% at day 45 and day 60, indicating that only 5% of ROR fish may not have been available for detection (combined smolt mortality and tag loss) at both ocean lines. In 2008 by day 70, 88% of Dworshak smolts had reached Lippy Point, and 100% of the captive fish were alive and tagged; therefore, all fish migrating past these detections site were presumably detectable.

In 2006, two Yakima fish were detected at Lippy Point and had passed by day 50. The proportion of live, tagged, captive fish was 85% at day 50, indicating that 15% of ROR fish may not have been available for detection at Lippy Point. In 2008, the mean travel time of Yakima smolts to Lippy Point was 56 days; however, we are unable to estimate potential nondetection because the captive tag study was terminated on day 37.

ROR Survival Compared With PIT Tag Studies.

Although it was not possible to directly measure tag loss or tag-induced mortality in free ranging salmon smolts (i.e., ROR), it was possible to further assess tag effects by comparing the survival estimates for ROR fish with that of PIT tagged smolts. As PIT tags have become the standard method for measuring salmon survival in the Columbia River, it is reasonable to compare acoustic tag performance to PIT tag performance. For instance, a short-term comparative survival study that used acoustic tags (similar in size to the 7 mm tag) and PIT tags found no difference in survival through a major hydropower dam in the Columbia River (Steig et al., 2005). The authors also noted that the sample size of PIT tagged fish used to achieve the same precision was two orders of magnitude greater than acoustic tagged fish (90,000 vs. about 800). Therefore, for our study, we used PIT tag survival estimates estimated independently for the same populations in the same migration year (see section “Methods”). Although release times and mean fish size were not identical for the two groups, the PIT tag estimates offer an alternative method for estimating survival within the Snake and Columbia Rivers using a much smaller tag that does not require surgical implantation (PIT tags generally are injected using a large-gauge hypodermic needle). We can thus use PIT tags as a benchmark of survival using very small tags. As our estimated decline in smolt survival with distance are consistent with the decline in survival of PIT tagged smolts with distance (see fig. 8), the negative effects of surgical implantation of our tags appear to be very minimal in ROR smolts, at least to the

last dam where PIT tag-based estimates of survival can be obtained for Dworshak smolts (Bonneville) and to John Day Dam for Yakima smolts. Downstream of Bonneville Dam, no comparison of PIT and acoustic tagged smolts is possible, but the smooth decline in survival obtained with acoustic tags with distance downstream of Bonneville Dam does not suggest that there was a sudden decrease in survival for acoustically tagged smolts.

Other means of quantifying tag effects include measures of swimming performance, predator avoidance, and physiological indices. Swimming performance (critical swim speed, U_{crit}) has been tested in several species of salmonids and results indicate that juvenile salmon tagged with acoustic transmitters (representing various tag burdens) are capable of attaining U_{crit} values comparable to control groups (Moore et al. (1990), species: Atlantic salmon, tag burden: about 2.2% of fish weight; Brown et al. (2006) fall Chinook salmon, 10.7%; Anglea et al. (2004) juvenile fall Chinook salmon, 6.7%; Chittenden et al. (2009), coho *O. kisutch*, 8%). Predator avoidance experiments also were conducted by Anglea et al. (2004), which demonstrated that juvenile fall Chinook salmon tagged with acoustic transmitters and exposed to adult rainbow trout were not consumed in significantly higher proportions than the untagged control group. Adams et al. (1998b), however, found that juvenile fall Chinook salmon of similar size, implanted with radio transmitters resulting in similar body burden by weight, were eaten by smallmouth bass *Micropterus dolomieu* in greater numbers. These contrasting results could be due to different experimental design, different predators, or the presence of the 31 cm antenna trailing behind the radio tagged fish in Adams et al. (1998b), which may have aided in prey detection and subsequent capture.

To measure physiological response to surgery and tag presence, blood samples of tagged and control fish are often taken following a specified period of time (e.g., soon after tagging and at the end of a study) or post-exercise. Hematocrit level is a common metric used to evaluate stress response, and several studies have shown that after 2–3 weeks hematocrit levels of tagged juvenile salmon were within normal ranges found in salmonids and were comparable to control fish (Chittenden et al., 2009; Martinelli et al., 1998; Moore et al., 1990). As the smolts tagged in these studies had similar tag burdens to smolts presented in this study, these earlier studies suggest that stress due to tagging may subside within several weeks after surgery.

Tag Size Tradeoffs

The use of different acoustic tags represents a trade-off between biological and technical limitations on any telemetry system designed to study fish movements and survival. Generally speaking, smaller tags impose less of a burden on the animal that they are implanted in, but smaller tags also are harder to detect, for several reasons: (1) smaller transducers will not as efficiently convert electrical power from the battery into sound waves at the frequencies of primary interest for marine telemetry systems (as they are farther off-resonance), so the acoustic power output (loudness) will drop; and (2) smaller tags necessarily have smaller batteries, which means that tag lifespan also is reduced relative to what could be obtained with a tag containing larger batteries, unless transmission frequency is reduced to compensate.

Shrinking the tag size makes it harder to detect tags and also tags are detectable for a shorter period of time. To achieve the same probability of detecting the passage of a tagged fish means that additional economic investments must be made in receivers to use in constructing the individual sub-arrays forming the telemetry system in order to compensate for the reduced signal strength (range) of the tags. Similarly, smaller tags place greater physical limits on the geographic range that migrating salmon smolts can be successfully studied over. Our current results indicate that dummy V7 and V9 Vemco acoustic tags do not have a substantial influence on survival rates for free-ranging or hatchery-reared smolts ≥130 and ≥140 mm, respectively, relative to the other sources of mortality, and that these tags can be used in studies potentially lasting for 5 months or more in duration. Similar survival trials have shown that salmon smolts down to 100 mm FL (Chittenden et al., 2008) can be tagged with Vemco V6-sized tags; this, combined with our results, suggests that telemetry arrays capable of effectively measuring salmon survival are now technically feasible for many stocks and species of wild Pacific salmon, and not just for hatchery smolts ≥130 mm FL. However, consideration of the increased cost of such systems means that researchers need to carefully design these systems in order to make them as economical as possible.

In conclusion, tagging salmon smolts to measure survival beyond rivers and into the ocean requires both successful surgical implantation of transmitters and medium to long-term (>1 month) retention of tags. A critical requirement is that the combined effect of surgery and tag size does not affect growth and survival. We used multiple approaches to quantify the effect of tag implantation on survival for Columbia River spring Chinook salmon smolts, including captive smolt studies at hatcheries, a comparison of the statistical fit of an alternative survival model (FL as an individual covariate) for free-ranging smolts, and a comparison with independent survival estimates obtained from PIT tags. Overall, tagging effects were minimal for the size range of fish that we tagged (7 mm tag: ≥ 130 mm; 9 mm tag: ≥ 140 mm). We also found that different populations within the same river basin may not have a completely equal response to tag implantation, with the Yakima smolts having a greater incidence of sutures tearing through the skin and subsequent tag loss over time. Finally, adjusted survival estimates (S_K) for ROR smolts to reflect tag loss and smolt mortality observed in captive populations are well within the 95% confidence intervals of unadjusted survival estimates, indicating that these sources of uncertainty are likely very small relative to the overall mortality we have measured.

Our results indicate that acoustic telemetry appears to be a reliable method for measuring survival of free-ranging smolts and testing alternative hypotheses concerning the cause of the poor ocean survival of some populations of smolts originating from the Columbia River basin (Schaller et al., 1999). Measurement of Chinook salmon smolt movement or survival over periods of many months appears to be quite feasible when smolts are implanted with 9 mm transmitters <11.5% of body weight and 7 mm transmitters <7.3% of body weight. Although movement measurements do not require precise estimation of the proportion of tagged animals reaching a sub-array, the more demanding task of estimating smolt survival over time periods up to at least 3 months post-surgery appears to be feasible, with estimates of survival apparently not substantially compromised by tagging-induced mortality or tag loss, compared to the smaller PIT tag. Future, long-term, survival studies (> 6 months) that are intended to quantify ocean survival beyond the three-month time period should also include long-term tag retention studies in hatcheries to establish whether smolt survival and tag retention on longer time scales is also feasible; recent work on coho salmon (Chittenden et al., 2009) indicates that high survival and tag retention out to at least 8 months post-surgery is feasible.

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Chapter 5.—Using Telemetry Techniques to Determine Multiple Redd Formation, Redd Residence Time, and Survey Life of Adult Coho and Chinook Salmon in Spawning Streams

Michael D. Sparkman[1]

Abstract

Effective management and conservation of salmon populations rely upon accurate estimates of population size over time (years). Two methods commonly used to estimate salmon escapement into streams are counting redds and counting live fish during spawning ground surveys. Redd counts, when used to index adult populations, or expanded to estimate the total number of adults, rely upon the assumption that a female makes just one redd. Fish counts, using the area-under-the-curve (AUC) escapement model, rely on an accurate estimate of the average time live fish spend in the survey area (known as survey life or SL) or on redds (redd residence time or RRT). Multiple redd formation (MRF), RRT, and SL can be difficult to measure accurately and have received little attention in California streams. This paper will provide telemetry methods to determine MRF, RRT, and SL for adult salmonids in spawning streams based upon 4 years of study. Telemetry can provide additional data as well, such as observer efficiency at seeing redds and live and dead fish, salmonid habitat use and migration patterns, pre-spawn predation, and egg retention. The methods are intensive, yet simple, and have proven to be an efficient, relatively low-cost method to accurately address key assumptions and variables used in fishery models, particularly for long-term population monitoring.

Introduction

Effective management and conservation of salmon populations rely upon accurate estimates of population size over time (years). Two methods commonly used to estimate Pacific salmon (*Oncorhynchus* spp.) escapement into streams are counting redds and counting live fish during spawning ground surveys. Redd counts, when used to index adult populations, or expanded to estimate the total number of adults, rely upon the assumption that a female makes just one redd. Fish counts, using area-under-the-curve (AUC) methodology, rely on an accurate estimate of the average number of days that a live fish spends in the survey area (survey life or SL) or a female fish spends on redds (redd residence time or RRT).

Multiple redd formation (MRF), defined as constructing and depositing eggs in more than one redd during reproduction, typically is assumed to be negligible or non-existent with respect to population escapement models (e.g., Hill and Irvine, 2001; Greene et al., 2005; Paulsen et al., 2007), and in research studies designed to determine survival from egg deposition to fry emergence in natural redds (Tagart, 1984; Sparkman, 2004). Most models and studies consider single redd formation by Pacific salmon to be the norm. Although there is a large body of literature describing salmonid reproductive behavior (e.g., Briggs, 1953; Groot and Margolis, 1991; Quinn, 2005), relatively little attention has been directed at proving or disproving whether adult female Pacific salmon make multiple redds during reproduction. There are three types of studies that have specifically been used to investigate MRF: (1) genetic analyses, (2) artificial spawning channels, and (3) PIT tagging adult female salmon. Bentzen et al. (2001) used multilocus microsatellite genotypes collected from pre-emergent juveniles to infer that 7% (1 out of 14) of the female Chinook salmon (*O. tshawytscha*) made two redds. Kuligowski et al. (2006) used polymorphic microsatellite loci collected from eyed eggs in redds of steelhead trout (*O. mykiss*) to infer that the eight redds were built by at least five adult females. Schroder et al. (2008) placed adult spring Chinook salmon in an artificial spawning channel and observed that 10% of the females constructed more than one redd. Murdoch et al. (2009) injected PIT tags into adult female spring Chinook salmon prior to their spawning in natural streams and determined that females constructed 1.01 redds/female.

RRT is less difficult to measure than SL because fish are more easily observed on a redd compared to locating and observing fish in various stream locations and habitat types. Three current methods are available for determining RRT: (1) direct observation of spawners with distinct natural markings (e.g., fungus, predator wounds) on redds (Neilson and Banford, 1983), (2) AUC of spawners divided by an independent mark-recapture population estimate of spawners (Parken et al., 2003), and (3) time lapse video recordings of spawners on specific redds (Shardlow, 2004).

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SL is an important variable used in the AUC escapement model (Perrin and Irvine, 1990; Korman et al., 2002; Parken et al., 2003). SL is a difficult variable to determine accurately, and several authors have indicated SL to be specific to species, stock, sex, stream, time of adult entry, and year (Perrin and Irvine, 1990; English et al., 1992; Lady and Skalski, 1998; Korman et al., 2002). In order to reduce systematic biases in estimated escapement over years, Perrin and Irvine (1990) and Hilborn et al. (1999) recommended determining SL on an annual basis. Perrin and Irvine (1990) reported eight independent methods to determine SL, with most methods consisting of variations in: (1) extensive mark-recapture and foot surveys, (2) repetitive counts of live and dead fish, and (3) AUC of counts of live fish divided by an independent mark-recapture population estimate. Korman et al. (2002) used radio telemetry to determine SL for adult steelhead trout.

This paper will provide telemetry techniques to determine MRF, RRT, and SL for adult salmonids in spawning streams based upon 4 years of study; results from the third year (YR 2007–08) are presented for illustration. Telemetry may be used to gather additional data as well: (1) observer efficiency at seeing redds, (2) observer efficiency at seeing live and dead fish, (3) salmonid habitat use and migration patterns, (4) pre-spawn predation, and (5) egg retention.

Site Description

The study was conducted in Prairie Creek, a tributary of Redwood Creek in Humboldt County, California (fig. 1). The Prairie Creek watershed lies within the Northern California coastal zone in Redwood National and State Parks, and is forested with old growth redwood (*Sequoia sempervirens*) and Sitka spruce (*Picea sitchensis*). Prairie Creek is a relatively pristine, fourth order, low-gradient stream (0.0032 m/m) that drains a 34.4 km^2 watershed. Mean annual discharge is 1.49 m^3/s and bank full discharge is 5.6 m^3/s. Prairie Creek supports annual runs of adult Chinook salmon, coho salmon, and steelhead trout that are listed as threatened under the U.S. Endangered Species Act (Federal Register, 1997, 1999, and 2000).

Adult salmon populations in Prairie Creek were surveyed annually by foot within pre-designated, stream-index reaches, which encompassed a total of 15 km of stream habitat. The 15 km was divided into five reaches, and within each reach, meter markers were placed every 50 m on nearby trees for associating distances to locations of redds, live fish, and carcasses. An adult counting and marking weir is located at Rkm 8.4, just downstream of major spawning areas and survey index reaches (fig. 1). Annual adult escapement over the past 9 years ranged from 70 to 660 for coho salmon, and 30 to 531 for Chinook salmon (W. Duffy, U.S. Geological Survey, California Cooperative Fish and Wildlife Research Unit, personal commun., 2009). Prairie Creek was ideal for this type of research because there is a large network of trails along the mainstem and tributaries, and a road parallels most of Prairie Creek. Additionally, Prairie Creek clears rapidly after storm events, thus increasing the probability of visual observations. In streams with poorer access, telemetry techniques may prove to be even more effective than other techniques (e.g., mark-recapture and foot surveys) because less time is spent trying to locate tagged fish.

Methods

Telemetry Equipment

Advances in telemetry technology have greatly increased the ability to quickly detect individual fish. An important aspect in choosing equipment for a study like this one is the ability to use radio transmitters (tags) that have a unique code assigned to a common frequency; depending on the company, there can be up to 521 codes per frequency.

LOTEK Wireless, INC (New Market, Ontario, Canada) digitally encoded radio telemetry equipment was used in this study, and therefore the method of fine tuning the receiver applies specifically to LOTEK equipment. In this study, I used a SRX_400 W5 scanning telemetry receiver, digitally encoded radio transmitters (Model MCFT-3A; Frequency 159.660 and 159.680 MHz), and two antennas (H; Yagi 4 element) that were tuned to the transmitter's frequency. Fixed stationary receivers were not used in this study because road and trail access in Prairie Creek were adequate to detect tagged fish nearly anywhere within the basin. In larger systems, stationary receivers are useful in recording the movements of tagged fish entering and leaving the system.

The receiver for mobile tracking was programmed and adjusted for the telemetry equipment used in this study. Each receiver was programmed with two different frequencies (e.g., 159.660 and 159.680 MHz) to match the radio transmitter tags used in this study. The scan time, which is the amount of time the receiver scans (listens) for radio transmitters on a given frequency, was set to equal 1.5 times the burst rate of the transmitter. That is, for a transmitter set with a 3 s burst rate, the scan time would be set at 4.5 s. The receiver would scan for the first frequency for 4.5 s and then scan for the second frequency for 4.5 s. Scan times were set beyond the burst rate in order to account for drift and timing of the transmitter's signal. The receiver also can be set to simply detect a single frequency when needed. Whether scanning for two frequencies or detecting a single frequency, multiple codes for a given frequency will be detected and displayed if multiple tagged fish are within detection range.

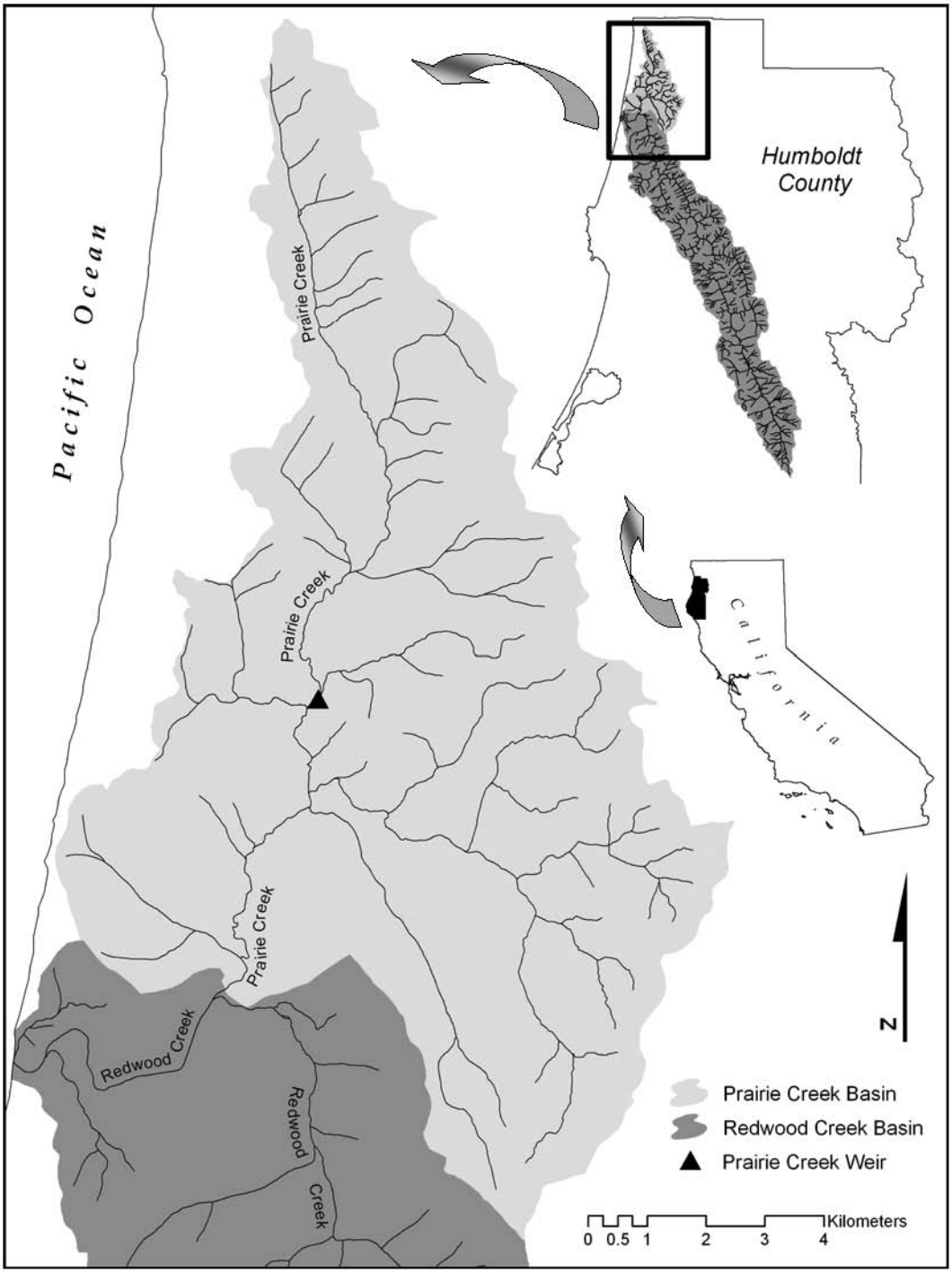

Figure 1. Map of Prairie Creek watershed with adult salmon weir (J. Garwood, California Department of Fish and Game, personal commun., 2009).

Gain can be thought of as the window of detection, or more accurately as an internal attenuation setting that can act as a filter by reducing the strength of the transmitter signal as well as ambient noise. Gain can have values ranging from 1 to 99; the larger the value, the greater the detection window. For example, a gain set at 90 will allow the receiver to detect transmitters at a greater distance from the antenna and receiver than a gain of 10. The main drawback with a high gain setting is background noise (static) increases; however, the chirp of the transmitter emanating from the receiver can still be heard and if the power is great enough, frequency and code will be displayed.

Power refers to signal strength, and can range from values < 10 to the maximum value of 235. The closer the antenna is to a tagged fish at a given gain setting, the stronger the signal strength and the greater the power reading. Gain settings and resultant power readings can be used to locate tagged fish. By decreasing gain and keeping power readings high (> 180) while approaching tagged fish, the location of the tagged fish can be pinpointed. The power of the signal strength also is influenced by: (1) antenna type, (2) antenna orientation and direction relative to the tagged fish, (3) condition of coaxial cable used to connect antenna to receiver, (4) signal interference from trees, undercut banks, water depth, and other physical obstructions, (5) water conductivity, and (6) sinuosity of the stream. When power readings become too low, the receiver will still transmit the chirp of the radio transmitter; however, frequency and code will not be displayed until power readings increase.

A variety of radio transmitter sizes are available, depending on the size of fish to be tagged. The general rule of thumb is to have the transmitter weight ≤ 2% of the fish's weight (Winter, 1983). The frequency of the transmitter in the U.S. is often dictated by Federal Communications Commission standards, and the exact frequency to be used depends on the State in which the study is conducted. Radio transmitters suitable for adult coho and Chinook salmon in this study were 46 mm long, 16 mm in diameter, weighed 6.7 g in water, and set at the factory to emit a signal every 3 s. The operational life of the radio transmitter is dependent on how often the transmitter sends a signal, and at 3 s, transmitter life is expected to be 572 days of continual use (H. Tam, LOTEK Wireless, personal commun., 2009). Several intermittent signal options also are possible with most transmitters; however, the transmitters I used were perfectly suited for this study. Each transmitter broadcasts the radio signal via a flexible, whip antenna (L = 460 mm). Three rubber rings (4 mm wide) cut from latex surgical tubing (2 mm thick; 6 mm inside diameter) were attached to each radio transmitter prior to insertion to decrease the probability of fish regurgitating the transmitter once inserted (Keefer et al., 2004).

Adult Capture and Tagging

Adult salmon were intercepted and captured at an adult counting weir, located just downstream of spawning grounds (fig. 1). Zimmerman and Zabcar (2007) describe the general procedure for operating adult salmon weirs. Salmon were captured for tagging throughout the spawning run in order to collect and compare data from early, mid, and late-returning fish, and to provide an average value for RRT and SL that represented the population at large. Several studies have documented that RRT or SL can vary depending on when the adult migrated upstream. In general, earlier returning adults spend more time in the stream or on the redd than later arrivals (Neilson and Banford, 1983; Perrin and Irvine, 1990; McPhee and Quinn, 1998). Once captured, candidate female salmon were placed into a typical holding cradle for measurement (Fork Length (FL); cm), and inspection and tagging. Females used in the study (for investigating MRF) did not show any signs of previous reproduction (e.g., expelling single eggs, caudal fin wear from digging in the substrate, and deflated belly).

Transmitter insertion methods generally followed the protocols for esophageal implants provided by Eiler (1990) and English et al. (2005). Esophageal implants are preferable to surgical methods because the process: (1) takes less than 2 minutes, (2) does not require anesthetizing fish, and (3 reduces the amount of stress associated with tagging. Before tagging, radio transmitters were sterilized in a 10:1 solution of water and iodine disinfectant for 10 minutes. Adult fish were then placed upside down in the cradle before tagging so that reproductive organs would not interfere with transmitter placement (Ward and Miller, 1988). Radio transmitters were inserted through the esophagus into the stomach cavity using a semi-flexible tube (Inner Diameter 5.9 mm, Length 360 mm) until the transmitter stopped at the posterior portion of the stomach. The insertion tube was then removed, leaving the transmitter in the stomach and the antenna protruding from the fish's mouth. Care was taken to avoid pushing the transmitter through the stomach wall. Over a 4-year period, a total of 36 female coho salmon and 6 female Chinook salmon were tagged with radio-transmitters. Several male salmon also were tagged.

I varied the frequency of the transmitter for every other fish when tagging multiple fish on the same day to minimize the probability of signal collision (error code on the receiver) when two or more tagged fish were within close proximity to each other in the stream. Fish tagged on the same day would occasionally be detected the following day in the same location, and if the frequency and timing of the signal pulse of the transmitters were identical, signal collision would occur.

Radio tagged salmon were then placed upright in the cradle and a second tag was applied to the leading edge of the dorsal fin. The secondary tags, similar to Peterson Discs, were small in size (length = 35 mm, width = 0.5 mm, height = 13 mm) and allowed for visual identification of a radio-tagged fish. The secondary tag was small enough to not bias live fish observation probabilities because the observer would see the fish first and then the tag. I used yellow tags because many spawning salmon will have yellow coloration on their back and fins from normal skin and tissue degeneration. After applying both tags, fish were occasionally held in a large tub for up to 10 minutes to assess immediate transmitter regurgitation, and then released upstream of the adult weir. However, most fish were simply released into the stream immediately after tagging because short-term transmitter regurgitation was not observed.

Mobile Tracking

Radio tagged fish were tracked and located nearly every day by one or two technicians. Depending upon the skill of the tracker, stream access points, and location of tagged salmon, one person was able to collect data on up to 15 fish in an 8-hour period. However, fewer fish were usually tracked each day due to natural mortality of spawning adults. To save time finding tagged salmon, two mobile tracking strategies were used: vehicle and foot. The Yagi 4 element antenna, attached to a pickup truck, was first used to get rough locations of each fish because the range in detection is about two times greater than for the H antenna at a given gain setting. The Yagi antenna was often aimed at the river to increase signal strength and probability at detecting transmitters; however, most of the time the antenna worked just as well pointing posterior to the truck. Gain was set anywhere from 60 to 90 and allowed for detecting transmitters up to 1.2 km away in the thickly forested streams of the basin. When a fish was detected, fish location was referenced to survey index reach number, tributary confluence, or mile marker on road signs. If a given fish was not located by truck, I assumed that the salmon: (1) had migrated out of range, (2) had left the study section, or (3) was close to another tagged salmon with the same transmitter frequency and timing of the signal pulse. Other possibilities included transmitter failure, or removal by a predator or poacher. The receiver will display an error code when two tagged fish with the same transmitter frequency are very close to one-another and the transmitters emit a signal within 100 ms of each other (J. Stevenson, BioAnalysts, Inc., personal commun., 2009). However, the error code also could be due to signal interference by trees and landforms. In those cases, I frequently obtained the correct code by waiting a few minutes for an uninterrupted signal to reach the receiver or by slightly changing the angle and direction of the antenna to increase reception.

Once all fish were generally located, I programmed the receiver out of scan mode and singled in on the nearest frequency (and code). Mobile tracking on foot included wearing waders and using the H antenna with the receiver. Polarized glasses also were worn to increase the ability to see tagged fish. Walking upstream decreased the probability of fleeing behavior. The gain of the receiver was reset to 60 and by angling the H antenna upstream, downstream, or directly towards the river, a given power reading would display when the receiver picked up the transmitter's signal, along with transmitter frequency and code. The direction of travel to track the salmon was determined by the highest power reading and antenna direction. I then followed the signal by observing signal strength and antenna direction at various distances from the tagged salmon. When power readings approached 200–230, I reduced the gain to 40, observed the immediate power reading decrease to a lower value, and continued to follow the signal. As the distance between the tagged fish and antenna decreased, the power readings increased and the sound of the transmitter's chirp also became louder. When power readings once again reached values near 200, the gain was lowered to 20 or 30 and tracking continued. When power readings were near 170 and gain was set at 20–30, I was usually able to observe the fish in a given habitat type (pool, run, etc.), or on a redd.

In streams that are very clear like Prairie Creek, salmon tended to be wary and frequently fled to nearby cover if disturbed. Thus, the ability to visually locate salmon and observe behavior was increased by standing alongside a tree or crouching within riparian vegetation. If the salmon was not visible, then chances are the fish was hiding in an undercut bank, log jam, or deep pool. I found that it was very common for adult salmon to hide in undercut banks and log jams in Prairie Creek. Naturally, the probability of seeing tagged fish was enhanced with increasing stream clarity; however, if stream discharge was very low, salmon tended to increase hiding behavior. If the fish was still not visible, I reduced the gain to 10–20, observed the power reading decrease, angled the antenna to get maximum power, and then waded in the direction to where power readings increased. Under normal circumstances with a gain of 10–20 and power near 150, the tagged salmon will be hiding within a few meters of the receiver and antenna. Once the salmon was located either visually or by relying upon power, gain, and antenna direction, pertinent data were recorded in a field notebook (appendix 1, sample data sheet).

Data Collection

Radio tagged salmon were tracked and located nearly every day 7 days a week, and detailed notes pertinent to study objectives were recorded for each fish (appendix 1). Each fish was assigned a specific data sheet, which greatly simplified data recording and data analysis. The amount of time spent observing a given female depended on how long it took to collect necessary data. Data collected on MRF, RRT, and SL data can be stratified into three categories: (1) survey index reach, (2) tributaries, and (3) watershed. The stratification allowed for discerning any differences in variables relative to surveyed mainstem index reaches, and non-surveyed areas in mainstem and tributaries. Data for watershed included survey index reach areas, and non-surveyed areas.

Multiple Redd Formation.—Adult female salmon may build test redds or digs (no eggs present) before building a "true" redd (Briggs, 1953; Sparkman, 2004) and therefore I had to observe actual spawning by female and male salmon before I considered a redd to be a "true" redd. I found that the effort spent residing on and building a test redd was less than 1 day and for true redds was many days. Test redds for coho salmon also were less than 1.5 m long (including upstream pot or depression) and much smaller than true redds. Typical signs of actual spawning included: (1) female in upright position with mouth open as eggs are expelled, (2) presence of male alongside female when she expels the eggs, (3) male quivering as he releases milt to fertilize eggs, and (4) digging action of female to cover the fertilized eggs. The process was repeated many times over multiple days until spawning was completed. Solitary females exhibiting digging behavior were not considered to be spawning, and on several occasions, I examined the digs and found no eggs present. When a female and male were found on a fresh redd, ribbon tape with detailed information (e.g., date, frequency/code of female, redd in progress, reference location in stream using meters) was hung on nearby riparian vegetation directly perpendicular to the upstream pot (future egg pocket for true redds). Test redds also were flagged with ribbon tape because I would not necessarily know if the test redd would become a true redd until the next day, or if spawning was observed. The flagging also helped to detect any increase in the size of the redd over time, which in turn helped validate additional spawning activity. I also flagged each new pot in subsequent days to further document additional spawning had occurred when not directly observing spawning activity.

Female salmon were tracked and located each day, including the day they died. Once dead, I removed the radio transmitter from the stomach and noted the location of the transmitter and recorded egg retention. The transmitter was then rinsed in stream water and de-activated by attaching a magnet on the transmitter near the reed switch. All radio transmitters were recovered from tagged fish each year.

Redd Residence Time.—The amount of time (d) that a female spends on the redd included: (1) initial redd construction, (2) spawning, and (3) guarding the redd. If any of these behaviors were observed, then that day would count towards RRT. Female salmon did not always reside on the redd throughout the spawning period. Sometimes they would be hiding nearby in undercut banks, log jams, or under overhanging branches, or simply residing in clear view within 1–10 m of the redd. This behavior tended to increase during low-flow conditions. In those cases when a female was not observed on the redd, I would either stay at the site until she appeared on the redd (usually within 15 minutes), or return at a later time during the same day. If the female salmon was within 5 m of the redd, I considered her to be next to the redd, which would then count as part of her RRT. I made the assumption that she would occupy the redd sometime during that day, which was supported by observing her on the redd later that same day, or on following day(s). RRT for each fish is determined by summing the number of days each female salmon was observed on a redd and RRT for AUC is simply the average of these values.

Survey Life.—The amount of time a live fish spends in survey reaches, tributaries, or within the watershed is easily determined using telemetry techniques. Similar to determining MRF and RRT, each fish is tracked daily and detailed notes on location are recorded. Notes on location for each fish included: (1) stream or tributary in which the fish was detected, (2) distance in stream referenced to meter markers, and (3) habitat type. SL for each fish is simply determined by summing the number of days each salmon was alive and SL for AUC is simply the average of these values.

