The Scientific Basis for Validation Monitoring of Salmon for Conservation and Restoration Plans

Report of the Validation Monitoring Panel to the Olympic Natural Resources Center

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TO THE OLYMPIC NATURAL RESOURCES CENTER

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Executive Summary

With large amounts of time, effort and money spent to improve the status of salmon in the Pacific Northwest, the question naturally arises - what must be measured to learn which actions are effective and which are not. The purpose of validation monitoring, with respect to salmon, is to establish a cause-and-effect relationship between the implementation and observed effects of management actions. The challenge associated with this type of monitoring is to establish a measurement approach in which management actions of a conservation plan can be related to responses by salmon, so that plausible relationships between habitat and populations can be assessed.

The University of Washington, Olympic Natural Resources Center convened the Validation Monitoring Panel to define the appropriate measurement approach. The panel was co-chaired by David Peterson, Professor/Unit Leader, US Geological Survey and Daniel Botkin, Research Professor, University of California. The other panel member were selected to provide diversity among disciplines and institutions, and to include both specialists in the study and management of salmon in the Pacific Northwest and those with additional relevant expertise from outside the region. The panel has concluded that if the goal is to increase the number of salmon (total or a specific stock), then the variable of interest must be the number of fish. Therefore, *counting fish through the process of validation monitoring is the only way that a link between cause and effect can be confirmed quantitatively*.

The primary question addressed in this report is:

> *If actions are taken in an attempt to improve the status of salmon populations (or a specific stock of salmon), what measurements are necessary, feasible, and practical to determine whether the actions are successful?*

What is necessary:

Genetics: Genetic characteristics of salmon populations must be considered in conservation plans and in monitoring activities that support those plans. Genetic data are critical for quantifying the status of local reproductive populations and evolutionarily significant units specified by the Endangered Species Act (ESA). Matching the degree of genetic scrutiny with the objective of the monitoring program (ESA compliance, stock composition research, etc.) is an essential component of validation monitoring, and experts in fish genetics should be consulted in the development of monitoring designs.

Spatial scales: Fish productivity and habitat requirements have a high degree of spatial and temporal variation. Therefore, the response of salmon populations to actions that affect habitat must be evaluated at broad spatial and temporal scales. In contrast, the effectiveness of some specific management actions for improving habitat is often best evaluated at small scales. A monitoring design that examines a series of related questions at nested hierarchical spatial scales can provide information on the response of salmon populations to a suite of management actions, as well as generate information on population response to conservation plans. This report describes the parameters to be measured depending on the spatial scale at which monitoring is conducted.

Statistical analysis: A scientifically and statistically valid experimental design that accounts for the complexities of salmon biology, including temporal variation, is needed to provide constructive feedback on the success of conservation efforts. Simply enumerating salmon numbers over time is insufficient for validation monitoring. To correctly assess trends in salmon populations, one needs to evaluate numbers over time in the context of a statistical framework that guides analysis from data collection through data analysis and interpretation. This report presents statistical concepts that can be used to guide quantitatively robust and efficient analyses at a variety of spatial and temporal scales. Statisticians and other quantitative analysts should be included in the design of all monitoring programs.

What is feasible:

Monitoring Methodology: Salmon monitoring programs must adhere to many principles, including (1) representativeness of monitoring locations, (2) a long sampling period (perhaps several decades), (3) adequate replication, (4) high accuracy and precision, (5) use of state-of-the-art techniques, and (6) high-quality data management. Although this is an ambitious list, these principles are required to obtain meaningful and legally defensible data. Monitoring designs and parameters, including specific case studies, described in this report will lead to high-quality data sets at a variety of spatial scales (basin, watershed, reach). A variety of recently developed technical tools for counting fish have been successfully applied at other locations in North America and hold great promise for the Pacific Northwest.

Variability and Uncertainty: Variability is a fundamental property of fish populations and a primary consideration in fisheries management and salmon conservation. Variability and uncertainty are themselves sources of information about salmon. Recognizing that current datasets may be incomplete, but that the decision-making process must move forward, the recommended approach is to (1) utilize the best scientific knowledge available when developing a monitoring plan, and (2) continually re-evaluate and learn from one's experiences through the process of adaptive management. This approach provides strong motivation for *long-term* monitoring, so that adequate time series of population data can be obtained for robust statistical analyses and confident interpretations.

What is practical:

Institutional Framework: An effective monitoring plan requires input from the scientific community regarding principles of data collection and analysis, but also considers the realities of legal, political, and social environments. Institutional settings, agency policies, and various legal requirements provide a context—and often constraints—for validation monitoring of salmon populations. The division of responsibility to manage fish and wildlife (primarily state agencies) and manage habitat (primarily federal agencies) poses a particular challenge. The direct or cumulative effects on species of concern can lead to sampling difficulties in implementing proposed plans. It is clear that increased coordination and cooperation among agencies and institutions will be needed for successful monitoring programs. An overarching requirement will be long-term commitment to support these programs with adequate administrative infrastructure and funding.

The Monitoring Imperative: With a lengthy list of requirements for and potential constraints to validation monitoring, why is there so much emphasis on proceeding with monitoring programs in the near future? How can we afford to invest in such a process? The answer is that the cost of *not* monitoring is simply too high. A vast sum of money has already been spent in the Pacific Northwest with the intent of benefiting salmon, with little or no confirmation of success—or failure. Without effective validation monitoring programs in place, the actual response of salmon populations to conservation strategies will remain largely unknown, and the validity of theorized relationships between habitat and salmon populations will be untested. Decision makers and the general public are increasingly concerned that government and natural resource managers are effectively using public funds to truly improve the condition of salmon populations. Validation monitoring provides the accountability that is necessary for a viable, long-term salmon conservation effort in the Pacific Northwest.

This report presents a scientific basis for counting salmon as a means to determine the effects of practices designed to improve the status of salmon. It includes the rationale for counting, benefits to be derived from counting, and suggested approaches to validation monitoring. This information is needed to support the scientific framework and management planning efforts related to the enhancement of salmon populations in the Pacific Northwest. Conservation plans must include a validation monitoring component, beyond simply providing habitat, in order to quantify the effects of management actions. It is imperative that we move this comprehensive science based approach forward in a timely way to ensure a credible evaluation of conservation efforts and to support the objective of those efforts—to protect and enhance salmon populations.

I. BACKGROUND AND OBJECTIVES

Major Goal of the Report

This report presents a scientific basis for counting salmon as a means to determine the effects of practices designed to improve the status of salmon. It includes the rationale for counting salmon, benefits to be derived from counting, and suggested approaches to validation monitoring. This information is needed to support the scientific framework and management planning efforts related to the enhancement of salmon populations in the Pacific Northwest.

The major question this report seeks to answer is:

If actions are taken in an attempt to improve the status of salmon (or a specific stock of salmon), what measurements are necessary, feasible, and practical to determine whether the actions are successful?

The management and conservation of salmon present society with several challenges. At present, there appear to be no clearly proven metrics for detecting salmon population response to specific management actions within five years or less. However, there is much public interest, political incentive, and desire by public agencies to develop useful policy at shorter time scales. Furthermore, scientific research on salmon has tended to focus on processes that occur at much smaller spatial scales than the management questions that face agencies and policy makers.

This poses a conflict between the question a governor might ask—"What should we do today to improve the status of salmon tommorrow?"—and the question a scientist might ask—"What is the cause-and-effect relationship between two variables in a single watershed over a 20-year period?" At first glance, these questions seem incompatible: political leaders and society want to move forward with decisions now, while some scientists are saying that monitoring is needed over decades.

Direct counts of salmon as the variable of interest for addressing both questions seems to the public and many elected officials as the obvious and common sense thing to do. However, some scientists and decision makers apparently view this as impractical or otherwise undesirable. But policy makers, legislators, and resource managers need a robust approach for quantifying the benefits of recent salmon conservation efforts. The simple fact is that billions of dollars have been spent with the objective of helping salmon populations recover or persist, but there are few if any confirmations of success. Society deserves to know if its social and financial investment in salmon conservation is paying off in terms of viable salmon populations.

Some argue that the investment has been insufficient and that much greater economic sacrifice will be necessary, although opposition to open-ended investment has also become more vocal. Recent U.S. Endangered Species Act (ESA) listings are expected to raise the cost of salmon restoration for communities throughout the Pacific Northwest (PNW). Increased social and political stress is sure to follow, and management prescriptions and conservation strategies will need scientific justification in order to maintain support and withstand inevitable challenges.

Many scientists and resource managers have assumed that measuring salmon populations in response to conservation practices is unlikely to produce statistically valid data or is difficult to accomplish. Population monitoring will certainly require a significant commitment of time and resources. Salmon numbers have rarely been used as a direct response indicator for conservation strategies, perhaps because acquiring statistically valid information is expensive and requires long-term data collection. As a result, many monitoring efforts have focused on measuring riparian vegetation composition, streambed characteristics, water chemistry, and other biophysical habitat characteristics.

This has led to a default monitoring approach of what is perceived to be feasible, rather than a comprehensive approach of measuring the abundance of salmon before, during, and after the implementation of a new conservation action. Equally rare is formal testing of new conservation actions, in which salmon abundance is compared in areas with and without new actions. The underlying rationale for the argument based on feasibility is that informal and unvalidated information is sufficient for drawing inferences. Unfortunately, this approach does not provide scientifically valid or legally defensible evidence of the success or failure of a particular conservation approach.

This report is the product of deliberations of a panel of experts on salmon biology, PNW ecosystems, and a broad range of ecological sciences. Our interdisciplinary group has reached consensus on the necessary measurements, and proposes this report as a conceptual approach for the many projects focused on improvement of salmon stocks. In summary, this report:

- Describes what is necessary, feasible, and practical in quantifying the status of salmon.
- Summarizes principles to be followed in selecting measurements and measurement procedures.
- Is directed towards planners who need to make difficult decisions on the allocation of resources for salmon conservation.
- Can be used by resource managers as a filter through which to pass the development and implementation of validation monitoring plans for salmon conservation.
- Is useful to elected officials who need to understand the status of salmon and include public concerns in decision making.
- Is not a guide for field application by resource managers.
- Does not address social values and is not an attempt by scientists to suggest natural

resource policy.

The Problem

Scientists and resource managers need a conceptual approach to guide future activities in validation monitoring for salmon conservation. After considering desirable future conditions, what needs to be measured to determine whether management actions are helping, hurting, or having no effect on salmon? Several critical issues must be addressed:

- The scientific criteria most effective in determining the status of a salmon stock and the condition of its habitat.
- The necessity, feasibility, and practicality of counting adult and/or immature salmon to determine the status of a stock or other demographic unit of salmon.
- Other factors that must be measured to allow the best estimate of the present and future status of salmon.
- The appropriate spatial and temporal scale of measurement.

There are many possible definitions and frameworks for monitoring natural resources (Peterson et al. 1995). However, in the PNW, monitoring on public lands usually is discussed in the context of the Northwest Forest Plan (NWFP, FEMAT 1993) and encompasses three kinds of monitoring: implementation (or compliance) monitoring, effectiveness monitoring, and validation monitoring (Mulder et al. 1999). These three kinds of monitoring are defined as follows:

> *Implementation monitoring* — Monitoring to document compliance with directions as stated in guidelines, plans, regulations, or laws. Example: Placing specific quantities and sizes of large woody debris in a stream to enhance aquatic habitat for salmon as specified in a state's guidelines.
>
> *Effectiveness monitoring* — Monitoring to document the status and trends of resource conditions. Example: Measuring the abundance and size distribution of large woody debris in a stream for 20 years to determine habitat quality.
>
> *Validation monitoring* — Monitoring to document cause-and-effect relationships, and to evaluate the link between implementing the standards and guidelines and the observed effects. Example: Measuring the abundance of salmon populations in a stream to determine if aquatic habitat modified by the addition of large woody debris results in a change in fish numbers.

Conservation plans, such as the NWFP, describe strategies and are designed to lead to successful outcomes for the future condition of salmon. The standards and guidelines (USDA and USDI 1994a,b) needed to realize successful outcomes often are the primary focus (or treatment) evaluated through a monitoring program (Mulder et al. 1999). Salmon conservation plans have rarely articulated all three components of monitoring described above. Indeed, the NWFP cites the value of effectiveness monitoring based on the explicit use of habitat condition as the variable of interest.

Having considered various points of view regarding validation monitoring, our panel concludes that *counting fish through the process of validation monitoring is the only way that a link between cause (standards and guidelines) and effect (trend) can be confirmed quantitatively*. Moreover, recent experience with monitoring salmon populations, as discussed later in this report, shows that such counts are feasible and practical. Therefore, counts of adult salmon are a necessary factor in validation monitoring.

Quantitative measurements are basic to science. If the goal is to increase the number of salmon (total or a specific stock), then the variable of interest is the number of fish. If one wants to determine if management actions are successful, and the goal is to increase the number of salmon, then the number of salmon must be measured. In the past, the kind of data required for validation monitoring generally has not been obtained, and as a result, one must initiate data collection for each salmon conservation program. Therefore, an effective monitoring program (and therefore any program of adaptive management) cannot start immediately, but must involve a set of transitions. These consist of (1) a transition from current knowledge to an adequate time series of data, and (2) an analysis of the time series, (3) inferences regarding the condition of salmon, and (4) decisions regarding future management *and monitoring*.

The Central Dilemma

There is an ongoing controversy about what is necessary, feasible, and practical to measure about salmon. In many cases, the primary factor of interest is the number of adults that return to a stream, or to a region, to spawn. In other cases, there is greater emphasis on enhancing specific genotypes or demographic units, typically what are called "native" or "wild" salmon stocks. However, for each level of concern, the relevant population data are of the same kind: how many salmon might be caught, whether fish production is increasing or decreasing, and whether a desired level of biological diversity is being maintained.

Although the previous introductory discussion suggests that counting salmon is necessary and feasible, over the past few decades, thoughtful scientific debate by scientists in the PNW has failed to reach consensus that direct measurement of salmon populations is appropriate. The argument against direct counts of salmon generally is that it is impractical or difficult to do with sufficient accuracy. This argument implies that the complexity of salmon biology, life histories, and the diverse aquatic and terrestrial ecosystems on which they depend make direct counts technically challenging. In many cases, measuring the condition of habitat appears more practical despite the complexity of salmon habitat requirements.

Although the ultimate objective of most salmon conservation plans is to increase salmon abundance and productivity, and in some cases to modify salmon diversity, existing conservation plans generally describe specific actions for habitat modification without quantitatively linking habitat and numbers of fish. For example, protecting riparian vegetation can influence water temperature, sediment level, and habitat complexity, and it is assumed that improved habitat condition will increase abundance or improve health of salmon. The challenge in validation monitoring is to establish a measurement approach in which management actions in a conservation plan can be related to population responses of the species of interest, so that what appears plausible can be determined to be correct or incorrect.

There is increasing evidence that direct counts of salmon are feasible and have been used successfully in the PNW and elsewhere (see Appendices). This report explores how such direct measurements may be implemented and interpreted to provide accurate data on fish populations for assessing the value of salmon conservation efforts. Enumeration of populations, in addition to surrogate measures (e.g., habitat characteristics such as redds), is needed to quantify the effects of management actions on salmon.

Given the expense—in terms of human and financial resources—of measuring salmon populations, data need to be collected efficiently and put to good use. On the Columbia River alone, over $3 billion has been spent on salmon research and restoration, essentially without any clear evidence of the benefit of this expenditure. The amount spent in the entire PNW on salmon research, restoration, management, hatcheries, and habitat improvement, far exceeds this number. Unfortunately, many (perhaps most) natural resources data are poorly documented and archived, resulting in those data being essentially unavailable and wasting valuable scientific and public resources.

Another indication of the interest and willingness of society to expend large amounts of funding to conserve salmon is the active discussion about the removal of dams on rivers. The National Park Service has purchased two dams on the Elwha River in Washington, important historical habitat of chinook and six other salmonid species, and planning is well underway for dam removal in the next few years. An even bolder proposal from conservation organizations and several scientific societies calls for the breaching of four dams on the Snake River in order to save several salmon stocks.

The estimated cost of breaching the Snake River dams and of associated activities is approximately $1 billion, with additional costs for managing sediment stored behind the dams as it moves downstream. There is already a great deal of money being spent on upstream and downstream salmon migration in the mainstem Columbia and Snake Rivers. Given these ongoing efforts and the apparent willingness of society and politicians to support large expenditures for salmon conservation, it is clear that the marginal cost of accurate monitoring of fish populations is a critical economic and scientific investment.

II. SOCIAL AND SCIENTIFIC CONTEXT FOR MONITORING SALMON

Major Societal Questions

The overarching goal of this report is to provide a conceptual approach for answering current management questions regarding salmon conservation. The report establishes the utility of monitoring through direct counting of fish and surveying of relevant environmental variables. The focus is on scientific issues and concepts as they relate to important societal questions. Discussions of resource controversies, developing technologies, and analytical methods are not intended to be comprehensive.

Data collected through monitoring will accumulate gradually, and there will be pressure and need to begin interpreting data immediately. It is unnecessary to delay interpretation until after the accumulation of long time series. As the records lengthen from single data points to decadal-scale time series, they will become interpretable through increasingly formalized statistical methods. The short-term interpretation must be conducted with the assistance of expert opinion, taking into account (1) the effects of management intervention itself (which may be unstudied and transient) on salmon habitat and numbers (e.g., channel adjustment to dam removal); (2) fluctuations in other variables affecting salmon populations (e.g., stream flow, ocean conditions, and hatchery releases); and (3) time scales of some effects that are several years (salmon life history) to several decades (re-establishment of large woody debris in channels).

In the short term, interpretation of data from monitoring systems will be more effective if it is based on conceptual models that summarize the best available, knowledge of salmon habitat and populations. These interpretations will also be facilitated by compilation of existing measurements of salmon numbers, redds, and related variables in the vicinity of the stream being monitored. Significant problems exist with most data sets in the PNW (e.g., unrepresentative sampling sites, irregular and discontinuous sampling). However, it will still be useful to examine these data for robust estimates of temporal variation, confidence intervals, and association with controlling variables as a prelude to designing monitoring schemes and interpreting early results.

Societal Actions and the Roles of Citizens, Government Agencies, and Elected Officials

The decision to take an action to enhance or conserve salmon is ultimately a societal decision. Divergent groups within society will continue to debate what policies to adopt and what is desirable to monitor. This report does not enter into this debate. But societal decision-making can be enhanced by scientific processes and by understanding what science can contribute. This report explains the basic scientific concepts and principles of monitoring, which can be considered once the decision is made to take some action intended to benefit salmon.

This report provides a conceptual approach based on "best available science" with a high likelihood of success if the recommended actions are followed. It is not intended as a blueprint for decision-making or as a technical manual of field methods. For example, a scientifically developed "best management" scenario for a harvest level may still carry risk for overharvesting due to measurement errors, environmental variability, and random variation in mortality and natality of the harvested population. Resource managers and politicians need to be aware of these risks and the risks of *not* selecting the best scenario. Only in this way can managers and politicians evaluate their potential choices (Belovsky et al. 1999).

Making Decisions with Incomplete Information

Science is a process of continued examination and reexamination of observations, inferences drawn from observations, tests of hypotheses, and a search for generalizations. The one key quality that connects all science is that a statement, to be considered scientific, must be open to disproof – one must be able to conceive of a test that will either support or disprove it. The dilemma that faces all scientific applications was addressed by Michael Crichton in his recent book, *Timeline*[1]:

> "A classic real-world scientific problem. Weighing risks, weighing uncertainties. Most people never understood that the majority of scientific problems took this form. Acid rain, global warming, environmental cleanup, cancer risks – these complex questions were always a balancing act, a judgment call. How good was the research data? How trustworthy were the scientists who had done the work? How reliable was the computer simulation? How significant were the future projections? These questions arose again and again."

Science is never complete, and the application of scientific data, information, and understanding to the real world never occurs with *complete* data or with *a complete, final* understanding. One often hears the question, "How can we make decisions without complete scientific information?" But with natural resources and ecological systems, this is rarely the question. Instead, for these complex systems that have only recently been the subject of scientific study, the question is more likely to be “How can we make decisions with almost no scientific information, or with very incomplete scientific data, information, and understanding?”

Some simplistic answers to this question are: (1) wait until the scientific data and understanding are complete, that is, do nothing now, or because scientific data and understanding will never be complete, never do anything; and (2) move forward and make decisions without reference to available science, because science can never be complete. Neither of these approaches is valid. The appropriate approach is through adaptive management, the process of continually learning from one's mistakes, while at the same time making policies based on the best available scientific data (see section III for discussion on adaptive management).

However, there is a danger lurking in this approach. Legislation, such as the ESA, states that decisions should be based on the "best available scientific data." But what if there are no data? Is the *opinion* of a scientist allowed to substitute for data? Making decisions with incomplete information is a societal choice, but we recognize it as such. Society is faced with having to make decisions with incomplete information and will remain in this situation if validation monitoring is not started.

<u>Uncertainty and Variability</u>

Variability is a fundamental property of fish populations and a primary consideration in fisheries management and salmon conservation. As fundamental characteristics of nature, variability and uncertainty are themselves sources of information about salmon, as well as inputs into societal decisions. Salmon travel great distances in space and time, and are influenced by a wide range of "natural" environmental factors (e.g., climatic variability), in addition to human activities. Because of this inherent variability, it is imperative that decision makers and resource managers consider appropriate spatial scales and time frames for evaluating the effects of various conservation practices on salmon populations.

Variability in salmon populations provides strong motivation for *long-term* monitoring, so that adequate time series of population data can be obtained for robust statistical analyses and confident interpretations. Although this variability increases the response time of effective adaptive management, baseline data accumulated through long-term monitoring are critical for accurately quantifying spatial and temporal variability for applications in fisheries management. For example, because salmon depend on fresh water flow, variability in flow contributes to variability in numbers of salmon. The connection between these two kinds of variability must be quantified to forecast the effects on salmon of changing hydrologic regimes.

Population data, in addition to the habitat variables on which salmon depend, must be quantified to understand the effects on salmon of prospective management actions. Monitoring programs are the means to collect data to quantify variability. Because of intrinsic variability of salmon populations, monitoring data will invariably fluctuate widely over many years. As a consequence, fisheries management must associate measures of effectiveness to a long-term planning horizon. One also needs to be aware that the range of any variable, including salmon numbers, increases as the period of observation increases.

Society generally accepts the notion of uncertainty regarding scientific phenomena that affect human life. Examples include forecasting floods, earthquakes, and influenza outbreaks. The accuracy of such forecasts has significantly improved as monitoring programs have been maintained for longer periods. With each of these phenomena, as with salmon, there is a public policy question about acceptable levels of risk. Concerning influenza, one might ask, "When does the risk of an outbreak warrant widespread inoculations?" Concerning salmon, a relevant question is "How high a risk of extinction (say, over a 50-year planning horizon) is acceptable before taking action?" This is a societal question for which scientific information, including data from monitoring programs, is essential.

Characteristics of Successful Long-term Monitoring

Meaningful and practical monitoring programs are difficult to design and expensive to implement. Identifying a limited set of useful and measurable parameters (i.e., what should be and can be measured to assess management effectiveness) and developing an appropriate sampling design (i.e., how, when, and where to sample) is challenging. Resource managers often are overwhelmed by the technical and logistical requirements, and scientists often retreat to creating "laundry lists." Furthermore, project-level monitoring plans generally are idiosyncratic. That is, the ecological and social context of each project requires development of a unique monitoring plan, because textbook examples or standard plans often are not available. Hierarchical (or nested) sampling designs often proposed by statisticians and scientists may be inappropriate, because selected parameters end up being monitored on different spatial and temporal scales. Finally, there is invariably the problem of sufficient and sustained funding to conduct a monitoring program.

The Nature Conservancy (TNC) is a good example of an organization that has successfully developed ecological monitoring programs. This organization typically collects funds to endow the management and monitoring effort at the time they raise funds to purchase a property. In addition, TNC focuses its monitoring efforts on a few specific parameters, such as distribution and abundance of a plant or animal species or overall condition and trend of an ecosystem. Finally, TNC hires individuals to develop and conduct monitoring programs as well as to supervise these activities when they are contracted to universities or other institutions.

The monitoring program developed and implemented for Channel Islands National Park (California) is an outstanding example of monitoring by a federal land management agency. One reason is that the monitoring was mandated in the legislation establishing the national park. Scientists and managers at the park devoted considerable energy to developing a plan for underwater marine sampling (permanent marine plots!) of ecosystems and populations as well as more traditional terrestrial plant and animal monitoring. This program has become a key source of information for management and policy development in the Channel Islands region, as well as throughout the National Park System.

The program developed by Trillium Corporation for monitoring sustainable forestry management in southern beech (*Nothofagus*) forests in Tierra del Fuego is another example. A team of scientists and company managers developed a monitoring plan that includes meteorology; hydrology and quality of streams; composition, structure, and function of representative aquatic ecosystems; regeneration, growth, and mortality of forest; effects of harvest practices on soil physical, chemical, and microbiological conditions; population levels of small mammals and birds; demographic studies of animals, such as red fox and guanaco; and exotic plant species. A research component of the monitoring plan includes a study of the effects of timber harvesting on flora and fauna, and a watershed-level study of nutrient balances in natural and treated forests.

The National Science Foundation's Long Term Ecological Research (LTER) program is well known for conducting long-term measurements of standard ecological metrics through a network of sites in terrestrial and aquatic ecosystems in North America. Time series of data from several of these sites have revealed insights on significant environmental issues. The LTER program emphasizes that high-quality data management is essential for successful monitoring programs. There must be good quality assurance and quality control on the data, thorough documentation (metadata), and careful archiving of the data. The cost for adequate data management generally is at least 25% of the total cost of a monitoring project based on LTER experience.

The Role of Modeling

Simply enumerating salmon numbers over time is insufficient for validation monitoring for several reasons. First, there are multiple factors (weather, ocean currents, etc.) in addition to the management actions being evaluated that can simultaneously influence salmon numbers. Second, these multiple factors are not constant among years. Third, one might want to examine which management action of several taken may be the most effective for increasing salmon numbers. Finally, one might want to forecast future trends. Therefore, to correctly assess trends in salmon numbers, one needs to evaluate salmon numbers over time through a model, which evaluates the influence of each factor as it varies among years.

Models (a term that typically refers to statistical or computer simulation models) are tools that provide insights that observations alone cannot provide. Models can be especially insightful by evaluating the effect of one action on salmon numbers while holding the effects of other factors constant. This allows one to assess the influence of each management action in isolation and determine which of the potential actions are most effective for salmon conservation, a task that would be very difficult and expensive in real-world application.