Miscellaneous Information.—Depending on time constraints and budget for research, various additional yet important information can be collected, such as: (1) observer efficiency at seeing redds (Muhlfeld et al., 2006), (2) observer efficiency at seeing live (Korman et al., 2002) and dead fish, (3) habitat use and migration patterns, (4) percent use of specific areas (e.g., survey reaches) within the watershed (Korman et al., 2002), (5) pre-spawn mortality, and (6) egg retention. Observer efficiency, defined as the probability of visual observation or as the number of observation days divided by the total number of possible observation days is easily determined for redds and live and dead fish. Observer efficiencies can be determined by the tracker (e.g., deciding whether I could have seen the redd, live or dead fish while surveying the stream), or by documenting whether an independent survey crew made specific observations (Muhlfeld et al., 2006). Habitat use and migration patterns are determined by documenting the location and habitat type of tagged fish each day, and percent use of a specific area is determined by summing the number of days a tagged fish was found in specific areas (e.g., survey reach or non-survey reach), divided by the total number of days a tagged fish was

located in all areas combined. Pre-spawn mortality can be determined by noting whether the fish survived to spawn, and egg retention can be determined by counting the number of eggs present in the tagged female carcass.

Results

We tagged 14 female coho salmon and one female Chinook salmon in study year 2007–08. Detection probabilities per tagged fish ranged from 93 to 100% and averaged 99.5% for all fish. One female coho salmon was preyed upon before spawning; the remaining female coho and Chinook salmon successfully spawned. None of the 15 females built multiple redds; however, 27% constructed small test redds before building a true redd. Of the four females that built test redds, only one built her true redd within 40 m of the test redd.

RRT for the female Chinook salmon equaled 4 d, and SL equaled 27 d. The female Chinook salmon was preyed upon while on the redd sometime after I observed her on day 4 and before my observation on day 5. RRT for female coho salmon in index reaches averaged 11 d and in tributaries averaged 10 d. SL in index reaches averaged 24 d and in tributaries averaged 10 d (table 1). Egg retention for 13 females ranged from 0 to 20 eggs and averaged 3 eggs per female.

Table 1. Redd residence time (d) and survey life (d) of adult female coho salmon in the Prairie Creek Watershed, 2007–08.

[SEM, standard error of mean]

Code	Redd Residence Time (d)		Survey Life (d)	
	PC Index	Tributaries	PC Index	Tributaries
11	8		35	4
12	9		44	
13		11	28	13
14	9		18	
16	15		21	
17	9		22	5
18	12		16	
22			18	
23		10		12
24	17		49	
25		11		13
29		5		14
31	8		11	5
32		13	6	17
Average	10.9	10.0	24.4	10.4
SEM	1.2	1.3	4.0	1.8

Discussion

The use of telemetry techniques to determine MRF, RRT, and SL overcame many of the shortcomings associated with previous methods reported in the literature. The high probability of detection (99%) of radio tagged fish eliminated biases in RRT or SL that are often associated with mark-recapture and intensive surveys because tagged fish could be located quickly every day. This in turn allowed for determining exact values of RRT and SL. Given that RRT and SL may need to be determined annually (Perrin and Irvine, 1990), telemetry techniques may prove to be the best technique for obtaining accurate and precise estimates of RRT and SL. The success of this research project ultimately depends upon locating each fish nearly every day, which in turn depends upon equipment reliability and skill with operating the telemetry receiver and antenna. The methods are intensive, yet simple, and have proven to be an efficient, relatively low-cost method to accurately address key assumptions and variables used in fishery models, particularly for long term population monitoring.

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Appendix

Appendix 1. Sample data sheet.

Agency/Entity Name:_____ Study Name and Year Page __of___

Date Tagged:_____ Tagger:_____

Species:_____ FL (cm)_____ Sex _____

Frequency:_____ Code:_____

				Receiver	Stream/	Habitat	Meter	Distance from	If up	Vis.	On	Next	Redd Size	
Date:	Trackers	Detect. No.	Time	Power/ gain	Reach	Type	Marker (m)	previous location	or down	ID?	Redd?	to Redd?	L x W (cm)	Notes

Chapter 6.—Acoustic Telemetry for Studying Migration Movements of Small Fish in Rivers and the Ocean—Current Capabilities and Future Possibilities

Douglas Pincock[1], David Welch[2], Scott McKinley[3], George Jackson[4]

Abstract

Acoustic telemetry offers a number of advantages over other techniques for tracking the movement of aquatic organisms. These include a good detection range (up to hundreds of meters with miniature transmitters), which works in both marine and freshwater environments, and the ability to determine the position of tagged fish with great accuracy and precision. A consideration of diverse techniques and technologies is needed for long-term monitoring (months to years) of the movement and migration of fish, particularly small fish, such as salmon smolts, from their freshwater habitats to the ocean and their subsequent spawning migration back to their natal rivers. Any study undertaken needs to consider the variables that can affect successful transmission and detection of acoustic signals. These include transmitter frequency and coding method and their impact on range, transmitter size, and system performance in high residency situations. Several factors, including the increased use of acoustic telemetry, the prevalence of long life transmitters, and the desire of researchers to develop collaborations in which all deployed receivers detect all transmitters, have created a requirement for coding methods that can support at least hundreds of thousands of unique identification codes. These factors are all extremely important for both engineering of array design and assessing receiver performance and its impact on the detection efficiency of receiver lines over which fish pass.

With an understanding of sources of error and their impact on positioning accuracy, it also is very feasible to provide fine scale positioning where needed without compromising the monitoring of large-scale movements. The potential to develop even smaller tags than the smallest currently available from a number of manufacturers (roughly 6 × 15 mm) will open up important and new possibilities for tagging fish too small to tag with existing acoustic technology.

Introduction

Acoustic telemetry has been a well-established tool for determining movements and behaviour of free-swimming fish for decades (for example, see Stasko and Pincock, 1977). While acoustic signals are the only viable means of telemetry in the ocean due to the very high losses experienced by other signals, radio telemetry has been used successfully in many fresh water environments. However, acoustic telemetry has some advantages that make it more attractive than radio telemetry in many of these applications, the key advantages being the ability to accurately locate tagged animals with an array of receivers and the absence of an external antenna.[5]

In recent years, there has been a significant expansion of acoustic Passive tracking (see Heupel et al., 2006, for a review) in which stationary receivers log the passage or residency of tagged fish over extended periods of time. Although passive acoustic tracking has been used in fresh water, to date its use has not been as prevalent as in the ocean. This is due in part, particularly in riverine environments, to issues that are either not fully addressed by existing equipment or not well understood by users including:

1. Propagation and noise conditions that differ from the ocean and vary enormously from location to location.

2. Many salmon smolts, by far the most studied species in rivers, require extremely small transmitters, in some cases, smaller than what is commercially available today.

In this paper, we will focus on passive tracking techniques and technologies that are appropriate for monitoring migration movements both in rivers and out into the ocean. The emphasis will be on techniques suitable for small fish such as salmon smolts. Our objective is to provide enough insight into the underlying technologies to justify a set of conclusions that provide guidance to scientists designing experiments.

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[5]While radio transmitters can be realized without an external antenna, the penalty in output power and hence range loss is significant.

Acoustic Conditions in the Ocean and Fresh Water

Overview

This section describes some key aspects of the underwater acoustic channel as background to understanding the possibilities and limitations of acoustic telemetry. Almost all research in this area has focused on the ocean, but we can draw on this because, other than absorption discussed below, the results generally are applicable to fresh water as well.

Propagation Loss

In addition to the normal spreading loss which increases with the square of the distance from the transmitter, acoustic signals also undergo an absorption loss expressed in decibels/meter. Transmission frequency and the conductivity of the medium are the key factors influencing absorption loss and leading to significant differences between ocean and river environments, as well as differences from one river environment to another. The general trend is that acoustic losses, and hence achievable range, for a given transmitter power increase with increasing frequency and/or conductivity. Table 1 provides a typical example with an assumed transmission level of 136 dB re 1 µPascal at 1 meter[6] and a good quality receiver (bandwidth = 1 kHz and threshold signal to noise ratio = 3 dB). Results were calculated using the passive sonar equation (Urick, 1983) with acoustic absorption based on salinity, frequency, depth, and water temperature (Tucker and Gazey, 1966), and using typical salinity levels (Office of Naval Research, no date). As can be seen from the data in table 1, there are substantial advantages of using low frequencies, even in fresh water.

Table 1. An illustration of the variation in range (in meters) with frequency and salinity.

[Transmission level = 136 dB re 1 uPascal @ 1 meter, depth = 10 meters, water temperature = 20 °C, remaining parameters described in text]

Frequency (kHz)	Salinity (parts per thousand)		
	0	10	35
	Pure fresh water	Typical brackish water	Ocean
50	9,210	3,550	1,690
100	3,720	1,400	650
200	1,380	660	320
300	710	420	230
400	460	320	190

We emphasize that the data in table 1 is illustrative and intended to show trends rather than what one might achieve in a passive tracking installation for two reasons:

1. The receiver specifications are very ambitious for a low power passive tracking receiver.
2. Assumed Noise Levels are very low – corresponding to those one would encounter in Sea State 0 conditions (Wenz, 1962)[7]

For example, if the Receiver bandwidth were increased to 5 kHz and the threshold signal to noise ratio to 12 dB, range for the Pure Fresh Water Column decreases from 1,380 to 430 meters at 200 KHz and from 460 to 160 meters at 400 kHz.

Frequency Constraints Imposed by the Acoustic Transducer

Because of their relatively small size and superior efficiency (Herman, 1975), Lead Zirconate Titanate (PZT) ceramic transducers are universally used to convert electrical to acoustic energy in acoustic telemetry transmitters. Furthermore, because of the need to operate near resonance for usable efficiency, cylindrical transducers are the only realistic choice[8] to produce omnidirectional radiation necessary for a telemetry transmitter.

Table 2 shows how the resonant frequency increases with decreasing transducer size and, when this information is combined with that of table 1, we see a difficult tradeoff between the need to use a low transmission frequency to achieve good transmission range and the fact that small electric to acoustic transducers are only efficient at higher frequencies. For example, if one chooses to use a 3 mm diameter transducer in an effort to produce a small transmitter, the optimum transmission frequency should be around 300 kHz where acoustic absorption will be very high (table 1). Although it is possible to use a frequency below resonance to mitigate this, the resulting loss in electric to acoustic efficiency will lead to shorter and shorter range the further one moves from resonance.

Table 2. Usable transmission frequencies for representative cylindrical electric to acoustic tansducers.

Transducer diameter (mm)	Approximate resonant frequency (kHz)
12	80
6	160
3	320

[6]Typical of what one might expect with a very small transmitter.

[7]This is only an issue at the lower frequencies shown because Sea State noise is not an issue beyond 100 kHz.

[8]Spheres, the only other possible structure, are significantly larger for a given resonant frequency as well as expensive and difficult to incorporate into a transmitter.

Of course, the transducer is only one component making up the transmitter and the impact of the other components on transmitter size will be discussed later. For now, it is sufficient to understand that one cannot arbitrarily reduce the size of this component without reducing the transmitter's range capability, in both salt and fresh water.

Signal Distortion in the Underwater Channel

Acoustic signals transmitted underwater suffer significant distortion and there is a large body of research describing these effects (see Urick, 1983, for example). The key characteristics of underwater sound that are relevant to communicating from mobile miniature transmitters to fixed or moving receivers are:

1. Significant spreading of transmitted pulses due to multiple paths by which the sound travels from transmitter to receiver due to echoes and ray bending.

2. Distortion of frequency and phase due to scattering and Doppler effects.

These vary not just from one location or environment to another, but also vary with time in a particular location due to many factors including weather generated noise and temperature gradients.

Although the distortion described above also exists for radio communication, the effects are orders of magnitude more severe in acoustic transmissions because of the low velocity of sound in water (approximately 1,500 meters per second). A full discussion of distortion in the acoustic underwater channel is outside the scope of this paper but a simple example is illustrative. For example, field tests in a typical shallow water situation (approximately 20 meters) in which a 10 millisecond pulse burst (69 kHz) was observed at a range of 600 meters produce the following results: stretching of the pulse to a duration of more than 60 milliseconds, amplitude variations of more than two to one during the first 10 milliseconds of detection and more beyond, and severe phase distortion including two almost 180 degree phase reversals.

Coding Data into Transmissions

Except in the simplest mobile tracking application (i.e., following a single tagged fish), data need to be encoded into transmissions to represent transmitter *Identification Codes* (ID Codes) and, in many cases, additional data from sensors (e.g., temperature, pressure). In the following discussion, we will define *Data Rate* as the total amount of useful information (whether it be ID codes or Sensor Data) successfully transferred to a receiver from all transmitters that are within range. Of course, this is not necessarily all the data transmitted as data will often be lost due to one or both of: *Transmission Errors* due to noise or distortion and *Collisions* (i.e., transmissions from two or more tags overlapping at the receiver which cause the receiver to fail to decode at least one).

Although the details of how data is coded are of little interest to users, an understanding of the relationship between the constraints imposed by the medium and their impact on the rate at which data can be successfully transferred is needed to assess the ability of a particular scheme to work properly in an intended application. For example, while a particular scheme may work well in an acoustically quiet environment where range requirements are relatively short, it may not in noisier conditions and/or when more range is required (i.e., the receiver has to not just detect transmitted pulses, but distortion of time intervals between successive pulses must be low enough to permit decoding of the data).

Data Bandwidth Requirements

Table 3 shows how overall data requirements increase with increasing number of tagged fish at a receiver. In the table and in what follows, we use the term *Resident Tagged Fish* to define the number of fish simultaneously within range of the receiver in question. Data in table 3 are based on 16 transmitted bits to represent the transmitter's ID Code and/or sensor data plus a 30% overhead for extra bits to detect transmission errors. The need for error detection will be discussed later.

In table 3, the term *Transmission Interval* refers to the time between successive transmissions of information from an individual transmitter. All Transmission Intervals shown in table 3 imply that the transmitter is silent most of the time, which is a virtual necessity for two reasons. First, it enables realistic transmitter life even when small batteries are used and, second, it allows multiple transmitters to be simultaneously present, the idea being that a transmitter sends its signal when others are silent. Of course, this cannot work perfectly and the issue of collisions that result will be discussed later.

Table 3. An illustration of the variation of required data rate (bits per second) on resident tagged fish and transmission Interval where each transmission includes 16 bits with 30% overhead for error detection bits.

Resident tagged fish	Transmission interval (seconds)		
	60	180	600
10	3.5	1.7	1.2
20	6.9	3.5	2.3
100	35	17	12
500	173	86	58

Data in table 3 can be easily extrapolated for other sets of ID and Sensor capabilities[9]. The important point, however, is that increasing the Transmission Interval will allow a higher number of Resident Tagged Fish for a particular Data Rate, of course at the price of less frequent updates from each transmitter. The importance of this is that, as we will show later, the maximum data rate achievable can be small and, therefore, the only way the user can ensure receiving data from a large number of resident tagged fish is by selection of tags with an appropriate Transmission Interval.

Although the data in table 3 is representative of today's (2009) equipment, it is becoming increasingly necessary to expand data requirements over those shown in the table. This is driven by one or both of:

1. The increasing number of fish acoustically tagged each year creating a need for more ID codes. Furthermore, the emergence of worldwide and regional receiver networks (See OTN, no date) is causing this requirement to expand rapidly since ID codes need to be unique (often on a worldwide basis).

2. The desire for more sensor data and/or more frequent updates from each transmitter.

As a final comment on data rate requirements, the use of a miniature acoustic modem to transmit an archive of stored sensor or other data will become more common (O'dor, et al., 2006) and can be regarded as a special case where the Transmission Interval is zero. Clearly, if such a capability is to coexist with passive or mobile tracking, a different, non-interfering frequency needs to be used.

Basic Signaling Element and Coding Method Taxonomy

Because of the distortion of amplitude, pulse length, and phase described above, the only realistic building block of any coding scheme is a tone burst (fig. 1) which, as the name suggests, contains a single frequency. An exception to this is that, for very short range (i.e. on the order of a few hundred meters or less) systems, some use of phase can be feasible.

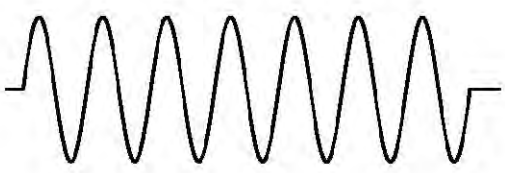

Figure 1. A single frequency tone burst. The diagram is not to scale as there would normally be many more cycles within the burst (For example, a 1 millisecond burst at 75 KHz would contain 750 cycles).

With a tone burst (which for simplicity, we will refer to as a Pulse) as the basic signaling element, the methods of coding data can be categorized as follows:

Single Frequency Versus Spread Spectrum.—In a Single Frequency scheme, all transmitted pulses are of the same frequency and the only means of coding information is the relative timing between pulses. In Spread Spectrum schemes, the bandwidth used is much wider than that of the information sent (Dixon, 1994). A simple example of a spread spectrum scheme would be the use of a number of pulses each having a different frequency.

Continuous Versus Coded.—In a Continuous scheme, each transmission consists of a single pulse and the data are encoded in the period between successive pulses (i.e., the Pulse Repetition Rate). In a Coded scheme, each transmission consists of a series of pulses with the intervals between successive pulses representing a binary number. Figure 2 shows a typical coded transmission where *Average Burst Length* indicates the average length of time needed to transmit the data.

Single Frequency Coded Focus.—Although Continuous coding is useful in a number of applications (e.g., mobile tracking of single fish), it is not appropriate for monitoring migration of large numbers of fish, therefore, we will not consider it further. Instead, we will focus on single frequency coded methods as their use is almost universal for applications that are the focus of this paper. The potential role of spread spectrum methods for the application focus of this paper also is discussed.

Need for Error Detection in Coded Tags

The combination of coded tags transmitting ID and Sensor information to a receiver constitutes a digital communication system and, like all such systems, there will be transmission errors (i.e., a deviation between what the receiver detects and what was actually sent).

The handling of transmission errors is very much driven by the nature of the application. For example, if images are being transmitted and a pixel is received in error (i.e., the

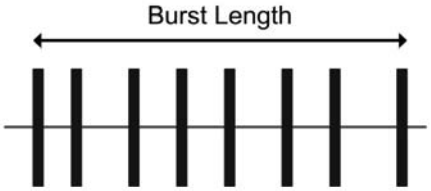

Figure 2. Typical pulse interval coding scheme.

[9]The data rates are proportional to the number of bits per transmission; for example, the required data rates if there were 24 bits per transmission would be 150% (24/16) times those in the table. One can adjust similarly for different error detection overhead.

receiver assigns the wrong value to it), it will not be visible to the viewer unless there are many such occurrences in each frame. However, it is not acceptable to assign the wrong value to the ID code and/or sensor data of a tagged fish; we want to be assured that a transmission error does not cause us to assume a fish was present that was not. This creates a significant challenge as the amplitude, phase, and frequency distortion of acoustic signals in the ocean described above will cause such transmission errors to occur orders of magnitude more frequently in an underwater acoustic channel than with radio or optical communication that we are more familiar with (Kilfoyle and Baggeroer, 2000).

The standard approach for the rejection of erroneous transmissions is to transmit extra bits in the form of an *Error Detection Code* (EDC), which is calculated according to some formula from the data bits and added to the transmission. At the receiver, the EDC is recalculated from the data bits received and compared to the received EDC. Transmissions in which the calculated and received EDCs differ are rejected as this could only occur as a result of a transmission error.

Will error detection techniques detect all possible transmission errors? The answer is no. Again, regardless of the scheme used, there will always be a non-zero probability that a transmission error will slip through the test creating a *False Positive* (i.e., a tag appears to be present but is not). The best one can do is increase the "robustness" of the EDC to the point that the probability of such False Positives becomes insignificant. Of course, the cost of more robust error detection is that a higher portion of the bits transmitted are for error detection rather than the actual data, hence reducing the effective data rate.

The statistical probability of a False Positive depends on the coding method, EDC, number of transmitters present, and the characteristics of the channel; therefore, a general discussion is beyond the scope of this paper. However, as an example, Pincock (2008) addresses False Positive probability and removal methods for a typical coding method and also shows that eliminating the EDC bits leads to an unacceptably high false positive rate in all but the least demanding situations.

Single Frequency Signaling Constraints

Clearly, for a given number of bits per transmission, the shorter the Average Burst Length (fig. 2) of coded transmissions the higher the Data Rate. However, this is limited by the two parameters defined below:

1. **Minimum Interval:** The smallest interval between successive pulses occurring in the coding scheme. It needs to accommodate the maximum Channel Clearing Time (i.e., the length of time for multipath echoes to decay to a level that they are no longer detectable by the receiver) that might be encountered.
2. **Timing Sensitivity.** This is the accuracy to which the difference between successive pulses has to be measured at the receiver for the code to work.

In both cases, these parameters need to be large enough to provide immunity to multipath and time variability of the acoustic channel between tag and receiver. In the following, we will refer to them as *Coding Parameters*.

Channel Clearing Time is much studied as it relates to acoustic communication underwater. For the typical range requirements for fish telemetry (approximately 100 to 1,500 meters), this could be as low as a few milliseconds or as high as hundreds of milliseconds with factors causing this to increase including range, noise level, and longer path lengths for detectable echoes from the surface or bottom (see Kilfoyle and Baggeroer, 2000, for an overview).

There is little quantitative information in the literature on the consistency of travel time from transmitter to receiver of successive pulses (the determining factor for setting the Timing Sensitivity of a coding scheme). The likely reason for this is that most coding schemes used in underwater communications are designed to be relatively immune to these variations. However, these schemes require more complexity in the transmitter and receiver than has been realistic for fish telemetry transmitters. As discussed below in connection with Spread Spectrum approaches, this has started to change but, with single frequency systems, this is a critical parameter since, if it is too short, communication errors will be high. To eliminate this risk, the tags we have used are based on very conservative values of this parameter (usually 10 milliseconds or more) for which we have seen no evidence of any lost data due to timing measurement amongst millions of detections from hundreds of different receivers. As shown below, except in applications where the Channel Clearing Time is very short (shorter than would be the case for most studies), there is little to be gained by trying to use values less than 10 milliseconds.

Single Frequency Coded Data Rate

The calculations below can be carried out for any coding scheme as long as the Average Burst length is known. In cases where this is held proprietary, users should expect the vendor to provide information on the average burst length for the coding method used as well as some indication of its level of conservatism (i.e., potential for decoding failures at longer ranges or higher noise conditions).

Maximum Theoretical Data Rate

As a starting point to understanding data rate limits, it is helpful to define *Maximum Theoretical Data Rate* as the rate that would be achieved if transmissions were constantly present at the receiver (i.e., each new transmission arrives the Minimum Interval after the preceding one so that there is no dead space and no interference between transmissions).

Thus, the average time between updates is just the Average Burst Time plus the Minimum Interval of the coding scheme. Table 4 shows the results of typical calculations[10] using various Coding Parameters for a scheme encoding 16 bits[11] per transmission (including a 30% allowance for an Error Detection Code).

As can be seen from table 4, data rate potential deteriorates significantly as Minimum Interval increases. We have included an extreme value of Timing Sensitivity (2 milliseconds which would be unreliable in many situations) to demonstrate that, unless Minimum Interval is shorter than would work in many situations, gains made by trying to shorten it beyond the conservative values we normally use are not large.

Table 4. Examples of maximum theoretical data rate calculations for a coded single frequency scheme encoding 16 bits per transmission with a 30% overhead for error detection code.

Minimum interval (milliseconds)	Time sensitivity (milliseconds)	
	2	10
20	51	15
100	19	10
150	14	8
200	11	7
300	7	5
400	6	5

Table 5. Average burst length in seconds for various combinations of a single frequency coding method's minimum interval and time sensitivity.

[16 bits per transmission with 30% allowance for error correcting code]

Minimum interval (milliseconds)	Time sensitivity (milliseconds)	
	2	10
20	0.3	1.0
100	0.8	1.6
150	1.2	1.9
200	1.5	2.2
300	2.1	2.9
400	2.8	3.5

[10]This ignores variations in Burst Length due to the number of bits coded into each interval but, for any reasonable value, these variations are small.

[11]The Burst Lengths can be adjusted proportionally for any other number of bits per transmission and/or a different allowance for an Error Detection Code.

Coding Robustness

Ideally, the vendor should provide enough information for the user to assess whether coding parameters are conservative enough for the conditions of a particular study. If this is not the case, table 5 provides the basis to estimate this from knowledge of the Average Burst length and Number of Bits per transmission. The data in table 5 is analogous to that in table 4 except that it shows the dependence of Average Burst Length instead of Theoretical Data Rate on the two coding parameters.

From the data in table 5 and the discussion of Channel Clearing Time and distortion of pulse arrival time above, we see that schemes with an Average Burst Time of about 3 seconds or longer are very conservative (i.e., will work with systems having a range capability of up to a kilometer or more and in virtually all noise conditions). However, the further one falls below this threshold the more restrictions on where the system will operate reliably arise (e.g., reduced range capability and/or need of quieter environments).

Although the above discussion focused on schemes sending 16 bits per transmission, it is a simple matter to adjust Burst Lengths proportionally for any other number of bits per transmission and/or a different allowance for any Error Detection Code.

Data Rate When Multiple Transmitters Are Present

If there were never more than one transmitter present at a receiver, tags could be coded with Transmission Intervals equal to the worst case Channel Clearing Time and the data rate achieved would be as shown in table 4. Of course, the innate inefficiencies of the telemetry application (i.e., a number of transmitters sending signals asynchronously with each other creating both collisions and dead space) mean that actual data rates achieved will be far less than the Maximum Theoretical Data Rate for the particular coding scheme used.

Because all transmitted pulses are the same in a single frequency scheme, the receiver is unable to assign the pulses of colliding transmissions to one or the other tags with the result that it will not decode some or all of those transmissions. These missed detections have the effect of reducing the actual amount of data received from what was sent and, in extreme cases, the loss of most or all data. Although the actual details of data rate achieved in such situations depend on the coding method used and, to some extent, the receiver's detection algorithm, the procedure below allows one to make estimates accurate enough to know what to expect in the field.

1. Define Tag Density as:

$$\text{Tag Density} = (\text{Resident Tags} \times \text{Average Burst Length}) / (\text{Transmission Interval})$$

2. Calculate the probability that a Tag m will not collide with a transmission from Tag n as:

$$P_{clear} = 1 - 2 \times (\text{Tag Density}) / (\text{Resident Tags})$$

3. For N Resident tags, the probability of each transmission getting through is defined by a Binomial Distribution for every one of N-1 tests succeeding with the probability of success for each test being P_{clear}. This is based on an assumption that the Transmission Interval is randomized about its nominal value, which is essential in this type of coding as, otherwise, two transmitters that collide may continue to do so repeatedly.

Table 6 shows results from the above calculation. These results and all other code performance results presented are statistical averages but analysis and simulation has shown that deviations from test to test are small. As well, due to the normalizing nature of Tag Density, data can be presented independently of Number of Resident Tags, Transmission Interval, and Burst Length with an error of less than 1%. Table 6 also includes effective Data Rate for various values of the critical Minimum Interval parameter.

From table 6, we can make two important observations.

1. Performance, in terms of the percent of transmissions actually detected at the receiver, will deteriorate for increasing Tag Density.

2. Because of the inherent inefficiency of one-way telemetry described above, the effective data rate is a fraction of the Maximum Theoretical Data Rate. For low values of Tag Density, this is because little data are being transmitted while, at higher values, more and more data are lost due to collisions.

The first observation above suggests that, in designing an experiment in which a number of Tags are expected to be present simultaneously at receivers, users should estimate worst case Tag Density anticipated for various Transmission Intervals. Then a Transmission Interval can be selected sufficiently long to decrease Tag Density to an acceptable level. Of course, lower values of Tag Density reduce the potential update rate from each tag, but this is preferable to getting little or no data at all, which would be the case if Tag Density is too high.

Table 6. Percentage of transmissions that will be detected and effective data rate as a function of tag density.

[16 bits per transmission, Timing Sensitivity = 10 milliseconds]

Tag density	Percent detected	Data rate (bits/second) and percentage of maximum theoretical data rate					
		Minimum interval (milliseconds)					
		300		150		20	
		Rate	Pct.	Rate	Pct.	Rate	Pct.
0.05	91	0.3	5	0.4	6	0.7	5
0.1	83	0.5	9	0.7	10	1.3	9
0.25	63	0.9	18	1.3	19	2.4	16
0.5	39	1.1	22	1.6	24	3.0	20
0.75	23	1.0	19	1.5	21	2.7	18
1.0	13	0.8	15	1.1	16	2.1	14
[1]1.25	8	0.5	11	0.8	11	1.4	10
1.5	4	0.3	7	0.5	7	0.9	6
2.0	1	0.1	2	0.2	2	0.3	2

[1]Some tags are detected even if Tag Density is greater than 1 as the randomness of the process will create some empty space.

Single Frequency Coding Summary

Single Frequency Coding is very effective when individual receivers are not required to simultaneously detect a large number of tagged fish in a short period of time. It also offers the advantage that relatively simple transmitter and receiver implementations are possible. The ability to use relatively simple receivers makes it possible to operate at very low power levels and, as a consequence, receivers can be relatively small and be deployed without servicing for a year and longer. This ability has led to the emergence of a number of large collaborative projects (e.g., AATAMS, no date; FACT, no date; POST, no date).

Although adoption of conservative coding schemes was necessary for the broad initiatives mentioned above, more aggressive coding (and, in particular, using a much shorter Minimum Interval) could be used in applications that are closed and where acoustic conditions are good (i.e., short Channel Clearing Time). However, Spread Spectrum approaches may be preferable to trying to push single frequency coding beyond its normal limits.

Lines and Arrays of Receivers

Passive tracking receivers are seldom deployed singly but rather as: (1) *Lines* (sometimes called Acoustic Curtains or Gates), whose purpose is to detect passage of tagged fish as they enter or leave a river, or pass a point as they move up or down a coast line (see POST, no date, for example); or (2) *Arrays* covering an area of interest to determine fish movements or residency within that area. In the following, we briefly discuss key considerations in designing Lines and Arrays.

Detection Efficiency of Lines

Because the primary purpose of a Line is to determine whether fish pass a certain point (e.g., in a migration pattern), the key design objective is to achieve a *Detection Efficiency* as close to 100% as possible (Pincock, 2009) where Detection Efficiency is defined as the percentage of tagged fish that will be detected assuming a uniform distribution of position and depth of passage and taking into account all anticipated noise and signal propagation conditions. Although it is possible to predict performance in some environments, variations in noise and propagation conditions in different locations and at different times in a given location mean that a program of range testing is usually the best way to establish that a line will achieve its objective. Pincock (2009) describes an approach to range testing based on a particular receiver (Vemco VR2), which can be readily adapted to other types of receivers as well. Two major points that need to be taken into account during such range testing are:

1. Ensuring that range testing covers the worst acoustic conditions that might be encountered, weather generated noise most often being the main variable. If this cannot be done, then range results need to be derated to take into account the more severe conditions under which the line has to operate.

2. Ensuring that range testing covers not just distance from the receiver but the range of depths at which fish are expected to pass (or all depths if this is not known).

Once a line is deployed, the use of *Sentinel Tags* (i.e., fixed transmitters placed, perhaps, at the midway point between adjacent receivers) can be very useful in verifying the effectiveness of the line because their continuous detection throughout the deployment can be evaluated.

In addition to passing through an area where a receiver can detect a transmission, the fish also has to spend enough time there to ensure detection. Determining whether this condition is met or not involves a calculation of the minimum time a passing fish would be in a reliable detection region[12] and the worst case interval between successive transmissions. For single transmitters passing through, the latter variable is just the Tag Delay. However, if multiple tags might be present, one has to take missed detections due to collisions into account. Pincock (2009) provides details of these calculations.

Positioning with Arrays

As defined here, an Array differs from a Line in that its purpose is not to monitor passage but rather to understand how fish move within the instrumented area. Positioning is often crude [e.g., fish presence or absence at a receiving site device (e.g., Dagorn, et al., 2007)] or may involve fine positioning (e.g., with precision of a few meters or sub-meters in some cases) within an array of receivers.

Presence or Absence at a Receiver

Clearly, this is a simple situation and the only caution we make is that, in analyzing data, one should take into account that the effective detection range at a receiver (i.e., the size of the region in which the fish is recorded as present or absent) will vary significantly (perhaps by a factor of 2 or more) with acoustic conditions. Weather generated noise is the most common, and generally most substantial, factor influencing detection range.

[12] i.e., Minimum path length through a region of 100% detection divided by maximum swimming speed.

Fine Positioning Systems

The basic principle of all fine positioning systems is the same: triangulation based on the time of arrival of a transmitter's signal at three or more receivers. Involving more than three receivers in the calculation can improve the accuracy of the system and, if they are spaced as a three dimensional rather than a planar array, three dimensional positioning is feasible. An alternative to three dimensional positioning is to determine the third dimension through the use of transmitters with depth sensors. In fact, because acoustic signals often curve on the vertical axis due to temperature gradients, the use of depth sensing transmitters is preferable in many cases.