Models also can be used to evaluate levels of management action that one would not want to impose without sufficient justification relative to their effectiveness in salmon conservation. In this case, the model can be used to conduct management "experiments." Models also can be used in a predictive manner to project salmon trends into the future, allowing one to compare future salmon observations with the projections and to determine the direction in which conditions for salmon are changing. Models extend the usefulness of observations and are appropriately used as a supplement, not a substitute, for an actual time series of observations.

There are now three distinct approaches to modeling represented in currently used decision support tools for salmon management. These approaches are (1) decision analysis, embodied most clearly in the Plan for Analysis and Testing of Hypotheses (PATH), (2) statistical analysis, embodied most clearly in the Cumulative Risk Initiative (CRI), and (3) expert system analysis, embodied most clearly in the Interior Columbia Basin Ecosystem Management Plan's Bayesian Belief Network (ICBEMP) and the Ecosystem Diagnosis and Treatment (EDT) method.

Of the three approaches, the decision analysis approach is most closely directed at providing management advice. And it is the most formal about factoring uncertainty into the analysis, so it has the potential to be the most useful to decision makers if it is successful. But the decision analysis approach is very difficult to implement successfully. Its success depends on the engagement of actual decision makers in framing the questions that need to be answered, identifying the management options that are under consideration, and in defining the values put on various possible outcomes. The decision analysis approach also requires clear communication between the technical analysts and the decision makers, including communication about complicated matters of risk, probability, and uncertainty. Such engagement and communication is difficult to achieve in the institutional setting of salmon management, where there is so much fragmentation of decision-making authority for different pieces of the management problem.

The statistical approach is scientifically the most classical of the three, and can operate effectively with a large degree of detachment from policy. It proceeds by testing hypotheses with available data. This has the advantages of clarity, rigor, and empirical objectivity. The limitation is that the scope of the questions that can be answered is restricted by the availability of data. In a data-poor domain, many pressing questions often go unanswered. This may be scientifically proper, but it does not address the needs of managers who recognize that "no decision" is still a decision.

Expert system approaches fill data gaps with expert opinion. In the context of salmon conservation, expert opinion allows consideration of the most concrete menu of specific options for actual management.

Institutional Constraints

Developing institutional and financial commitments for long-term monitoring has been a major challenge for most governmental agencies. Budget cycles of agencies are usually 1-2 years, much shorter than the period required to get results from validation monitoring efforts. This makes it difficult to secure funding for collecting long time series of data, especially because priorities of agencies change frequently. Because some institutions and agencies feel they are unable to wait for results and need to move forward with policy statements and management actions, there often is an unwillingness to undertake long-term commitments.

Most management agencies simply lack the personnel to design and conduct effective validation monitoring. Either people are not technically qualified or are unable to conduct research because of existing commitments. Research organizations also are often reluctant to be involved with validation monitoring, because (1) there are concerns about long-term commitment of resources, (2) complex issues make it difficult to develop designs that are likely to yield clear results, especially in a relatively short time period, and (3) researchers receive minimal reward from such efforts (e.g., peer-reviewed publications) compared to the amount of effort required. Personnel turnover also limits the ability of agencies to undertake validation monitoring.

Legal Constraints

Several federal laws and policies recognize the responsibility of federal agencies to manage habitat for fish and wildlife and for states to manage fish and wildlife populations. These laws include the Organic Administration Act, the Multiple Use-Sustained Yield Act, the Federal Land Policy and Management Act, the Sikes Act, and the Wilderness Act. Management of populations by states extends to federal lands and does not require approval from federal land management agencies, nor are states subject to the requirements of the National Environmental Policy Act. Federal agencies are required to obtain permits from state agencies in order to handle or collect fish for any purpose.

The division of responsibility to manage fish and wildlife (by state agencies) and habitat (by federal agencies) presents challenges in conducting validation monitoring. Most studies that have monitored fish populations have not been cooperative in nature, and the success of cooperation between state and federal agencies varies greatly. The type of interagency relationship depends to a large degree on the previous history of interactions, the expertise of people involved, and the type of issues being addressed. Conducting validation monitoring studies will certainly require greater cooperation among the appropriate state and federal management agencies than has occurred previously.

Validation monitoring efforts may be constrained by other existing laws and regulations. A primary one is the federal Endangered Species Act (ESA). Federal agencies responsible for ESA enforcement often are reluctant to allow activities to occur that may be viewed as being potentially detrimental to listed organisms. Another example of potential conflicts is the effect of laws dealing with cumulative effects and related issues. State and federal agencies have laws and regulations that are designed to prevent cumulative effects from activities such as timber harvest, with restrictions on size and extent of clearcuts and the number and area of roads. Finally, because sampling fish through research and monitoring efforts could lead to an incidental "take," there may be problems in acquiring the appropriate permits. At the present time, there is no clear institutional strategy or legal requirement to deal with these conflicts.

Salmon Conservation Efforts in the PNW Relevant to this Report

Although elected officials and the public no doubt feel as if they are doing something to alleviate the "salmon crisis," there are few data on how riparian restoration and salmon recovery projects in the PNW have affected salmon abundance. Salmon numbers continue to decline in many locations, some to the point of being listed as threatened or endangered under ESA. Every significant restoration and recovery plan adopted in the PNW recognizes the need to validate the assumption that improved habitat conditions will improve salmon abundance. To the extent that these plans are driven by ESA listing, compliance with the requirements of ESA and therefore success of the plans must be measured in terms of a long-term increase of viable salmon populations and suitable habitats. ESA requires that policy decisions be based on the best available scientific data, which both explicitly and implicitly support long-term monitoring. Therefore, validation monitoring is becoming increasingly important as scientists and the general public assess the uncertainty of outcomes of conservation plans.

Northwest Forest Plan (NWFP) — The NWFP was sponsored and organized by President Clinton. It was developed and is being implemented primarily by the USDA Forest Service and the U.S. Dept. of Interior Bureau of Land Management. The Forest Ecosystem Management and Assessment Team (FEMAT) developed long-term alternatives for resolving conflicts over managing forest ecosystems. In 1994, the courts accepted the preferred alternative for the NWFP and mandated implementation. The plan implicitly relies on science as the primary tool to define forest management strategies, and a primary objective is to develop and adopt a monitoring program leading to adaptive management practices. A Regional Ecosystem Office (REO) was established to focus scientific expertise on implementation issues associated with the NWFP. REO scientists also comprise the Research and Monitoring Committee, which provides assessments of research programs and assists with the development of monitoring plans.

The NWFP requires three types of monitoring: (1) implementation monitoring, (2) effectiveness monitoring, and (3) validation monitoring (see Types of Monitoring in section I). Validation monitoring, as defined in the NWFP, is intended to determine if a cause-and-effect relationship exists between management activities and the indicators or resources being managed. It was anticipated that agencies would develop specific monitoring strategies for priority resources, including aquatic and riparian areas. This has been accomplished for several terrestrial species, but much less progress has been made for validation monitoring of salmon under the NWFP.

Washington State Department of Natural Resources Habitat Conservation Plan (HCP) — The Department of Natural Resources (DNR) developed their HCP strategy as a means of complying with ESA listing and associated effects on habitat management. The DNR HCP is a multi-species plan that includes conservation for salmon. As part of the HCP, DNR will conduct three levels of monitoring, similar to those required in the NWFP, and will report to the U.S. Fish and Wildlife Service and the National Marine Fisheries Service in quantifiable terms of incidental take of listed salmon species. DNR is currently developing validation monitoring protocols, with the objective of detecting changes in populations of spawning adults and of salmon-habitat relationships.

Washington Statewide Strategy to Recover Salmon: "Extinction Is Not an Option" **—** Since the advent of ESA, federal regulatory agencies and the courts have become increasingly involved in defining how the national commitment affects state and local governments, private industry, agriculture, and the general public. The Washington Statewide Salmon Recovery Strategy, developed at least partially to maintain state and local control of decisions that affect the state's residents and commerce, includes budget and policy initiatives that give state and local governments the tools they need to meet ESA requirements. Federal acceptance of the plan is based on successful implementation of specific criteria, including a comprehensive monitoring program. Adaptive management is a cornerstone of the recovery strategy, and adaptive management cannot be implemented without monitoring. The plan defines three types of monitoring in a similar way as the NWFP. Monitoring the status of fish stocks over time is the responsibility of the Washington Department of Fish and Wildlife and tribal fishery co-managers. The validation monitoring plan is currently under development and review.

The Oregon Plan for Salmon and Watersheds **—** In response to proposed ESA listings of coho salmon, Oregon's governor established the plan with endorsement from the state legislature. The plan represents Oregon's effort to maintain state control over conservation measures, which will be evaluated by the appropriate federal agencies. Monitoring is a key element of the Oregon plan. State agencies focus on monitoring trends in fish populations and watershed health to evaluate the effectiveness of current management programs and to adapt their programs as needed. The monitoring and assessment section of the plan includes a commitment to monitor abundance and distribution of salmon in order to detect population changes and track recovery. Protocols for effectiveness monitoring and validation monitoring are not specified, although the concepts are included in the plan and are being integrated in planning of future recovery strategies.

III. PRINCIPLES OF VALIDATION MONITORING AND ADAPTIVE MANAGEMENT FOR SALMON CONSERVATION

<u>Validation Monitoring as a Process</u>

The process of validation monitoring includes three overlapping phases: (1) sampling and data collection, (2) data management, and (3) analysis and interpretation. Issues such as quality assurance and quality control apply across all phases, but each phase is marked by important considerations that should be addressed in validation monitoring plans.

Sampling and data collection

Considerations in the sampling phase pertain to obtaining data of the highest possible quality within financial and human resource constraints. Explicit recognition of the following issues is an important part of validation monitoring planning:

Representativeness — Do proposed monitoring sites and methods provide a reasonable representation of the total area in question? Do they represent the full range of conditions produced by natural disturbance processes (Reeves et al. 1995)? If they represent only a subset of the range of conditions in the area in question, what assumptions are made about extrapolating results to the watershed or region as a whole? The relative emphasis on current status versus long-term trend may affect the sampling design and monitoring locations.

Adequate time — Is the duration and frequency of monitoring sufficient to evaluate the effects of a management activity on salmon populations? Implicit in this question are two further considerations: (1) are the environmental effects of the management action likely to be expressed within the timelines of the monitoring plan? and (2) is the time period of monitoring long enough to detect measurable changes in salmon populations that result from those environmental effects?

Replication — Are management actions going to be replicated in space or time? If so, do monitoring plans include provisions to capitalize on repeated "treatments?" Because many ecosystem-level experiments are impossible to duplicate (Hurlburt 1984), innovative treatments involving systematically phased implementation (e.g., Walters et al. 1988, 1989) should be considered.

Precision and accuracy — What is the level of precision and accuracy of the monitoring methods relative to the attributes being measured? Are monitoring methods sufficiently precise to detect differences caused by management? What is the level of uncertainty (error) associated with these methods?

Feasibility — If the monitoring study implements one or more treatments, is it reasonable to believe that these treatments will be accomplished within the timelines of the study? Will landowners grant access to monitoring sites according to the schedule (and will weather conditions hinder or prevent seasonal access)? Will it be possible to obtain scientific study permits from the appropriate regulatory agencies to sample fish? Will sampling equipment withstand the rigors of repeated field use?

Technology — Does the monitoring plan make use of new technology to achieve sampling goals? Has the technology been tested and proven reliable? Are backup sampling plans in place in the event of technological failures?

Data management

The process of validation monitoring, especially if it extends over large areas and long time periods, generates very large data sets. Proper management of large databases is essential to the overall effort. Some key issues are:

Verification — Verifying data and checking for errors is time consuming and tedious, but it is one of the most critical steps in data management. Are sufficient resources budgeted to ensure data quality and to verify that data entered into electronic databases accurately reflect field measurements?

Archiving — Are data archived in a way that protects their security (proper backup and redundancy) and stores them in a format that can be imported into database management and statistical analysis programs? Are participants in the monitoring program aware of the locations of archived data? Are data archived such that storage methods keep up with technologies, thereby avoiding future data loss when current storage media become non-functional.

Accessibility — Data from validation monitoring projects must be available in electronic format to team members. With publicly owned natural resources (salmon almost always fall into this category), data are eventually made available to the general public. Today, more and more monitoring programs utilize the Internet for data sharing, with access to Web sites often password-protected to safeguard data security until analyses have been completed. However, there are electronic repositories of salmon data available on-line to the public, including some information (e.g., counts of adult salmon at dams) available in near real time. For example, the StreamNet site (http://www.streamnet.org) maintains a variety of data pertaining primarily to salmon in the Columbia River Basin. In addition, accurate metadata must be completed and made available to the scientific community and general public.

Analysis and interpretation

Monitoring data are not useful unless accompanied by thoughtful analysis and interpretation. There are many analytical techniques available, and it is not the purpose of this report to provide a comprehensive review of them. However, careful consideration must be given to analysis in advance of data collection and data management. Consultation with appropriate experts can resolve the following issues:

Analytical technique — It is important that analytical techniques be properly matched to the types of data being collected. As with any scientific question, analytical tools should be sufficient to test hypotheses but not so complex that they divert attention from the central issues. Selection of an appropriate analytical technique will help resolve some questions about sampling frequency and duration.

Cause and effect — Ascribing changes in salmon population abundance to management actions has potential pitfalls (Hilborn and Winton 1993, Lee 1993). Because salmon populations are naturally variable, it is possible that short-term shifts in abundance may be unrelated to a management activity being monitored. For example, one might attribute an increase in population to the effects of an enhancement or restoration effort when in reality the population change was caused by climatic variability or of factors not under management control. Conversely, blaming salmon declines on factors other than the factors being monitored often is speculative in the absence of appropriate biophysical data. Unless efforts are undertaken to control or account for potentially limiting environmental factors, such as the use of paired watersheds with treatments carried out in one and not in the other, great care is needed in interpreting population variability. Although these cautions would seem obvious, the history of salmon management is replete with policies built on mistaken scientific assumptions and hasty interpretations of population trends (Larkin 1977, Lichatowich 1999).

Uncertainty — Expressing uncertainty involves providing an estimate of potential error associated with the sampling methods themselves, and the probability of committing errors in interpreting results of studies designed to test hypotheses. The latter are often termed Type I and Type II errors, where Type I is the rejection of a true null hypothesis (e.g., concluding that there was a restoration treatment effect when in fact there was not one) and Type II is acceptance of a false null hypothesis (e.g., there was no difference between salmon populations in treatment and non-treatment watersheds when in fact there were more fish in the treatment watershed). Sampling uncertainty is commonly expressed as a confidence interval about the mean of a series of measurements, while Type I and II error estimates are based on probabilities of occurrence. It is important that analyses of validation monitoring data include uncertainty estimates and descriptions of how uncertainty was factored into the interpretation.

Trends — Detection of population trends is needed to relate changes in salmon abundance to management actions. But clear population trends are notoriously difficult to identify, and most investigators have concluded that (1) monitoring must occur over relatively long time periods (on the order of a decade and preferably more) and (2) management-induced changes must be relatively large for statistically measurable changes in salmon populations to occur (e.g., Hilborn and Winton 1993, Rieman and Myers 1997, Korman and Higgins 1997, Ham and Pearsons 2000).

Shifts in population age classes or community composition may yield detectable changes more rapidly than population censuses. Habitat changes that promote the abundance of certain age classes often do so at the expense of other age classes (e.g., increases in pools and reductions in riffles may favor older individuals at the expense of young-of-the-year). If annual changes in stream flow and ocean conditions can be factored into analyses, it might be possible to discriminate the effects of management effects from other sources of variability (Holtby and Scrivener 1989, Tschaplinski 1999). However, at present there appear to be no clearly proven metrics for detecting salmon population response to habitat management actions within five years or less. There is also a time lag between physical cause and biological effect that further complicates trend detection. Changes in land management may take decades to produce significant changes in stream channels or fish populations. In some cases, delayed responses are precipitated by rare natural events in watersheds (e.g., landslides, debris flows) where previous management activities occurred (Montgomery 1995, Harding et al. 1998).

Risks and opportunities — Analysis and interpretation of validation monitoring data should identify risks of management alternatives as well as opportunities for learning. Recent assessments at large spatial scales (FEMAT 1993, Quigley and Arbelbeide 1997) have employed risk assessment techniques in analyzing management alternatives. Population viability analysis is another risk assessment technique that is being used to identify salmon restoration priorities (http://research.nwfsc.noaa.gov/cri/documents.htm). Risk analysis applied to salmon populations is a rapidly developing area of scientific inquiry, and currently there are no widely accepted standard methods.

Adaptive Management

Adaptive management is a process of learning from one's achievements, mistakes, and experiences, then modifying a particular management action or strategy. Specifically, adaptive management involves the following steps:

1. Collect baseline data, so that the situation at the beginning is known quantitatively.
2. Develop a set of policy actions and hypothesize their outcomes.
3. Monitor quantitative variables, so that the situation is tracked as it changes.
4. Use the monitoring data to test the hypotheses.
5. Compare between the goals of the management and the results observed in monitoring:
   a. If monitoring indicates that goals are approached but not as well as desired, modify management actions (a "mid-course correction").
   b. If monitoring indicates that goals are not being met, then adjust management actions to improve the outcome.
   In either case, monitoring can help point the way to appropriate changes in policy and practices.
6. Repeat the process of #2 through #5 indefinitely. Monitoring becomes part of management.

Adaptive management involves, wherever possible, the careful examination and use of relevant existing data, including standard scientific measurements and historical information. Before a set of policies is put into place everywhere all the time, it is tested in formal experiments (following standard scientific and statistically valid experimental design, with treatments and controls) in a small portion of the area. If the data support the conclusion that the management action causes a desirable change, then the area in which the policy is applied can be expanded. In reality, threats of extinction or serious declines might not permit these steps, so management actions may need to proceed without adequate baseline measurements.

While the concept of adaptive management is straightforward, it has rarely been applied in biological resources as it has in other fields of applied science. Past failure to use adaptive management is probably related to (1) accepted paradigms not being adequately questioned, (2) management directed towards ideological and political goals unrelated to the condition of the biological resource, (3) lack of knowledge on how to implement adaptive management or failure to recognize opportunities to do so and (4) inflexibility of bureaucracies to alternative practices. In this sense, most agencies do not have a "Plan B" and may not change course in a timely way even when monitoring indicates failure. A possible solution is to establish several sets of policy actions, perhaps in order of priority and tested simultaneously in different places. Another possible solution is to develop of set of policy actions, begin by testing the one of highest priority and, if that fails, test the next highest in priority (or the one that the failure of the first suggests should be raised to the next in priority).

IV. KEY SCIENTIFIC CONCEPTS AND VARIABLES FOR MONITORING

SALMON

The condition of salmon stocks can be measured in several ways. In addition to the total number of fish and their total biomass, various life stages can be enumerated; life stage specific survival rates can be measured; and population attributes such as size, condition, age structure, and genetic characteristics can be determined. The appropriate parameters to be measured depend on the values and objectives of the public, interest groups, and policy makers. The parameters to be measured also depend on the spatial scale at which monitoring is conducted and resources are available to conduct measurements (See Table 1).

An important consideration in establishing a representative monitoring plan is the genetic composition of the stock to be evaluated. However, identifying and distinguishing among fish with different genetic characteristics can be technically challenging. Natural genetic variance and current or historical hatchery inputs contribute to the spatial distribution of genetic character. An unknown extent of mixing between native and hatchery stocks can confound the issue. Data on genetic characteristics of salmon populations are critical for quantifying the status of local reproductive populations (demes) and evolutionarily significant units specified by the ESA.

Matching the degree of genetic scrutiny with the objective of the monitoring program (ESA compliance, intensive stock composition research, etc.) is an essential component of validation monitoring. Advances in the technological tools available to investigate fisheries genetics can enhance our understanding of stock composition. This report includes minimal detail on genetic sampling, however, it is critical to consider the role of genetic characteristics in the conservation of salmon populations and to consult with experts in fish genetics prior to monitoring.

Spatial Scale and Design of a Monitoring Strategy

Fresh water habitats

Developing a validation monitoring approach that relates habitat conditions to population attributes of Pacific salmon is complicated by the high degree of spatial and temporal variability in habitat conditions and the fact that habitat requirements vary among salmon species and with life history stage. In the discussion of salmon, three spatial scales are typically used: the reach (a portion of a stream, usually less than about 2 km in length), the watershed (the land area draining into a river or river system, usually in the range of 100 to 10,000 km^2), and the basin (multiple watersheds contributing to a major river system, usually greater than 10,000 km^2) (See Table 1).

Table 1. Examples of measurements that could be employed at each of three spatial scales to characterize salmon populations and habitat condition.

Scale	Measurement objective	Stock metrics	Habitat metrics
Basin	• Total fish population • Interannual variability • Spatial distribution of salmon across the basin	• Adult counts at the river mouth • Extensive redd or spawner counts • Population genetic characteristics	• Climate • Vegetation type • Basin discharge
Watershed	• Effects of a suite of management actions • Population response in treated vs. untreated watersheds	• Redd or spawner counts • Smolt output • Juvenile surveys • Adult (egg)-smolt survival rate • Juvenile or smolt size or condition • Metapopulation genetic characteristics	• Topography • Geology • Watershed discharge • Distribution of channel and valley types
Reach	• Effects of site-specific management prescriptions • Seasonal utilization of different reach types	• Juvenile abundance/ density • Life-history stage specific survival rate • Growth rate • Juvenile size or condition • Local population genetic characteristics	• Sediment levels • Riparian condition • Habitat complexity • Water temperature

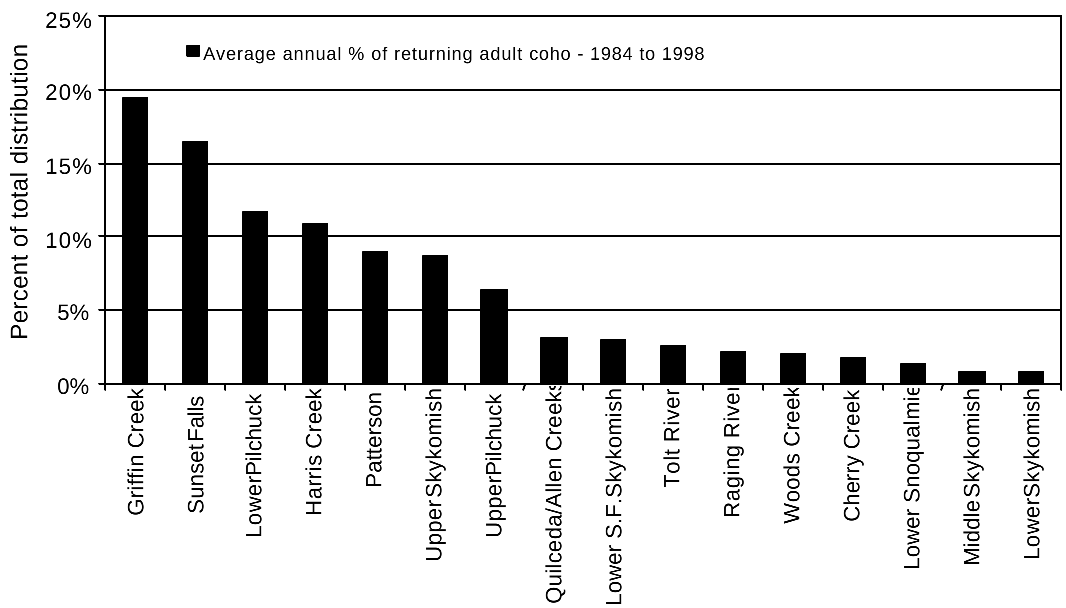
At the basin scale, the primary objective is to develop an understanding of the total number of fish utilizing the basin and their spatial distribution. In validation monitoring, basin-level information provides a basis for interpreting watershed-level population data (i.e., how treatment of some watersheds in the basin affects their use by salmon relative to untreated watersheds) and provides an indication of interannual variation in population size and genetic structure. At the watershed level, monitoring questions are more closely related to the specific management measures being evaluated, and the population parameters measured may vary as a result. The number of returning adults coupled with measurements of smolts can be an indicator of freshwater survival for some species (e.g., coho), although the relationship between adults and smolts can be highly variable. Additional measures include size, growth rate, condition, and genetic characteristics. These parameters provide information on health of the fish, which can have a significant impact on survival.

At the reach level, the information being collected often is dictated by the management actions or habitat attributes being evaluated. For example, if measures designed to reduce fine sediment delivery to a stream reach are being evaluated, egg-to-fry survival rates might be an appropriate metric. However, if the goal is to evaluate salmon response to increased pool habitat, population surveys of juvenile salmon during summer and winter might be a more appropriate measure. Because reach-level sampling tends to be labor intensive and expensive, it often is conducted at relatively few sites. However, the value of this reach-level information can be enhanced by coupling it with an extensive survey of juvenile population density in the watershed, using a survey protocol such as the Hankin and Reeves (1988).

Measurements related to the biophysical environment also are useful in validating the effect of a conservation plan. At the reach scale, detailed measurements directly related to a specific management action are appropriate. Abiotic measures at the reach scale include information on channel form, sediment levels, nutrient levels, and habitat complexity. Biotic measures include invertebrate and fish community composition, presence and abundance of indicator species, and productivity and condition of riparian vegetation. At the watershed scale, habitat can be characterized with coarser-scale variables. Abiotic factors include topography, geology, water discharge, and distribution of channel reach types within the watershed. Biotic characteristics include distribution of vegetation types in the watershed and distribution of aquatic species. At the basin scale, habitat variables include coarse-scale characterizations of regional conditions, such as climate, geology, and topography, as well as basin-level discharge and vegetation types.

Relationships between fish abundance and habitat attributes have been quantified at the scale of individual habitat units or stream reaches (Bisson et al. 1982). For example, coho have been shown to prefer pools to swift-water habitats for summer rearing. Although this preference is expressed consistently across stream reaches and watersheds, the actual density of coho using pools may vary considerably. Regional variability is illustrated by the 540-fold variation in the production of stream-rearing salmon and trout reported in the scientific literature (Bisson and Bilby 1998). Even within a single large basin, considerable variability in salmon abundance occurs among watersheds (See Figure 1). In addition, the habitat needs of fish change as they develop. The properties of good spawning habitat are much different than the attributes associated with high quality winter rearing habitat. However, both types of habitat are required for the fish to complete their freshwater life stage. The variable range of production supports the need for specific in-stream monitoring, until generalizations can be developed that allow prediction of how production will vary with stream type and conditions.

Figure 1. Spawning coho salmon abundance for tributary watersheds of the Snohomish River basin, western Washington. Values represent the average proportion of total adult salmon counted during each year from 1984 through 1998 and are normalized for stream length within each watershed (Pess et al. unpublished data).