It is not difficult to measure time of arrival with sufficient precision; triangulation algorithms are well known and seldom limit the accuracy with which position can be estimated. Therefore, the two most significant potential sources of error are:

1. Level of synchronization between the clocks of the receivers; and
2. Accuracy to which one knows the actual position of the receivers.

For example, there is little point in trying to calculate position to sub meter accuracy if the time of day as seen by the various receivers differs by milliseconds[13] or if the position of the receivers is only known to an accuracy of a few meters.

Synchronization of Receiver Clocks.—This issue is typically resolved by having detections transmitted to a central site with either a wired (e.g., HTI, no date) or wireless (e.g., Vemco, no date) connection so that all detections are referred to the same time of day.

Receiver Positioning. —Unlike time synchronization, which is resolved through the design of the equipment, this issue often needs to be resolved in the field. The ideal solution is to "survey in" each receiver (i.e., accurately determine its position by some means). This is not always possible, in which case the researcher needs to take into account imprecision in receiver locations in interpreting data.

Positioning with Passive Tracking Arrays

The fine positioning systems described above can be quite elaborate and the requirement for wired or real time wireless connections to a base station can impose significant deployment issues, including limiting the extent of the area that can be reasonably covered, usually less than 1 kilometer in any dimension. As a result, there has recently been increasing interest in adding positioning capability to detections from arrays of passive tracking receivers. Such receivers can certainly log detection times to the required resolution but, because detections will be logged over a period of weeks, months, or longer, the clocks of the various receivers will drift out of synchronization[14]. As a consequence, detections will be of no use for positioning unless processing of the data includes a method for relating them to a single absolute time. This can be accomplished by placing Sentinel Tags in fixed positions. With knowledge of these positions, the position of the receivers, and the detection times as seen by each receiver, it is possible to correct for time drift within each receiver and, hence, position the tagged fish.

It is unrealistic to expect that such an approach will rival 1 meter or better accuracy often obtained from a system communicating each detection in real time to a base station. But accuracies on the order of 10 meters or better are achievable if the system is configured properly (D. King, personal commun., Nov. 20, 2008). This is sufficient for many applications and the approach can be very useful, especially given its flexibility and potential for expansion of the array over an arbitrarily sized area.

Future Directions

Advances in relevant technologies, particularly in the electronics area, will impact the capability of acoustic telemetry systems that can be offered. At the same time, there are major limitations on what is possible imposed by the characteristics of the underwater communications channel. In this section, we will focus on the three areas of most importance to studying movements of small fish in rivers and the ocean, namely transmitter size, data bandwidth, and fine positioning system.

[13]One millisecond being the length of time for underwater sound to travel 1.5 meters.

[14]With the crystals available today and suitable for use in low power autonomous receivers, this drift is on the order of several seconds/month so that maintaining synchronization to no worse than a few milliseconds for the duration of a deployment would require an improvement of a thousand fold or more in the crystal.

Transmitter Size

Transmitter Components and Physical Arrangement

Figures 3 and 4 show representative physical arrangements of components used for miniature transmitters and form a useful starting point for the discussion. For comparison purposes, the same components are shown in both figures 3 and 4 except that, for reasons explained below, a smaller acoustic transducer is shown in figure 4.

Figure 3(a) shows the unencapsulated components (battery cells, electronics board, and acoustic transducer from left to right), and figure 3(b) shows this arrangement encapsulated in epoxy inside a cylindrical tube. This traditional packaging has the advantage of being rugged and usable to significant depths but the disadvantage of significant additional volume and weight due to the amount of epoxy used. Volume and weight reductions are possible through elimination of the cylindrical tube and protecting the components with a thin conformal coating (For example, using parylene). However, a consequence of the smaller amount of protection for the components is the potential for failure at large depths, not normally an issue in river environments.

Figure 3(c) shows a prototype transmitter (Vemco V5) that illustrates the potential for size reduction using a simple rearrangement of the components in figure 3(a) and conformal coating. Figure 3(c) also demonstrates the limited potential for further size reduction without reducing transducer size from the roughly 5 mm diameter cylinder shown in figure 3.

Figure 4 shows the potential for further size reduction[15] with a smaller acoustic transducer and a different arrangement of components. Of course, as discussed above, the use of a small transducer implies higher transmission frequency and/or lower electric to acoustic efficiency and, hence, reduced range.

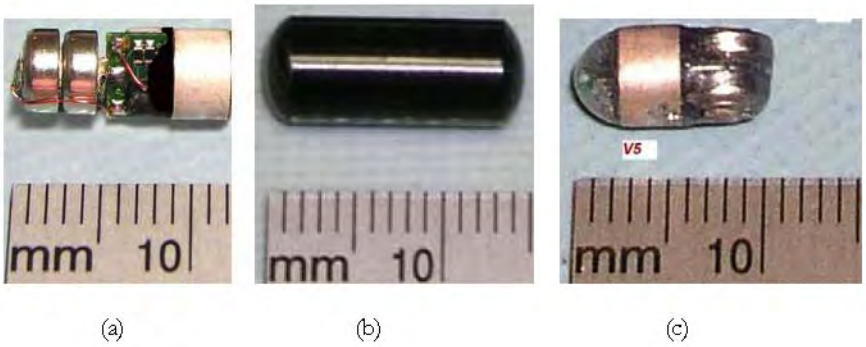

Figure 3. A representative commercial transmitter (Vemco V6) before and after encapsulation.

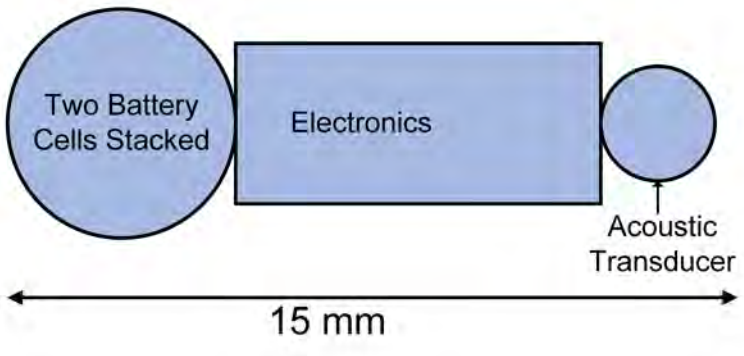

Figure 4. Alternative flat arrangement of components.

[15]But not necessarily any reduction in weight in water since the additional potting substance used has a specific gravity of approximately unity.

Potential for and Limitations to Size Reduction

Batteries.—For several decades, Silver Oxide batteries have been the only choice for miniature acoustic transmitters because no other formulation is available in a suitable size while being capable of delivering sufficient peak current to drive the acoustic transducer during transmissions. Figures 3 and 4 are based on 4.8 mm diameter cells, the smallest currently available. This leads to a requirement for two cells to provide a nominal supply of 3 volts[16], which is preferred, first, because the semiconductors commonly used may require it and, second, to provide sufficient power capability during transmissions. Semiconductors able to operate from voltages on the order of 1 volt are fairly available; so elimination of one of the cells is of course feasible. However, the reduction in transmission power arising from the use of a single cell can lead to inadequate range capability for many applications.

Of course, breakthroughs in battery technology could change the above situation but this appears unlikely for two reasons. First, the situation has changed little in the last few decades and, second, the requirements for this application are somewhat unique and, therefore, research in battery technologies is largely focused elsewhere.

Acoustic Transducer.—Like batteries, the technology of these components has not changed significantly for decades, therefore the issue is to optimize what is available.

As can be seen from figures 3 and 4, the acoustic transducer is an important contributor to the overall size. The transducer shown in figure 3 is approximately 6 mm in diameter while the one in figure 4 is less than one-half that, significantly reducing size. However, as discussed previously, the penalty in terms of range achievable can be severe (e.g., taking transducer size reduction size too far could very quickly lead to range capabilities less than 100 meters in realistic fresh water situations).

Electronics Board.—The boards shown in figures 3 and 4 have already been reduced to close to the minimum size as they contain little more than a single integrated circuit (in the form of a bare chip) and tuning elements. Technological advances or a higher level of customization could lead to some reduction in length, width being less important as it is already not a limiting factor in transmitter size. Therefore, size reduction of this component is not a major issue, at least for the foreseeable future.

Data Bandwidth

Data bandwidth is limited by the characteristics of the medium coupled with the nature of the application, which dictates the level of aggressiveness that can be used in coding data into transmissions with very conservative coding being essential in all but special situations. We have explored the limits for Single Frequency Coding and improvement beyond this will require the use of Spread Spectrum techniques. As the technical impediments to the use of Spread Spectrum methods are starting to fall because of the emergence of integrated circuits, which provide sufficient processing at electrical power levels suitable for biotelemetry transmitters and associated receivers, we anticipate their use will become more common with associated improvement in data bandwidth. At the same time, the characteristics of the medium and application limit what might be possible and even two orders of magnitude improvement for general purpose applications seems unlikely.

Improve Performance with Two-Way Communication?

In some other applications (e.g., acoustic modems), much higher data rates can be achieved by adapting transmissions to suit the current acoustic conditions (including the presence of other transmitters) through a two-way dialog between transmitter and receiver. Although the size impact of including a receiver in a small transmitter is not insignificant, the real issue is the current requirement. Even assuming a receiver that consumes only 100 microamperes (very ambitious and, if achievable at all, implying powerful interrogations from the receiver), the battery shown in figure 3 would be exhausted in about 4 days. Of course, with larger transmitters, the life would be longer and could be extended by having the receiver on only a portion of the time. Clearly, however, this is far from the transmitter life most studies require (months to even years).

Advances in electronic technology will improve the situation but probably not dramatically because receiver power consumption is dominated by that of the required analog preamplifier and, unlike digital circuitry, technology advances that would reduce power requirements of analog amplifiers are very gradual.

Fine Positioning

From the discussion on fine positioning above, one can see that positioning accuracy is driven by the nature and location of the deployment and the accuracy with which one knows the position of the receivers and sentinel tags. Technological advances cannot overcome these physical limitations.

However, one could well see convenience features in various systems; one example might be a system using surface buoys, clock synchronization using GPS, and communication of detections to be processed via satellite.

[16]Although Lithium formulations produce 3 volts from a single cell, they are not available in the required small size and, even if they were, their peak current would be too low to produce the required transmission power.

Conclusions

As mentioned in the introduction, the purpose of this section is to summarize the biological significance of the technological capabilities and constraints described above and make some recommendations on issues biologists need to consider when designing experiments.

Transmission Frequency.—It is well known that in the ocean transmitters operating at higher acoustic frequencies suffer considerably more range reduction than lower frequency transmitters because of absorption effects. Because absorption in fresh water is lower, it is often assumed that there is little penalty for using high frequency transmitters in rivers and lakes; however, as can be seen from table 1, this is not the case. Therefore, in evaluating the viability of a high frequency transmitter for a particular application, one should test feasibility with calculations similar to the above using specified transmitter and receiver characteristics and, if results are satisfactory, confirm performance with in situ range testing.

Performance of Coding Schemes.—The discussion below focuses on Single Frequency Coding. Similar calculations are possible for Spread Spectrum schemes but require some knowledge of how the coding is accomplished.

- ***Assessing Data Capability.***—As the data demands of applications are growing (more ID Codes, more Sensor Data, more Resident Tags at receivers, etc.), solutions provided by vendors are becoming more complex and it is not always easy or even possible for the user to understand their appropriateness for a particular application requirement. In this paper we have presented a unified way of looking at any Single Frequency Coding system and assessing its ability to meet a given data requirement. In particular, with knowledge of the Transmission Interval and the Average Burst Length of each transmission[13] one can obtain results such as:

    1. Limits on how many tags can be resident at a receiver and still guarantee a high percentage they are all detected in a reasonable length of time.

    2. Effective data rate, and hence the rate at which each tag's presence and/or sensor data would be updated.

  The sample calculations presented are based on 16 bits per transmission, but can easily be adjusted proportionately for other payloads.

- ***Assessing Robustness.***—Ideally, the vendor should provide enough information for the user to assess whether coding parameters are conservative enough for the conditions of a particular study. If this is not the case, table 5 and associated text provide the basis to estimate this from knowledge of the Average Burst length and Number of Bits per transmission.

- ***False Positives.***—Regardless of the approach to coding and error detection, false positives will occur and, therefore, it is very important for the designers of any experiment to have an understanding of the statistical probability of occurrence and take this into account during analysis.

Line Detection Efficiency.—The objective in designing a receiver Line (or Acoustic Curtain) should be to ensure that close to 100% of the tagged fish passing will be successfully detected under all anticipated conditions. While it is tempting to relax this requirement, any significant deviation from 100% can lead to large errors in estimates of actual number of fish passing (Pincock, 2009).

Positioning with Passive Tracking Systems.—We expect to see growing use of this technique. The main challenge for users being their ability to accurately measure the position of fixed receivers and sentinel tags (if used).

Technological Advances.—The major anticipated advances relevant to studies involving small fish[16] are reductions in transmitter size and increased use of spread spectrum coding to achieve higher data rates. We have shown that transmitter miniaturization to about 5 mm (width or diameter) by 10 mm long is feasible with today's technology. There is the possibility of a further reduction to about 5 mm by 8 mm through the use of a single battery cell instead of two but such a transmitter would only be useful for short ranges (100 meters or less).

Acknowledgments

The technical overview presented here is derived from the work of many developers over the past decade. You know who you are.

Gilles LaCroix and the Pacific Ocean Shelf Tracking Project (POST) provided motivation for development of the technology and carried out extensive field work to prove its effectiveness for monitoring long term movements of salmon smolt.

The authors offer this as a contribution to the Census of Marine Life.

[16]Initiatives like integrated tags with data storage, acoustic upload of data, multiple sensors, etc., will not be applicable to small fish for the foreseeable future.

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Chapter 7.—Guidelines to Indirectly Measure and Enhance Detection Efficiency of Stationary PIT Tag Interrogation Systems in Streams

Patrick J. Connolly[1]

Abstract

With increasing use of passive integrated transponder (PIT) tags and reliance on stationary PIT tag interrogation systems to monitor fish populations, guidelines are offered to inform users how best to use limited funding and human resources to create functional systems that maximize a desired level of detection and precision. The estimators of detection efficiency and their variability as described by Connolly et al. (2008) are explored over a span of likely performance metrics. These estimators were developed to estimate detection efficiency without relying on a known number of fish passing the system. I present graphical displays of the results derived from these estimators to show the potential efficiency and precision to be gained by adding an array or by increasing the number of PIT-tagged fish expected to move past an interrogation system.

Introduction

Use of passive integrated transponder (PIT) tags in fish monitoring and research has rapidly increased over the last decade. These tags have become a primary tool for monitoring juvenile salmonid movement and for estimating survival past large hydroelectric dams in the Columbia River basin (Achord et al., 1996; Skalski et al., 1998; Muir et al., 2001a, 2001b; Paulsen and Fisher, 2001). Much valuable information has been gained by adapting similar technology in streams to detect movement or presence of PIT-tagged fish (Armstrong et al., 1996; Zydlewski et al., 2001; Connolly et al., 2005). Although detection of PIT tags by an interrogation system depends on multiple levels of technology associated with transceivers and antennas, along with their wiring and data management linkages, this paper primarily focuses on the part that has the greatest connection with the stream and its fish: the antenna and the arrays that antennas form.

Under normal operating conditions, a PIT tag passing through the rectangular opening of a properly designed and sized antenna should have very high potential to be detected, but factors such as tag orientation (Zydlewski et al., 2006) and presence of another tag (Greenberg and Giller, 2000) can decrease this potential. In many cases, the antenna or an array of multiple antennas cannot be sized for expectations of reading all PIT tags passing, such as when the stream width is wider or the water column is deeper than the maximum-sized antenna or arrays that can be supported by a transceiver unit. However, if the entire channel can be spanned, pass-through antennas may be appropriate for maximizing detection efficiency. As Connolly et al. (2008) noted, this orientation is likely to provide the best probability of detecting a PIT-tagged fish, and it is very suitable for: (1) stable-flow streams; (2) streams with little or no large debris; and (3) studies limited to investigating fish movement during low-flow periods. It also is of use if deployed in a manner that allows the antenna to break away under a predetermined load and to be readily repositioned. The pass-through orientation is particularly suited for taking advantage of existing structures such as bridge crossings, culverts, or engineered study streams.

In other situations, it may be best to anchor antennas so that they are parallel with the stream substrate in a pass-by orientation. As reported by Connolly et al. (2008), this orientation can perform exceptionally well during low-flow conditions, but the column of water available to fish during high water may be more likely to exceed the read range of the antenna. The efficiency of an antenna or array under these conditions may be particularly reliant on the behavior of the fish (e.g., bottom vs. surface-oriented movers). Pass-by and hybrid antennas described in Connolly et al. (2008) have been proven to hold during flow and debris conditions that would have disabled most pass-through antennas. Table 1 lists some of the potentially complex combinations of biological and physical aspects that should help guide where, when, and how antennas are installed.

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Table 1. Some primary factors to consider about antenna placement and array configuration.

Biological factors

• Behavior of fish
  • Extent of lateral movement zone
  • Extent of vertical movement zone
  • Seasonality
• Density of PIT-tagged fish passing antennas (i.e., tag detection can be inhibited if two tags are in the field at the same time)
• Potential for fish to stage near the antennas (i.e., a stationary tag could inhibit reading of a passing tag)

Physical factors
• Amount of interference from ambient electromagnetic fields (i.e., "noise") • Ability to provide and maintain power to the system (e.g., plug-in, batteries, solar assisted) • Ability to anchor antennas given expected water velocities, substrate movement, and debris loads • Percent coverage of stream by arrays: laterally and vertically, based on read distance of tag (function of antenna construction and the type and size of PIT tags used)

Where possible, the use of a known population of PIT-tagged fish, such as salmonid smolts with a strong one-way migratory tendency, would likely prove to be the best method for determining detection efficiency. If direction of fish movement is known, the derivation of detection efficiency is rather simple, and variability can be assessed with replication under similar flow, stream temperature, and other conditions influencing fish movement behavior. However, use of a known tagged fish population passing the interrogation site to assess detection efficiency is not always feasible because of cost and permitting restrictions on fish handling and releasing for the species or life stage of interest.

Connolly et al. (2008) used an indirect method for determining estimates of detection efficiency because they did not know the number of PIT-tagged fish that passed the interrogation system. While their work was based on results of tagging fish with full-duplex PIT tags, the results should be applicable to a wide range of biological and even inanimate objects (e.g., rocks, wood), and to use of half-duplex PIT tags and detection equipment. The current work uses estimators described by Connolly et al. (2008) to address the objective of providing useful guidelines for configuring the structure of antenna arrays to maximize learning about fish movement and survival, while considering cost and effort allocations.

Methods

Following Connolly et al. (2008), I used the three-array detection probability model in the User Specified Estimation Routine (USER) program (Lady et al., 2003) to calculate the efficiency of detection, and the Delta method (Seber, 1982) to determine standard error and variance of this estimate. The USER program can be downloaded from the website http://www.cbr.washington.edu/paramest/user/ (accessed October 20, 2009), and a manual for the program is available in Skalski (2003). Formulas for the estimators are described in Connolly et al. (2008, appendixes 1 and 2).

A span of likely performance metrics for detection efficiency was used to generate continuous lines or curves for graphical display. Graphs were prepared to address practical questions about what configuration to install or what effort to expend on PIT tagging, such as: "If a second array was added, how much would detection efficiency be increased?" or "If the number of PIT-tagged fish was increased 10-fold, how much improvement in precision of the detection efficiency estimate would be gained?"

Results

To help readers get a sense of how detection efficiencies and population estimates can be derived from an indirect methodology based on pattern of detection, I offer a simplified example in table 2. The theoretical discussion provided by Zydlewski et al. (2006) and the analysis tools suggested by Connolly et al. (2008) will aid the reader to deal with empirical data and with the much more complex calculations associated with deriving estimates of detection efficiency and its variability when three arrays are installed.

The overall estimate of detection efficiency for an interrogation system is much influenced by the detection efficiency of the individual arrays in the system, and the precision of the estimate is much influenced by the number of PIT tags passing the system (fig. 1). The overall detection efficiency of a system with two or more arrays generally is greater than any of its individual arrays. It takes at least two arrays to derive an estimate of efficiency when relying on an indirect method of estimation.

Adding a third array can further increase an interrogation system's overall detection efficiency (fig. 2). This addition of a third array also serves to enhance precision of the estimate of detection efficiency.

Table 2. A practical example of how detection efficiency is derived for a two-array interrogation system based on the differential pattern of PIT tag detection of the arrays.

Example setting: A two array PIT tag interrogation system is in place, and a number of PIT tags from known downstream migrating fish have been detected
Data:
• 700 PIT tags have been detected on the upstream-most array (A1). • 500 PIT tags have been detected on the downstream-most array (A2), 350 of which had been detected on A1 and 150 of which were only detected on A2.
Question: What was the detection efficiency of the system?
• From the data above, we can conclude that A2 missed 350 that were read on A1, which equates to a 50% detection efficiency for A2. • If the 500 tags read by A2 represents 50% of all tags available, then a total of 1,000 would have had to pass both A2 and A1. • Because A1 detected 700 of the 1,000 tags that passed, then A1 must have had a 70% detection efficiency. • Adding all unique tags read by A1 (=700) and A2 (=150) equates to 850, which means that the entire system had an 85% detection efficiency.
Question: How many PIT-tagged fish passed the system?
• 1,000 (as derived above).

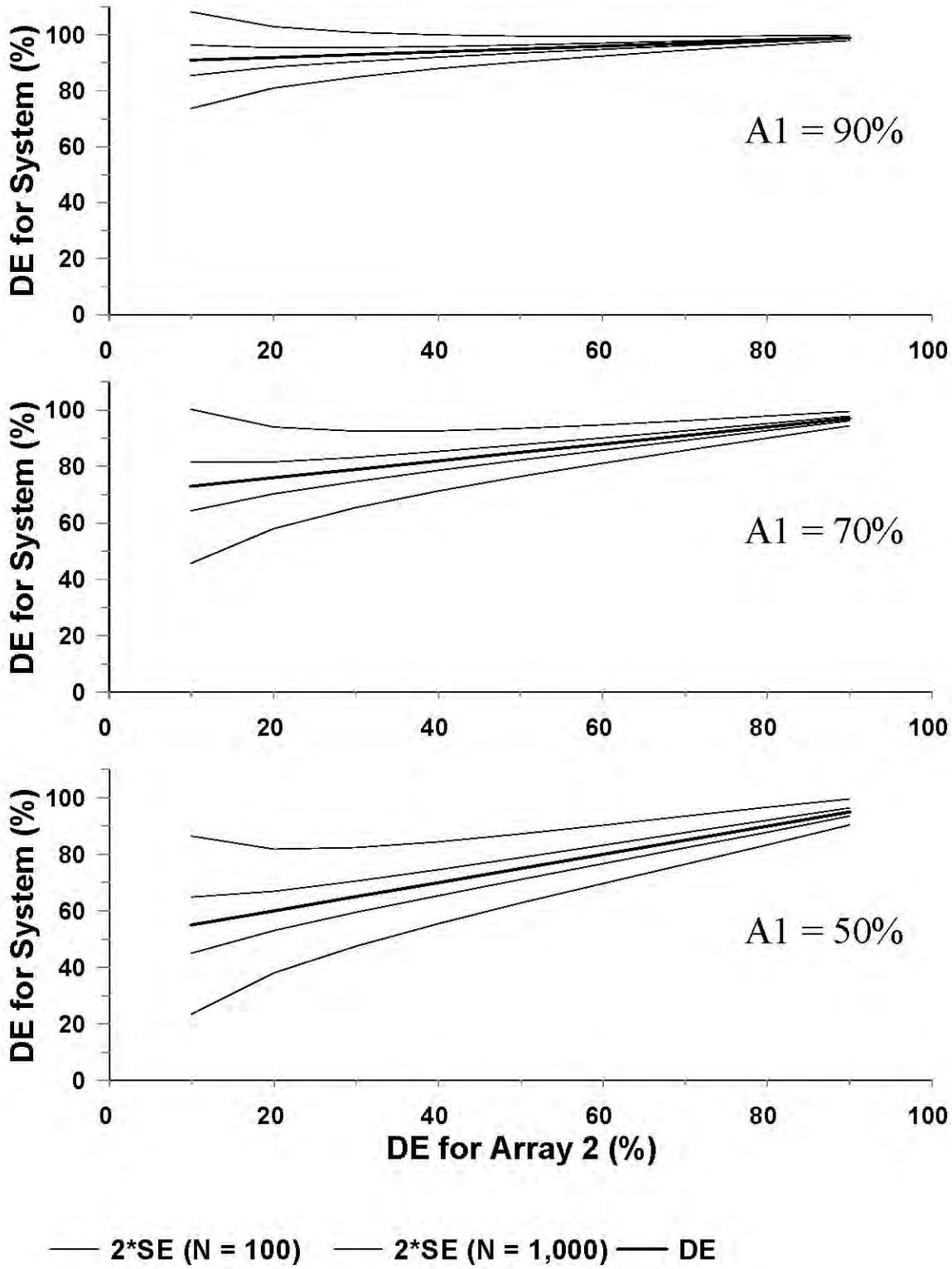

Figure 1. Effect on detection efficiency (DE) of adding a second array when the DE of the first array (A1) is 90%, 70%, or 50%. The sets of lines above and below the central line (estimate) represent variance of the estimate (± 2*SE) when the estimated number of PIT tags to pass the interrogation system is either 1,000 (inner set of lines) or 100 (outer set of lines).

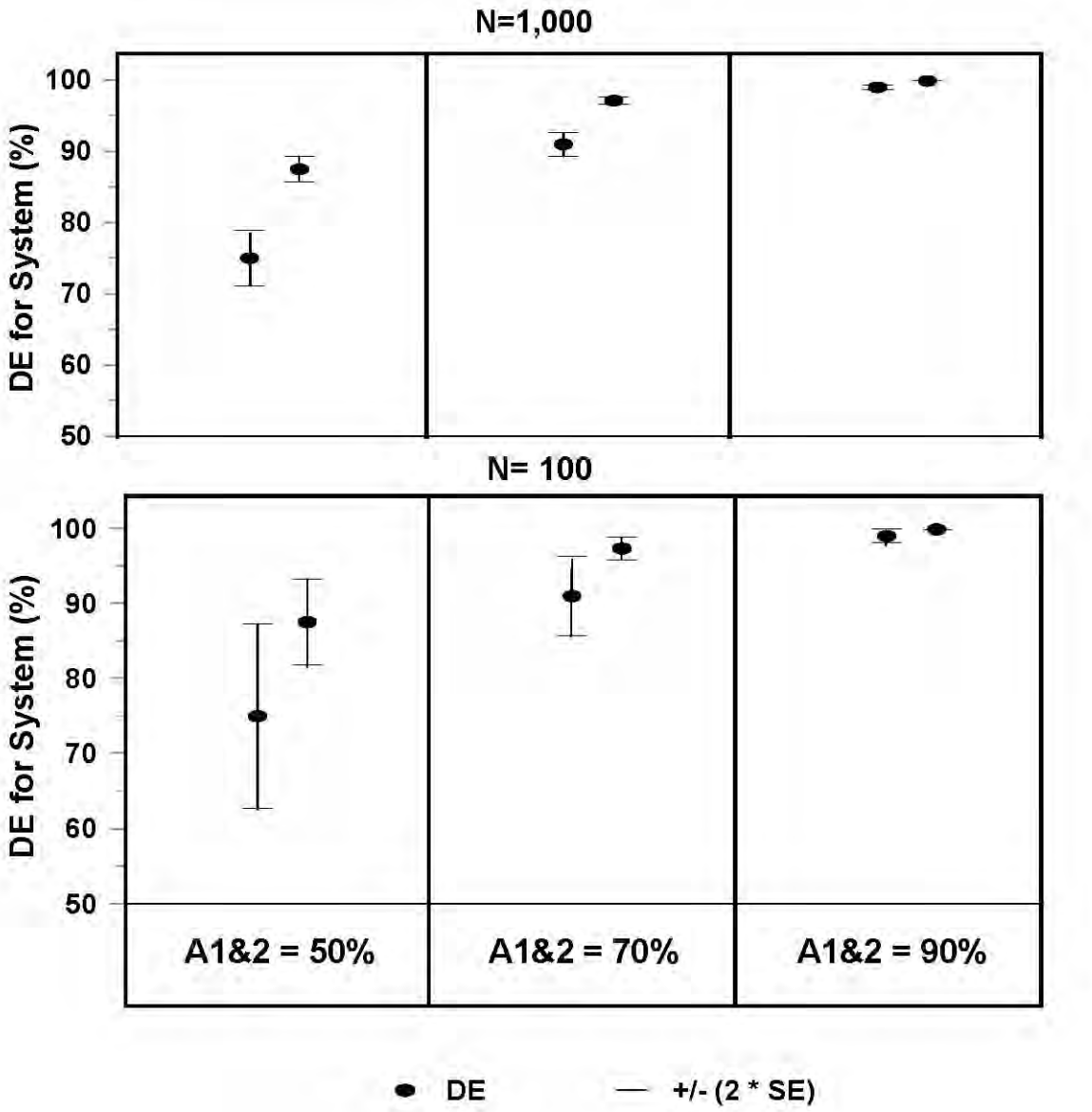

Figure 2. Effect on detection efficiency (DE) of adding a third array when the DEs of the individual first and second arrays (A1 and A2) are 50%, 70%, or 90%, and when estimated number of PIT tags to pass the interrogation system is either 1,000 or 100. The first and lower estimate in each panel is the DE for the system with two arrays, while the second and higher estimate is the DE when a third array of the same individual DE is added (e.g., the top left panel depicts the system's DE when all arrays have an individual DE of 50%, and when the number of PIT tags estimated to pass is 1,000).

Discussion

A wide range of possible detection efficiencies from potential combinations of arrays has been graphically presented, which should provide guidelines for practical situations that field personnel and managers are likely to face. Even with intensive efforts to direct all or most fish within the read-range of instream antennas, tag detection efficiency is likely to be less than 100% for a number of reasons. Electrical properties of a PIT tag interrogation system can change with changes in water level, which may partially or completely expose an antenna to air, and with changes in water temperature, conductivity, and air temperature (Connolly et al., 2008). These problems can be partially or completely solved by using transceivers that automatically change their settings (self tune) to changing environmental conditions, thus improving performance. Ambient electromagnetic fields (EMF) of similar frequency, which can be generated by nearby power lines, electric fences, pumps, or electrical devices in homes or businesses (Zydlewski et al., 2006; Horton et al., 2007), can compromise a system's ability and consistency to detect tags. Multiple fish swimming through or holding in the detection field at the same time can compromise the ability to detect a tag (Greenberg and Giller, 2000). Because of these factors, investigators should strive to determine detection efficiencies for periods of time with similar conditions (Horton et al., 2007).

Study goals, target species, and budget will dictate need for specific designs of interrogation systems. The extra cost associated with interrogation systems that can help differentiate between upstream and downstream movement and that provide a high level of detection efficiency may not always be warranted. Although traps and weirs can be used to obtain similar life-history information, these tools are expensive to operate because of staffing needs, and can be difficult to operate year round due to high flow and debris loads. Antennas can be constructed to be placed in a variety of configurations and can be highly adaptable to the challenges of stream environments. By using the guidelines offered in this paper, it is hoped that users of PIT tag technology can better maximize their learning about fish movement and survival.

Acknowledgments

I wish to thank Earl Prentice (Prentice and Associates) and USGS's Ian Jezorek and Kyle Martens for their thoughts and discussion over the past few years regarding use and utility of PIT tag interrogation systems. I thank Russell Perry of the USGS for helping develop the estimates of variance for detection efficiency.

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Chapter 8.—Advances in Coded Wire Tag Technology: Meeting Changing Fish Management Objectives

Geraldine Vander Haegen[1] and Lee Blankenship

Abstract

Technological developments can contribute to significant advances in knowledge and management of fish resources. In the last 20 years, there have been remarkable advances in electronic tags that have enabled remote data collection from tagged animals. However, the long-standing or traditional tags (including passive integrated transponder (PIT), Coded Wire, anchor, and Visible Implant tags) remain critical for fish management and research and far outnumber newer complex electronic tags. Coded Wire Tags (CWTs) are lengths of magnetized stainless steel wire 0.25 mm in diameter and typically 1.1 mm long. The management of Pacific salmon by the United States and Canada relies heavily on the use of CWTs (Johnson, 1990) and programs around the world have benefited from their development. In spite of their relatively long history, the use of CWTs continues to expand. Along with the tag's unique characteristics (e.g., very small size, huge code capacity, and lack of effect on the host), this increase in use can be attributed partly to continual improvements in application and detection technology. These include a change from binary to decimal coding, the development of electronic detection for field use, and the development of AutoFish System™ for tag injection and adipose fin clipping of juvenile salmonids. Electronic tag detection enables sorting of fish with and without CWTs in the absence of an external identifying mark. AutoFish can be used to process up to 60,000 fish per day with just one operator and it requires no human handling or anesthetic. Because of these technological advances in the CWT system, managers in the Pacific Northwest of the U.S. and Canada were able to implement a mass marking program that identifies hatchery salmonids by excision of the adipose fin while maintaining the critical stock assessment program. In the process, a valuable tool was gained for responsibly managing the extensive hatchery salmonid populations in this region.