Spatial heterogeneity in productivity and temporal variation in habitat requirements dictate that the response of salmon populations to actions that affect habitat condition is best evaluated at broad spatial scales. In contrast, the effectiveness of some specific management actions for improving habitat is often best evaluated at small scales. A monitoring design that examines a series of related questions at nested hierarchical spatial scales can provide information on the response of salmon populations to a suite of management actions, as well as generate information on population response to conservation plans. Monitoring in this way can be a useful way to document the outcomes of a large experiment, in which habitats at each spatial scale are selected as “replicate plots” under separate management regimes.

At the level of an entire basin (i.e., a very large area, say 10,000 km^2 or more), understanding of population characteristics (e.g., number of returning adult salmon, number of emigrating smolts, genetic variation) is required to provide a context for interpreting information collected at progressively finer spatial scales. Monitoring of salmon would appear most effective if it were not done in small watersheds that are too small to provide all the stages of freshwater rearing habitat of a salmon species. Therefore, monitoring should begin at a watershed of a stream order high enough to include all habitat types. The failure to consider a broad range of spatial and habitat factors is one reason why past monitoring has not been effective.

Monitoring at the reach level can indicate the influence of management actions on habitat characteristics and of how the altered habitat attributes influence survival or productivity of a particular life stage or local reproductive population. Understanding the effect of individual management actions on habitat and population response for a particular life history stage or set of genotypes provides a basis for interpreting observed changes in population performance.

Marine habitats

Salmon spend most of their lives in the ocean, therefore it seems plausible that it is the ocean where the abundance of returning adults is determined. The large number of juveniles produced in fresh water has high mortalities (90-99%) early in ocean residence. However, it is a combination of the number of juveniles produced in freshwater, their condition as they reach the ocean, and the characteristics of the ocean as habitat—abundance of food and challenges such as predators, diseases, fishing, and variations in currents—that determine the number that return.

There are limits to the number of salmon that can be produced in the ocean. It was formerly believed that the "bottleneck" to production of adults is the number of salmon that enter the ocean, but this is no longer accepted. The failure of hatchery additions in the 1980’s and 1990’s to restore runs to the high levels of the 1960’s and 1970’s, despite the release of millions of young salmon, led to the abandonment of this idea. This failure of hatcheries suggests that the number of salmon returning to specific streams is a function of what happens in the ocean. Thus, in theory, there is an aggregate effect in the ocean on all stream production. This means that ocean and climatic conditions must be considered when evaluating recovery programs in freshwater. One method of assessing ocean effects is the determination of marine survival by using marked fish, although it generally is impossible to mark all wild fish, so this approach yields the best results when populations are dominated by hatchery releases.

Freshwater conditions do affect the numbers of returning salmon, and it seems likely that manipulations of freshwater habitats and of salmon in these habitats may affect survival and therefore the returning number of adults positively and negatively. The time period when young salmon enter the ocean would seem to be the most vulnerable stage in the ocean life of these fish, and vulnerability would also appear to be related to the size of a salmon when it enters the ocean: the smaller, the more vulnerable. Therefore, an assessment of size when entering the ocean and a knowledge of the interaction among species of salmon in the first marine year may assist in the design of effective restoration programs. However, many of these concepts currently are suppositions, not supported by rigorous scientific study.

V. EXPERIMENTAL DESIGN PRINCIPLES FOR MONITORING SALMON

A scientifically and statistically valid experimental design is needed to ensure the success of all resource monitoring efforts. This is especially true for monitoring salmon populations, because consistency is needed across diverse conservation and monitoring plans in order to infer the outcome of management actions at broad spatial scales. Many agencies operating at different spatial scales have some form of jurisdiction over salmon. In a study of the coastal rivers of Oregon south of the Columbia, 17 government agencies (from city to state to federal) had jurisdiction over some aspect of a salmon and its life cycle (Botkin et al. 1995).

The guidance provided here is intended to fit monitoring schemes seeking to answer specific management questions, and to be used as a standard for developing monitoring plans that are scientifically valid and externally consistent. The ideal monitoring plan is a robust scientific inquiry that employs a parsimonious data set to infer answers to both biological and broad societal questions regarding salmon conservation.

As previously mentioned, it is preferable to monitor salmon populations over a sufficient period of time to reliably quantify the distribution and abundance of salmon associated with a particular conservation action or strategy. Unfortunately, as previously noted, we often do not have the luxury of implementing a long-term experiment or monitoring program without developing management policy.

Substituting Space for Time

Because limited appropriate locations remain for controlled experimentation and monitoring, the *space-for-time concept* can be used to validate the effects of an action. This concept substitutes similar regions in space (e.g., several stream reaches) for a long time series of sampling in one reach. This approach assumes that separate reaches or other spatial units are similar enough that differences in conditions among regions are due only to a specific action. Therefore, differences in space are analogous to before-after actions in time. For example, it may be impractical to conduct a multi-year assessment on the effects of an existing dam, followed by long-term monitoring of how removing the dam will affect salmon populations. However, one can monitor two streams that are as similar as possible, both having similar dams, with the exception of the action of dam removal. The space-for-time approach can also be done retrospectively, by using historical records to extend a time series prior to an action (e.g., prior to dam construction). In fact, where historical data exist, retrospective studies can be a powerful approach, especially during the transition from no monitoring to a point in time when an adequate time series of data exists.

A variation of this approach is the *time-for-time concept*, which assumes a dynamic similarity between cause and effect on a number of time scales. For example, short-term (seasonal to year-to-year) changes in weather alter stream flow and ocean temperature, influencing habitat and ultimately salmon abundance. One assumes that these changes are analogous to longer-term climatic variability that would similarly affect populations. To the extent that this is true, from the relationship between biophysical conditions and salmon populations on shorter time scales, one can understand, and possibly predict long-term consequences of climate variability on salmon habitat and populations.

The space-for-time and time-for-time concepts both have limitations, and can be criticized for lack of comparability between sites and time periods. However, they are widely used in other biological disciplines to study organisms with complex behavior in space and time. They may be the only alternatives if long-term monitoring before and after a salmon conservation action is not an option. As with any quantitative analysis, it is important to document assumptions and potential shortcomings that are relevant to scientific interpretation and decision-making.

Controlled Experimentation as a Component of Adaptive Management

To be successful, the adaptive management framework requires that the fundamental hypotheses associated with each management action be tested in a scientifically defensible way. Although hypotheses may not be formally stated, they are implicit in the objective of any management action. In the best adaptive management, the hypotheses are spelled out. For example, in the case of the statement "buffer strips of riparian vegetation 10 meters wide on either side of a second-order stream are maintained to protect spawning salmon and rearing juvenile fish," the hypothesis is that this riparian protection width will in fact protect spawning and rearing fish.

A controlled experiment to test this hypothesis would involve measuring success of salmon spawning and juvenile rearing in long stream reaches; or measurements could be conducted in whole tributaries, in channels with and without the prescribed buffer strip. The design would be to measure salmon population parameters for several generations in the stream system with the riparian zone "intact," then remove the riparian buffer and measure the same parameters again for several generations. Alternatively, using the space-for-time approach, several similar streams would be studied – one with no buffer, one with a 10-meter buffer, and others with smaller and larger buffers. Ideally, there would be more than one replicate, but realistically, sampling may be limited to a small number of streams. However, for this or any approach, there are many sources of variation (e.g., a shift in ocean temperature regime) that can obscure treatment effects.

The reverse of this before-after analysis design would be to make salmon measurements in stream channels without riparian buffer protection and follow these population parameters over time through the long period of riparian recovery. In any case, if there were discernible differences in salmon populations between streams with and without buffers (with other factors held constant), the management plan would presumably be continued. The adaptive part would be to move toward similar riparian buffer protection on all streams in the region.

To make the example more realistic, the question would more likely be in the form, "How wide a riparian buffer is required to maintain salmon spawning and rearing success?" The experimental design would need to accommodate measurement of salmon populations under a range of riparian buffer widths and over sufficient time that a range of natural disturbances can occur. The adaptive part of the management in this case would be to follow the experimental results and use a riparian buffer width that protects a level of salmon success judged *a priori* to be necessary. Because a long time is needed to see the effects of riparian buffer manipulation on salmon success (probably at least 30 years) and because producing the minimal buffer widths on some streams required of the experimental design may be environmentally unacceptable, a space-for-time substitution approach may be more feasible.

In this scenario, as many stream reaches or entire watersheds as possible would be aggregated by categories of buffer width, and monitoring of salmon spawning and juvenile rearing success would be conducted on each, and where possible, historic data would be used to provide a retrospective approach as well. This design requires attention to selecting streams that could serve as reference sites, that is streams with "intact" riparian buffers. Again, the adaptive part of the management action would be to shift the strategy of buffer protection to the configuration that most closely matches the minimum acceptable buffer width. This procedure can utilize the many available sites with altered riparian buffers as a result of former land management practices. It should be noted that identifying a true reference or "control" site can be extremely difficult due to past human activities and other sources of variability, which can reduce the value of such a site for comparisons with "treatments."

For the process to work best — that is, experiments built into management plans — the experimental design should be part of the plan from the outset. In addition, continual monitoring of salmon spawning and rearing success in the example above must be endorsed as providing the basis for evaluating the effects of a management action. There also must be an up-front commitment to shift from management plan A (e.g., a particular buffer width along salmon-bearing streams) to plan B (a different buffer width) in response to experimental results.

An Inventory of Existing Management Approaches

An inventory of all management actions with the avowed purpose of maintaining, enhancing, and restoring salmon populations, as measured by spawning and rearing success (e.g., number of redds per unit stream length, number of fry produced per female) is urgently needed. This inventory would facilitate the development of hypotheses and experimental designs *a posteriori* and then determine if adequate monitoring is in place to (1) evaluate results in terms of hypotheses and experimental designs, and (2) potentially lead to alternate management actions. In most cases, it will be unlikely that such criteria have been met. Therefore, the critical issue is whether ongoing management actions can be retrofitted with appropriate hypotheses, experimental design, and monitoring to allow implementation of adaptive management strategies. If not, then a new management plan likely will be needed.

Public Participation in Validation Monitoring

One of the greatest obstacles associated with monitoring is its cost. Few agencies have the capability to commit large sums of money for projects that may extend indefinitely. Consequently, any possibility of reducing costs is worth exploring. The costs of monitoring can be broken down into design, field assessments, laboratory analysis, information storage and retrieval, and data analysis and reporting. Of these, the most suitable for public participation is field assessment.

There are many examples of successful involvement of the public in monitoring. The individuals involved vary from school children to interested amateurs. In the United Kingdom, amateurs are responsible for many surveys and monitoring of wildlife populations. For example, the British Trust for Ornithology has a long history successfully monitoring bird populations (e.g., Prater 1981, Marchant et al. 1990, Gibbons et al. 1993). Hunters also have been a productive source of information (e.g., monitoring population age structures through the collection of duck wings).

Most wildlife monitoring is relatively short term, but there are examples of longer-term monitoring programs that involve the public. For example, private citizens maintain many first-order meteorological stations. These often involve a major commitment in time. Similarly, amateurs often make observations for phenological networks, and some phenological time series now extend for 100 years or longer. Given sufficient motivation, it is likely that various individuals and groups are willing to take on a commitment to monitor salmon populations.

A number of issues need to be addressed when considering public involvement in monitoring. For example, choice of observer is important, but very sensitive. The best observers are ones who are located close to the sites being monitored, are normally resident in the season of interest, are willing to receive training in observation techniques (even when these are contrary to their own "best" methods), and understand the significance of their work. Quality assurance and quality control are increasingly important as more people are involved in a project, and a system is needed for the checking/calibration of the results collected by observers. The Forest Service Forest Health

Monitoring Program has demonstrated how difficult this is, even when the observers are qualified professionals (Cline et al. 1989).

There already is evidence that volunteers are willing and able to measure salmon populations. For example, on the Chinook River in Washington, there is an active program of monitoring salmon including high school students trained to use a catch-and-release method. An informal survey taken during a public meeting at the Olympic Natural Resources Center in 1997 indicated that 74% of those in attendance were interested in participating in a monitoring program, with 52% willing to collect field data. In a study of the effects of forest practices on salmon in Oregon, it was learned that the local organization of fishing guides offered to conduct measurements at no cost. The guides obviously have useful expertise because of the time they spend on the rivers.

An important caveat to public participation is that proper training must be provided on identifying species, avoiding sampling injury and stress to handled fish, data collection, and data management. Participants must be committed to the sampling schedule and should have all appropriate permits (e.g., state scientific study permits, ESA-related permits for incidental take).

VI. CASE STUDIES OF COMMON CONSERVATION PRACTICES: A FRAMEWORK FOR VALIDATION MONITORING

In this section, case studies of the most common conservation and restoration practices illustrate a range of issues, management approaches, and appropriate validation monitoring techniques. This analysis considers scale issues, optimal locations for monitoring, population parameters, and measurement of indicators of change, as well as ecological theory and experimental design. The case studies are guided by the overarching questions:

- How does one quantify a change in salmon numbers?
- How does one quantify the effects of specific management actions?

Case Study: Validation Monitoring for Management Actions Involving Hatcheries, Harvest Regulation, and Dams

Validation monitoring for potential management actions involving hatcheries, harvest regulation, and dams was considered together because salmon responses to all of these actions largely occur at the spatial scale of an entire river system. A common quantitative approach that simultaneously considers all three actions is required. Social and political realities exclude the possibility of setting up a classic experiment in which two of the three actions are held constant, except on a few rivers (e.g., Rogue River, Oregon). This requires the employment of regression analysis in which the influence of all three actions must be considered simultaneously to assess the impact of each. For example, when one looks at dam modifications, one needs to know what the variation in ocean catch and hatchery releases have been, and a similar diversity of considerations would be needed for the other variables.

Rationale for management actions

Each of the three kinds of management actions — hatcheries, harvest, and dams — have been posed for a variety of reasons. These reasons dictate the measures needed for validation monitoring. For example, hatchery releases may negatively impact salmon populations by increasing density to the point that survival is dramatically reduced due to short supplies of resources (e.g., food) in freshwater and marine environments. Furthermore, hatchery fish may alter the "wild" genetic stock, so that individuals cannot survive and reproduce as well as wild stocks. Therefore, it would be useful to assess whether hatcheries are beneficial or harmful to wild stocks and whether dependency on hatcheries can be reduced.

Commercial, recreational, traditional and subsistence harvesting may negatively impact salmon populations by reducing the return of adult salmon to river systems, thereby limiting total reproductive output and/or selectively limiting certain genotypes (e.g., hatchery versus "wild" stocks). Therefore, it would be useful to assess whether harvesting is detrimental to salmon returns.

Dams may negatively impact salmon populations in a number of ways. First, adults may be inhibited from returning to spawning grounds, which reduces total reproductive output and stream productivity due to reduced nutrient transport from the ocean. Second, smolt mortality en route to the marine environment may increase when fish pass through turbines, encounter spill water supersaturated with dissolved gasses, and are exposed to high predation below dams. Third, modified flow patterns may reduce the types and abundances of freshwater habitats, modify food webs between seasons, and alter the freshwater plume in estuaries where salmon, especially smolts, make the transition between freshwater and marine environments. Therefore, it would be useful to assess the degree to which dams reduce salmon returns and nutrient transport from the ocean.

Monitoring

Recommended measurements depend on the purported effects of hatcheries, harvesting, and dams summarized above. It is assumed that all hatchery fish are marked before release. This is already generally true for large releases from hatcheries, but there may be opposition to this from groups that independently release fish and do not want them harvested, if only marked fish can be killed. The proposed measures are categorized as either absolutely necessary (minimum) for assessing changes in salmon status or highly desirable (maximum) for determining cause and effect.

<u>Minimum measurements</u>

Measures of conservation success include:

- Returning adults of each salmon species. *This is the central variable of interest* and the measure in which most people are interested.

- Proportion of returning adults of each salmon species that are hatchery versus naturally spawning. This is philosophically important to many people and is a component of biological diversity (genetics and variety of species). It is also important to know the effect of hatchery returns on natural spawning returns for each salmon species. Modifying hatchery releases may affect these proportions.

Measures of management actions include:

- Ocean catch of each salmon species (and by possibly by stock to identify run, although this is difficult with naturally spawned fish). This allows us to assess how many adults might have returned to spawn (the central variable) without ocean harvesting. Stock identification, possibly through genetic analysis, is necessary so that ocean-harvested fish can be attributed to their natal river, which is being monitored. The total ocean catch is a harvest management action that can be varied. We must know ocean catch for the river being monitored to distinguish the effects of hatcheries and dams when ocean harvest is variable among years.
- Number of returning adults of each salmon species taken by hatcheries. This lets us know how many salmon remain in the stream to reproduce naturally and transport nutrients from the marine to stream environments via their corpses. This is a hatchery management action that can be varied.
- Freshwater catch of returning adults of each salmon species. This also lets us know how many salmon are left in the stream to reproduce naturally and transport nutrients from the marine to stream environments via their corpses. This is a harvest management action that can be varied. Furthermore, there is great interest in this, because government agencies use this to adjust the number of licenses and allowable catch.
- Number of hatchery smolts of each salmon species released. This is the main hatchery management action for which we want to know response in the number of returning adults. We also need to know the hatchery release of smolts for the river being monitored to distinguish the effects of harvest and dams when hatchery releases are variable among years.

Baseline measurements are crucial for assessing changes in dam management. Therefore, before changing the management of a dam, data must be available for each salmon species on (1) the number of returning adults and (2) the proportion of hatchery verses naturally spawning returning adults to compare the same measures over time following modification of flow over the dam. In addition, the following measures are necessary:

- Adult success (measured as either percent surviving or percent dying) in passing over the dam.
- Smolt mortality (measured as either percent surviving or percent dying) in passing over the dam.

Environmental factors that might be correlated with variability in salmon returns and productivity, via salmon survival, growth, and reproduction, include physical factors or processes that influence freshwater and ocean environments:

- Stream flow (daily and hourly gauging station data).
- Ocean wind direction and velocity in the regions inhabited by salmon.
- Ocean temperature in the regions inhabited by salmon.
- Ocean currents in the regions inhabited by salmon.
- Upwelling in areas utilized by salmon during ocean migrations.
- Competitors and predators (e.g., mackerel, birds) encountered by salmon during estuary and ocean migrations.

<u>Maximum measurements (in addition to above minimum measures)</u>

Measures of conservation success include:

- Returning adults of each species to some major tributaries in the river system. This is the same as above, except conservation success can be attributed to particular portions of the river system. A tractable number of representative tributaries should be monitored.
- Proportion of returning adults of each salmon species that are hatchery versus naturally spawning in some major tributaries in the system. This is the same as above, except effects can be attributed to particular portions of the river system.

Measures of management actions include:

- Timing of release of smolt of each species by hatcheries (time of year and length of time). This is an element of hatchery management that might be varied.
- Age of release of smolt of each species from hatcheries. This is an element of hatchery management that might be varied.
- Body size of smolt and returning adults of each species. This is an index of health and vigor, especially reproductive potential of adults.
- Age of smolt entering ocean and returning adults of each species. This is an index of health and vigor, especially reproductive potential of adults.
- Ocean bycatch of each species, including (1) bycatch mortality, which measures mortality in addition to actual harvest, and (2) bycatch release, which measures potentially higher

mortality due to stress.

Case Study: Validation Monitoring Applied to Smaller Scale Management Actions in Forested, Agricultural, and Urban Areas

A validation monitoring plan appropriate for the comparison of land uses or changes in a given land use should begin with a spatially explicit characterization of watersheds comprising the area of interest. Such analyses typically rely on remote sensing imagery and appropriate GIS databases. A hierarchical watershed approach to landscape characterization seems the logical initial step in any validation monitoring protocol for salmon populations. The necessary GIS layers include:

- Landform (upland or lowland)
- Land use (forested [including species composition and stand age], agricultural, and urban [including human infrastructure])
- Other layers (e.g., hydrology, geomorphology, sediments, water quality)

Issues of spatial and temporal scale

These issues are centered within the above hierarchical land form/use categories and keyed to salmon. Given this focus on salmon, the area designated for validation monitoring should be 10 to 30 km^2 or more, sufficient in size to cover all non-ocean portions of the life cycle including migration (adult escapement and smolt out-migration), spawning, and fry rearing. The absolute minimum time frame would cover one generation. However, to provide any really useful data, the time frame should encompass at least a sufficient number of generations to place the monitoring on a scale of riparian tree succession (15 to 100 years, e.g. succession of red alder to conifer regrowth).

Although long-term records of salmon abundance (e.g., spawner counts from index streams or experimental watersheds) have been useful in detecting trends (e.g., Hall et al. 1987, Hartman and Scrivener 1990, Kareiva et al. 2000), the large variability in such data have made it difficult to detect the effects of management on salmon population trends (Lichatowich and Cramer 1979, Hall and Knight 1981, Hall 1984, Hilborn and Winton 1993). Bisson et al. (in press) surveyed long-term salmon studies in the PNW and estimated the average interannual coefficient of variation for coho, steelhead, and sea-run cutthroat juveniles, smolts, and adults to be approximately 50-60% (See Table 2). In a separate and independent analysis of metadata and data from the Columbia Basin, Ham and Pearsons (2000) estimated an interannual coefficient of variation (a statistical measure of variability expressed as a percent of the mean) for fall chinook, spring chinook, and steelhead adults to be 70-80%.

Table 2. Average coefficients of variation of the interannual abundance of adults, juveniles, and smolts of three salmon species based on multi-year studies in the PNW. Number of populations in parentheses. (Bisson et al. in press)

Species	Coefficient of variation (%)		
	Adult	Juvenile	Smolt
Coho	72 (21)	53 (25)	50 (11)
Steelhead	60 (3)	66 (6)	50 (5)
Cutthroat	92 (1)	54 (6)	64 (3)

Assuming these two similar estimates approximate the actual variability of anadromous salmon populations, it would take two or more decades to detect all but large changes in population responses to management over and above natural variation. Further, if the population estimates are inaccurate, our ability to detect management related change would be even further limited (e.g., Rieman and Meyers 1996, Dunham et al. submitted). There is also a time lag between physical and biological effects that further complicates assessment of management effects. Changes in land management may take decades to produce related changes in stream channels and their component salmon populations. In some cases (e.g., Montgomery 1995, Harding et al. 1998), delayed responses to management actions are the result of rare natural events in watersheds, such as landslides, where management activities occurred years before.

Signal-to-noise ratio in salmon and habitat data

The signal-to-noise ratio is one of the most important concepts available for determining cause-effect relationships in ecosystems. High background variability and/or the presence of long-term trends may significantly increase the difficulty of detecting trends such as salmon population densities. As indicated above, interannual variation in estimates of salmon population densities routinely can be very high. It is possible to calculate the time periods of monitoring necessary to detect the effects of a management intervention with respect to this level of natural variation. Detecting a 50% difference would require 26 years of monitoring, a 30% difference 70 years, and a 10% difference 620 years. Many changes in salmon populations induced by management interventions would, therefore, need to be sufficiently large to discriminate significant differences from background noise.

If restoration attempts are conducted on a narrow spatial or short temporal scale, it is unlikely that effects on salmon population parameters will be detectable. For example, it is unlikely that a change in riparian buffer width from say 15 to 25 meters will produce detectable changes in salmon populations, especially in the short term, although there may in fact be a change. It is more likely that broad-scale differences in a watershed land use, such as agricultural versus urban versus forested, will result in quantitative differences at a level of resolution that is detectable.

Age structure and habitat use

Shifts in salmon population age structure or community composition may have the potential to yield detectable changes over a shorter time frame than population census data. Strong relationships between salmon abundance and habitat attributes have been developed at the individual stream reach level (e.g., Bisson et al. 1982). Changes in habitat may allow increased abundance of certain age classes at the expense of others. For example, increase in pools and decrease in riffle habitat may favor older individuals at the expense of young-of-the-year. Once stream flow and ocean conditions are included in the analysis it might be possible to separate management impacts from natural variation (e.g., Holtby and Scrivener 1989, Tschaplinski 1999). However, at present there is no demonstrated way to accomplish such analyses on a shorter (e.g., 5-year) time line. Useful validation monitoring clearly requires a long-term commitment.

Issues that could be addressed and possible appropriate measurements of salmon population characteristics at the basin, watershed, and reach scales are summarized below (See Table 3). At the basin scale, remote sensing offers an opportunity to gather extensive data, for example, sonic data on adult escapement at the basin mouth and redd counts over the basin scale by remote imagery. At the watershed scale, surveys would be conducted by a combination of remote sensing (e.g., light aircraft) and on-the-ground measurements. At the reach scale, more detailed salmon life history and habitat use data are gathered on site. Each of these scales would address different management questions

Table 3. Scientific and managerial issues related to salmon populations, and possible measures of salmon populations appropriate for three spatial scales.

Scale	Managerial Issues	Possible measurements
Basin	• Total population size • Interannual variability	• Adult escapement at river mouth • Extensive redd counts • Population genetic characteristics
Watershed	• Effects of a suite of management actions • Spatial distribution across basins	• Redd counts by watershed • Smolt output • Juvenile surveys • Adult (egg) to smolt survival • Metapopulation genetic characteristics
Reach	• Effects of specific management actions • Seasonal utilization of reach types	• Egg-fry survival • Juvenile abundance/density • Life history-specific survival • Local population genetic characteristics

Validation monitoring measurements

Agencies, tribes, and local communities are increasingly interested in protecting and restoring salmon populations within watersheds. The following types of measurements and approaches are considered essential to provide the necessary data to quantify salmon populations at the watershed scale:

- *Total adult escapement into and smolt migration out of the entire watershed*. This can be estimated from judiciously selected sub-samples but would be much better as a continuous record using new infrared or laser side-scanning techniques (see Appendices 1a and 1b on Technical Tools) or direct counts or trapping at weirs.
- *Spawning activity as measured by redd counts for the entire watershed*. This might be done largely through aerial photography coupled with selected on-the-ground validation and information about the timing of the runs by different species obtained from the escapement scanning. Fry densities should be determined by snorkeling using the Hankin and Reeves (1988) technique. The entire watershed should be inventoried on a habitat-specific basis and not based on sub-samples. Fry condition can be estimated at the population level for separate tributaries by developing length-weight relationships for juveniles collected by trapping (minnow traps), or possibly by electrofishing.
- *Developing a model of crosscut issues for watershed-salmon characterization*. The major characteristics to be monitored along with the attributes of the salmon populations outlined above should be:
    - Stream flow (annual discharge hydrograph over the full length of available record).
    - Geomorphology (channel and off-channel structure and placement of large woody debris).
    - Sediments (especially spawning-size gravels per unit length of channel).
    - Water quality (nitrogen, phosphorous, and specific contaminants of concern).
    - Riparian zone (vegetation composition and age structure).