Introduction

The first International Symposium and Educational Workshop on Fish Marking Techniques was held in 1988 and resulted in the publication of a book that summarized techniques considered state-of-the-art in fish tagging (Parker et al., 1990). Since that meeting, rapidly developing technology and micro-electronics have provided new fish tags with remote tracking and monitoring capabilities. At the same time, manufacturers of already established tags, including Coded Wire, passive integrated transponder (PIT), Visible Implant, and external anchor tags, also have applied new technologies to increase the performance and utility of these products. Traditional tags remain crucial to fisheries management and research and the number applied annually far exceeds the number of all other types of tags because they provide the ability to identify numerous stocks on a large scale, are relatively inexpensive and easy to apply, and have a huge data capacity.

The Coded Wire Tag (CWT) (fig. 1) is a well-established tagging technology. Invented in the 1960s, the CWT is a small piece of stainless steel wire 0.25 mm in diameter and 1.1 mm in length (although other lengths are used for certain applications) with a code etched on the surface. Coded Wire Tags are non-transmitting and must be extracted and viewed under a low-powered microscope to retrieve the code, although their presence can be externally detected with electronic detectors. When used appropriately, CWTs typically have little impact on tagged fish (Blankenship and Thompson, 2003; Davis et al., 2004b; Brennan et al., 2005; Vander Haegen et al., 2005). Because of their small size, they can be used in species or life stages that are too small for other tagging methods.

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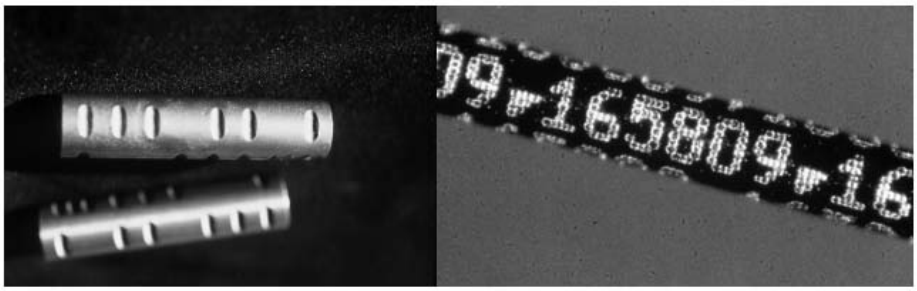

Figure 1. Coded Wire Tags were originally encoded with colors. This was soon replaced with a binary code etched onto the surface of the tag (left). Later, as laser technology developed, the numeric code was directly printed on the wire (right). This is known as a Decimal Coded Wire Tag. The tag size did not change, the actual size of a standard Coded Wire Tag remains 1.1 mm long and 0.25 mm in diameter.

Since their invention, CWTs have become the most extensively used tags for fisheries management. The management of Pacific salmon by the United States and Canada relies on the use of CWTs, releasing about 50 million tagged salmonids annually (Nandor et al., 2010) to collect information about such things as stock distribution, survival, and catch. In spite of having been invented nearly 45 years ago, no other method has been developed that can provide the code capacity, ease of use, cost effectiveness, and unambiguous data that are the signature characteristics of the CWT. Around the world, the use of CWTs continues to expand as researchers and managers take advantage of these features and the continual improvements to the CWT system initially targeted at the Pacific salmonid program. The improvements have been in three areas: a change from binary to decimal coding, the development of electronic tag detection for field use, and the development of the AutoFish System™ for tag injection and adipose fin clipping.

Development of New Coding Methods

The original CWTs were coded with bands of color adhered along the length of the wire. The strips of color sometimes peeled off, the colors were difficult to distinguish from each other when the tags were recovered, and the colors were often interpreted differently by various readers. The coding was soon changed to a binary code that was engraved on the wire using lasers (Jefferts et al. 1963). This improvement provided much more stability to the code and vastly increased the number of codes available. As laser technology advanced, the coding was changed from the binary code to a decimal code in which the numeric code is printed clearly on the wire (fig. 1). This newest format is easier and quicker to read than the binary code, and reduces reading errors. This change further increased the number of codes available so that it is virtually infinite. Northwest Marine Technology ensures that each code is only printed once, a critical requirement for coherent tagging programs because it prevents ambiguous tag recovery data when tagged populations intermingle.

Development of AutoFish System™

Along with technological innovation, fisheries management needs drive advances in tagging technology. In the Pacific Northwest of the United States, the States of Washington, Oregon, and Idaho, Treaty Tribes in those States, and the United States government implemented a fish management initiative, called mass marking, which requires all hatchery Chinook salmon (*Oncorhynchus tschawytcha*), coho salmon (*O. kisutch*) and steelhead (*O. mykiss*) be identified by removal of the adipose fin. Fisheries and Oceans Canada also is beginning to implement such a program. Mass marking is used to distinguish hatchery fish from wild fish, which allows the extensive hatchery program in this region to be genetically managed in conjunction with wild fish (Mobrand et al., 2005).

Hatcheries in the Pacific Northwest rear and release about 40 million coho salmon and 150 million Chinook salmon annually that are required to be marked under the mass marking initiative. Further complicating the process, increased requirements for injecting CWTs arose as part of the implementation of mass marking. Because there is only a short time between when the fish are large enough to mark and tag and when they need to be released, most of these Chinook and coho salmon must be processed within a 90-day window. Although it is plausible that the yearling coho salmon could all have been marked and tagged manually with scissors and Mark IV Automated Tag Injectors, marking and tagging the huge volume of Chinook salmon in the allotted time could not be done manually and required a new approach.

Northwest Marine Technology, the Washington Department of Fish and Wildlife, the Bonneville Power Administration, and the U.S. Fish and Wildlife Service therefore teamed up to develop an automated machine that could be used at hatcheries to help reach the mass marking goals. The development took about 10 years and the result is called the AutoFish System™. It can do any combination of sorting by size, excising the adipose fin, and injecting CWTs into the snouts of salmonids at more than 7,500 fish an hour. There is no human handling or anesthetic used in this system, and it can be operated by one trained operator and an assistant. AutoFish is faster and achieves superior clip and tag quality than manual marking and tagging (Hand et al., 2007) because of the consistent handling and sorting methods and the rigorous quality control checks performed on every fish. There are currently 26 AutoFish Systems in use and more than 200 million fish have been processed with them. AutoFish can accommodate fish from 57 to 147 mm total length.

AutoFish is contained within a 44-ft long trailer (fig. 2) that can be easily moved between fish rearing facilities. At the beginning of each tagging project, the trailer is positioned near the ponds holding the fish to be tagged. The trailer is leveled and connected to a power and water supply. Fresh water is continually delivered to the trough and sorter and to each of the marking and tagging lines. Water is not recirculated in the trailer, and once it has been used, it is returned back to the hatchery pond with the processed fish. The sorter and tagging lines are calibrated for the size of the fish on hand. The operator will measure about 1,000 fish with the sorter to designate the size ranges and install the corresponding components in the marking and tagging lines. This set up takes approximately 4 to 8 hours and requires only two staff.

Each AutoFish System has the computer controls at the front of the trailer, with the sorter and six marking and tagging lines in the main work area (figs. 2 and 3). Most trailers also have a work table at the rear where additional personnel can CWT and adipose clip fish manually. This can increase efficiency under certain circumstances such as where there is a wide length distribution in the fish or where some portion of the fish being processed will be adipose clipped only.

The AutoFish System requires precise fish measurement. To correctly place a CWT in the snout and accurately excise the adipose fin, the size of the fish must be matched to the head mold on the CWT injector and the adipose fin clipping mechanism. Each head mold and clipping mechanism can accept fish within a particular size range, so the fish must be sorted to those categories before they arrive at the tagging lines.

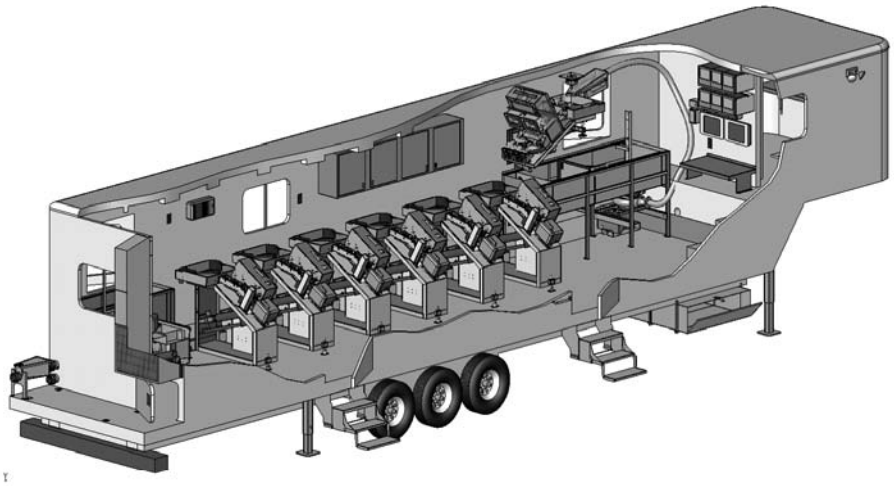

Figure 2. AutoFish is completely contained within a mobile trailer that can be moved between tagging sites. The main components of AutoFish are the sorter and the marking and tagging lines. The front of the trailer includes some office space and houses the computer controls. The back of the trailer is outfitted with a small work area for manual clipping and tagging.

Figure 3. The main working components of AutoFish are the sorter (left, in background) and the marking and tagging lines (foreground).

The sorter has four components (fig. 4)—the holding trough, the internal fish delivery pump, the sorter Volitional Entry Device (VE), and the measuring and diverting device. A fish pump is used to load fish into the aluminum holding trough through a window in the trailer. The internal fish delivery pump lifts the fish up to the sorter VE. Some water is removed so that the VE does not overflow, but the fish are never completely dewatered.

AutoFish relies on VEs to move the fish to the sorter and marking and tagging lines (fig. 5). The VE is a shallow, bright environment with upwelling water that takes advantage of the fish's natural instinct to seek a darker, more protected location, in this case, the entry to the sorter. After leaving the VE, the fish go through the measuring and diverting device. This component uses digital imaging to measure the length of each passing fish to within 1 mm accuracy. Based on their length, individual fish are diverted to the appropriate marking and tagging line. The sorter can process about 10,000 fish per hour.

AutoFish is controlled and monitored by computers. Monitors display images from cameras focused on the sorter VE. This information is used to automatically maintain a constant fish density by continually calculating the surface area covered by fish and activating the fish pump to add more fish as needed. Monitors also display images from the sorter cameras as they calculate fish length. This information is collected and summarized and can provide hatchery managers with details about their fish such as length distributions, number of fish processed, and the numbers of fish loaded into each pond after processing. The constant automated tracking also helps the AutoFish operator monitor and adjust the system performance.

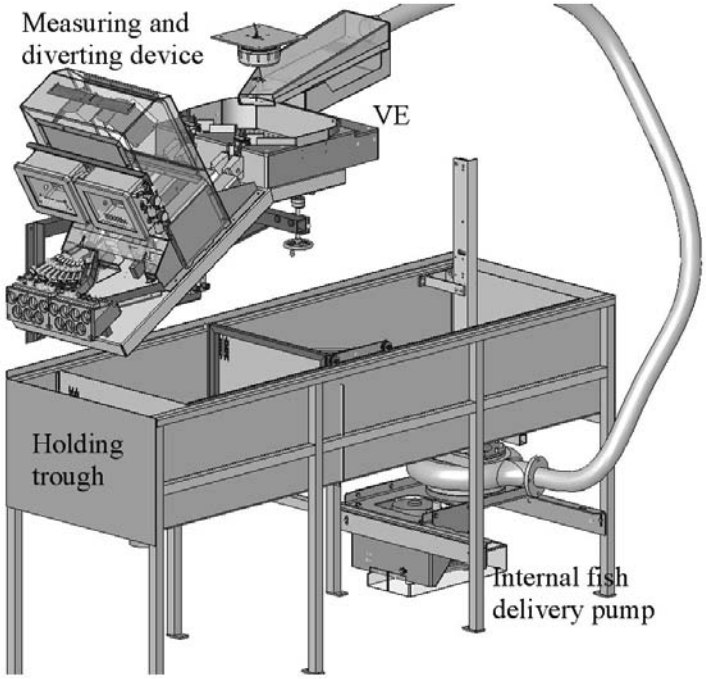

Figure 4. The sorter is used to sort fish into precise size categories that match the setup on the marking and tagging lines. The fish are loaded into the holding trough, and then lifted into the Volitional Entry Device (VE) by a pump before they move through the measuring and diverting device. The sorter uses cameras to measure the length of each fish to within 1 mm accuracy, and they are then diverted to the appropriate marking and tagging line.

Figure 5. Fish are not anesthetized or handled by humans once they are in the trailer. AutoFish relies on Volitional Entry Devices (VE, the white trays at the top of the sorter and each marking and tagging line) to move the fish through the measuring and diverting device and the marking and tagging lines. The VE is a shallow, bright environment with upwelling water that takes advantage of the fish's natural instinct to seek a darker, more protected location, in this case, the entry to the sorter or marking and tagging line.

After sorting, fish arrive in the second VE, which is used to move fish into the marking and tagging lines (fig. 6). Because fish swim volitionally through the AutoFish System, they remain upright and oriented head first, the position needed for marking and tagging. However, the VE does not guarantee that fish enter the line one at a time. A series of gates is used for this. Sensors determine when the fish are present, and they are held back or allowed forward as needed. Once through the gates, the fish arrive in the clamping mechanism at the bottom of the line. This mechanism is custom fit for each fish size range. The clamps are lined with foam to ensure that the fish are not injured, but are immobilized in water during clipping and tagging. Each fish is restrained for about 1 second.

The clipping arm is controlled by machine vision that finds the location of the adipose fin and moves the clipper to that location. The clipper itself is gimbled so that it will lay flat against the fish's back to ensure that the clip angle is optimized. Machine vision also is used to verify that the adipose fin was completely removed by comparing images before and after fin clipping (fig. 7). A headmold ensures that the fish is properly positioned for tagging. As the arm moves down to remove the adipose fin, a CWT is simultaneously injected. After clipping and tagging, each fish is released from the clamping mechanism and slide into a Quality Control Device (QCD). The QCD is a magnetometer that electronically verifies the presence of a CWT. Fish without a CWT or without an adipose clip are diverted for later processing, while the majority of the fish (about 99%) are returned directly to the pond.

AutoFish is an important part of salmon management in the Pacific Northwest, and it is now being used in the Great Lakes region of North America where extensive fin clipping and coded wire tagging will be used to manage salmonids.

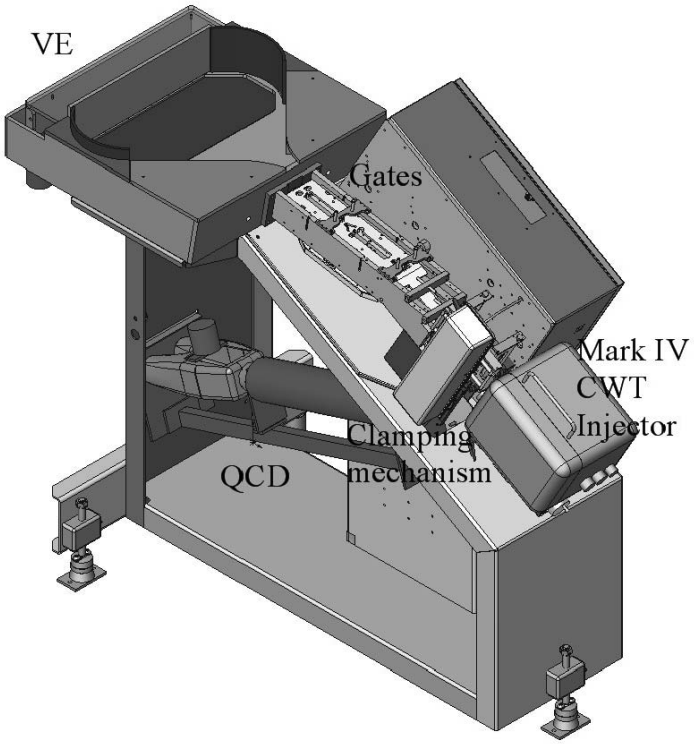

Figure 6. After sorting, the fish are marked and tagged in one of six lines in the trailer. The fish arrive at the top of the line in a Volitional Entry Device (VE), and move through a series of gates to a clamping mechanism that holds them during the adipose fin clip and injection of the Coded Wire Tag. QCD is the Quality Control Device, a small electronic tunnel detector that is used to automatically detect Coded Wire Tags in juvenile salmonids after tagging, and to divert untagged fish for further processing.

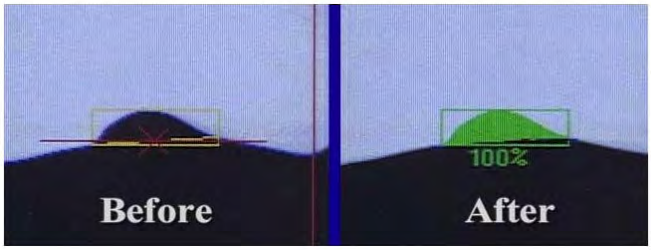

Figure 7. AutoFish achieves high quality standards through consistent handling and rigorous quality-control checks on every fish. AutoFish uses machine vision to find the position of the adipose fin and to verify that it was correctly removed. The area the fin occupies in an image of the fin before it is clipped ("Before") is compared to the area in an image taken after clipping ("After"). The percentage of missing fin (shown in green) must meet a standard or the fish is rejected and automatically diverted for further processing.

Development of Electronic Tag Detection

Before the implementation of the mass marking initiative, the removal of the adipose fin had been sequestered to designate a fish with a CWT so that tagged and untagged fish could be sorted visually and the tags recovered in a coast wide sampling program by trained samplers and fishermen who voluntarily returned the snouts of fish without an adipose fin to the managing agencies. As the concept of mass marking hatchery salmonids developed and its benefits became clearer, extensive surveys of marking and tagging methods found that the most reasonable way to visually identify (mass mark) hatchery fish was by removal of the adipose fin (Pacific States Marine Fisheries Commission, 1992; Pacific Salmon Commission, 1995). Other methods were described as being too expensive or too slow to apply, or adversely affected survival. However, given the importance of the data collected by the recovery of CWTs, the removal of the adipose fin could not be adopted for mass marking without first providing a reliable method of identifying a fish carrying a CWT. As for mass marking, no second visible tag or mark was found to be suitable (Pacific Salmon Commission, 1995), and thus Northwest Marine Technology designed some new tools and modified existing ones to provide field samplers with a way to detect CWTs electronically (fig. 8). The Handheld Wand Detector is a portable field detector that senses the magnetic moment of a CWT when it is moved in close proximity to the tag. Tunnel detectors, which are larger and heavier than wands, are most useful at sites where large numbers of fish are processed, such as at hatcheries or fish processing companies. Tunnel detectors are designed to have the entire fish passed through them and will sound an alarm or, with a gate, divert the fish when a tag is detected. Tunnels can be suitable for live or dead adult fish.

When they were first introduced, several Pacific Northwest fish management agencies evaluated and informally reported on the reliability of electronic detection equipment and generally found that 80–100% of tags can be detected using wands, and 99–100% of tags can be detected using tunnels. Blankenship and Thompson (2003) found that samplers using wand and tunnel detectors found 99.9 and 100%, respectively, of CWTs in adult coho salmon returning to several hatcheries in Puget Sound. With proper use, electronic detection reduces the number of false positive detections (collecting a snout when no tag was present) compared to visual sampling (Vander Haegen et al., 2002). It is clear that detection rates are affected by sampling technique, and it is important to ensure that samplers are properly trained and given adequate time and opportunity to sample for tags.

Figure 8. Electronic detection is used to sort fish with tags from those without tags in the absence of an external mark. Handheld Wand Detectors (left photos) are easily adapted to any sampling location while tunnel detectors (right photos) are more suitable for sites with large numbers of fish to be sorted.

Detection rates also can be influenced by fish size because the distance from the wand to the tag (i.e., the depth of the tag in the tissue) may exceed the wand's detection range even when the wand is in contact with the skin. This problem was addressed by the development of a mouth wanding technique for salmon (Vander Haegen et al., 2002) and by improvements in wand technology. Over the last 5 years, the Handheld Wand Detector has benefited from several upgrades to eliminate interference from radio waves, and to improve waterproofing and stability. These improvements resulted in a more reliable field sampling tool and an increased detection range (from 2.5 to 3.2 cm), both of which contribute to more tag recoveries.

In addition to providing electronic tag detection for salmonids, the invention of the Handheld Wand Detector provided options for researchers working with other species to sort tagged and untagged fish when no visible mark could be used to designate a fish with a CWT. In addition, it allows non-lethal collection of data from CWTs when detecting its presence or absence provides the required information. This scheme can be expanded in some cases by putting the tag in different body locations (at the base of different fins, or behind a particular scute in sturgeon, for example) to designate groups (Bonar et al., 1997). The Handheld Wand Detector can then be used to discriminate the presence of tags at different sites without having to remove the tags.

Expansion of Species Tagged

The CWT remains the smallest tag available and thus smaller animals and earlier life stages can be identified with CWTs than with most other tags. The development of electronic detection, the versatility of the CWT, and their benign nature have resulted in the CWT being adapted for research programs involving hundreds of different species around the world. Species representing at least 37 families have been tagged with CWTs (appendix 1). In general, CWTs have consistently high retention rates for the life of the animal. For example, CWTs have been recovered 24 years after tagging in sturgeon (*Scaphirhynchus platorynchus*), 22 years after tagging in lake trout (*Salvelinus namaycush*) and 13 years after tagging in white seabass (*Atractoscion nobilis*).

Coded Wire Tags are used to identify individual animals or batches of animals to accomplish numerous objectives. Because they rarely affect the host, CWTs have been used as standards for evaluating the effects of other marks or tags when double tagging is required (e.g., Van den Avyle and Wallin, 2001). Stock enhancement is on the rise as worldwide fish populations decline. However, the approach to enhancement is much more scientifically based than it was 20 years ago, and the success of these programs are often rigorously evaluated. Coded Wire Tags have played an important role in helping researchers to distinguish hatchery from natural origin animals, estimate the contribution rates of stocked fish to fisheries or local populations, and evaluate the economic feasibility of stock enhancement programs (e.g., Drawbridge et al., 1995; Agnalt et al., 2004; Davis et al., 2004a; Brennan et al., 2007). Coded Wire Tags are suitable because many stocked fish are released when they would be too small for other tags, and because large numbers of fish generally require tagging. The development of electronic detection has been important for this use as it allows researchers to sort tagged from untagged fish, in some cases, providing all information needed without having to kill the fish to retrieve the tag.

Coded Wire Tags also are widely used to investigate spatial and temporal patterns of fish movement within specific habitats and growth rates (e.g., Miller and Able, 2002; Weitkamp and Neely, 2002; Able et al., 2006; Adlerstein et al., 2007; Verweij and Nagelkerken, 2007). In these projects, researchers often require individual identification, so they use the sequential CWT format, and the projects are designed so that characteristics of the fish can be observed between the time of first capture and tagging and the final recapture when the tags are recovered. These projects provide growth and movement data for large numbers of animals, in contrast with projects using electronic tags to get very detailed movement data about a few animals. They also benefit from being able to tag fish that are too small for other tags, and from the ability to sort tagged and untagged fish using electronic detection. In sturgeon and other larger fish, tag location provides coding information without having to remove the tags.

There are many published studies that have relied on the use of CWTs to evaluate hatchery practices – anything from the type of rearing containers to the type or method of feeding (e.g., Unwin and Quinn, 1993; Leber, 1995; Tipping et al., 2003; Garcia et al., 2004; Doupe and Lymbery, 2005). These studies benefit from CWTs as they can be used to tag the large numbers of juvenile fish involved without harm, and the tags will be retained for life.

Summary

Tagging methods for fish research and management are continually changing in response to technological developments in design and materials. The introduction of tags with new capabilities (e.g., CWTs, PIT, radio, acoustic) is typically followed by a rapid advance in knowledge about a particular species or population that significantly impacts management options. For example, after the introduction of CWTs, Childerhose and Trim (1979) stated that "more information about ocean distribution, and the numbers of fish in specific fisheries, was gathered in 12 months than had been gathered in the previous 12 years" (p. 126). This seems logical because new tag capabilities would provide opportunities to explore questions that were previously limited by the available technology. The introduction of new tag capabilities is a relatively rare event, but improvements in these technologies (new and old) are more or less continual. These incremental

improvements lead to expansion of uses in more species or different sizes of a species, faster and easier application, longer tag life, improved tag retention, increased detection range, and increased code capacity.

In any research or management program using tags, it is critical to identify the objective of tagging and the information that is to be collected. Usually the reasons for tagging can be broken down into three broad categories: hatchery evaluation and management, learning about movement and migration patterns and other life history characteristics, or fisheries management (population statistics and stock assessment). Once the tag has been matched to the objective, it is critical to the success of the program to evaluate the capabilities of the tag within the context of a specific experimental design and to consider the physiological and behavioral effects that the tag may impose upon the host. Tag retention, recovery methods, sample size, and coding capability are important as well as a tagging/marking system that is benign in regards to mortality and growth or changes in migration or predation. It can be tempting to quickly discount more traditional tagging methods in favor of newer technologies. However, the most successful research programs have used a variety of fish identification methods either concurrently or over time to answer questions rather than relying on a single tagging method and devising experiments that are limited by that method. In his plenary address at the international symposium "Advances in Fish Tagging and Marking Technology" held in 2008 in New Zealand, Ken Leber (Mote Marine Laboratory, FL, USA) provided an excellent example of how his research program was able to progress by using a variety of fish identification methods, including CWTs, Visible Implant Elastomer, acoustic tags, and genetics. His work illustrates the importance of understanding different tagging technologies that are available, and their associated biases and limitations (Bergman et al., 1992).

The CWT was a brilliant invention and its very design is largely responsible for its broad use. The continual technological improvements to the tag itself, the injection systems, and the detection tools have provided the flexibility for adapting this technology to varied, and sometimes conflicting, research and fish management objectives. Advances in new and existing tag technology mean that the options for researchers are always expanding. It is therefore important to frequently evaluate whether the tags being used are the most suitable or whether they are limiting the scope of the research questions that can be addressed.

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Appendix 1

The use of Coded Wire Tags has expanded rapidly with technological developments. A search of the published literature showed that species from at least 37 families have been tagged with Coded Wire Tags. Full references are below the table. Additional references are available at www.nmt.us.

Family	Representative references
Acipenseridae - sturgeons	(Bordner et al., 1990; Isely and Fontenot, 2000; Fadaee et al., 2006)
Anguillidae – freshwater eels	(Thomassen et al., 2000)
Astacidae – crayfish	(Isely and Eversole, 1998)
Carangidae – jacks	(Ross and Lancaster, 2002)
Centrarchidae – sunfishes	(Buckmeier, 2001; Fletcher et al., 1987; Heidinger and Cook, 1988)
Centropomidae – snooks	(Brennan et al., 2005)
Cichlidae – cichlids	(Klar and Parker, 1986)
Clupeidae – herrings	(Isely and Tomasso, 1998; Richardson and Minkkinen, 1995)
Cyprinidae – carps and minnows	(Heidinger and Cook, 1988)
Engraulidae – anchovies	(Leary and Murphy, 1975)
Escocidae – pikes	(Dorsey, 2004)
Fundulidae – topminnows	(Able et al., 2006)
Galaxiidae – galaxiids	(Crook and White, 1995)
Haemulidae – grunts	(Verweij and Nagelkerken, 2007)
Hexagrammidae – greenlings	(Buckley et al., 1994)
Ictaluridae – North American catfishes	(Heidinger and Cook, 1988)
Lutjanidae – snappers	(Brennan et al,. 2007)
Majidae – spider crabs	(Bailey and Dufour, 1987)
Moronidae – temperate basses	(Mattson et al., 1990; Wallin and Avyle, 1994)
Mugilidae – mullets	(Leber et al., 2005)
Nephropidae – clawed lobsters	(James-Pirri and Cobb, 1999; Uglem and Grimsen, 1995;Wickins et al., 1986)
Nereidae and Glyceridae – marine worms	(Joule, 1983)
Palinuridae – spiny lobsters	(Sharp et al., 2000)
Pandalidae – pandalid shrimp	(West and Chew, 1968)
Parastacidae – crayfish	(de Graff, 2007)
Penaeidae – penaeid shrimps	(Webb and Kneib, 2004)
Percichthyidae – temperate perches	(Ingram, 1993)
Percidae – perches	(Heidinger and Cook, 1988; Peterson and Key, 1992)
Petromyzontidae – lampreys	(Meeuwig et al., 2007)
Pleuronectidae – righteye flounders	(Sulikowski et al., 2005)
Polynemidae – threadfins	(Friedlander and Ziemann, 2003)
Polyodontidae – paddlefishes	(Fries, 2001)
Pomacentridae – damselfishes	(Beukers et al., 1995)
Pomatomidae – bluefishes	(Able et al., 2003)

Family	Representative references
Portunidae – swimming crabs	(Fitz and Wiegert, 1991)
Salmonidae – trouts and salmons	(Blankenship, 1990; Elrod and Schneider, 1986; Kolari and Hirvonen, 2006; Lehtonen et al., 1998)
Sciaenidae – drums and croakers	(Miller and Able, 2002; Willis et al., 1995)
Scorpaenidae – scorpionfishes (rockfishes)	(Buckley et al., 1994)
Sparidae – porgies	(Doupe and Lymbery, 2005)
Teraponidae – grunters or tigerperches	(Ingram, 1993)
Unionidae – freshwater clams	(Layzer and Heinricher, 2004)
Veneridae – short necked clam	(Lim and Sakurai, 1999)

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Chapter 9.—Corps Fish Study Nets Useful Data[1]

JoAnne Castagna[2]

In 2005, in a New York City conference room with large windows overlooking the Port of New York and New Jersey, Dr. Mary Fabrizio, Chief of the Behavioral Ecology Branch of the Northeast Fisheries Science Center, presented to scientists the results of an extensive fish tagging study she performed for the U.S. Army Corps of Engineers.

As the study's principal investigator, Fabrizio told the scientists, "The findings will be used to update the Environmental Protection Agency's criteria that determine what dredged material from the port is environmentally safe to place in the Historic Area Remediation Site."

After undergoing a series of biological and chemical analyses, dredged sediment from the channels within the Port of New York and New Jersey is placed in the Atlantic Ocean at the HARS if found acceptable as remediation material.

The HARS is an approximately 15.7 square nautical mile area – 3.5 nautical miles east of Highlands, New Jersey, and 7.7 nautical miles south of Rockaway, New York.

Remediation material is used to cover or "cap" the dredged sediment that was placed there previously which does not meet EPA's current placement standards. This cap remediates the site and improves the habitat conditions for aquatic life in the HARS.

"After consultation with the Corps' New York District, the U.S. EPA Region 2 sets the final criteria for what is suitable for placement in the HARS. Several years ago the EPA indicated they wanted to update this criteria by using a risk-based approach," said Monte Greges, Chief of Dredged Material Management Section, U.S. Army Corps of Engineers, New York District.

"One of the parameters that goes into creating this risk-based criteria is the residency time of fish in the HARS because it is assumed that the more time the fish spend at the HARS, the more organisms they will eat that have been impacted by dredged material placed there."

"The New York District felt that the EPA's information on residency time was incomplete and needed to be improved, so we initiated and funded a fish tag study to better answer the question of how much time the fish actually spent within the HARS boundary," said Greges. "The results from this study were provided to the EPA for use in their development of this risk-based criteria for dredged material proposed for HARS placement."

The Corps' U.S. Engineer Research and Development Center, Waterways Experimental Station in Vicksburg, Miss. managed the study and contracted the NEFSC to perform it.

The study was from June 2003 to June 2004 and included 145 healthy adult fish captured at the HARS. The species captured included 122 black sea bass (*Centropristis striata*) and 23 summer flounder (*Paralichthys dentatus*) or "fluke," both important recreational and commercial fishing. The two species studied were active at the HARS from May to December. During the winter, these species move to deeper offshore waters.

To monitor activity, fish were tagged with ultrasonic transmitters that were surgically implanted in their abdominal cavities. The transmitters are 30 mm long and 9 mm in diameter and were programmed to send 68 KHz signals, or pings, once every 3 to 5 minutes for about an entire year.

To pick up the signals, 72 receivers were strategically moored throughout the HARS, 800 meters a part. Every signal detected by a receiver was decoded electronically and the receiver recorded the identification number of the transmitter, the date, and the time of the day the signal was detected.

These records were accumulated in the memory of the receiver. The receivers were retrieved in summer 2003 and summer 2004. When the receiver was retrieved, scientists downloaded the data to a computer. Scientists had collected 1.4 million records.

Preliminary results revealed information on the fishes' use of the HARS habitat, seasonal activity and dispersal out of the HARS.

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[2]U.S. Army Corps of Engineers, New York District

Preliminary Results

- *Habitat usage*: The ocean floor of the HARS is composed of varying levels of dredged sediment. During the summer, both fish species spent most of their time in the shallow areas of the placed sediment.
- *Seasonal activity*: Black sea bass exhibited greater activity in the HARS during the summer than during the fall. Summer flounder activity patterns were more complex.
- *Dispersal*: All fish were captured and released within the HARS boundaries, but each species moved or "dispersed" out of the HARS at different times and rates. A handful returned to the HARS 1 year later.

Fabrizio said the study was extremely interesting and she learned the importance of using appropriate equipment, selecting sufficient staff to conduct the work at sea, and coordinating the logistics required for a large field study.

"Deploying and retrieving sensitive acoustic equipment at sea for long periods of time is difficult," said Fabrizio. "Each time we attempted to retrieve the 72 receivers, we usually needed about 10 full days, which we had to schedule around the weather, including Hurricane Isabel in September 2003."

"If I did the study again I would use acoustic receivers with modem capabilities – this allows the scientists on board the vessel to download the information from the receiver's memory without having to retrieve the gear off the bottom of the sea," she said. "However, this equipment was not yet developed when we started our work and it's very expensive."

Fabrizio was still satisfied with the equipment used and was confident it would work because she performed pilot studies prior to performing this study at the HARS.

When it came to field deployments and retrievals of the receivers, Fabrizio said that the most important aspect was the skill of the captain and the capabilities of the vessel. "Never underestimate the complexity of these tasks! Hire a captain who has years of experience and is a good trouble shooter—he or she is worth every penny!"

She added, "It was also very interesting learning from, and working with the captains of the vessels that assisted us on this study."

The results of the study answered questions about the length of time fish reside at the HARS, but there are additional data that were obtained that still need to be analyzed. "In complex studies such as these, it is not unusual for the analysis phase to require as much time, or sometimes more, as the field work," said Fabrizio.

"Some of the findings we will examine further include the black sea bass's increased activity during dusk, the bass's dispersal out of the HARS early in the summer, and both species preference for the shallow complex habitats at the HARS."

"Data from this study will benefit both the public and the environment. Scientifically defensible data will be used by the EPA to create the new HARS criteria, a more realistic picture of human and ecological risk will be ascertained and dredged material that poses an unacceptable risk for introduction into the food chain will not be disposed in the ocean," Greges said.

For additional information about the U.S. Army Corps of Engineers, New York District dredging projects and studies, please contact the author at Joanne.castagna@usace.army.mil

Dr. JoAnne Castagna is a technical writer-editor for the U.S. Army Corps of Engineers, New York District.

Chapter 10.—Review Summary and Conclusions

The Editorial and Review Subcommittee of the PNAMP Fish Population Monitoring Workgroup

±Shaun Clements[1], Albert Giorgi[2], Tracy Hillman[3], Dayv Lowry[4], Kevin Malone[5], Jennifer O'Neal[6], Charles Paulsen[7], Keith Wolf[8], and Nik Zymonas[9]

Summary

This compendium is a Special Report publication of the Pacific Northwest Aquatic Monitoring Partnership (PNAMP) and the Fish Population Monitoring Workgroup (FPM). The overall goal of the PNAMP and the FPM was to bring expert authors together to provide tagging, telemetry and marking (TTM) methods, design considerations, case studies, logistical considerations, and reported results in a single resource document. This was accomplished by integrating robust science and by establishing direct lines of communication. This document provides convenient access to a considerable body of the best science available on TTM. According to many managers and scientists, including organizations such as the American Fisheries Society, such a document has been lacking for nearly two decades.

This compendium provides relevant information from a series of case studies, technology reviews, methods, and techniques papers. PNAMP sought to provide these to help optimize the use of TTM technology and designs. All Chapters in this compendium and its findings were reviewed by the FPM's Editorial and Review Subcommittee (ERC) composed of university researchers, technical experts, and ecological practitioners. PNAMP, the FPM, and the ERC believe that by providing some analysis of the status quo, the opportunity for improved and comparable data collection can generate more reliable information and improved analyses, resulting in better informed and more cost-effective decisions. The status quo seems to be primarily maintained by a pervasive lack of communication regarding what has been learned from new information on technology and purpose.

Editorial and Review Subcommittee Process

This chapter generally is provided to: (1) describe the peer-review process; and, (2) highlight interpretation of the manuscripts' major themes and utility. The overall intention is to summarize the totality of the chapters' individual and combined considerations.

Authorship of the ten main chapters and the five special sections came from 127 contributors representing approximately 39 State, Federal, Tribal, and academic entities, as well as several non-governmental organizations. Consequently, the ERC recognizes that contributions came from a diverse set of experienced individual TTM practitioners, private companies, and academic institutions (ED: a full list of participants is found following the Acknowledgments section).

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Once papers were received, the FPM and editors initiated a workshop to establish the ERC. Team members reviewed one to three papers each, with each paper reviewed by at least two team members, using an electronic review form to document questions, establish the validity of the paper, verify assumptions and the application of the techniques, and comment on overall quality and methods. The review included three parts: (1) a set of questions to evaluate the manuscript's content and accuracy; (2) a list of applicable management questions that were evaluated for how well the manuscript addressed them; and, (3) a section for providing two or three brief paragraphs summarizing the paper for possible future research or use in the region. Sample questions dealt with topics including: (1) an overall rating of the paper; (2) an assessment of the technical accuracy, clarity of presentation, and how well the paper's topic was addressed; (3) whether the research questions were clearly stated; and, (4) an assessment of the clarity of tables, figures, and charts. Each form was then provided to the second reviewer and the reviewers collaborated among themselves and the authors to complete the review. Finally, the USGS provided additional science and policy reviews where USGS employees were authors.

The ERC confirms that TTM data provides an information source that can be used for management and policy decisions regarding the management and monitoring of aquatic populations and their ecological attributes in the Pacific Northwest. The ERC recognizes the publication can help to inform and increase the robustness of research, monitoring, and evaluation tools. Inasmuch, the FPM and many participants have commented that this product will serve important purposes at many levels as it is disseminated by the PNAMP Steering Committee.

Conclusions

1. Information derived from current TTM programs carry a higher than necessary risk of being improperly applied for population monitoring and resource management decisions.
2. Necessary improvements in the TTM arena include: increased and/or sufficient inferential power to answer key management questions, consistent science-based and tested designs, programs that are targeted on more broadly agreed-to goals, and enhancement in reporting.
3. Current programs generally use ad hoc and an undetermined variety of TTM techniques to track animals during rearing and migration life phases. This means that assumptions and uncertainty coupled with error and bias likely have statistically significant and/or considerable effects on data integrity, validity, and its use.
4. Many practitioners agree that the current approach also does not provide satisfactory information to fully understand or address sources of data variability or other factors, such as atypical mortality and/or watershed condition.
5. Many current data analyses do not provide probable causes and corrective actions. Taken in whole, we find that these programs are unable to provide regionally comparable or spatially congruent information at this time. This also carries with it the risk of managers and policy leads or advisors using deficient or biased data to answer key management questions.
6. Research, monitoring, and evaluation (RME) efforts should focus on improving the accuracy of population monitoring, and these efforts should be integrated and done in a collaborative manner. Similarly, a dynamic form of data integration and analysis is necessary for the best possible information to be used in essential adaptive management processes.
7. The use of more contemporary information gleaned from dedicated and ongoing literature reviews, compilations such as this effort, and continued analyses of the status quo with a focus on options for improvements, will improve confidence in decision and policy processes.
8. Dissemination of this compendium should be broad and efforts to continue and update these works should progress in a formal and strategic manner.

AFS Symposium Proposal
Washington-British Columbia Chapter Meeting

Symposium Title: Using Hydroacoustic Telemetry Tools to Understand Movement and Ecology of Critical Species and Improve Management Applications

Short title: Methods of Fish Tracking

Moderator: Anna Kagley[1]

Proposal

A variety of stocks throughout the Pacific Northwest including many salmonids, trout, sharks and groundfish are in decline. For example, Puget Sound Chinook salmon are now listed as Threatened under the Endangered Species Act. An increased understanding of these species residence time, origins, migration pathways, predator/prey interactions, and habitat use is needed to help reverse this trend. We are currently using acoustic telemetry to help fill this information void. Currently there are over 20 organizations deploying more than 900 tags and over 200 receivers in every Puget Sound basin and coincident with this is an international monitoring effort (POST project) using the same technology from California to Alaska. This symposium is a summary of this collaborative effort initiated over the last several years and an overview of the upcoming research plans.

This united approach will give a clearer picture of the status of Pacific Northwest stocks in the riverine, estuarine and nearshore environments and contribute to a greater ecosystem level of understanding. This in turn will help direct future fisheries management decisions surrounding recovery and help focus future protection and restoration efforts.

Number of talks: 25, from Provincial, State, and Federal Government as well as private industry.

Length of talks: 20 minutes (15 minutes for talk, 5 minutes for questions)

Number of panel discussions: 1

Length of panel discussion: 2 hours; including 5-15 minute presentations.

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Presentations

Overview

Hide & Seek: A Summary of Fish Telemetry

Tom Quinn[1] and Kurt Fresh[2]

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Thomas Quinn received his PhD in Fisheries at the University of Washington in 1981, studying migration and orientation of salmon. He then worked for the Department of Fisheries and Oceans, Canada at the Pacific Biological Station in Nanaimo, B.C. until joining the faculty in the School of Fisheries at the University of Washington in 1986. He has remained at the University of Washington, teaching and conducting research on the behavior, ecology, evolution and conservation of salmon and trout.

Enhanced understanding of the movement patterns of migratory and resident fish species within Puget Sound waters will provide important information for stock conservation of many commercially and culturally important species. Several of these species are currently listed as Threatened or Endangered under the U.S. Endangered Species Act. In addition, this information is needed to understand the trophic connection between these species and their predators, such as the threatened southern resident community of killer whales. To further this understanding, we continue to use passive and active detections of ultrasonic transmitters, implanted in various fish species, including salmon. An extensive network of listening stations is aiding in the determination of home ranges for these individuals, use of shoreline and open water habitats, movement between basins within Puget Sound and across the boundary into Canada. Also, active tracking of a smaller number of individuals continues to provide more precise information on movement patterns. This is a summary of these efforts to date and insight into future directions.

Columbia River/Hydropower

Response of a Spawning Population of Spring Chinook Salmon to Flow Alteration in a Regulated System

Steve Corbett[1], Mary Moser[2], Andy Dittman[2], Don Larsen[2], and Darran May[2]

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Steve Corbett is a research technician for NOAA Fisheries in the Fish Ecology Division at the NWFSC, Seattle. Prior to coming to NWFSC in 2008, he has worked in various areas of fisheries research in the Pacific Northwest for the Army Corps of Engineers, Forest Service, EPA, USGS and the National Park Service. He received a B.S. in Fisheries Biology from the University of Idaho. He loves to gamble.

The Yakima River is a hydrologically regulated system managed to balance the needs of irrigation while sustaining populations of spring Chinook salmon (Oncorhynchus tshawytscha). Each autumn, coincident with spawning, flow is significantly and abruptly reduced in the upper Yakima River, while during the summer the hydrograph is artificially high. We used radio telemetry to document movements of adult spring Chinook salmon in the upper Yakima River during flow alteration. Adult salmon (total length 60-93 cm) were collected in June as they migrated into the upper Yakima River, implanted intragastrically with radio transmitters and released 7 km upstream of the collection site. Radio-tagged fish were relocated using a combination of fixed site receivers and mobile tracking surveys. Several fish migrated from the release site to points upstream (mean distance 85 km; range, 46-110 km) and moved at a mean rate of 3 km/day (range 0.5-6.2). Of these fish, most were last relocated in areas of historically high spawning density and a proportion of radio tags were recovered in the carcasses of post-spawned fish. Decreased flows appear to have prompted some fish to move upstream and preliminary results have management implications related to flow reduction timing, ramp-down rates, and maintenance of minimum flows.

Juvenile Chinook Salmon Migration Behavior and Fate Determination in the Lower Columbia River Using Mobile Tracking Data

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Lynn McComas is a Research Fisheries Biologist working for NOAA Fisheries' Northwest Fisheries Science Center in Seattle, Washington, USA. Mr. McComas obtained a B.S. from the University of Idaho, at Mosco, ID. For the past 18 years he has worked on juvenile salmonid passage issues in the Columbia River, USA. He is currently involved in development and use of acoustic technology to estimate smolt survival in that system. Prior to working for NOAA, Mr. McComas worked for the Finnish Came and Fish Research Institute for 11 years collecting Atlantic salmon smolt distribution and population data, and for the University of Washington as a resident field station research biologist.

A mobile tracking unit using Juvenile Salmon Acoustic Telemetry System (JSATS) technology was developed to assess fate and fine-scale migration behavior for juvenile salmonids emigrating through the lower Columbia River and estuary. Position estimates were processed for acoustic-tagged targets from recorded three-dimensional vector (range, bearing, and depth) offsets relative to the tracking vessel GPS records across successive tag transmissions. During 2007 and 2008 outmigration periods, 920 unique, free-ranging targets were acquired, resulting in tracks up to several kilometers in length. While most targets were observed in the main river, smolts were also tracked through previously undocumented island channel routes, and using protected areas in the estuary during flood-tide cycles. Mobile targets did not appear to migrate linearly, either in depth or cardinal direction. In addition to normally migrating individuals, several sites were identified in both years where targets were apparently stationary on the river bottom. Stationary target depth estimates were verified by depth-sounder readings, and immobile status of the target was confirmed on 2 to 4 dates, from 24 hours to 22 days following initial contact. The presence of several stationary targets within relatively small areas may suggest evacuation following predation events on tagged individuals.

Columbia River/Hydropower

Movement and Fate of Non-Migratory Subyearling Chinook Salmon Detected on Autonomous Acoustic Receivers in a Hydropower Reservoir

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Geoff McMichael is a senior research scientist at the Pacific Northwest National Laboratory in Richland Washington. He has been involved in the development and use of the Juvenile Salmon Acoustic Telemetry System (JSATS) since the first field tests in 2004 and is the JSATS Program Lead for PNNL.

Subyearling fall Chinook salmon (n=1,771) were captured and implanted with JSATS acoustic transmitters and a PIT tags as they passed Little Goose Dam on the Snake River, Washington. Following recovery overnight, fish were released between 31 July and 13 October 2007. Autonomous receivers placed every kilometer in the lower 19 km of the Lower Monumental Reservoir recorded over 26 million detections of acoustic-tagged salmon in this study. Most release groups of fish migrated from the release location to the first line of acoustic receivers (22 km) where they were regrouped into seven 'virtual' releases. Proportions of each release group that migrated and survived, delayed and survived, or died was estimated based on detection histories from the acoustic receivers over multiple time periods and spatial scales. Most of the fish that emigrated from the reservoir did so within the first 2 weeks. Over all spatial scales and time periods, an estimated 36% of the fish survived and emigrated from the reservoir, 11% remained in the reservoir beyond the 8-week life of the acoustic transmitter, and the remaining 53% died. Of the fish that remained in the reservoir and were alive, 72 (37% of the number estimated to have been delayed and alive) were detected in the PIT-tag system in spring 2008 as they migrated seaward after surviving the winter in freshwater.

Migration Pathways of Acoustic-Tagged Juvenile Salmonids in the Columbia Estuary

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Ryan Harnish graduated from Montana State University in the fall of 2007 with a masters degree in fish and wildlife management and is currently a research scientist at the Pacific Northwest National Laboratory in Richland Washington. Since Ryan began working at the lab,he has assisted with several JSATS projects, including a study to determine potential tag effects associated with implanting transmitters in juvenile salmon and a study to determine survival and behavior of juvenile salmon and steelhead migrating through the Columbia River estuary. Today he will be reporting some of the results from the 2008 [e]stuary study.

We examined migration characteristics of acoustic-tagged juvenile salmonids passing through the Columbia River estuary during the spring and summer of 2008. We were interested in use of pathways other than the main Columbia River channel. Using data collected from 11 acoustic receivers deployed among the estuary islands in Cathlamet Bay, off Harrington Point, and in Gray's Bay, we determined the percentage of steelhead and yearling and subyearling Chinook salmon that used these off-channel areas, when they were detected, specific migration pathways, travel times, and survival rates. A greater percentage of subyearling Chinook salmon were detected in off-channel areas than either yearling Chinook salmon or steelhead. Steelhead took less time than yearling and subyearling Chinook salmon to migrate from rkm 86 to the mouth of the Columbia River, regardless of migration pathway. Subyearling Chinook salmon had significantly higher survival probabilities than yearling Chinook salmon and steelhead through each migration pathway. Survival of yearling and subyearling Chinook salmon and steelhead varied within each species by migration pathway. Most notably, steelhead migrating through the main channel had lower survival than those that migrated through off-channel areas.

Columbia River/Hydropower

Use of Acoustic Telemetry to Assess Migratory Behavior of Subyearling Chinook Salmon at the Mouth of the Columbia River

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Jessica Carter works at the Pacific Northwest National Laboratory in Richland Washington. She is the JSATS data manager for PNNL and has been involved with JSATS since 2004.

More than 28,000 of the nearly 64,000 JSATS-tagged juvenile steelhead and Chinook salmon released into the Columbia River basin since 2005 were detected on receiver arrays near the mouth of the Columbia River (at river kilometer (RKM) 2.8 and 8.3). These data were analyzed to gain a better understanding of migratory behavior as the fish neared the Pacific Ocean. Subyearling Chinook salmon and steelhead were present nearly equally throughout the day at both arrays. Yearling Chinook salmon were present throughout the day at both arrays, but their presence at the lower array peaked in the early morning hours and decreased throughout the day and evening. First detections of yearling and subyearling Chinook salmon and steelhead were more likely to occur on outgoing tides at both arrays. Yearling and subyearling Chinook salmon were consistently detected with greater frequency on the northern portion of the array at RKM 8.3. Steelhead were more likely to be detected on the south side of the channel in 2005, although they were more evenly distributed across the array in 2008. At RKM 2.8, the cross-channel distribution of yearling Chinook salmon and steelhead was variable between years, while subyearling Chinook salmon were more often first detected on the northern portion of the array during all years.

Puget Sound

Monitoring of Marine and Anadromous Fishes in Puget Sound through a Collaborative Acoustic Telemetry Network

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Fred is a doctoral candidate at the University of Washington School of Aquatic and Fishery Sciences. Fred is studying the behavior and habitat use of Puget Sound salmon and trout - including resident chinook, steelhead, cutthroat and bull trout. Fred's major professor is Tom Quinn. Fred is a facilitator of acoustic telemetry studies among a variety of organizations in the Puget Sound. He has been conducting telemetry studies since 1998. He has worked for the USACE for the past 16 years. His work includes fish passage studies at Corps navigation and flood control dams and habitat restoration planning in the Puget Sound nearshore.

Acoustic telemetry is being used at various scales throughout the world to monitor migrations of marine mammals and fishes. Most applications are conducted by individual investigators at small scales or by single large organizations at greater scales. In the Puget Sound, a collaborative and integrated telemetry network has been developing that allows monitoring at multiple scales from individual streams and estuaries, to Puget Sound-wide (2500 miles of shoreline), and along the North American coast-line. The collaboration includes a wide variety of organizations (25 total) and more than 40 investigators or collaborating staff with deployment of over 250 acoustic receivers. These groups and researchers have formed an informal consortium that plans, communicates, and implements telemetry research in all geographic areas (freshwater, estuary, marine) of the Puget Sound. The Puget Sound work is beginning projects with the Pacific Ocean Shelf Tracking (POST) project, an international monitoring network along the west coast that allows tracking of fish as far as Alaska (www.postcoml.org). To date, over 19 species of fish, including freshwater, anadromous and marine, have been studied. In Puget Sound four ESA listed species are monitored – Chinook, bull trout, steelhead, and green sturgeon. The partnership allows development of optimized study designs integrating tagging and receiver deployments for multi-species and multi-objective investigations that could not be realized by individual researchers or organizations.

Puget Sound

A Summary of Acoustic Tagging Programs for Migratory and Resident Chinook Salmon in Puget Sound

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Anna Kagley started with NWFSC's EC Division at Montlake as a high school student volunteer in 1987. She continued to work part-time with EC while attending the University of Washington, and became a permanent employee after receiving a B.S. in fisheries in 1993. After college, she worked for several years on project examining biomarkers in the blue mussel. In 1995, she changed career paths and locations (but stayed with EC) and transferred to Newport, OR to work with Dr. Mary Arkoosh on salmon immune response projects. In 2003 she returned to Seattle and joined the Fish Ecology Division. She is currently involved in field projects studying salmonid habitat use and telemetry.

An increased understanding of Puget Sound Chinook salmon residence time, origins, migration, predator/prey interactions, and habitat use is needed to help recover these threatened (ESA) salmon stocks. Currently there are over 1000 tags and hundreds of receivers in every Puget Sound basin. To date, we have focused on two types of Puget Sound Chinook salmon; ocean-type, which follow the traditional life-cycle model, and residents ("blackmouth"), which do not leave Puget Sound. We hypothesized that the ocean-type fish (based on run timing and size) would rapidly exit Puget Sound, but many tagged fish were still present in the winter months. In turn, we expected resident-type salmon to remain in Puget Sound. We have detected over 75% of these fish on at least one receiver, with a surprising amount of rapid, short-term, long distance movement. Within smaller geographic areas, we also observed "movers" and "sitters." We will examine these fish movement patterns for correlations with tides, diel patterns, water quality, trophic interactions and other possible environmental predictors. This approach will give a clearer picture of Puget Sound Chinook salmon behavior and survival, and assist in future management decisions.

Puget Sound

Migratory Patterns and Behaviour of Resident Chinook Salmon (*Oncorhynchus tshawytscha*) in Hood Canal, WA

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Joshua Chamberlin began studying salmonids at NOAA's NWFSC in 2006. Currently he is working on his Master's thesis at the University of Washington.

Puget Sound has long supported a year round fishery for Chinook salmon (Oncorhynchus tshawytscha) suggesting the presence of a significant resident population. However, little scientific effort has been focused on understanding the behavior of these resident fish. In 1995 the Washington State Regional Fisheries Enhancement Program implemented a program to release yearling fall Chinook salmon from local hatcheries in order to supplement the fisheries that targeted these resident fish. Hood Canal, a ~104km fjord adjoined to the northern end of Puget Sound, is an area where one such hatchery program operates. The goal of our study was to track a group of yearling fish released in Hood Canal and analyze their movement in an attempt to determine the extent of their residency with Puget Sound. In May 2008, we tagged 60 fall Chinook from the Hoodsport hatchery yearling release program in southern Hood Canal with Vemco V7-2L acoustic transmitters (AMIRIS Systems Inc.). Fish were tracked for roughly 3.5 months within a network of 62 receivers placed throughout the length of Hood Canal. A total of 45 fish were subsequently moved from south to north toward the entrance to Puget Sound. However, only three fish were detected at or near the mouth of the canal and none were detected leaving Puget Sound. Our preliminary results suggest the tagged fish resided in Hood Canal during our monitoring period though future telemetry studies are necessary to enhance our findings.

Movement of Coho Smolts in Marine Waters.....

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Scott is a biologist with the Squaxin Indian Tribe.

Coho salmon (Oncorhynchus kistutch) *populations in South Puget Sound (SPS), defined as the marine waters south of the Tacoma Narrows, began a precipitous decline in the late 2+90's. Marine survival rates plunged from an average of over 36% in the mid 1980's to less than 1% by the late 1990's. To investigate this phenomenon a modeling suite utilizing Ecopath with Ecosim was conducted for SPS that looked at marine trophic interactions. Model results suggested that SPS has experienced a trophic shift that has negatively impacted early marine survival. In 2004 the Squaxin Island Tribe installed a permanent year round acoustic detection network in seven of the narrow passages that characterize South Puget Sound. Field testing showed that tagged fish passing these arrays had a probability of detection that approached 100%. Between 2004 and 2006 264 hatchery and wild coho were tagged and released. Over 70% of these fish were detected in the Tribe's acoustic array. Preferred holding areas and migration routes were identified over multiple years. Apparent mortality of tagged smolts as defined by detections at the Tacoma Narrows approached 90%.*

Puget Sound

Nearshore Habitat Use and Behavior of Hood Canal Trout

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Fred is a doctoral candidate at the University of Washington School of Aquatic and Fishery Sciences. Fred is studying the behavior and habitat use of Puget Sound salmon and trout - including resident Chinook, steelhead, cutthroat and bull trout. Fred's major professor is Tom Quinn. Fred is a facilitator of acoustic telemetry studies among a variety of organizations in the Puget Sound. He has been conducting telemetry studies since 1998. He has worked for the USACE for the past 16 years. His work includes fish passage studies at Corps navigation and flood control dams and habitat restoration planning in the Puget Sound nearshore.

Anadromous coastal cutthroat trout are a sought after recreational fish in estuary and nearshore areas in Puget Sound. Scientific study of how Cutthroat trout use these marine nearshore areas is little studied and likely even less understood. Acoustic telemetry is being used to study the habits and habitats used by cutthroat in three sub-basins of the Puget Sound including the Hood Canal, South Puget Sound, and Whidbey Basin. In Hood Canal, cutthroat trout have been captured and tagged at the University of Washington Big Beef Creek research station for the past three years. A total of 25-30 fish (smolts, sub-adults, and adults) were tagged per year with genetic samples and utilized the receiver network deployed for that study. In the first two years of study, 93-96% of tagged fish migrated through the estuary into Hood Canal with 60% detected at the edge of the delta. Fish migrated either north (apprx. 60%), south (37%), or moved in both directions (25%). Fish displayed a wise array of behaviors including transients with complex movements with some migrating greater than 200 km; 25-33% of fish crossed the Hood Canal (3km of open water) with multiple fish crossing multiple times, and some fish remained in localized areas for days to weeks displaying site fidelity. There is also a high degree of hybridization of cutthroat and steelhead in Big Beef Creek, genetic analysis will allow future comparison of the behavior of tagged fish in each species with that of tagged hybrids.

Puget Sound

Early Marine Survival and Behavior of Steelhead (*Oncorhynchus mykiss*) Smolts Through Hood Canal and the Straits of Juan de Fuca

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Megan has been with the Behavioral Ecology Team at the Northwest Fisheries Science Center for three years now. In that time she has focused on steelhead early marine survival and behavior, as part of a larger study investigating hatchery approaches to steelhead conservation. She also participates in numerous field activities aimed at understanding the biology and population dynamics of steelhead in the Hood Canal. Megan has previously worked at nearly every other natural resource agency in the area, namely Washington Department of Fish and Wildlife, Oregon Department of Fish and Wildlife, US Geological Survey, and the Army Corps of Engineers.

The depressed status of Puget Sound steelhead trout (Oncorhynchus mykiss) *populations contrasts with the healthier condition of those along the Washington Coast. Acoustic telemetry methods were used to investigate survival, migration timing, and migratory behavior of steelhead smolts from four Hood Canal streams and one stream flowing into the Strait of Juan de Fuca. Estimated population-specific survival rates for wild and hatchery smolts from river mouths to the northern end of Hood Canal (28.1 to 75.4 km) ranged from 67% to 85% in 2006, and from 64% to 84% in 2007. Survival was much lower from the north end of Hood Canal to the Strait of Juan de Fuca (135 km) in 2006 (23% to 49%), and could not be reliably measured in 2007. Travel rates through Hood Canal (8 – 10 km·d-1) were significantly lower than those estimated as the fish migrated through northern Puget Sound and in the Strait of Juan de Fuca (26 - 28 km·d-1), while the mortality rates per unit distance travelled were very similar in the two segments. Simple models utilizing both resultant mortality rates from river mouths through the Strait of Juan de Fuca and a range of typical smolt-to-adult survival rates for steelhead suggest that early marine survival rates are less than those in the Pacific Ocean.*

Migratory Patterns of Bull Trout and Steelhead in the Skagit River, Washington

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Ed Connor received a Ph.D. in Ecology from the University of California, Davis. He is an aquatic ecologist with Seattle City Light, where he is the City of Seattle's endangered species recovery coordinator for the Skagit River. He is currently working on research studies, habitat restoration projects, and conservation land acquisition projects for bull trout, steelhead, and Chinook salmon in the Skagit River watershed. He is a long-time member of the habitat restoration and land acquisition committees of the Skagit Watershed Council, and currently serves on the Puget Sound Steelhead Technical Recovery Team and Puget Sound Bull Trout Recovery Unit Team.

We have been tracking the migration of bull trout, juvenile steelhead, and adult steelhead in the Skagit River using an array of acoustic receivers deployed throughout the Skagit River watershed, Skagit Bay, and the Puget Sound. Bull trout implanted with acoustic tags have been tracked in the Skagit River, Skagit Bay, and nearshore waters of the Puget Sound since 2002. Bull trout were found to have diverse life history patterns throughout the Skagit watershed that are determined by seasonal variability in food availability, foraging efficiency, hydrology, and water temperature regimes. We have been tracking the outmigration patterns of steelhead smolts in the Skagit River since 2006. Steelhead smolts were found to migrate rapidly through the lower Skagit River and the Puget Sound. The majority of steelhead smolts migrated northward through Skagit Bay and Deception Pass, and then westward into the Pacific Ocean through the Strait of Juan de Fuca. The pre- and post-spawning migratory behavior of adult steelhead was also investigated in 2008. The results of these studies are providing new information on the life history traits of threatened bull trout and steelhead in the Puget Sound.

Puget Sound

Mechanisms for Pelagic Prey Subsidies to Demersal Predators in Rocky Reefs: Insight From Movement Patterns of Lincod (*Ophiodon elongatus*)

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Anne Beaudreau is a doctoral candidate working with Tim Essington at the University of Washington's School of Aquatic and Fishery Sciences. Her research focuses on the predatory role of lingcod, a top fish predator, in nearshore fish communities of the San Juan Archipelago, Washington. In general, she is interested in using field-based and quantitative tools to address ecological questions relevant to marine resource management. Anne is originally from Rhode Island but is hoping to stay in the Northwest after her degree.

Mobile predators and prey can play important roles in structuring food webs through foraging activities that transfer energy across a heterogeneous landscape. Lingcod are top predators in rocky reefs along the west coast of North America that consume a wide variety of pelagic and demersal fish species. Herring and sand lance account for 11% of the total energy budget of lingcod in the San Juan Archipelago, WA, during summer months. Whether energy from pelagic habitats is transferred to benthic habitats by lingcod through active foraging for pelagic prey ("recipient-control") or by movement of pelagic fishes into rocky reef habitats ("donor-control") has important implications for local food web dynamics. This study quantified use of space by lingcod relative to environmental factors in the San Juan Channel to make inferences about temporal and spatial conditions in which lingcod feeding on pelagic prey occurs. During the summer, lingcod utilized small ranges, rarely moved away from nearshore rocky habitats, were most active during the day, and showed relatively even activity levels across tidal periods. Our findings suggest that the mechanism by which lingcod acquire pelagic prey may be primarily donor-controlled, and 2) pelagic fishes serve as an important but variable spatial subsidy to sedentary lingcod in nearshore rocky reefs.

Puget Sound

Chinook Salmon Smolt Behavior and Habitat Use Near the SR520 Bridge in Lake Washington as Determined by Fine-Scale Acoustic Tracking

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Mark is a research biologist with the U.S. Fish & Wildlife Service in Lacey, Washington. Since 2003, Mark has been studying movement patterns and habitat use of juvenile Chinook salmon and predators in Lake Washington using acoustic tracking technology. Most of his work has used the fine-scale tracking system developed by HTI.