Once a conceptual model has been developed relating these crosscut issues to salmonid population parameters, a specific statistically valid sampling procedure must be developed. An initial step would be to divide the basin under study into 3,000- to 5,000-meter reaches for all channels as designated on a map, with the reaches selected for on-the-ground measurements selected randomly or stratified randomly by stream orders or watershed size.

Production of juveniles migrating from experimentally-controlled watersheds, expressed as numbers of migrants per adult female, is a useful measure of the effects of logging on salmon populations, as shown by the Alsea Watershed (Oregon) and Carnation Creek (British Columbia) watershed studies. These two parameters—adult escapement and numbers of downstream migrants—are often neglected in multi-year investigations because of the necessity of two-way fish traps and the time and expense of daily trap cleaning and checking. However, they yielded valuable data that were relatively immune to variations in year-to-year abundance, suggesting that two-way fish traps will be a valuable asset to multi-year studies. Recently, the importance of movement in resident salmonid populations has been documented as an important means of dispersal for mobile population members. Because knowledge of movement is critical to understanding any long-term study of salmonid ecology, two-way traps should be employed in all long-term studies whether of anadromous or resident populations.

Existing long-term monitoring studies have revealed the value of continuous monitoring for periods of decades rather than years. Many of the studies lasting 5-10 years have not produced reasonably clear answers to the questions they were designed to address. One of the most daunting problems has proved to be interannual variations in population abundance on the order of 50% or greater for all life history stages of small stream-dwelling species such as coho salmon, steelhead, and sea-run cutthroat trout. This relatively high level of variability will require continuous monitoring for at least two decades in order to detect even coarse-scale changes in population abundance, as well as creative experimental designs that partition variation due to yearly climatic and other differences (Walters et al. 1988, 1989).

VII. CONCLUSIONS

The scientific case for validation monitoring of salmon populations in the PNW is compelling: validation monitoring is the only means by which a cause-and-effect relationship between management actions and salmon abundance can be inferred. Validation monitoring is supported by clear quantitative concepts and available technical tools, and scientists are increasingly working with resource managers to plan for and implement assessments of salmon populations as part of conservation plans. The conceptual foundation for validation monitoring is already institutionalized through prominent planning efforts by federal agencies (NWFP) and state agencies in Washington and Oregon. This report affirms this commitment to validation monitoring and provides robust scientific guidance for developing monitoring plans and programs.

While many of the concepts and techniques associated with validation monitoring are relatively straightforward, there are significant challenges to implementing and maintaining a successful monitoring program. First, validation monitoring must be an explicit component of salmon conservation planning efforts at all spatial and temporal scales. Second, the objectives of validation monitoring must be clearly stated, so that the data collected are relevant to the goals of a particular conservation effort. Third, strong institutional commitment of human and financial resources is needed to sustain a long-term monitoring program. Finally, validation monitoring should be conducted within an adaptive management framework to allow for periodic evaluation of the data and modification of the monitoring approach. Attention to the details of quantitative and statistical analyses, data management, and quality assurance is required for all monitoring efforts.

Although impediments to direct assessments of salmon populations exist, there is growing recognition that these obstacles must be overcome if credible validation monitoring is to occur. Cultural values within institutions and relationships between overlapping jurisdictions (e.g., between federal agencies and state resource agencies) have established practices that create barriers to collaboration on wildlife population assessments. But successful examples are starting to emerge through cooperative efforts in salmon conservation and restoration. Coordination between institutions and partnerships between public and private organizations will be needed to facilitate assessments of salmon populations across different ownerships.

The legal responsibility of federal land management agencies to include assessment of populations is becoming evident. The Eleventh Circuit Court of Appeals recently supported the need for direct population monitoring in addition to habitat assessment in a February 1999 case, the Sierra Club versus Martin (Forest Supervisor of the Chattahoochee and Oconee National Forest) and Joslin (Regional Forester of Region 8). In this case, the Forest Service argued that its analysis of habitat data was sufficient to determine no impact to diversity or viability of known sensitive and endangered species within timber project areas. The Sierra Club challenged that, pursuant to Sections 219.19 and 219.26 of the Land and Resource Management Act, the Forest Service must gather quantitative population data to reliably gauge the impact of timber projects on any proposed, endangered, threatened, or sensitive species. The court found no merit to the Forest Service approach of utilizing habitat data in place of population data. This case provides a compelling legal argument for validation monitoring of animal populations, in addition to the scientific rationale presented in this report.

We are on the threshold of a period of major societal investment in salmon conservation in the PNW. The stakes are high, and politicians and the general public will be watching to see if this investment has significant returns in terms of improving the condition of salmon. The scientific community can make an important contribution to this effort by providing principles and guidance for effective planning and management. This is an unprecedented opportunity to begin developing the monitoring efforts and data sets that will provide the scientific basis for salmon conservation and decision making for generations to come.

As we move forward with more standardized approaches to monitoring in the PNW, there will be difficult choices regarding how scientific effort and funding should be allocated to maximize the benefit of validation monitoring for salmon conservation. Concentrating funding on a few well-designed monitoring efforts staffed by specialists with adequate resources would significantly improve the chances of yielding information useful for decision making. Basins with well-supported monitoring programs can potentially provide study sites for more detailed studies on mechanistic relationships, and management practices can be fine tuned for other basins as needed. However, if the majority of validation effort is imposed on just a few streams, it is possible that the streams may not be representative of ecological conditions and conservation objectives elsewhere in the PNW. Conversely, if too many streams are examined with limited funding, validation may not be sufficiently rigorous, because adequate measurements may not be obtainable.

In order to optimize allocation of resources for validation monitoring in the PNW, the following approach is suggested:

- Select rivers, such that the array of human impacts and management actions on salmon can be addressed.
- Monitor a sufficient number of rivers to obtain a confident assessment of whether salmon are increasing or decreasing in the region.
- Identify categories of rivers based on which specific human impacts can be quantified, with sufficient replication in each category to obtain statistical confidence in results.

If resources are allocated according to scientific criteria, there is a higher probability that the data will be quantitatively robust, legally defensible, and have the potential for extrapolation to diverse locations and situations. The cost of validation monitoring is relatively small compared to the anticipated total cost of salmon conservation in the PNW. The cost of *not* monitoring salmon populations is that there will be insufficient data for evaluating the progress of conservation actions and that governmental institutions may be open to liability. As salmon conservation and restoration strategies in the PNW evolve, we encourage decision makers, planners, and resource managers to move forward with due attention to scientific principles in the development of programs and allocation of resources.

GLOSSARY OF TECHNICAL TERMS AND ACRONYMS

Adaptive management areas – Landscape units of federal forest land designated to pilot approaches to achieve desired ecological, economic, and social objectives through adaptive management. Management is continually evaluated and modified based on data on resource conditions that become available over time.

Anadromous – Migrating from salt water to spawn in fresh water; Describes fish that spend their adult life in the sea but swim upriver to freshwater spawning grounds in order to reproduce.

ANOVA – Analysis of variance; A statistical procedure that allows the significance of multiple treatments to be determined by quantifying different components of the variance in the data.

Basin – Spatial scale that includes a few to many watersheds, typically greater than 10,000 km^2; Validation monitoring at this scale provides a context for understanding population characteristics at progressively finer scales.

Bycatch – Species taken in a fishery targeting on other species or on a different size range of the same species; That part of the bycatch without commercial value is discarded and returned to the sea, usually dead or dying.

Deme – A group of individuals more genetically similar to each other than to other individuals; a local, randomly interbreeding population.

ESA – Endangered Species Act; Administered by the U.S. Fish and Wildlife Service and National Marine Fisheries Service, the ESA requires all federal agencies to undertake programs for the conservation of endangered and threatened species, and prohibits federal agencies from authorizing, funding, or carrying out any action that would jeopardize a listed species or destroy or modify its "critical habitat."

FEMAT – Forest Ecosystem Management and Assessment Team; Group established in preparation of the Northwest Forest Plan to develop long term alternatives for resolving conflicts over managing forest ecosystems.

Fry – Young salmonids that have absorbed the yolk sac and emerged from the gravel and are up to one month of age; or any cultured salmon from hatching through 14 days after being ponded.

Genotype - The complement of genes in an individual; or the entire genetic constitution of an organism.

HCP – Habitat Conservation Plan; A process authorized under Section 7 of the Endangered Species Act which allows a land owner to propose a plan to manage land in a way that will provide habitat for threatened of endangered species. Upon ensuring that the plan provides for viable populations over time, the U.S. Fish and Wildlife Service or National Marine Fisheries Service may allow an Incidental Take Permit.

Incidental take – As defined in Section 7 of the Endangered Species Act, the taking of a listed species permitted by an incidental take permit, allowed as a result of an acceptable Habitat Conservation Plan.

Metadata – Information that describes the content, quality, condition, and other characteristics of a dataset to help users locate and understand data.

Metapopulation - A collection of populations in scattered habitat patches separated from each other by nonhabitat; These populations may act as possible sources for recolonization.

Multiple Regression – A formal statistical analysis that allows consideration of factors in addition to those that can be intentionally altered.

NWFP – Northwest Forest Plan; The President's forest plan that put new environmental regulations into effect in the summer of 1994. The intent of the NWFP was to comply with court orders and provide a workable solution between the courts and industry.

Phenotype – The sum total of the observable or measurable characteristics of an organism produced by its genotype interacting with the environment.

Phenological – Relating to natural phenomena that are seasonal in occurrence.

PNW – Pacific Northwest region of North America; In the context of this report, it generally refers to British Columbia, Washington, Oregon, and northern California.

Reach - A spatial scale that includes a section of stream between two defined points, typically less than about 2 km long; Validation monitoring at this scale can investigate population responses to specific management applications and resulting effects on habitat conditions.

Redd – Nest in the streambed created by a female fish that holds eggs and sperm covered with gravel.

REO – Regional Ecosystem Office; Office established to focus scientific expertise on implementation issues associated with the Northwest Forest Plan. These scientists also comprise the Research and Monitoring Committee.

Restoration – The renewing or repairing of a natural system so that its functions and qualities are comparable to its original, unaltered state.

Riparian – Area of land at the aquatic/terrestrial interface.

Smolt – (verb) The physiological process that prepares a juvenile anadromous fish to survive the transition from fresh water to salt water; (noun) A juvenile anadromous fish that has smolted.

Spawning – The act of reproduction of fishes; The mixing of the sperm of a male fish and the eggs of a female fish.

Stock - A group of fish spawning in a particular lake or stream at a particular season, which to a substantial degree do not interbreed with any other such group.

Type I error – The rejection of a true null hypothesis; A false conclusion of effects.

Type II error – The acceptance of a false null hypothesis; A false conclusion of no effect.

Watershed – A spatial scale that includes the region draining into a river, river system, or body of water that provides habitat conditions for all stages of freshwater rearing for a salmonid species, typically 100 to 10,000 km^2; Validation Monitoring at this scale can investigate population responses to multiple management applications.

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APPENDIX 1: TECHNICAL TOOLS FOR VALIDATION MONITORING

There is an ongoing controversy about what is necessary, feasible, and practical to measure about salmon. Our report recognizes this and describes it as Athe central dilemma@. While direct counts of salmon may be difficult, it is certainly feasible. To demonstrate this point and provide encouragement to those who may contemplate including direct counting of salmon as part of a validation monitoring plan, we have provided some technical tools for validation monitoring in the following appendix. Appendix 1A outlines the quantitative and statistical considerations in data analysis, and Appendix 1B documents successful counting experiences and techniques in Alaska, British Columbia and Yukon Territory.

APPENDIX 1A

QUANTITATIVE AND STATISTICAL CONCEPTS FOR DATA ANALYSIS

Data Analysis

The complex relationships addressed here, and the urgency of assessing the success of management actions for conservation, limit our ability to obtain the precision desired by scientists in the short term. However, inferences on the success of management actions for policy formulation can still be made in the short term.

There are two types of things one measures: (1) things that interest you and that you wish to explain, and (2) things that can affect the item of interest. In this report, we are interested in the number of returning adult salmon. Once one has both types of measures, then we need to determine which of the second type of measures are related to the first type, and how well they might be related. One ultimately would like to attribute the relationship (correlation) to "cause and effect" and claim that the better one of the second type of measures is related to the first type, then the greater its importance. However, this may not be true, because the correlation could occur by chance, or could be the result of some third factor that affects both measures. Nonetheless, correlations at least indicate whether a potential cause-and-effect relationship exists.

Consider the list of minimal monitoring measurements. In this case, the factor of interest is returning adults, including hatchery and natural spawning fish. Other factors are those that might affect these numbers of adults. Once we have monitored all of these factors, we want to find out which of these factors are actually related to the number of adults, and how strong these relationships are. But cause and effect cannot be attributed. For example, a recent study of two rivers in Oregon indicates that the greater the number of salmon released from hatcheries, the smaller the number of returning adults. This negative correlation suggests that hatchery releases are not benefiting the number of returning salmon and may be detrimental to the return. Although we do not know that there is cause and effect between hatchery releases and numbers of adults, we do know that the negative correlation suggests that the expenditure of funds on hatchery releases may not be helpful, given other past conditions.