Chinook salmon (Oncorhynchus tshawytscha) *smolts en route to Puget Sound through Lake Washington must pass beneath the SR520 bridge, a major four-lane, 19-m wide structure. Knowledge of how the bridge influences smolt behavior and habitat use, and ultimately fitness and survival, may aid conservation and recovery efforts of this federally Threatened species. We used a fine-scale acoustic tracking system to evaluate tagged smolt behavior in June-July, 2007-2008 along a 560 m length of bridge spanning a major migratory corridor. Broad differences in migration behavior were observed in different release groups of fish. Some fish moved quickly and uni-directionally through the site (active migration behavior). Others spent longer periods of time in the area often milling and/or moving circuitously throughout the study site and adjacent areas (holding behavior). These site-scale behavioral differences did not appear to be a consequence of the bridge; rather, localized fish behavior in the immediate vicinity of the bridge differed depending on which site-scale behavioral pattern was exhibited. Many actively migrating fish passed beneath the bridge without delay. Others delayed for brief periods (< 1 minute to 46 minutes). Holding fish often selected for areas immediately adjacent to the bridge where they usually milled for several hours. Holding fish also selected for deeper water when they were near the bridge than when they were not near the bridge. Concurrent with the Chinook study, tracking and diet data were collected from two predators (smallmouth bass and northern pikeminnow) which will aid in determining habitat overlap and potential predation risk to Chinook smolts.*

Fine-Scale Movement Patterns and Habitat Use of Northern Pikeminnow in Lake Washington in June and July

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As part of a large study to evaluate movement patterns of Chinook salmon smolts near the SR 520 bridge on Lake Washington, we also documented the habitat use and movement patterns of northern pikeminnow, an important predator of Chinook salmon smolts. We used a fine-scale acoustic tracking system developed by Hydroacoustic Technology, Inc. (HTI), Seattle, Washington to track tagged fish in a 17.2 ha area along a 560 m stretch of the west end of SR 520 bridge from late May through early August in 2007 and 2008. A total of 42 northern pikeminnow were captured, tagged with acoustic tags, and released at the study site. Most fish left the study area shortly after release and provided little information. We were able to get good tracking data on approximately 10 fish. In general, the fish that used the site did not show any statistical selection for or against the bridge or areas near the bridge. That is, the bridge and areas near the bridge were generally used in proportion to their availability. Use of the bridge varied widely between individuals. Most often, northern pikeminnow selected moderately dense to dense vegetation during all times of day and night, and strongly selected overwater structures other than the bridge during the day only. Offshore open water areas and the offshore edge of vegetation were most often selected against. Northern pikeminnow selected for 4-6 m water column depth during all diel periods. Northern pikeminnow remained nearshore during the day, and used both nearshore and offshore areas during dusk and night. Some tagged fish in 2007 were also tagged with a Vemco depth tag. We obtained good tracking information on two fish: one moved offshore at night and was near the surface; the other also moved offshore but was near the bottom.

Puget Sound

Summer Habitat Use and Seasonal Movement Patterns of Smallmouth Bass in the Lake Washington Ship Canal and Lake Washington

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We studied the summer habitat use and seasonal movement patterns of smallmouth bass (Micropterus dolomieu) *in Lake Washington and the Lake Washington Ship Canal (LWSC). The LWSC (maximum depth, 13 m) is a 14-km long, narrow waterway that connects Lake Washington (maximum depth, 60 m) to Puget Sound. We used two types of acoustic tracking systems. Fine-scale, fixed-array systems by HTI were used to determine localized summer habitat use patterns, and Vemco receivers were used to determine broader-scale seasonal movement patterns. HTI systems were used at six sites: three in the LWSC and three in Lake Washington. Nine Vemco fixed receivers were deployed along the LWSC and in Lake Washington. Vemco fixed receiver data was supplemented with mobile tracking data. For 2004-2007, we tagged 104 smallmouth bass with HTI tags, and in 2006-2007 we tagged 69 bass with Vemco tags (some bass were tagged with both types of tag). During the summer, smallmouth bass were generally close to shore in water that was less than 4 m deep. Those associated with an overhead structure were generally in shallower water than those that were not associated with an overhead structure. Smallmouth bass were often closely associated with at least one of three habitat types: overwater structure, steep sloping shoreline (riprap or bulkhead), or the offshore edge of aquatic macrophytes. Based on Vemco data, smallmouth bass were often mobile and had large home ranges. Most moved from the LWSC to Lake Washington in the late summer and fall and then overwintered in the lake.*

Puget Sound

A Pilot Study of Mortality and Tag Loss in Captive Puget Sound Herring Surgically Implanted with Acoustic Tags

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We surgically implanted 150 captive 2-year-old herring with dummy acoustic tags in a controlled study to assess tagging mortality and tag loss (tag shedding) at the USGS Marrowstone Biological Laboratory on Marrowstone Island, Washington. The herring were assigned to one of four treatments: 1) 25 fish were given anesthesia with MS222 only, 2) 25 fish had anesthesia plus surgery (no implant), 3) 50 fish had a Vemco V7 tag implanted, and 4) 50 fish had a Vemco V9 tag implanted. The herring were monitored for 4.5 months. There was no mortality in the control groups. Four percent of the tagged herring (4 fish) died and a further 4% (4 fish) shed their tags but survived. Most of the mortality occurred soon after surgery and the peak of tag shedding was around week 6. We observed no difference in mortality or shedding between the tag types. The results are encouraging for further field work with herring.

Daily, Seasonal, and Yearly Patterns of Movement for Sixgill Sharks (*Hexanchus griseus*) in Puget Sound.....and Beyond

Kelly S. Andrews[1], Greg Williams[1], and Paul Levin[1]

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Kelly received his B.S. from Western Washington University in 1996 and his M.S. from San Diego State University in 2003. Since then he has been a fisheries ecologist at the Northwest Fisheries Science Center for the last six years. His primary interest lies in examining the role of habitat with respect to species interactions and community processes. Related to the symposium, Kelly has been examining the movement patterns of groundfish species in Puget Sound for the last 5 years in order to understand what processes are responsible for the observed patterns in movement.

The patterns of movement for apex predators will determine their impact on local communities and their susceptibility to natural or anthropogenic perturbations to their environment. Sixgill sharks Hexanchus griseus are the largest resident fish in Puget Sound and are known to feed upon a wide variety of prey in other parts of the world. We have been studying their patterns of movement for three years to address their potential role in the Puget Sound ecosystem and their potential susceptibility to fishing pressure. On a daily basis, sub-adult sixgill sharks generally have limited movement (<5 km). Many sharks occupy core areas during the winter, while their ranges expand in the summer. Sub-adult sharks have begun to leave Puget Sound after 2.5 years of residency since tagging. Larger sharks are the least detected and have been detected outside Puget Sound for up to 2 years and then return. These patterns of movement and stable isotope analyses suggest that Puget Sound is a region where mature individuals come to give birth and juveniles remain in the nearshore waters for some period before leaving Puget Sound for the outer coast.

Data

Large-Scale Movements and Survival of Snake and Yakima River Spring Chinook: The Big Picture from the Pilot-Phase POST Array

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David Welch is the president & founder of Kintama Research Corporation. David has a B.Sc. in Biology and Economics from the University of Toronto and a Ph.D. in Oceanography from Dalhousie University in Halifax. For the first 20 years of his career David worked for the Department of Fisheries and Oceans at the Pacific Biological Station in Nanaimo, on Vancouver Island. David developed the original concept of building continental-scale marine tracking arrays to resolve problems in marine fish population management in early 2000. He founded Kintama in 2000 to begin evaluating sensor technology for this purpose and to develop the required technology for building large-scale efficient telemetry arrays. Amongst other awards, in 2007 he received the Prix de Distinction, Fisheries & Oceans Canada (DFO) for "*outstanding scientific contributions related to national and international climate change research*" for his work on global warming and its potential impacts on Pacific salmon. In 2008 he was awarded the Prix d'Excellence from DFO in "*Recognition of Exceptional Scientific Contributions to the Government of Canada*".

We review our current POST array work to test several "big picture" issues concerning Columbia River salmon management and conservation: (a) Survival and tag retention of hatchery smolts implanted with dummy acoustic tags indicate that survival of freely migrating salmon can be followed up to the detection site in Alaska; (b) Measured in-river survival of acoustically tagged hatchery smolts matches independent PIT-tag survival estimates; (c) Survival of both barged and run-of-river hatchery smolts can be measured to N Vancouver Island, ~800 and 1,500 km from release, respectively, and provide essentially identical survival curves; (d) All survival curves show a similar smooth shape, with little evidence for different mortality rates in different parts of the migration path, including the dammed section of the Columbia. Our preliminary results thus do not support the assumption that ocean survival is necessarily better than freshwater survival. If correct, this conclusion has important implications for salmon conservation, given that much of the debate around salmon conservation focuses solely on freshwater recovery efforts. However, we caution that our current results do not yet encompass the full range of smolt entry times or sizes, results for wild stocks, or results for a broader range of stocks and species.

Data

Optimal Design & Operation of the Pacific Ocean Shelf Tracking Array (POST)—Making Ocean Measurements Cost-Effective & Policy Relevant

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David Welch is the president & founder of Kintama Research Corporation. David has a B.Sc. in Biology and Economics from the University of Toronto and a Ph.D. in Oceanography from Dalhousie University in Halifax. For the first 20 years of his career David worked for the Department of Fisheries and Oceans at the Pacific Biological Station in Nanaimo, on Vancouver Island. David developed the original concept of building continental-scale marine tracking arrays to resolve problems in marine fish population management in early 2000. He founded Kintama in 2000 to begin evaluating sensor technology for this purpose and to develop the required technology for building large-scale efficient telemetry arrays. Amongst other awards, in 2007 he received the Prix de Distinction, Fisheries & Oceans Canada (DFO) for "*outstanding scientific contributions related to national and international climate change research*" for his work on global warming and its potential impacts on Pacific salmon. In 2008 he was awarded the Prix d'Excellence from DFO in "*Recognition of Exceptional Scientific Contributions to the Government of Canada*".

POST is currently the world's largest fish telemetry system. Careful engineering of the 1st generation" array enables and essentially complete census capability-but at a significant cost. Here I review POST from the twin perspectives of (a) the broader scientific findings from the array and (b) technical operation & maintenance of a large scale observing system.

POST was designed around a particular acoustic tag (the V9), and detection efficiencies of ca. 95% are possible. However, at least 13 tag variants are now marketed by Vemco, many of which are both smaller and acoustically quieter. As biologists gravitate towards smaller tags; POST requires a facelift. Current work is focused on refining operational approaches and designing the 2nd generation" array to achieve arrays of "certified performance' at lowest cost. This will allow research studies that can achieve a known accuracy and precision in the results before the study begins. Work in this area provides the critical benefit of demonstrating that the new designs are "provably best", and therefore provide the best possible economic value and highest scientific data yields. Certified performance of the POST array will also provide the opportunity to design & conduct explicit experiments in the ocean to test key hypotheses.

See the Big Picture: Innovative Software Tools for Interpreting Columbia River Acoustic Tag Study Results

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Fish respond to many stimuli in the environment. Both fish behavior and the environment are dynamic and vary over time. This constantly changing interplay between fish and then environment creates challenges for fisheries managers. In order to gain a clearer picture of these relationships, fisheries managers use various tools including acoustic tags, to reveal both fine-scale fish behavior as well as fish survival over large watersheds. During the 2004-2008 spring and summer outmigrations, juvenile yearling Chinook (Oncorhynchus tshawytscha), *sockeye salmon* (O. nerka), *steelhead* (O. mykiss), *and sub-yearling Chinook smolts were tracked with acoustic tags in three dimensions as they approached and passed into turbine intakes, spillways, and surface bypass channel entrances at numerous dams on the Columbia River. These tagged fish were detected at many in-river sites as well. Using advanced data analysis tools, we visualized thousands of tag detections over multiple years in relation to different environmental factors including predatory events, river flow, and turbidity. An improved understanding of fish response to certain conditions was gained, but many more questions were generated. These innovative software tools enable fisheries managers to formulate better decisions based on both fine and broad temporal/spatial scales, as fish respond to a constantly changing environment.*

Data

The Hydrophone Data Repository (hydra.sounddatamanagement.com): Demonstration of a New Research Collaboration Website

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Jennifer Scheuerell is the owner and founder of Sound Data Management LLC. Jennifer received her M. Sc. from the University of Washington School of Aquatic and Fishery Sciences in 2004. Jennifer has been designing and building custom research databases for fisheries research scientists for nearly 10 years.

The Hydrophone Data Repository, or Hydra, was developed to enable research collaboration for Pacific Northwest fisheries researchers from federal and local agencies, universities, and tribes who are in aggregate using several hundred hydrophones to conduct studies on movement patterns of aquatic animals. Each research program is characterized by numerous tagged animals that move and a relatively limited number of acoustic receivers that are located to address a significant question for individual programs. Importantly, these tagged animals move over larger domains than individual receiver arrays. These researchers have recognized the value of coordinating placement of hydrophones to improve their collective listening capability and ability to address emergent, larger-scale management questions. Hydra provides the required data services to make such collaboration possible. Researchers upload the files generated by their hydrophones to Hydra and then download detections of only their tags from every hydrophone file in the system. Hydra securely archives each hydrophone file and then ensures data integrity as it parses data directly from hydrophone-generated files to a relational database via an automated protocol. Tag detections are immediately available when the receiver file is uploaded. Additional features of Hydra will also be presented.

Tag Travel: Free, Open Source Software for Animating the Movement of Tagged Animals Through an Array of Sensors

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Many different tagging methods produce spatial and temporal information on the presence, absence, and movement of animals in their environment. While these types of data are useful for addressing both management and ecological questions, they can be difficult to visualize, particularly when considering multiple individuals. I will discuss and demonstrate the newly released TagTravel software, a free GUI tool for animating the paths of tagged animals as they move through an array of sensors. The software includes the ability to map geographic features associated with the sensor array, and can simultaneously map environmental measurements (e.g. daily temperature, moon phase, etc). The software is freely available on the open-source code sharing site http://www.ecologybox.org.

Data

Identifying Movement Patterns of Resident Chinook Salmon and Links to Environmental Properties in Puget Sound Using Acoustic Tag Data

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Stephanie Moore is a senior postdoctoral fellow with the University Corporation for Atmospheric Research and NOAA's Northwest Fisheries Science Center. Her contributions are centered on linking climate to variations in coastal ecosystems. Currently she is investigating climate impacts on harmful algal blooms in Puget Sound and on the outer coast of Washington State. Stephanie obtained her PhD from the University of New South Wales, Australia, in 2005. She worked with local government in Australia to develop the Estuarine Management Plan for Wallis Lake; the largest commercial oyster producing area and largest area of seagrass habitat on the New South Wales coast. She was a research associate with the University of Washington's Climate Impacts Group and the School of Oceanography from 2005 until 2008.

Preliminary results are presented from analysis of acoustic tag data to identify movement patterns of resident Chinook salmon in Puget Sound from 2006 to 2008. Patterns of fish detections were compared on a seasonal timescale for each of the receiver locations. Fish with multiple detections were classified as "movers" if they were detected at multiple receivers or "sitters" if they were detected at only a single receiver. Information on environmental properties from the Washington State Marine Waters Monitoring Program will be used to assess habitat quality for resident fish and will be compared with fish movement patterns.

Panel Discussion: On the Trail of JAWS—The Salish Sea Sharks

Mark Pederson: **Moderator Introduction**
Margenex International; margenex@comcast.net

Mr. Pedersen is Vice President of the Washington/British Columbia Chapter of the American Fisheries Society and member of the Chapter Marine Fish Committee. He is the former Assistant Director of Washington Department of Fisheries Marine Fish Program. He has a BS degree in Fisheries and MS degree from the University of Washington. Since 1992, he has been a private consultant working on mitigating potential environmental impacts related to major shoreline projects in Washington. Recently, he has been selected by the Marine Stewardship Council to be one of the expert assessors for MSC certification of the Oregon pink shrimp fishery and Pacific NW midwater trawl fisheries for Pacific whiting. He has also worked as a fisheries expert for the World Bank, evaluating or preparing Strategic and Social Assessments for proposed coastal infrastructure projects in Peru and Mauritania (W. Africa).

The sixgill shark (Hexanchus griseus) *is the largest predatory shark regularly encountered in the Salish Sea. Their ecosystem role is largely unknown, but they are a top predator. Their relative, the spiny dogfish* (Squalus acanthias), *is closely intertwined with the sixgill because it is a target for commercial fisheries, and sixgills are caught incidentally. Dogfish had been an important component of Salish Sea fisheries to the late 1940s, when the fishery collapsed from overfishing and market demand. Population levels slowly increased to sustain commercial fisheries of 2000 mt since 1978. Recent concerns regarding dogfish stocks have reprioritized assessment efforts. The IUCN lists the sixgill shark as lower risk/near threatened species. Understanding life histories of apex predators is crucial in understanding the marine ecosystems response to human perturbations and for effectively conducting ecosystem-based management. This session brings together a unique group of scientists/managers to identify current ecological roles and issues; summarize latest research; and discuss future action for Salish Sea sharks.*

Greg Bargmann: **Management of Sixgill Sharks: Past, Present, and Future**
Washington Department of Fish & Wildlife; bargmggb@dfw.wa.gov or Gregory.bargman@dfw.wa.gov

Greg Bargmann has been employed as a marine fish biologist and unit manager for the Washington Department of Fish and Wildlife since 1974. Previous to that time, he has been employed as an instructor at Green River Community College and as a research biologist for the National Marine Fisheries Service. He enjoys working with little understood and neglected species such as sharks, smelt, and squid.

Low level fisheries for sixgill sharks have been occurring for decades in Puget Sound. For most of this time the species received little attention from management or research agencies. Beginning in 2000 interest in harvest of this species increased and the Department of Fish and Wildlife eliminated harvest by both recreational and commercial fisheries. Subsequently a multi-agency research investigation was launched to learn of the abundance and biology of this species. The results of this investigation and implications for future management of sixgill sharks and other similar species will be discussed.

Phil Levin: **Movement Behaviour in Sixgill Sharks: Implications for Ecosystem Impacts on and by an Apex Predator in Puget Sound–Georgia Basin**

NOAA/NWFSC; phil.levin@noaa.gov; Kelly Andrews, Peter Horne, and Greg Williams

Dr. Phillip Levin is program manager of the Science for Ecosystem-based Management Initiative and leader of the Ecosystems and Climate Team at NOAA's Northwest Fisheries Science Center. Before joining NOAA, Levin was an Assistant Professor of Marine Biology at Texas A&M University (1994-96), and an Assistant Research Professor at the University of California, Santa Cruz (1997-99). He received his Ph.D. in zoology from the University of New Hampshire in 1993 and was a postdoctoral fellow at the Institute of Marine Science, part of the University of North Carolina. Levin has focused his work on the ecology and conservation of temperate marine fishes, but he has also conducted research on mammals, birds, invertebrates, and macroalgae of coral reefs, estuaries and freshwater rivers and streams. His current research focuses on bridging the gaps between behavioral ecology, conservation biology and fisheries science, and developing quantitative approaches to inform ecosystem-based management of marine systems.

The manner in which organisms move through their environment is crucial to the success of individuals and can generate observed spatial patterns of the population. We have been examining the patterns of movement in sixgill sharks as a means to better predict the consequences of environmental change and/or human perturbation on this species. In 2005-2008, we acoustically tagged >40 sixgill sharks in Puget Sound with pressure sensor transmitters and quantified their movement patterns via passive monitoring and active acoustic tracking. Acoustic monitoring suggests that sharks occupy core areas during late fall-early spring and diffuse away from these core areas in warmer months. Continuous tracking over 24h revealed limited movement. A model of a bounded correlated random walk suggests sharks move much less than predicted from acoustic monitoring. We conclude that we are missing a critical set of movement behaviors. Using what we know about movement, we quantitatively describe a suite of behavior that must have occurred, but did not observe. We next use this empirically-based movement model to explore the potential impacts of human perturbations on sharks and their potential to influence the marine community. Results suggest these large predators may have a substantial ecological impact and are at risk of local depletion from fisheries.

Kelly Andrews: **Diel Patterns of Behavior in Sixgill Sharks, Spiny Dogfish and Ratfish: Patterns, Causes and Ecosystem Consequences**

NOAA/NWFSC; kelly.andrews@noaa.gov; Greg Williams, NOAA/NWFSC; Debbie Farrer, WDFW; Nick Tolimieri, NOAAA/NWFSC; Chris Harvey, NOAA/NWFSC; Greg Barmannn, WDFW; and PHil Levin, NOAA/NWFSC

Kelly received his B.S. from Western Washington University in 1996 and his M.S. from San Diego State University in 2003. Since then he has been a fisheries ecologist at the Northwest Fisheries Science Center for the last six years. His primary interest lies in examining the role of habitat with respect to species interactions and community processes. Related to the symposium, Kelly has been examining the movement patterns of groundfish species in Puget Sound for the last 5 years in order to understand what processes are responsible for the observed patterns in movement.

Understanding life histories of apex predators is crucial for understanding how marine ecosystems respond to human perturbations as well as for effectively conducting ecosystem-based management. Even so, we lack basic knowledge of many large predatory fishes. In Puget Sound, we are investigating diel vertical movement patterns of sixgill sharks, the largest resident predatory fish in Puget Sound, to determine what drives changes in their behaviour. We acoustically tagged 39 sixgill sharks with pressure sensor acoustic transmitters and monitored their movement patterns via passive and active acoustic receivers in Puget Sound, WA. Sixgill sharks show very consistent diel patterns of vertical movement where they inhabit shallower waters at night and move into deeper waters during the day. This pattern is consistent between both sexes and across the entire size range of individuals collected (100-300 cm total length). Seasonally, sixgill sharks inhabit deeper waters in the fall and winter, while moving to shallower waters during the spring and summer. The sixgill shark also shows much more activity at night and during the summer. In addition, pairs of sharks tracked simultaneously made synchronous ascents and descents throughout entire 24-hour tracking periods. These behaviours are consistent with the hypothesis that sixgill sharks are responding to similar stimuli and that they are using these periods of increased activity to forage for prey. Potential prey of sixgill sharks that make similar diel patterns of vertical movement include ratfish, pacific hake and Dungeness crabs. We have begun to monitor the movements of spotted ratfish and spiny dogfish in the same waters as sixgill sharks to investigate interactions within the community.

Shawn Larson: **Sixgill Shark (Hexanchus griseus) Conservation Ecology Project Update**

The Seattle Aquarium; Shawn.Larson@seattle.gov; Jeff Christiansen; Joel Hollander; and Denise Griffing

Shawn Larson is the Curator of Research and Animal Health Coordinator at the Seattle Aquarium. She has worked full time at the aquarium since 1994 and received her Ph.D. from the School of Aquatic and Fishery Science at the University of Washington in 2003. She is an active member of the aquarium's dive team and participates in most of the aquarium's underwater research programs. She leads 14 concurrent research projects underway at the aquarium and coordinates activities of outside researchers wishing to conduct projects at the aquarium.

Jeff Christiansen is a Biologist and Diving Safety Officer at the Seattle Aquarium (beginning in 1982) and serves as Director of the Sixgill Shark Research Project. He received a Bachelors of Science degree in Fisheries from the University of Washington in 1980. Mr. Christiansen specializes in temperate water vertebrate and invertebrate culture, both for captive husbandry and basic research. Mr. Christiansen is a PADI Master Scuba Diver Trainer with numerous specialty certifications.

Denise Griffing is Project Coordinator for the Sixgill Shark Research Project and has served in several paid/volunteer capacities at the Seattle Aquarium since 1993. She received a Bachelors of Science degree in Computer Science from Rensselaer Polytechnic Institute in 1986. Ms. Griffing's areas of expertise include communications, video/data analysis, and database management.

The Aquarium's Sixgill Shark (Hexanchus griseus) *Population Ecology project is a long-term conservation research program to address gaps in the body of scientific knowledge on these relatively unknown animals. Aquarium biologists have been informally monitoring sixgill shark sightings by local divers for the past 10 years and formally studying sixgill population ecology for the past six years. Living mainly at abyssal depths (2000-5000 feet) but also in shallow waters of Puget Sound, Washington, sixgills are thought to be long-lived and slow-growing, and appear to have established movement corridors and territories that remain relatively fixed over time. Sixgills are an at risk species because as apex predators they are important members of marine communities; and, owing to their low reproductive rates, are thought to be extremely vulnerable to exploitation. No information exists on how many sixgills are in Puget Sound, whether they are year-round or seasonal, local or migratory, or whether they use local water primarily for feeding or for recruitment. The Aquarium's sixgill population ecology research involves four interwoven techniques to determine aspects of basic sixgill biology using (1) genetics research, (2) visual marker tagging, (3) acoustic tracking and (4) video analysis. This research should substantially improve scientific understanding of abundance, diversity, relatedness and movement characteristics of movement in these deep water sharks in Puget Sound.*

The mission of the aquarium is to inspire conservation of the marine environment while the mission of our research program is to conserve individuals as well as the species. This mandate dictates that this research must be done utilizing minimally invasive and non-lethal SCUBA based techniques without manual restraint of the animal. The aquarium began tagging and tracking these animals in 2003 and in 2008 began collecting data from our archived video taken since 2003 resulting in preliminary statistics on absolute numbers of sharks seen, number of sharks tagged, number of returned sharks, sex and size distribution. Final population genetics parameters and summary statistics for sixgills within Puget Sound will also be presented.

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Chapter 1.—EAARL: An Airborne LiDAR System for Mapping Coastal and Riverine Environments

Amar Nayegandhi, C.W. Wright, and J.C. Brock

LiDAR, an acronym for Light Detection and Ranging, is an active remote sensing technique that determines the distance between the sensor and the target by accurately measuring the round-trip time of a pulse of laser energy (Wehr and Lohr, 1999). The Experimental Advanced Airborne Research Lidar (EAARL) is an airborne LiDAR system that provides unique capabilities to survey coral reefs, nearshore benthic habitats, coastal vegetation, and sandy beaches (Wright and Brock, 2002). Operating in the blue-green portion of the electromagnetic spectrum, the EAARL is specifically designed to measure submerged topography and adjacent coastal land altitudes in a single scan of transmitted laser pulses (fig. 1). Four main features separate the EAARL from traditional airborne bathymetric LiDAR: (1) a relatively short (1.3 ns) laser pulse, (2) a radically narrowed receiver field-of-view (FOV)(1.5–2 mrad), (3) digitized signal temporal backscatter amplitude waveforms, and (4) software as opposed to hardware implementation of real-time signal-processing elements. The short pulse and narrow FOV are beneficial in coastal environments to determine bare-Earth topography under short vegetation, as well as in riverine environments where large changes in topography occur over a very small area. The small receiver FOV rejects ambient light and multiplies scattered photons from the water column and bottom-reflected backscatter (Feygels et al., 2003), thereby ensuring relatively high contrast and short duration of the bottom return signal. The EAARL system can accommodate a large signal dynamic range, thereby making it suited to mapping topography over a variety of reflective surfaces in the coastal zone, ranging from bright sand to dark submerged sea-bottom.

EAARL uses a very low-power, eye-safe laser pulse, in comparison to a traditional bathymetric LiDAR system that allows for a much higher pulse-repetition frequency (PRF) and significantly less laser energy per pulse (approximately 1/70th) than do most bathymetric LiDARs. The laser transmitter produces up to 10,000 short-duration (1.3 ns), low-power (70 μJ), 532-nm-wavelength pulses each second. The energy of each laser pulse is focused in an area roughly 20 cm in diameter when operating at a 300-m altitude. Based on test flights over typical Caribbean coral reef environments, EAARL has demonstrated penetration to greater than 25 m, and can routinely map coral reefs ranging in depth from 0.5 to 20 m below the water surface.

The EAARL system uses a “digitizer only” design, which eliminates all hardware-based high-speed front-end electronics, start/stop detectors, time-interval units, range gates, etc., typically found in LiDAR systems. The EAARL system instead uses an array of four high-speed waveform digitizers connected to an array of four sub-nanosecond photo-detectors. Real-time software is used to implement the system functions normally done in hardware. Each photo-detector receives a fraction of the returning laser backscattered photons. The most sensitive channel receives 90% of the photons, the least sensitive receives 0.9%, and the middle channel receives 9%. The fourth channel is available for either water Raman or 1064-nm infrared backscatter depending on the application. All four channels are digitized synchronously with digitization beginning a few nanoseconds before the laser is triggered and ending as long as 16,000 ns later. A small portion of the outgoing laser pulse is sampled by fiber optic and injected in front of one of the photo-detectors to capture the actual shape, timing, and amplitude of the laser pulse shortly after it is generated. The backscattered laser energy for each laser pulse is digitized into 65,536 samples, resulting in more than 150 million digital measurements being taken every second. The resulting waveforms are partially analyzed in real time to locate the key features such as the digitized transmit pulse, the first return, and the last return. The real-time waveform processor automatically adapts to each laser return waveform and retains only the relevant portions of the waveform for recording. Thus, the storage space required for returns from tall trees or deep water is more than the storage requirement for beach or shallow water backscatter. In addition to the LiDAR, the EAARL sensor suite includes a digital three-band color infrared camera, a red-green-blue (RGB) digital camera, a dynamically tuned Inertial Measurement Unit (IMU), and precision kinematic Global Positioning System (GPS) receivers that together provide for sub-meter geo-referencing of each laser and photographic pixel.

Post-processing of EAARL data is accomplished using a custom-built Airborne Lidar Processing System (ALPS) that combines laser return backscatter digitized at 1-ns intervals with aircraft positioning data derived from the IMU and GPS receivers. The ALPS software enables the exploration and processing of LiDAR waveforms and the creation of Digital Elevation Models (DEMs) for bare-Earth, canopy-top, submerged topography, and vegetation canopy structure. The EAARL system utilizes Earth-centered coordinate and reference systems, thereby eliminating the need for referencing submerged topography data to relative water level or tide gauges.

The EAARL has been operational since the summer of 2001, when it was used to survey the coral reef tract in the northern Florida Keys (Wright and Brock, 2002; Brock et al., 2004). Subsequent surveys in 2002, 2004, and 2006 along the Florida reef tract have enabled the creation of submerged topography products at Biscayne National Park (Brock et al., 2006a), Florida Keys National Marine Sanctuary (Brock et al., 2007), and Dry Tortugas National Park (Brock et al., 2006b). Several surveys have been conducted using the EAARL system in a variety of coastal communities, including barrier islands along the Atlantic coast (Nayegandhi et al., 2005) and around the margins of an urbanized Gulf of Mexico estuary (Brock et al., 2002; Nayegandhi et al., 2006). An EAARL survey also was conducted along the Platte River in central Nebraska in March 2002 (Kinzel and Wright, 2002). The Platte River is a braided sand-bedded river that presents technological and logistical challenges with regard to collecting topographic and bathymetric measurements. The vertical accuracy of the system when compared with Real-Time-Kinematic (RTK) GPS surveys was estimated to be 16–22 cm root mean square error (RMSE) in the Platte River (Kinzel and Wright, 2002). Subsequent shallow river surveys conducted in the Lower Boise River, Idaho, yielded vertical accuracies of 14–18 cm RMSE (unpublished data). Further studies have estimated the vertical accuracy of the EAARL system to range from 10 to 14 cm (RMSE) for submerged topography (0.1–2.5 m water depth) and 16–20 cm for sub-canopy topography under a variety of dense coastal vegetation communities along the margins of Tampa Bay, Florida (Nayegandhi et al., in press). Specific design considerations for the EAARL system, which make it an ideal system for mapping the topography and morphologic habitat complexity of shallow reef substrates, include the high spatial (20-cm-surface footprint at nominal flying altitude of 300 m AGL) and sample (1-ns digitizing interval) resolution. The EAARL system also is designed to map substrates in shallow water (<5 m) where traditional hydroacoustic ship-borne instruments cannot operate efficiently, field surveys are time-consuming and cost-prohibitive, and traditional bathymetric LiDARs are not applicable. These design considerations also are uniquely well suited for the seamless and simultaneous mapping of shallow, clear channel-bed topography in rivers and streams, and for resolving the bare-Earth topography of the surrounding floodplain.

Chapter 2.—Stream and Riparian Habitat Analysis and Monitoring with a High-Resolution Terrestrial-Aquatic LiDAR

Jim McKean, Dan Isaak, and Wayne Wright

Management of aquatic habitat in streams requires description of conditions and processes both inside the channels and in the adjacent riparian zones. Biological and physical processes in these environments operate over a range of spatial scales from microhabitat to whole river networks. Limitations of previous survey technologies have focused management and research activities on either ends of this spectrum. Environmental monitoring also is very challenging as habitat conditions and specie use can vary over a wide range of temporal scales. We used a narrow-beam airborne green LiDAR, the Experimental Advanced Airborne Research LiDAR (EAARL), to study channel and floodplain conditions and processes at length scales from several meters to tens of kilometers with a spatial resolution of about 1 meter. We also monitored channel change over a period of 3 years using repeated EAARL surveys. The EAARL mapped beds of channels correctly, but tended to smooth the edges of steep banks. In 10 kilometers of unconfined channel, there is a hierarchy of spatial scales of salmon spawning habitat controlled by a combination of post-glacial valley evolution and modern channel hydraulics. Wavelets are a powerful technique to analyze the continuous EAARL data and describe habitat distribution in the frequency domain. This terrestrial-aquatic LiDAR could catalyze rapid advances in understanding, managing, and monitoring aquatic ecosystems.

Chapter 3.—Advanced Tools for River Science: EAARL and MD_SWMS

Paul J. Kinzel

Disruption of flow regimes and sediment supplies, induced by anthropogenic or climatic factors, can produce dramatic alterations in river form, vegetation patterns, and associated habitat conditions. To improve habitat in these fluvial systems, resource managers may choose from a variety of treatments including flow and/or sediment prescriptions, vegetation management, or engineered approaches. Monitoring protocols developed to assess the morphologic response of these treatments require techniques that can measure topographic changes above and below the water surface efficiently, accurately, and in a standardized, cost-effective manner. Similarly, modeling of flow, sediment transport, habitat, and channel evolution requires characterization of river morphology for model input and verification. Recent developments by the U.S. Geological Survey with regard to both remotely sensed methods (the Experimental Advanced Airborne Research LiDAR; EAARL) and computational modeling software (the Multi-Dimensional Surface-Water Modeling System; MD_SWMS) have produced advanced tools for spatially explicit monitoring and modeling in aquatic environments. In this paper, we present a pilot study conducted along the Platte River, Nebraska, that demonstrates the combined use of these river science tools.

Chapter 4.—Using Bathymetric and Bare Earth LiDAR in Riparian Corridors: Applications and Challenges[1] need footnote text

Robert C. Hilldale, Jennifer A. Bountry, and Lucille A. Piety

LiDAR products have greatly advanced the technological capabilities in river and floodplain assessments, however, depending on application and data-quality needs certain challenges remain. The focus of this paper is to describe (1) how bare earth and bathymetric LiDAR is currently being applied in multi-disciplined river and riparian restoration assessments in the Pacific Northwest, and (2) how LiDAR products might be improved to expand future capabilities in these studies. Examples applications will be provided from several river studies. This paper is expected to benefit both users and data providers of airborne LiDAR.

There is a growing need to precisely and accurately represent river bathymetry with high resolution to study fluvial environments for flow hydraulics, flood routing, sediment transport, aquatic habitat, and monitoring of geomorphic change. This is especially true for long study reaches at watershed scales where field survey methods can be time consuming and costly. Hydraulic modeling and geomorphic studies require well represented terrain, above and below water, in order to decrease uncertainty in conclusions resulting from such studies. To date, the Bureau of Reclamation has acquired airborne LiDAR bathymetry (ALB) on rivers in Washington, California, and Idaho and has made use of ALB flown in Nebraska. Future bathymetric LiDAR flights are currently being considered and more will likely be needed. This paper highlights some of the areas in which improvements to ALB would benefit those interested in riverine studies. These include improved definition in high relief areas, improved resolution, decreased error and standard deviation, improved water surface detection, and improved guidelines related to water clarity requirements. Some of these issues might be realized through a decrease in output power, processing multiple returns, and improved understanding of variation in data quality.

Bare earth LiDAR has been utilized in Pacific Northwest restoration assessments to delineate geologic controls and surface breaks (e.g., terraces, alluvial fans) along the river system, determine channel slopes, identify historical channel paths, determine connectivity of present channels, locate human features, and map vegetation. Bare earth LiDAR has been particularly advantageous in densely vegetated areas where access is difficult for distinguishing historical channels and surfaces underneath a vegetation canopy. The resolution of LiDAR needed for these applications typically is 1 meter spot spacing for both first return and bare earth. When utilizing LiDAR in vegetated, steep, and wetted areas, data quality is often difficult to ascertain. LiDAR tends to represent most terrain well, but checks with ground survey data can reveal significant differences in critical areas. For example, quality-control checks generally are not located in areas of poor GPS coverage with dense vegetation and high relief, leaving questions related to data quality in these areas that typically are of greatest interest. Improvements in post¬processing and quality-control checks could greatly increase utilization and confidence when using LiDAR as a monitoring tool, for numerical modeling, and tracking temporal changes to topography.

Chapter 5.—Application of the SHOALS Survey System to Fisheries Investigations in the Columbia River

By Kenneth F. Tiffan, Paul G. Wagner, Keith S. Wolf, and Paul A. Hoffarth

We used a Scanning Hydrographic Operational Airborne LiDAR (Light Detection and Ranging) Survey (SHOALS) system to collect high-resolution bathymetry for 33 km of the Hanford Reach. Data were used in conjunction with hydrodynamic and predictive habitat models within a GIS (Geographical Information System) framework to evaluate the effects of a varying hydrograph on juvenile fall Chinook salmon rearing habitat and risk from stranding and entrapment. Furthermore, we were able to estimate the number of juvenile fish that were stranded and entrapped in pools when operations at Priest Rapids Dam caused rapid decreases in river flows. Our findings were ultimately used to estimate impacts of power generation operations at Priest Rapids Dam and develop long-term policy and operational guidelines to protect juvenile fall Chinook salmon during the spring rearing period.

Chapter 6.—Use of Airborne Near-Infrared LiDAR for Determining Channel Cross-Section Characteristics and Monitoring Aquatic Habitat in Pacific Northwest Rivers: A Preliminary Analysis

Russell N. Faux, John M. Buffington, M. German Whitley, Steve H. Lanigan, and Brett B. Roper

Aquatic habitat monitoring is being conducted by numerous organizations in many parts of the Pacific Northwest to document physical and biological conditions of stream reaches as part of legal- and policy-mandated environmental assessments. Remote sensing using discrete-return, near-infrared, airborne LiDAR (Light Detection and Ranging) and high-resolution digital imagery may provide an alternative basis for measuring physical stream attributes that are traditionally recorded by field crews in these monitoring efforts. Here, we compare physical channel characteristics determined from airborne LiDAR versus those measured from field surveys using a total station. Study sites representing three different channel types (plane-bed, pool-riffle, and step-pool) with bankfull widths ranging from 2.5 to 18.6 m were examined in the upper John Day River basin, Oregon. LiDAR was flown on each study reach at a native pulse density of about 4 pulses/m_2, with up to four returns per pulse. Channel cross sections and stream gradient were determined from LiDAR-derived digital elevation models (DEMs) and directly compared to total station measurements. The ability to remotely sense bankfull elevations and associated channel geometry was of particular interest in this study. Because bankfull mapping from LiDAR depends on topographic indicators (breaks in streambank slope), bankfull elevation was determined objectively from plots of hydraulic depth (flow area divided by width) as a function of flow height at each cross section, with bankfull defined as the maximum value of this function, or as the first plateau in the hydraulic depth function in channels with multiple terraces. The latter definition allows a blind test of remote sensing capabilities for cases where no field observations of bankfull elevation are available.

Preliminary results show that, with the exception of one outlier, the first-terrace elevations determined from LiDAR DEMs differed from those of the total station by 0–40 cm (15 cm RMSE), corresponding channel widths differed by 0.23–5.23 m, and reach-average water-surface slopes differed by 0.0–0.0018 m/m. Furthermore, the LiDAR-derived cross-sectional profiles generally corresponded with those of the total station measurements above the water-surface elevation. However, first-terrace elevations frequently differed from field observations of bankfull stage, indicating that successful remote sensing of bankfull geometry using airborne LiDAR requires field observations to train identification of bankfull topography in LiDAR DEMs. When properly applied, remote sensing using airborne LiDAR has the potential to extend the spatial coverage, speed, consistency, and precision of physical stream measurements compared to existing field based techniques, and can be used to quantify higher-order topographic metrics (e.g., areas, volumes, curvature, and topology) beyond the point and line metrics currently measured by channel monitoring programs.

Chapter 7.—Managing, Manipulating, and Serving LiDAR Terrain Data and Orthoimagery for Riverine Habitat Assessment and Remediation Project Design for Salmon Recovery in the Pacific Northwest[1]

By Kristin Swoboda, Kurt Wille, Mike Beaty, and Greg Gault

The recent advent of affordable, high quality LiDAR and orthoimagery, acquired from aircraft platforms, offers new opportunities and challenges for end users and data managers supporting riverine habitat assessment and remediation project planning for salmon recovery in the Pacific Northwest. These include: (1) handling and manipulating extremely large, highly detailed datasets, (2) data processing and delivery to meet end user needs, and (3) the use of web services technologies to improve access and performance. This paper provides an approach for managing and delivering LiDAR data (points and surfaces) and orthoimagery for use by Reclamation engineers, hydrologists, and geologists in support of hydraulic modeling, tributary and reach assessments, and engineering design.

Chapter 8.—Mapping Intertidal Eelgrass Landscapes in Hood Canal (WA) Using High Spatial Resolution Compact Airborne Spectrographic Imager (CASI) Imagery

Ralph J. Garono, Charles A. Simenstad, Robert Robinson, Chris Weller, and Steve Todd

Intertidal eelgrass (Zostera marina) beds are a vital resource for many Pacific Northwest estuarine organisms including juvenile chum salmon (Oncorhynchus keta) and an important indicator of estuarine condition. Consequently, there is a need for current information describing eelgrass abundance and distribution. Recent studies suggest some eelgrass populations in Puget Sound may be declining. Remote sensing methods commonly are used to develop data sets describing the location and extent of landscape features, such as eelgrass beds, for large areas; however, there are a number of challenges that limit the use of remote sensing to map intertidal eelgrass beds in Pacific Northwest estuaries. We selected Compact Airborne Spectrographic Imager (CASI) to map intertidal eelgrass beds in Hood Canal because it gave us precise control over acquisition time, and spatial and spectral resolution. Controlled timing of image acquisition was necessary to collect imagery from intertidal eelgrass beds exposed during low tide. A high degree of spectral resolution was necessary to separate spectrally similar cover classes (e.g., green macroalgae and eelgrass). During June and July 2000, we collected 19-band CASI imagery with a pixel size of 1.5 m. We used a combination of unsupervised/ supervised classification to classify imagery for about 1,100 ha shoreline. We mapped 12 cover classes using training data collected from 174 sites. We found good agreement between classified eelgrass cover classes and existing eelgrass beds during our accuracy assessment. We concluded that 19-band CASI data were adequate to map eelgrass beds and to separate them from spectrally similar cover classes.

Chapter 9.—Using Remote Sensing to Assess Anthropogenic Influences on Stream Temperature

Mimi D'Iorio and Carol Volk

In-stream water temperatures are regulated by a variety of intrinsic and extrinsic environmental variables dictated by the natural and anthropogenic state of a fluvial stream system. To evaluate how landscape scale processes relate to in-stream conditions, this study applies an integrated remote sensing and GIS-based approach to compare in situ measured stream-water temperatures with remotely derived proxies for land cover and land use in the John Day basin of east-central Oregon. Preliminary findings suggest that stream temperatures correlate more strongly with landscape variables assessed at the watershed level than at the reach scale, suggesting that instream conditions may be regulated by watershed characteristics present well beyond the traditional riparian corridor. This research lends insight to fish habitat modeling strategies by testing the utility and application of remotely derived landscape variables as proxies for stream habitat function, fish performance, and restoration potential.

Chapter 10.—Modeling Watershed Condition and Trend—How the Aquatic Riparian Effectiveness Monitoring Program (AREMP) is Evaluating Watershed Condition and Trend in the Pacific Northwest

Peter Eldred and Kirsten Gallo

The Aquatic and Riparian Effectiveness Monitoring Program (AREMP) is a multi-Federal agency program developed to assess the effectiveness of the Northwest Forest Plan (NWFP) in maintaining or restoring the condition of watersheds in the NWFP area. The NWFP encompasses the range of northern spotted owl habitat, about 58 million acres in western Washington, western Oregon, and northwest California. AREMP's goal is to evaluate the status and trend of watershed condition at the 6th-field subwatershed scale. To do this, a random sample of 250 subwatersheds was selected from 1,400 subwatersheds that have at least 25% Federal ownership along the stream channels. About 30 subwatersheds a year are visited to collect field data from 4 to 8 randomly selected stream reaches in each subwatershed. GIS and remotely sensed data are used to evaluate the upslope and riparian condition in the 250 sample subwatersheds, along with field data where available. This information was aggregated with a decision-support model to produce a watershed condition score for each subwatershed. The watershed condition was evaluated at time 1 (1994) and time 2 (2004) to assess trends. The results of the status and trend for the first 10 years was published in 2004. The program is now evaluating the trend and condition for the next 5-year period for a report update. This paper gives an overview of the analysis process and how the program is evolving.

Watershed condition and trend is evaluated using decision-support models. Decision-support models document decision processes and allow the same process to be applied consistently across time and space. The models developed by the monitoring program are used to evaluate whether the subwatersheds are in good condition, meaning the physical and biological processes are intact to create and maintain salmonid habitat. Decision support models work by evaluating individual attributes (such as road density) and calculating an evaluation score for each attribute that ranges between -1 and 1, with -1 being poor and 1 being good. The model then aggregates the evaluation scores of all attributes into a single watershed condition score. To account for the ecological diversity within the NWFP area, a decision-support model was constructed for each of the seven different physiographic provinces. The models were built in workshops attended by local agency professionals. Lacking onsite instream measurements, surrogates for watershed condition must be used, such as number of road and stream crossings. The workshops consisted of an informal group process through which participants came to consensus on how the model evaluated individual attributes and aggregated the scores of individual attributes. Each attribute has a "fuzzy curve" associated with it. The curve defines the values at which the attribute scores a 1 or a -1 and the shape of the transition between the two scores. The transition may be abrupt, such as water temperature reaching a lethal threshold, or gradual as the density of roads increase the habitat score gradually decreases. Following the workshops, models were constructed and run, and the results returned to the workshop participants. Participants compared the model results with their knowledge of the condition of watersheds and suggested refinements to the model as necessary.

Some of the watershed parameters evaluated in the model are road and stream crossings, road densities inside riparian areas, road miles by slope position, miles of road on unstable slopes, percentage of large conifers in riparian areas, percent of urban and agricultural areas, and area by fire condition class. These parameters rely on GIS data. The GIS layers for streams, roads, and vegetation did not exist in a continuous uniform layer for the Forest Plan area. Continuous layers were assembled from various sources. Compiling data from multiple agencies and sources is problematic because data standards (and therefore data layers) are not consistent between agencies. Available data for private lands generally are at a lower resolution than data for public lands. A Pacific Northwest hydrography framework layer exists for Oregon and Washington, but stream density on the layer varies greatly across ownerships, with a wide range of standards and mapping intensities being used. For vegetation, the interagency vegetation mapping project (IVMP) layer was used. This is a uniform layer for the Oregon and Washington portion of the NWFP area developed from Landsat satellite imagery. For California, a vegetation layer derived from a combination of Landsat imagery and aerial photograph interpreted polygons was developed (CALVEG). BLM, Forest service, and USGS map data (DLGs) were used for the GIS road layer. The GIS parameters were used with in-channel physical, chemical, and biological data where they were available in the decision-support models.

The watershed status and trend evaluation is expanding from the original sample of 250 to all 1,400 6th-field subwatersheds with at least 25% Federal ownership in the NWFP area. Because of the high cost of field visits and the large extent of the project area, the program is only able to visit a very small number of subwatersheds each year. So far about 170 subwatersheds have been visited since 2002. To determine the status and trend of all subwatersheds, the program will be relying on GIS and remotely sensed data. A new vegetation layer, the Interagency Mapping and Assessment Project (IMAP), is being developed from Landsat imagery. IMAP uses the Gradient Nearest Neighbor method to assign plot information to every pixel. IMAP rasters will be created for they entire NWFP area for 1994 and 2006. This method provides a wide range of vegetation attributes in a 30-m grid. Consequently, we can use more detailed information in evaluating vegetation and compare current attribute levels with the historic range of variability. Change detection overlays will be created by looking at all intervening years instead of just comparing 2 years as was done in the past. This creates a complex series of changes that can be thought of as a life history of a pixel. Subtle changes can be picked up with more confidence, and variation due to clouds and shadows become less important. The resulting change layer will have attributes not just for whether a pixel has experienced a stand replacing event, but also for how it is recovering and subtle changes such a thinning can be picked up.

A landslide model developed by Dan Miller calculates landslide susceptibility for each pixel of a watershed area using topography derived from DEMs, vegetation, and roads. To develop the parameters for the landslide model, landslides digitized from aerial photographs in 14 watersheds were combined with field data. Landslide polygons were overlaid with topography, vegetation, and road buffers to determine how these three factors influenced the occurrence of landslides. Because of the small sample size, it was not possible to tease out different parameters for different regions, so one parameter file is used for the whole NWFP area. Three rasters are created, the landslide susceptibility just for the topography, topography and vegetation, and landslide susceptibility with topography vegetation and roads. The effect of vegetation is portrayed by multiplying the landslide grid for topography by 0.5 for DBH greater than 4 in. and 1.48 for DBH less than 4 in.. The effects of roads can be overlaid on top of the vegetation and topography by multiplying landslide susceptibility within 100 m of a road by 2.73. One way of addressing the problem of inconsistent stream mapping is to develop a new stream layer base on 10-m DEMs. This would provide a more consistent stream layer and allow the mapping of stream intrinsic potential based on topography and streamflow. Intrinsic potential is a measure of a stream's capacity to provide high-quality habitat for salmonids based on channel gradient, valley constraint, and mean annual discharge. Having streams that match the DEMs allows the calculation of catchment size for stream reaches (required to model mean annual discharge) and stream gradient. We would like to combine this information in future watershed condition assessment to evaluate how much of high-quality habitat may be blocked by barriers.

We are currently rebuilding all our decision-support models and adding new attributes. This will allow us to take advantage of new information that has become available and incorporate the opinions of a new group of workshop participants. The more the program relies on GIS and remotely sensed data, the more important the quality of these data becomes. Acquiring and updating quality data for such a large area has always been a problem. The DEMs that are currently available were interpreted off old USGS topography maps. Looking to the future, the program would like to improve the quality of the data used. LIDAR is potentially a source of vastly improved DEMs that could be used for determining stream channels, streamflow, stream gradient, and topography. Improved topography will improve our landslide model and improved stream information will increase the quality of many of our decision-support model parameters for evaluating watershed condition. The size of our study area has made LIDAR data cost prohibitive, but hopefully through cooperation and increased usage of LIDAR, it will be possible to have complete coverage in the near future. LIDAR or some other remotely sensed imagery may be used to improve our road layer, especially on private land. As our program relies more on remotely sensed data, we will have to strive to remain aware of new technologies as they become available.

Chapter 11.—Projecting Watershed Condition with Interagency Mapping and Assessment Project (IMAP) Vegetation Data and Landscape Models

Melinda Moeur, Janet Ohmann, Miles Hemstrom, Theresa Burcsu, and James Merzenich

The Interagency Mapping and Assessment Project (IMAP) is a collaboration between Federal, State, and non-government partners in Washington and Oregon to build a collection of landscape-level data and state-and-transition models for conducting mid-scale assessments (5th-field hydrologic code watersheds and larger). IMAP data and models can be used for analyzing resource decisions and their effects on important regional programs like forest health and restoration, watershed condition, species' habitats, and long-term timber supply. The state-and-transition models are initialized with current vegetation data developed from Landsat ETM satellite imagery and other spatial data. Output from the landscape models provides a means for comparing likely outcomes of alternative management strategies and disturbance regimes on forested landscapes over time horizons from one to several centuries. In this paper, we provide an overview of the IMAP program and refer the reader to original publications for additional detail. We also present examples of IMAP data and models for assessing the vegetation component of watershed condition.

Chapter 12.—Discussion on Remote Sensing for Aquatic Monitoring

Ralph A. Haugerud

The special session on Remote Sensing for Aquatic Resource Monitoring concluded with an expert panel discussion. Panel members were Jennifer Bountry (hydraulic engineer, Bureau of Reclamation), Mimi D'Iorio (GIS analyst and database manager, National Oceanic and Atmospheric Administration), Russ Faux (president, Watershed Sciences, Inc.), Steve Lanigan (team leader, Aquatic and Riparian Effectiveness Monitoring Program, U.S. Forest Service), and Amar Nayegandhi (computer scientist, Jacobs Technology, contracted to U.S. Geological Survey). The panel was moderated by Ralph Haugerud (geologist, U.S. Geological Survey) and there were significant contributions from the audience. The dialogue is summarized below in question and answer format. This summary is followed by discussion of what we learned in the course of the special session and identification of some next steps for the Pacific Northwest aquatic monitoring community.

SPECIAL SECTION 3

Summary of Fish Tagging and Evaluation Techniques Currently Used in the Columbia River Basin

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Introduction

This document is intended to provide fisheries managers, researchers and other interested parties with a concise description of the fish tagging technologies currently used by the State, Tribal and Federal fish management agencies in the Columbia River basin. Perhaps more importantly, this document also will serve as a vehicle to convey the fish management communities' needs and desires for future fish tagging technologies.

The ultimate goal in the future would be to have a fish tagging system that would allow the measurement of in-river reach and route-specific fish survivals in terms of both juvenile survival and smolt-to-adult returns. This means the tag itself must be small and inexpensive enough to mark large numbers of juveniles early in their life history and benign enough to have little effect on fish behavior. It also needs to be able to measure long-term survival. This future tag would need to have the capability to be read through all routes of passage in the out-migration corridor and again as the adults return. Ideally, the system that is developed would not require any further handling of the fish after initial handling and tagging occurs. The following list summarizes some of the management needs (in no particular order):

1. Route-specific survival and passage efficiencies.
2. Forebay survival and delay.
3. Project-specific survival.
4. Reach and system survival and travel times.
5. Estuary and near-ocean survival and passage metrics.
6. Adult returns for various migration histories (latent mortality).
7. Lamprey survival and passage.
8. Fry survival and migration characteristics.

The currently available tagging technologies listed below are arranged in no particular order. Each tag technology treatment will include the following sections:

1. Background – a brief description of the technology (including detection and information network infrastructure) and history of development with major changes and dates;
2. Current uses of the technology with a focus on the Columbia Basin;
3. Advantages and disadvantages of the technology in the context of the management needs listed above;
4. Future development given what we currently know; and
5. Funding, including adequacy of current funding and future needs.

Passive Integrated Transponder (PIT) Tag Technolgoy

Introduction

Passive-Integrated-Transponder (PIT) tags are glass encapsulated, implantable radio-frequency identification (RFID) devices that contain integrated circuit chips. They are passive, which means they do not contain an internal energy source, e.g., batteries. Consequently, the tag remains functional for the entire life of a tagged animal. After implantation, the PIT-tag remains inactive until it is energized by the electromagnetic field generated by low radio frequency waves emitted by an antenna connected to a transceiver. A PIT-tag system consists of the tag, antenna, and transceiver. Improvements in the performance of a system can be made by improving any of the three main components.

Most of the PIT-tag equipment installed throughout the Columbia River basin for monitoring salmonids utilizes full-duplex (FDX) technology. In FDX technology, the electromagnetic fields created by the antennas are always active (i.e., on) and the PIT-tags are detected only when they enter the electromagnetic field produced by the antennas. The passive tags enter the field, become energized and begin to modulate the field, and then the transceiver determines what their tag codes are by interpreting how they modulate the field. In the ISO-based FDX-B technology that is currently being utilized, the frequency of the electromagnetic field is 134.2 kHz and it takes 31 msec for a complete tag message to be decoded.

Although the half-duplex (HDX) technology also includes a 134.2 kHz carrier field, it operates quite differently from the FDX technology. In the HDX technology, the antenna generates the 134.2-kHz field for X amount of time (typically about 50 msec) and then it shuts off the field for a short period of time so that it can "listen for" the tag code being transmitted by the HDX PIT-tag. Unlike the FDX tags, the HDX tags actually do actively transmit their tag codes.

In this summary for the Tagging Technologies Work Group, the two PIT-tag technologies will be addressed separately. In each section, the current status and applications, and future direction of the PIT-tag technologies will be presented. In addition, a list of advantages and different management questions that the region's fisheries managers want addressed, and which of those questions the PIT-tag technologies are able to address.

Full-Duplex Pit-Tag Technology

Background

Full-duplex (FDX) PIT-tag technology was selected for monitoring salmonids for several reasons. It can detect tagged fish moving at high speeds and it has tags that are small enough (12.5-mm length by 2-mm diameter; 0.1 g in air) to tag juvenile salmonids as small as 60 mm in fork length. However, because the tags are so small, the transceiver needs to interpret the small level of modulation caused by the small 12-mm tags. As a result, the FDX-B systems typically have relatively small antennas (95 percent or more of the antennas installed are smaller than 3 × 3 ft), although many larger antennas of various dimensions have been successfully installed. Furthermore, the tag's read ranges are relatively short (measured in feet and inches) compared to active tag technology, which is measured in yards and miles.

Currently, most of the FDX components used throughout the Columbia River basin are manufactured by Digital Angel Corporation. Recently, to make a system work in the corner collector flume at Bonneville Dam with a 12-mm tag, Digital Angel had to improve all three components of a PIT-tag system. As a result of that effort, the fisheries community will be switching to the new 12-mm SST-tag model in 2007. It was also necessary for Digital Angel to design a new transceiver to enable PIT-tag interrogation systems to work in remote stream locations. NOAA Fisheries worked with Digital Angel to produce a transceiver that can handle multiple antennas (the multiplexing transceiver can switch among six antennas and it auto-tunes each antenna) while basically using the power needed to operate one transceiver. Furthermore, researchers have worked hard to improve how they design antennas for in-stream research on fish passage and survival. As a result, today's largest antennas are twice the size they were when the multiplexing transceivers were first introduced 3 years ago.

NOAA Fisheries is currently leading an effort supported by BPA and the Corps to investigate expanding PIT-tag detection into mainstem Columbia and Snake River hydropower project spillways and turbines. NOAA Fisheries issued a contract in 2006 to Digital Angel to investigate the technical feasibility of designing a detection system for a spillbay at Bonneville Dam. Digital Angel has indicated that to be able to implement tag detection into the unfavorable spillbay environment, it may be necessary to design a non-ISO system. For example, because water velocities are around 60 ft/s as the water explodes out of the spill gate on the tailrace side, the company may need to reduce the message length significantly in order to get multiple reads when the fish (and tag) is traveling that fast. Furthermore, the company may need to design a larger tag; however, fisheries researchers have stipulated that any new tag that is designed must be capable of being read by the existing FDX PIT-tag systems.

Tags

Starting with the 2007 out-migration year, the standard 12-mm PIT-tag model will be the SST tag (TX1400SST) manufactured by Digital Angel. This tag was designed to work in large antennas better than the ST tag, which has been the standard tag for the Columbia River basin since 2003. Tests conducted in 2006 in the Bonneville Dam corner-collector antenna that measures 17 × 17 ft demonstrated that this was true, as approximately 70 percent of the SST-tagged fish were detected compared to around 40 percent for the ST-tagged fish. This difference in detection levels also was because the transceiver and antenna for this system were optimized to detect the SST tags.

The SST tags also are making it possible for researchers to design larger antennas for in-stream interrogation systems with the current multiplexing transceiver (FS1001M). With the SST tag, they are now able to design antennas that measure 20 × 4 ft.

The SST tags have basically the same physical characteristics as the ST tags (length = 12.5 mm, diameter = 2.1 mm, and weight in air = 0.102 g). Because of their small size, it is possible to tag smaller smolts and parr (down to about 60 mm in fork length), as well as adult salmonids. Digital Angel designed this newer PIT-tag so that they will be able to fabricate it using an automated process developed for the ST model. This keeps tag manufacturing costs down.

In 2006, Digital Angel also introduced a shorter 8-mm tag model (8 × 2 mm) that has a shorter read range than the longer 12-mm tags. These shorter tags were requested by researchers wanting to tag fish in the 50–60 mm range who were willing to settle for getting detection in the juvenile fish facilities but not in the corner-collector or some of the larger vertical-slot antennas for returning adult salmonids. This 8-mm tag model is based on the ST-tag technology and not the SST-tag technology and thus the read range is similar to a 12-mm BE tag, which was the tag model used in the basin before the ST tag. Digital Angel also produces larger FDX-B tags (18–23 mm in length and 3-mm in diameter) that also are based on the ST tag technology.

Transceivers

Digital Angel currently manufactures four different models of FS1001 transceivers.[1] The FS1001J transceivers are used in the small flumes and pipes at the juvenile fish passage facilities. The FS1001A transceivers are used to detect migrating adult salmonids in the fish ladder orifices and the smaller vertical-slot locations, and in larger pipes, e.g., the full-flow systems, at the juvenile fish passage facilities. The FS1001AB transceivers are used in the vertical-slot locations at Bonneville Dam. The FS1001M transceivers are the auto-tuning and multiplexing transceivers that are used for the in-stream interrogation systems. It should be noted that this entire series of FS1001 transceivers is in its last years of use because the electronic technology that they are based on is now about 10 years old. Moreover, some of the FS1001 transceiver parts are starting to become difficult to procure.

Digital Angel had to manufacture a new transceiver model for the Bonneville Dam-Second Powerhouse corner-collector fish passage system to ensure detection of a 12-mm tag in a 17 × 17 ft antenna. To accomplish this, the manufacturer incorporated Digital Signal Processing (DSP) into the transceiver design. As a result of changes needed for improved performance, these new G2 transceivers costs almost three times the price of a FS1001 transceiver.

Antennas

To be able to make antennas larger over the past few years, PIT-tag researchers have experimented with different types of wire and different brands of capacitors. For example, the Bonneville Dam corner-collector antenna used Litz wire. Different shield designs also have been integrated into antenna designs in order to improve performance. Currently, there are no real standards in antenna design and construction as different groups have found solutions that work for them. The general push at this time is to try to improve the transceivers so that they have higher signal sensitivity, which will enable larger antennas to be constructed. This was the approach Digital Angel took for both the G2 transceiver and the FS1001M developments. Currently, the antenna width is the most limiting factor in expanding the applications where PITtag technology can be incorporated.

Environmental conditions also place limitations on antenna designs. NOAA Fisheries has been working on trying to apply PIT-tag technology to learn more about salmonid movement in estuaries. At this time, because high salinity conditions significantly reduce the field that an antenna can produce, only small antennas can be used. This obviously limits the types of research questions that can be answered with this technology in saline environments. Accordingly, researchers are encouraging the PIT-tag manufacturers to investigate ways to improve the performance of this technology in these types of environments.

A dam's spillway is another unfavorable tag detection environment, as the spillway gates are made from metal and that metal has to remain in place, unlike in past installations, e.g., in the Bonneville Dam-Second Powerhouse corner collector, where it was structurally possible to remove all of the rebar in the immediate vicinity. Water itself reduces the performance of the current antennas with the current transceivers – in order to generate the required fields, it has been necessary to incorporate air gaps into the orifice antennas, vertical slot antennas, instream antennas, and the corner-collector antenna.

[1]Digital Angel also manufactures a 2001 transceiver that is used for hand scanning and smaller in-stream applications.

Current Uses and Applications

Since the late 1980s, PIT-tags have been the main tool used for monitoring salmonid migrational behavior and timing in the Columbia River basin. They also are used extensively for determining survival rates of juvenile fish through Columbia and Snake River reaches and for individual stocks; typically, this is done by calculating smolt-to-adult return rates (SARs). Numerous large-scale studies using PIT-tags have been undertaken to examine differences in SARs between transported and non-transported fish. PIT-tags also are being used in research to examine delayed mortality observed in the Snake River Chinook salmon and to estimate avian predation rates.

Research applications expanded dramatically in the mid-1990s when the ability to collect subsamples of targeted fish using separation-by-code was added to many of the PIT-tag systems at the mainstem Columbia and Snake River hydropower dams. Using separation-by-code, researchers have investigated route-specific passage information, as subsamples of the tagged fish are collected so they can be examined physically. These subsamples can be collected at the same hydroelectric facility or at another dam downstream. PIT-tags also are commonly used in radio-telemetry studies, either as a double tag or to identify groups of fish that should or should not be radio-tagged (e.g., fish from the Snake River or fish from the Upper Columbia River). Researchers also have used the separation-by-code tool to collect some of their study fish at multiple dams to monitor how physiological changes occur as the salmonids migrate downstream.

Advantages

The advantages of FDX PIT-tag technology include the following:

- It is a small tag (most tags used are 12.5 × 2 mm; new 8-mm tag now available).
- Can tag small smolts (60 mm with 12-mm tags and down to 50 mm with 8-mm tags).
- Can tag adult salmonids.
- Tags are long-lived because they are passive, i.e., no battery is needed, thus the tags can last longer than the lifespan of salmonids.
- Tags are inexpensive (about $2/tag).
- A cheaper tag means that large numbers of fish can be tagged. This enables the fisheries community to tag groups of fish from the same hatcheries every year to learn more about year to-year variation in migration and survival.
- Almost all mainstem Columbia and Snake River hydropower dams are now outfitted with PIT-tag systems that detect both migrating juvenile and adult salmonids.
- Interrogation systems are currently installed in the juvenile fish bypass facilities located at most of the federal Columbia and Snake River hydroelectric dams.
- Installation of full-flow detection systems at many mainstem dams (currently, these juvenile detection systems are installed at Ice Harbor, Lower Monumental, McNary, John Day and Bonneville Dams) would enable PIT-tag systems to be operated year round.
- Interrogation systems are currently being installed into Columbia Basin tributary streams and yield fish movement information that was unknown previously.
- Intensely monitored watersheds are starting to utilize PIT-tag technology in their monitoring programs.
- Digital Angel is willing to work with the region's fisheries community in developing new technologies to enable detection of tagged fish in locations currently inaccessible. For example, researchers are currently working on determining whether it will be possible to detect PIT tagged fish transiting individual spillway bays at mainstem Columbia and Snake River dams.

Disadvantages

The disadvantages of FDX PIT-tag technology include the following:

- There are limitations on antenna size; the largest antenna currently deployed at the mainstem hydroelectric dams is 17 × 17 ft.
- Researchers currently cannot detect PIT-tagged fish passing through spillways or turbines at the mainstem dams and so we cannot get route-specific passage and survival information on fish passing through these routes.
- Due to detection interference, the technology normally requires the removal of all rebar from the area where antennas are installed and therefore, installations can be expensive.
- Not enough in-stream PIT-tag detection systems are currently installed to yield information on the research questions outlined in the in-stream applications section below, e.g., fish movement during the fall and winter months, or learning about different life-history strategies of salmonids.

[1]Digital Angel also manufactures a 2001 transceiver that is used for hand scanning and smaller in-stream applications.

- Estuarine applications are very limited because the saline water attenuates the electromagnetic field produced by the antennas and thus, it is only possible to install small shielded antennas (5 × 2 ft) in these locations.
- The current multiplexing transceiver can only handle six antennas, yet researchers already have sites that need more antennas or larger antennas to answer the management questions.
- The existing range of auto tuning in the current set of transceivers is limited.
- Unable to tag salmonid fry or juvenile lamprey with current PIT-tags (even using the 8-mm tags).
- Potentially, a fish's long-term survival rate (SARs) may be impacted by being PIT-tagged in the juvenile life stage, as it appears that fewer PIT-tagged fish are returning as adults than would be expected. However, some of the returning fish could have lost their tags. (John Williams, personal commun.)
- For fish tagged as juveniles, the tag can be expelled during late maturation before or during spawning activity.

Future Development

Tags

Digital Angel has indicated that it plans to make a larger PIT-tag in the near future that incorporates the SST technology.

The company has a patent on PIT-tag implantation that prevents BPA and the Corps from purchasing tags that will be injected into fish from other tag manufacturers.[2] This patent is active until 2010. Because of this exclusive patent, BPA and the Corps have negotiated fixed prices for the tags they will purchase until 2010. The price per tag in 2007 will be $1.90 for each SST tag. In 2008 and 2009, the price for each SST tag will be $1.80. Then in 2010, it will be $1.70.

As indicated in the Introduction section above, the development of a fish-tracking system for the individual spill bays may require a new PIT-tag to be designed. Although it is not known what the tag dimensions will be, it is known that it will be a passive tag because an earlier investigation showed that the amount of read range gained by adding a battery to a PIT-tag would be modest.

Transceivers

In order to meet the demands of stream researchers as they try to expand PIT-tag detection into larger streams, NOAA Fisheries is leading an effort to develop a new multiplexing transceiver. NOAA Fisheries recognizes that the fisheries community needs to be able to monitor fish movement in both large and small tributaries in order to better understand salmonid behavior and migration timing. For instance, in-stream PIT-tag detection systems in both the Twin Creeks on the Olympic Peninsula and Gold Creek in the Methow River basin have documented significant movement of juvenile fish during the fall. The goal is to have prototype in-stream transceivers installed by the end of 2007. Juvenile fish migration in the fall also has been documented in Beaver Creek in the Methow River basin and Rattlesnake Creek in the White Salmon subbasin using an in-stream PIT-tag detection system.

Note that FDX tags manufactured by other companies can also be read in the fish passage facilities of the mainstem Columbia and Snake River hydropower projects.

Furthermore, development of future in-stream systems will help advance our understanding of some of the life history strategies exhibited by fall Chinook salmon. The in-stream systems also would help us learn more about the fate of adult migrants after they have been detected at Lower Granite Dam; that is, if critical tributaries had PIT-tag detection capability, the presence of adult fish could potentially be monitored on the spawning grounds. The goal is to have prototype in-stream transceivers developed by the end of 2007.

Moreover, the region will soon need to support the development of a new line of transceivers to replace the three models used at the mainstem hydroelectric fish-passage facilities. This effort should be able to utilize what was learned in both the G2 transceiver and multiplexing transceiver developments to speed up its development. It is likely that the three FS1001 transceiver models will be replaced with a single model, which will make O&M tasks easier for the Pacific States Marine Fisheries Commission, which manages the regional PIT-tag database system.

Antennas

It is anticipated that antenna construction and size will change when the next generation of transceivers is produced. The in-stream users of the technology have indicated to Digital Angel a preference for antennas that do not need an air gap.

[2]Need footnote

In-stream Applications

In-stream PIT-tag detection systems are now starting to reveal new fish migration patterns, such as more active movement during the fall months. Further development of in-stream detection systems will yield fish movement, survival and habitat use information related to:

- Investigating questions about whether or to what degree some populations of salmonids (steelhead/rainbow trout and cutthroat trout) are resident or anadromous, because both life histories can occur in the same watershed. The resident or anadromous question has implications for Endangered Species Act interpretations and rulings.
- Investigating different life history strategies of salmonids within streams and how they contribute to the full salmonid population within a watershed.
- Collecting information on the behavior, survival, and life history strategies of wild versus hatchery fish. Again, collecting this type of data has implications for Endangered Species Act interpretations and rulings.
- Investigating the different ways that salmonids utilize different types of habitats available to them throughout the year.
- Advancing our understanding of some of the life history strategies exhibited by fall Chinook salmon.
- Monitoring adult fish presence on the spawning grounds of critical tributaries. These systems could yield information on whether an individual adult fish that was successfully detected at a mainstem hydroelectric project goes on to spawn in its native stream, i.e., post-hydropower system spawning success.
- Anchoring techniques for smaller streams are still being developed, and in streams with high or swift flows and heavy debris loads, keeping antennas installed and operating is challenging.
- If "grid" power is unavailable, options for alternative power sources can be an issue in determining where these in-stream systems can be deployed.

Other future research includes the need to design a study to investigate NOAA Fisheries scientists' concerns about long-term tag effects on salmonids.

Current Funding and Future Needs

Both BPA and the Corps of Engineers have been, and are presently supporting research projects that use PIT tags. BPA also currently funds a NOAA Fisheries-sponsored project that is developing future PIT-tag technology. Funding for this project varies from year to year depending on what technology is being developed. Currently, BPA is providing some of the funding for development of a new multiplexing transceiver and for investigating the feasibility of developing a system for interrogating PIT-tagged fish in individual spillway bays. NOAA Fisheries also is contributing some funds to support these efforts.

BPA should be commended for its funding support in development of new and improved PIT-tag technologies over the past 25 years. During that time, BPA has recognized that not every R&D undertaking would lead to an improved product, but overall its support has enabled advances in PIT-tag technologies to keep pace with regional research needs. It is important to keep this development process active or there will not be the necessary improvements to PIT-tag technology to expand our understanding of salmonids. Besides looking into potentially developing a PIT-tag detection system for spillbays, there is interest in developing PIT-tag systems for turbines and for applications that are not directly associated with the mainstem federal hydroelectric facilities (e.g., in-stream and estuarine applications). As PIT-tag projects have grown in scale and have broader application, the funding of these developments has come from multiple agencies. We envision that this trend will continue into the future.

Radio Telemetry

Background

Trefethen (1956) reported the first use of telemetry to study fish in 1956. This study used acoustic telemetry to examine the passage of adult Chinook salmon at Bonneville Dam. Acoustic telemetry was used extensively to examine fish passage issues in the Columbia River basin until 1970. However, acoustic telemetry worked poorly in turbulent areas, such as those downstream of dams especially during periods of spill. In addition, acoustic telemetry required the receiving unit to be submerged in water, which resulted in tracking limitations for highly mobile species or over great distances. Because of these limitations, NOAA Fisheries began developing an extended range radio transmitter for use in the Columbia River basin in 1970 (Monan and Liscom, 1971).

Radio-tagged fish can be mobile-tracked by vehicle, on foot, by boat, or by air, which allows efficient surveys of remote or very large study areas. Other tag technologies (e.g., freeze brands, CWT or PIT-tags) typically either do not provide the same level of detail or are not as applicable for tracking individual fish within the freshwater portion of the basin.

Radio telemetry has been used to study passage behavior for adult salmonids in the Columbia River basin since 1971(Monan and Liscom, 1971) and juvenile salmonids since 1980 (Faurot et al., 1982). The first application of radio telemetry to assess juvenile survival in the Columbia River basin was in 1997 (Hockersmith et al., 1999). Most fish radio telemetry studies within the basin have used transmitters operating at 30 or 150 MHz.

Current Uses and Application

NOAA Fisheries are the only researchers in the basin using 30 MHz radio transmitters. The NOAA Fisheries transmitters are on one of nine frequencies spaced 0.01 MHz apart (30.17 to 30.25 MHz). For each frequency, the NOAA Fisheries code set has 505 unique codes or a total of 4,545 unique transmitters (code and frequency combinations). For studies requiring sample sizes greater than 4,545 individuals, the code/channel combinations are repeated. The smallest NOAA Fisheries transmitters currently used in the Columbia River basin weigh 0.6 g, are 200 mm^3 in volume, and have a tag life of 10+ days at a 2-second pulse rate.

All other researchers using radio telemetry in the Columbia River basin use 149–151 Mhz transmitters and most of these tags are manufactured by Lotek. The Lotek transmitters are on 1 of 25 frequencies ranging between 149.320 to 149.800 MHz (spaced 0.02 MHz apart) or from 150.320 to 150.800 MHz (same spacing). For each frequency, the Lotek code set has 521 unique codes for a total of 12,500 unique transmitters (code and frequency combinations). This code set became available in 2003. Prior to this, the Lotek code set was 5,300 unique transmitters. The code/channel combinations are repeated for studies requiring sample sizes greater than 12,500 individuals. Due to the numbers of studies using Lotek transmitters in the Columbia River basin, extensive coordination of frequency and codes among various research projects is required. The smallest Lotek transmitters currently used in the basin weigh 0.37 g, have a volume of 215 mm^3, and have a tag life of 5+ days at a 2-second pulse rate. Larger transmitters are available with commensurate increases in signal strengths and battery life.

Radio telemetry receiving equipment can vary but typically are either sequential scanners, which are programmed to scan a frequency for a set period of time and then move on to the next frequency of interest, or digital spectrum processors (DSP), that are capable of scanning all frequencies (within a defined range) simultaneously.

Radio telemetry receiver systems for studies in the Columbia River basin use multi-element Yagi air antennas or tuned loops at riverine passage gates. A variety of underwater antennas (Beeman et al., 2004) including stripped coax, underwater dipoles, or underwater quad-poles are used to isolate passage routes at dams. Radio telemetry detection probabilities on riverine gates are typically between 90 and 98 percent. Detection probabilities within the various passage routes at mainstem Snake and Columbia River hydropower projects typically are 95 to 100 percent.

Advantages

Radio telemetry has worked very well for evaluating both adult and juvenile salmonid passage at dams, resulting in structural and operational improvements. Radio telemetry also has worked very well in assessing fish behavior in the near-dam environment. Radio telemetry has been a useful tool to evaluate project survival, dam survival, pool survival, route-specific survival, passage efficiencies, forebay survival and delay, tailrace egress, travel times, avian predation, straying of adult returns, spawning distribution and timing, and adult fallback at dams. Currently, radio telemetry can be used to study all species of adult salmonids, adult Pacific lamprey, and juvenile salmonids as small as 90-mm fork length within the freshwater portions of the Columbia River basin. Unlike with acoustic transmitters, turbulent hydraulic environments do not effect detection of radio transmitters. In addition, the ability of radio transmitters to be detected in the air is a major advantage over acoustic telemetry for studying highly migratory species through large river systems.

The most recent juvenile salmonid radio tag effect study evaluated the effects of 1.4 g transmitters relative to fish that were only PIT-tagged (Hockersmith et al., 2003). In that study, the authors concluded that yearling Chinook salmon, which were either surgically or gastrically tagged with a 1.4 g radio transmitter, had survival and migration rates similar to PIT-tagged fish over a period of 6 days or less and a migration distance of 106 km. However, they further found that regardless of tagging method, the radio-tagged fish had significantly lower survival than PIT-tagged fish when the migration distance was increased to 225 km and the travel time was greater than 10 days.

It is noteworthy that juvenile radio transmitters used today are more than 50 percent smaller than the transmitters used in 1999 and are suitable for tagging fish as small as 90 mm. In addition to smaller tags, shorter and lighter antennas are currently available. If the reduced survival for the radio-tagged fish was due to the size of the tag, today's smaller radio transmitters may allow radio telemetry to be used to estimate survival for juvenile salmonids over longer distances and longer time periods.

Disadvantages

Radio telemetry is limited to use in the freshwater environment because salinity attenuates the signal from the transmitter. Therefore, this tag technology cannot be used to evaluate estuary or near-ocean behavior or survival. Depths greater than 9 m also can limit the detection of radio transmitters unless underwater antennas at depth are used. All radio transmitters currently used in the Columbia River basin require an external trailing antenna, which may effect swimming performance of juvenile fish or attract predators. Although radio transmitters continue to decrease in size and weight, they are unlikely to become small enough to use for studying fry or juvenile lamprey. The radio transmitters currently used in the basin do not have a tag life long enough to be used to evaluate adult returns for various juvenile migration histories. In addition, the radio transmitters currently used in the basin have a limited code set that is much smaller than those available for other technologies, including PIT-tags, coded wire tags, and acoustic transmitters.

Future Development

Future developments in radio telemetry are likely to include continued miniaturization of transmitters while maintaining tag life needs, increasing the numbers of unique transmitters that can be used at the same time, sensor technologies, and possibly eliminating the external antenna. As transmitters continue to be miniaturized, radio telemetry may be useful to evaluate survival and behavior past multiple mainstem hydropower dams and over longer river reaches. Sensor technology applications of radio transmitters currently include depth, motion, and water temperature. Although these sensors can be added to transmitters for adult fish studies, adding them to tags used for studying juvenile salmonids would significantly increase the size of the tag. This limits sensor application to large fish in the population. In addition, electromyogram transmitters have been used to measure physiological responses for free-swimming fish in other systems.

Much of the past radio telemetry work has focused on behavior at the mainstem Columbia and Snake River hydropower projects. To accomplish this behavior work, the pulse rates of the tags have been relatively high, ranging from 1 to 2 seconds. As a result, the life of the tag has been relatively short (between 9 and 18 days). However, setting the pulse rate on tags at a slower rate, e.g., once every 10 seconds, would significantly increase tag life and make it more suitable for system wide applications.

Additionally, vendors have been continuing to reduce the size of the radio tags, and tags that are as small as 0.25 g are not far off, especially if resources are directed towards that effort. Regardless of the potential for longer life and smaller radio tags, some have voiced concern over the presence of the external antennas and the potential effects that may have on the fish. However, recent advancements in antenna material and length have been made. Available information on the effects of the antenna on fish was collected using the original, longer antenna designs. Thread-like material is now available and the length can be reduced to less than one-half of the historical length. Further testing may show that these advancements have significantly reduced or eliminated any measurable effect of the antenna on the fish.

Thus, there is a reasonable expectation that smaller and longer lasting tags can be developed with antennas that may have little to no measurable effect on the fish. Radio telemetry, when used in combination with PIT-tag technology, has the potential to address six of the eight management needs outlined in the introduction. It is unlikely that radio technology will allow managers to address estuary or lamprey needs. However, it should be pointed out that no single technology may be able to accomplish all eight management needs effectively. The most effective strategy may be to continue to develop several tag technologies that, used in combination, are highly effective at addressing all management needs. The alternative would be a single tag technology that addresses most of the needs well, but does a mediocre job at addressing the remainder of the needs.

Lastly, although it appears not to be an area of need at the time, the need to collect information on the energy expenditure of juvenile fish migrating past mainstem hydroelectric dams may be identified in the future. EMG tags used to collect this information have been successfully applied using larger fish in the past. It is reasonable to expect that this technology could be miniaturized for use in the future. This will likely take time and resources, but waiting until the need exists to begin to develop a tag for this capability will only lengthen the time it will take to develop the ability to gather this type of information.

Acoustic Telemetry

Background

Advances in the field of electronics have led to significant reductions in the size and function of acoustic telemetry systems since their first use in the 1950s. These advances have led to an increase in the utility of these systems to monitor the migration behavior and survival of juvenile salmonids in the Columbia River basin. Researchers now utilize this technology to look at finer scale behavior, including behavior in three dimensions. Additionally, these smaller transmitters are allowing for studies of yearling Chinook salmon and steelhead to be more representative of the untagged population, relative to the size distribution of migrating smolts.

Acoustic telemetry (AT) systems utilize sound waves to transmit information from a transmitter, through the water, and then into a hydrophone, and ultimately to a data logger or receiver. By their nature, AT systems are susceptible to interference from ambient noise, however, the operating frequency and complexity of an encoding scheme can help minimize such interference. Current AT systems offer varying degrees of tag size, transmission life, frequencies, and encoding schemes; each system offers different advantages and disadvantages.

Current Uses and Application

The AT systems currently being used in the Columbia River basin are the Vemco system, Hydroacoustic Technology Inc. system (HTI), and the Juvenile Salmon Acoustic Telemetry System (JSATS). Relevant specifications for each system are provided in the following matrix. These specifications are based on the smallest commercially available tag described on the vendor's website and are typical of systems used in 2006 field studies.

Specifications	HTI	JSATS	Vemco
Weight in air (g)	0.65	0.62	3.1
Dimensions (mm)	16.4 × 6.7	17.0 × 5.5	20.0 × 9.0
Frequency	307 kHz	416.7 kHz	69 or 81 kHz

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SPECIAL SECTION 4

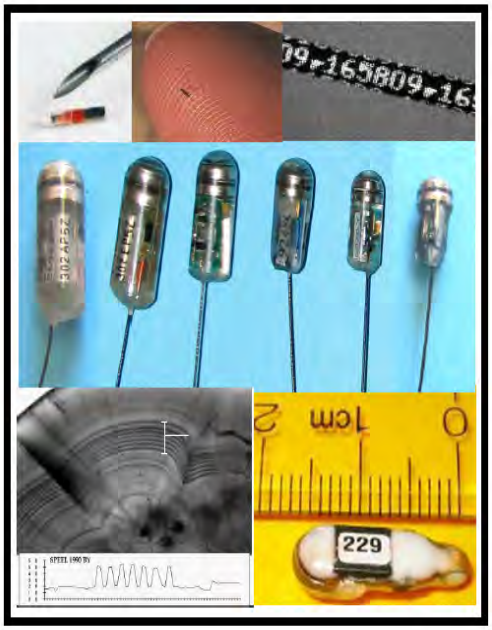
The Northwest Power and Conservation Council – Staff Summary of the Recommendations from the ISRP/ISAP's Tagging Report #2009-

The full review document can be downloaded at: www.nwcouncil.org/library/isab/isabisrp2009-1.htm

Examples of findings and citations are also found in **Chapter 1** (in this publication) and in the subsequent summary memo from Jim Ruff to the Northwest Power and Conservation Council.

INDEPENDENT SCIENTIFIC REVIEW PANEL
INDEPENDENT SCIENTIFIC ADVISORY BOARD

TAGGING REPORT



A comprehensive review of Columbia River Basin fish tagging technologies and programs

March 17, 2009
ISRP/ISAB 2009-1

May 28, 2009

MEMORANDUM

TO: Council members

FROM: Jim Ruff -- ISAB ex officio

SUBJECT: Management Recommendations from ISRP/ISAB's Tagging Report #2009-1

Background

An exhaustive, comparative independent science review of various fish tagging technologies used in the Columbia River basin was completed in March 2009 along with recommendations for making the tagging programs more productive and efficient. The review was conducted jointly by the Independent Scientific Review Panel (ISRP) and Independent Scientific Advisory Board (ISAB), culminating in a "Tagging Report--A Comprehensive Review of Columbia River Basin Fish Tagging Technologies and Programs" dated March 17, 2009 (ISRP/ISAB 2009-1). A link to the science report can be found at http://www.nwcouncil.org/library/isab/isabisrp2009-1.htm.

The ISRP had suggested such a review following its 2006 evaluation of over 100 tagging-related projects requesting program funding during the project review cycle for fiscal years 2007-2009. Over several project review cycles and in various other reports, the ISRP has raised issues about tagging technology. Such a review was timely because data from tagged or marked fish are used in the basin to provide information useful for effective decision-making in the Columbia River Basin (CRB).

Fish of various species, stocks and sizes are tagged annually to obtain data on their numbers, harvest rates, behavior, migration and mortality rates, habitat use, and the success of hatchery and other enhancement programs. Results from these tagging investigations influence decisions on hydrosystem management such as spill for fish passage at mainstem dams and smolt transportation; harvest regimes in the ocean and river; hatchery practices; and endangered species risk assessments.

Consequently the Council, in a July 2007 letter, requested an independent science review of tagging technologies used in the Fish and Wildlife Program and the Corps' Anadromous Fish Evaluation Program (AFEP). Specifically, the Council requested that the ISAB and ISRP jointly address six questions:

6. Can the coordination of fish tagging projects and programs, both within and outside of the program, be improved?

7. Can the compatibility between the results of different tagging studies be increased?

8. Can the Council, through its Fish and Wildlife Program, best encourage the development and use of innovative tagging technologies relevant to program RM&E needs?

9. Do gaps exist in the basin's capacity to collect life history information at the project or program scale because of lack of relevant technology?

10. Can criteria be developed for determining the most cost-effective tagging technology during the project review process?

11. How can this element of the program be made more cost-effective?

The ISRP and ISAB's report begins with recommendations and responses to the Council's questions. This is followed by summaries of fish tagging programs for three management domains: hydrosystem passage and operations; hatchery and harvest management; and estuary and ocean conditions monitoring. The report concludes with a brief summary of statistical considerations in tag programs. The appendices provide descriptions of the primary tagging technologies used in the basin and tables identifying ongoing projects recently funded through the Council's Fish and Wildlife Program, the Corps' AFEP, and the Pacific Salmon Commission's (PSC) Northern and Southern Funds.

This memo will summarize the science panels' major recommendations related to the Council's questions in five areas, identify those recommendations already being implemented in the basin, and suggest some management implications for the next Fish and Wildlife Program project review cycle.

Recommendations to Improve Coordination of Tagging Projects and Programs

1. All of the Council's Fish and Wildlife Program (FWP) projects involving tagging or marking of fish should include a coordination plan in the proposal describing: a) protocols for coordinating with other similar studies; and b) plans for data archiving and data sharing.

2. A web-based information network should be developed to help coordinate all CRB fish tagging projects and programs, e.g., networked web sites maintained by each agency funding tagging/marking projects. Web-based information should include the type of study (tributary, hydrosystem, estuary or ocean); principal investigator's name and contact information; species studied; ESU; location of study; dates; tagging technology used; and links to reports or published research results.

3. Establish a tagging/marking standing committee (e.g., panel of experts) designed specifically to improve coordination of tagging/marking projects and programs of the FWP, the Corps' AFEP, and the Lower Snake River Compensation Plan. In addition, such a committee could coordinate the future development and review of criteria for cost-effectiveness of FWP tagging projects and programs.

Recommendations to Improve the Cost-Effectiveness of Tagging Projects and Programs

1. Develop an inclusive FWP monitoring/tagging framework for all salmon and steelhead ESUs, major population groups, and independent populations, including both listed and unlisted species, to evaluate population status and trends, hydrosystem passage and operations, hatchery and harvest management, and estuary and ocean condition domains.

2. For FWP proposals during the next project review cycle, project sponsors should provide a review of the applicability and costs of different tagging technologies appropriate for their research or management objectives. In addition, proposal budgets should include itemized costs per unit, e.g., cost per tag and cost per receiver, and number of units to be purchased. This information will aid in evaluation of the overall costs of tagging and marking programs in the Basin.

Recommendations to Encourage Development and Use of Innovative Tagging Technologies

1. At present, the most effective strategy is to continue to develop several tag technologies that, when used in combination, are highly effective at addressing all FWP management needs. An alternative would be to develop a single tag technology that addresses most of the needs well, but does a mediocre job at addressing the remainder of the needs.

2. Continue to develop innovative techniques or improve existing techniques for surgical insertion of internal tags or external attachment of acoustic, radio, or data storage tags that reduce handling times, fish injury and stress.

Recommendations Related to Specific Tagging Technologies

- For genetic markers: (1) continue to develop standardized single nucleotide polymorphism (SNP) markers for all CRB salmon and steelhead ESUs; (2) continue to develop fishery and management models that use genetic data for both ocean harvest and in-river fisheries; and (3) support pilot and proof-of-concept trials for Parental-Based Tagging of hatchery populations of salmon and steelhead.

- For otolith thermal marking, further development of the otolith thermal marking technique, using pilot or proof-of-concept trials, as an alternative to coded wire tags (CWTs) to mark 100 percent of CRB hatchery salmon and steelhead.

- For PIT tags, further development of prototype in-stream transceivers for detection in key tributaries to monitor smolt and adult movements in both large and small tributaries to better understand salmonid behavior and migration timing, fate of juvenile, smolt, and adult migrants before and after dam passage and to spawning grounds.
- For acoustic tag technologies: (1) continue to miniaturize acoustic tags to increase battery life while reducing battery and tag size (or use of variable pulse rate tags that can be switched on and off); (2) develop an acoustic receiver system that can track fish tagged with all types of acoustic tags used in the CRB through the river and near-shore ocean over the continental shelf; (3) continue to develop ocean receivers that can be remotely downloaded; (3) develop sensors to detect when an acoustically tagged fish dies; and (4) evaluate the long-term effects of acoustic tags on salmon survival.
- For radio tag technologies: (1) develop miniaturized radio tag transmitters with longer battery life and no trailing antennas; (2) develop and use underwater antennas in depths greater than 9 meters; (3) increase the number of unique tagging codes; (4) develop sensor technology (depth, motion, water temp., etc.) for juvenile salmon tags; and (5) use radio tag technology together with PIT tags to address management needs in freshwater.

Recommendations to Close Gaps in Basin's Capacity to Collect Life History Information

1. Since there is a large gap in the capacity to collect data on the status and trends of wild fish populations in the basin, it is recommended the region employ PIT-tag technology in tributaries where complete counts of adults-in and smolts-out using weirs are infeasible. At those sites where a complete count of adults-in and smolts-out using weirs is effective, maintain that data collection. In addition, because the risks of capturing and PIT-tagging wild fish are significant, great care must be taken, especially if the population is small. To reduce the risks in handling wild fish for tagging, develop and implement projects to determine whether hatchery fish can be used as surrogates for wild fish (raised to match size/weight). Tag/mark 100% of CRB hatchery fish to facilitate hatchery broodstock management and evaluations of the impacts of hatchery straying on natural populations.
2. In the next FWP project review cycle, all tagging projects should address and document the statistical validity of tagging and tag recovery rates. Sample size calculations should be based on statistically valid methods and documented. Develop statistically valid sampling designs to estimate: (1) straying of adult hatchery-origin and natural-origin salmon and steelhead; (2) mortality of juvenile lamprey migrating downriver through the hydrosystem projects; and (3) mortality of adult lamprey migrating upriver through the hydrosystem projects.
3. Implement the relative reproductive and long-term monitoring projects identified in the Ad Hoc Supplementation Monitoring and Evaluation Workgroup (AHSWG 2008).
4. Develop and implement projects to address the long-term effects of all tag types on both juvenile and adult fish, e.g., initiate a comprehensive study to determine why PIT-tagged Snake River wild spring/summer Chinook salmon may be producing lower SARs than unmarked wild Chinook salmon (ISAB /ISRP 2007-6) and the extent of PIT-tag losses (Knudsen et al., in press). Long-term data are especially needed on the effects of acoustic and radio tags on juvenile and adult salmonids. Continue tagging studies with objectives to better standardize surgical protocols, tag size/weight criteria, and battery performance. Conduct studies to determine the rate and extent of tag shedding or loss for all tag types.
5. Develop PIT-tag detectors that can be used in mainstem dam spillways, removable spillway weirs, turbines, and selected tributaries to collect PIT-tag data on migration timing, straying, and survival by routes of passage to spawning tributaries, which currently cannot be done. Flat plate PIT-tag detector units, similar to the one developed for the corner collector at Bonneville Dam's second powerhouse, need to be developed for these other routes of passage and for dams and key tributaries throughout the hydrosystem.

Recommendations to Improve the Compatibility of Results of Fish Tagging Studies

1. During the next FWP project review cycle, all projects involved in ocean port sampling and lower river sampling for CWT recovery should address the tagging and tag recovery issues (statistical validity of tagging rates, tag recovery rates, and fishery sampling rates) presented in the Pacific Salmon Commission's Action Plan to Address the CWT Expert Panel (PSC Tech.Rep. No. 25, March 2008).

2. FWP and AFEP projects should be developed and implemented to evaluate and monitor the effects of handling stress and tagging on salmon growth, survival, migratory behavior, and other biological characteristics to determine whether estimates of vital rates using data from tagged hatchery fish are representative of wild fish.

Recommendations Already Being Implemented or Addressed in Basin

A number of the science panels' recommendations are already being implemented or acted on in the basin. Several examples are provided below.

- Development of an inclusive FWP monitoring/tagging framework for all salmon and steelhead ESUs, major population groups, and independent populations, including both listed and unlisted species, to evaluate population status and trends, hydrosystem passage and operations, hatchery and harvest management, and estuary and ocean condition domains has already begun as part of the interagency anadromous sub-basin research, monitoring and evaluation review effort.

- To evaluate and monitor the effects of handling stress and tagging on salmon growth, survival, migratory behavior, and other biological characteristics, the Corps' AFEP has been funding and implementing a study to evaluate the comparative performance of acoustic-tagged and PITtagged juvenile salmon in the basin.

- The science panels' recommendation to tag/mark all CRB hatchery fish to facilitate hatchery broodstock management and evaluations of the impacts of hatchery straying on natural populations is consistent with a Hatchery Scientific Review Group's recommendation.

- The major recommendations related to genetic markers are largely consistent with recommendations from the Report of the Expert Panel on the Future of the Coded Wire Tag Recovery Program for Pacific Salmon dated November 2005. Some of the science panels' recommendations related to genetic markers may be advanced in near future by a proposed CRITFC project entitled Influence of Environment and Landscape on Salmonid Genetics (project #2009-005-00). This project was developed under the Columbia River Fish Accords.

Proposed Management Implications for Next FWP Project Review Cycle

1. All of the Council's FWP projects involving tagging or marking of fish should include a coordination plan in the proposal describing: a) protocols for coordinating with other similar studies; and b) plans for data archiving and data sharing.

2. To facilitate coordination of tagging projects, a web-based information network should be developed for all Columbia River Basin (CRB) fish tagging projects and programs, e.g., networked web sites maintained by the agency funding tagging/marking projects. Web-based information should include the type of study (tributary, hydrosystem, estuary, ocean); principal investigator's name and contact information; species studied; ESU; location of study; dates; tagging technology used; and links to reports or published research results. Initially, this type of information could be readily incorporated as part of Bonneville's new Taurus web-based database system for all Bonneville-funded FWP projects.

3. During the next FWP project review cycle, all projects involved in ocean port sampling and lower river sampling for CWT recovery should address the tagging and tag recovery issues (statistical validity of tagging rates, tag recovery rates, and fishery sampling rates) presented in the Pacific Salmon Commission's Action Plan to Address the CWT Expert Panel (PSC Tech. Rep.No. 25, March 2008).

4. During the next FWP project review cycle, all tagging projects should address and document the statistical validity of tagging and tag recovery rates. Sample size calculations should be based on statistically valid methods and documented.

5. For FWP proposals during the next project review cycle, project sponsors should provide a review of the applicability and costs of different tagging technologies that are appropriate for their research/management objectives. In addition, proposal budgets should include itemized costs per unit, e.g., cost per tag and cost per receiver, and number of units to be purchased.

6. The region should establish a tagging/marking standing committee (e.g., panel of experts) designed specifically to improve coordination of tagging/marking projects and programs of the FWP, the Corps' Anadromous Fish Evaluation Program (AFEP), and the Lower Snake River Compensation Plan. Such a committee could also coordinate the future development and review of criteria for cost-effectiveness of FWP tagging projects and programs. This committee could be co-chaired by NOAA Fisheries and Bonneville or Corps, with other participants to be determined.

SPECIAL SECTION 5

PNAMP provides leadership through the development and the advancement of recommendations and agency level agreements that are considered for adoption by the participating agencies.

PNAMP has adopted the following goals:

- Improve communication between monitoring programs across State, Tribal, and Federal organizations.
- Improve scientific information needed to inform resource policy and management questions and decisions.
- Seek efficiencies and cost-effectiveness across monitoring programs through compatible and cooperative monitoring efforts.
- Promote science-based credibility of monitoring and assessment efforts.
- Share resources and information between monitoring programs across State, Tribal, and Federal organizations.

In addition to adopting a monitoring coordination structure with Steering Committee guidance, PNAMP has identified and developed working groups for five key elements of monitoring: watershed condition monitoring, effectiveness monitoring, fish population monitoring, estuary monitoring, and data management. PNAMP has adopted a Charter to formalize the agreement among federal, state, and tribal entities to participate in the coordination of scientific monitoring programs. PNAMP has also developed a coordination plan to facilitate aquatic monitoring in the Pacific Northwest titled, "Strategy for Coordinating Monitoring of Aquatic Environments in the Pacific Northwest."

The Fish Population Monitoring Workgroup

The purpose of the Fish Population Monitoring Workgroup is to advance the science of monitoring and evaluation and provide recommendations for monitoring fish populations in the Pacific Northwest. The workgroup initiated the task to review and catalog tagging, telemetry, and marking protocols in the region among other priorities. The workgroup seeks to assist in developing a broad regional strategy for monitoring anadromous fish and the ecosystems they inhabit and transit to improve design effectiveness, scientific rigor, information sharing and cost efficiencies in the region.

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