There are well-established statistical procedures that define these relationships, the strength of relationships, and the inferences that can legitimately be drawn from them (Hilborn and Mangel 1997):

- One should graph the data and examine if patterns are revealed. The graph can show if there are any trends in the data (overall patterns of increase or decrease). One can also see whether each measure varies greatly or not; this in itself can be very helpful in decision making.
- A common mathematical method to examine these relationships is multiple regression. This is a formal way of determining if two or more factors are correlated and the strengths of the

correlations.

Formal statistical analysis (multiple regression) allows consideration of factors in addition to those that can be intentionally altered. Factors such as hatchery releases, dam alterations, and changes in harvesting can be intentionally altered. However, wind velocity, ocean currents, and stream flow are not under human control. Therefore, this method allows one to assess the impact of intentionally altered factors, while controlling for the variation in factors that cannot be intentionally altered.

The ability to use these formal mathematical and statistical methods requires that monitoring take place over a reasonable length of time. The length of the monitoring record needed increases with the number of factors being considered, with a longer record providing greater confidence in identifying correlations and assessing their strengths. To consider three intentionally alterable factors (e.g., dams, hatchery and harvest) and two unalterable environmental factors (e.g., oceans conditions and fresh water flows), one needs a minimum of seven years of data. However, a long-term record, say 30 years, would greatly increase statistical power and confidence in the interpretation of trends.

In reality, managers initially will be confronted with a far shorter salmon monitoring record than is needed for multiple regression ($\geq$ 7 years). How should decision making proceed if only 2-6 years of data are available? Other formal methods have been developed for use with limited data; for example, Bayesian statistics (Hilborn and Mangel 1997) addresses the issue of whether limited data should force a change in prior beliefs. Following this method, one can infer from relevant past experience elsewhere and the limited data from the study system the likelihood that observed changes in the number of returning salmon adults is due to recent management interventions. For example, if hatchery releases on two rivers are stopped, and the number of returning salmon increases for two years, the Bayesian approach helps decide the likelihood that cessation of hatchery releases is the causal factor. Other statistical techniques, such as bootstrapping, allow one to better examine influences of different factors with fewer than ideal numbers of observations. Unfortunately, for the foreseeable future, policy inferences will rely on suboptimal amounts of information, because reference (baseline) data often are unavailable.

An additional approach to more confident assessments is the use of multiple regression design that is partially experimental. Maintaining two of the alterable factors (hatchery, harvest, and dams) constant and varying just one would permit more powerful statistical analyses with fewer data. This may be possible for selected rivers (e.g., Rogue River and Snake River).

In summary, our past failure to adequately monitor Pacific salmon limits our immediate ability to conduct validation monitoring. Many years of data acquisition may be required to make strong inferences about management actions. However, greater confidence can be achieved in management options with each year's input to a properly designed database.

Statistical Concepts and Applications

There are a number of important statistical considerations for monitoring salmon:

- Directly relevant measures (e.g., population size and recruitment) generally are more expensive to obtain than indirect measures (e.g., habitat and weather). Reducing the costs of direct counts (e.g., by acoustic or laser techniques) usually is a priority.
- Monitoring requires a long-term commitment, because spatial and temporal variability are high for many variables, and reference (base line) data are sparse or lacking.
- Multiple variables are better than a single "best" variable because they reduce uncertainty and may be helpful in addressing new factors during the course of monitoring.
- Quality and relevance of the data can be increased by (1) state-of-the-art monitoring designs, (2) explicit treatment of whether inference from a sample is valid, (3) explicit treatment of spatial scale, and (4) analysis of Type II error (false conclusion of no change) before implementing a program.

Randomized designs developed for laboratory and agricultural research require that treatment and control be applied to a sufficient number of randomly selected units to eliminate the confounding effects of natural variation among units. Problems of confounding arise in field experiments when experimental units are too costly to replicate (Eberhardt and Thomas 1991) or the investigator forms an F-ratio based on variance among observations rather than variance among experimental units (Hurlbert 1984). Problems of confounding arise in most monitoring programs because there is only one "treated" unit, "treatments" cannot be assigned randomly to spatial units, or spatial units are clustered in a single (non-randomly assigned) affected area. Problems of confounding can be reduced by using temporal information in before-after control/impact BACI designs (Green 1979), recent extensions of BACI designs (Underwood 1997), intervention analysis (Stewart-Oaten et al 1986), and statistical control for some (though not all) sources of chance variation (Jassby and Powell 1990, Dutilleul 1993). Statistical methods can rarely eliminate all sources of confounding in field research (Mead 1988).

However, statistical methods can still be used to constrain interpretation (Carpenter 1990) and put a probability level on an outcome rather than declaring a decision at a fixed error rate in non-replicated experiments (Reckhow 1990). Eberhardt and Thomas (1991) provide a balanced treatment of the problems arising in field research from small numbers of experimental units, small areas of experimental units, and inability to eliminate confounding by random assignment of treatments to units.

Rather than repeat the sound guidance on design in Eberhardt and Thomas (1991) or in Meade (1988), we provide here a checklist of statistical concepts whose application will improve the quality of any monitoring program:

- Examine the data. Useful descriptions of the data come from frequency distributions, bivariate plots, and lagged autocorrelation plots.
- Use all of the information. Use multi-way designs rather than a series of one-way designs. Weight variables by uncertainty, rather than discarding those with high uncertainty. Combine locally controlled experiments with larger scale surveys (Eberhardt and Thomas 1991),
- Distinguish the observations (sample) from the population or target of inference. Over what area and time are the observations thought to be representative?
- Use statistical control where manipulative control is not possible. Use factors (analysis of variance [ANOVA] or classification variables) and covariates (regression variables) in statistical control as appropriate.
- Consider the use of Bayesian treatment of uncertainty (e.g., Reckhow 1990), in addition to classical frequentist treatments based on decisions declared against fixed tolerance of error (e.g., Type I error at 5%). Bayesian methods are unfamiliar to many ecologists, but they are less rigid than frequentist methods and usually easier to explain to people with minimal statistical training.
- Quantify the error. In the frequentist tradition familiar to most ecologists, this means calculating Type I error (the p-value) correctly or providing correct confidence limits. Type II error (false conclusion of no effect) can be addressed by computing power directly (if this is possible) or by computing minimum detectable differences based on some estimate of variance in the variable of interest.
- If the classical Fisherian machinery of experimental design (randomization, replication, and local control) is used, define the experimental unit, limits on randomized assignment of treatment and control, and limits on spatial and temporal extrapolation of the results. This machinery may not be directly applicable to a monitoring program for the reasons listed above.
- If variance is partitioned according to a model (as in ANOVA and regression), report the estimate of strength for each model component either as an ANOVA or analysis of deviance (ANODEV) table.
- Revise and review the monitoring program and associated statistical design at frequent intervals, using data as it is acquired. This allows a flexible or adaptive approach to monitoring based on timely information.

APPENDIX 1B

Monitoring Salmon Abundance in Alaska, British Columbia and the Yukon Territory; a Synopsis of Projects in 2000

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Executive Summary

Abundance of juvenile and adult salmon abundance is monitored in thousands of streams and rivers throughout Alaska, British Columbia, and the Yukon Territory every year. A variety of methods have been developed to estimate the abundance of salmon in these regions, and many monitoring programs have existed for decades. The goal of this report is to provide an overview of techniques researchers and managers have used to effectively monitor salmon populations.

Visual-based survey methods include surveying streams from aircraft, count towers, and while hiking. Aircraft surveys are flown over several thousand streams annually in Alaska, British Columbia, and the Yukon, making it the most ubiquitous method used to estimate salmon abundance. Aerial surveys are fast, usually inexpensive, allow coverage of large numbers of streams in a short time, and are particularly useful for surveying remote areas. Surveys made on foot, typically while hiking upstream, require more effort, and provide less total stream coverage. Count towers allow observers to count salmon from elevated positions above the river. Count towers are the least-used visual estimation method, but are still heavily relied upon in some areas. Count towers are typically staffed to count fish over the course of the entire salmon run, and thus do not require as much extrapolation as periodic aircraft or foot surveys. All visual estimation methods are restricted to use on relatively clear streams.

Weirs are fence-like structures that span streams to funnel fish into traps or through narrow openings where they can be counted. Weirs offer a method that can generate robust, accurate, and precise estimates of salmon abundance, but are generally high cost and require significant time and materials to install and maintain. Weirs can be used on both clear and somewhat turbid streams, and are least effective at times when water levels are highly variable and streams carry large amounts of organic debris. Weirs are the most ubiquitous monitoring method used in the region.

Acoustic techniques transmit and receive sound waves in water to obtain unique reflected signals from fish. Acoustic systems can sample a large volume of water and offer the ability to count fish in very turbid water. Acoustics cannot differentiate among species and therefore requires that mixed-species runs of salmon be sampled with capture gear to apportion total counts. Acoustic methods have been the most successful in counting juvenile sockeye salmon in lakes. Shallow water, variable substrates and variable bathymetry in rivers hinder the successful use of side-looking acoustic systems to count salmon. Acoustic systems have been the most cost-effective and efficient when used on large and/or very turbid river systems. Acoustic systems are expensive to purchase and develop for a given river system and require skilled operators. The frequent need to share equipment and expertise among projects has resulted in a patchy geographic distribution of acoustic systems. Long-term acoustic salmon monitoring projects occur in just two regions of Alaska and

there are none in British Columbia and the Yukon.

Resistivity counters measure the change in conductivity of water as fish swim over a set of wires. Resistivity counters are relatively inexpensive and can operate without staff on site once adequate ground truth work has been conducted. Resistivity counters can distinguish among fish sizes and so can be used to distinguish among species in cases where there is strong size separation among co-migrating species. These counters were originally developed and refined in Europe and have only recently begun to be used to count salmon in northwestern North America.

Mark-recapture studies derive estimates of abundance by marking individuals from a population and then re-sampling the population at a later place or time to determine the abundance at the original marking location. Mark-recapture studies are used throughout the region and are transportable to the greatest number of habitat types. Mark-recapture studies are labor intensive and require capturing fish at least two times or locations.

Video recording of migrating salmon is a relatively new technique that offers great promise for achieving accurate, precise abundance estimates. Video cameras can be located above and/or under the water to record fish passage. Video imagery can be captured without people present and can be replayed later at fast or slow speeds to count fish and discriminate among multiple species or dense aggregations of fish. Video recording of salmon is in its infancy, however, and is used in relatively few places in Alaska and British Columbia.

In summary, monitoring salmon is feasible under a variety of conditions, and many methods have been developed and continue to be refined. Numerous long-term monitoring projects have allowed researchers to assess and detect changes in the fish abundance over time. Although choice of method is usually dictated by information needs and habitat type, there is some evidence that technological advances radiate unequally across the different regions that salmon inhabit. In addition, every monitoring method has its own limitations or features that are very important to understand when it comes to making inferences pertaining to changes in abundance over time. Therefore, a dedicated effort to synthesize experience with available techniques and their quantitative features would be useful. We foresee that funding to monitor escapement in this region will continue to increase over the next two decades. We predict that this increased funding and increased demands on abundance data will lead to greater numbers of systems monitored and to significant improvements to all techniques.

Introduction

The purpose of this report is to provide an overview of methods used to enumerate and estimate salmon abundance in Alaska, British Columbia, and the Yukon Territory. The report has been prepared for the Validation Monitoring Panel, a group formed by the University of Washington to address the scientific basis for validation monitoring of salmon for conservation and restoration plans. The emphasis of the report is on current methods that have successfully provided long-term data sets (i.e., > 5 years) useful for fisheries research and management. This is not an exhaustive inventory of projects and techniques. Some detail is provided for a suite of example projects representing a range of methods. Example projects were chosen to demonstrate a wide species, geographical and jurisdictional range of particularly useful escapement monitoring programs.

Features such as stream size, fish behavior, and research objectives influence choices for selecting salmon monitoring programs, and their implementation thus varies greatly among sites. Numerous permutations and considerations have arisen from the need to tailor each method to a particular site. This report is not intended to describe the nuances of each method, but is instead intended to provide an updated overview of common methods in northwestern North America. Reviews by Cousens et al. (1982) and Irvine and Nelson (1995) provide some additional detailed discussion of the techniques and limitations of each method.

Monitoring Methods for Adult Salmon Escapement

Weirs and fishways

Weirs, sometimes termed fences, are barriers that allow water to pass downstream while obstructing fish migration upstream or downstream. Weirs can be designed to funnel fish through a narrow passage where they can be easily counted, or to direct fish into a trap where they can be handled before being released upstream or downstream of the weir. Weirs are generally regarded as the most accurate fish counting technique and are thus one of the most ubiquitous methods used to estimate salmon escapement and are often used to validate or derive correction factors for other methods. Multiple uses of weirs include standard counting of salmon escapement, collecting fish for tagging or gathering biological information, and calibrating abundance estimates generated from other surveys. Weirs have been constructed on numerous river types, but are most feasible on rivers with minimal variation in water flow and depth because seasonal flooding can cause erosion around the weir anchor points, clog the weir with debris and ultimately breach or top the weir. Site choice, weir design, and construction materials are thus critical for minimizing flood impacts. Permanent weirs are usually used on larger rivers and designed with removable panels that can be removed seasonally. Temporary weirs are usually used on smaller streams and assembled and disassembled each year. Permanent fishways around waterfalls, velocity barriers or other in-river obstructions make ideal locations to enumerate adult salmon. In order for counts from fishways to be useful, the original falls or obstruction must be impassible to salmon.

Two significant drawbacks of weirs are that they are usually expensive and that they can alter fish migratory behavior. Weirs are designed to block migrating fish and force them into small openings or chutes to continue migrating, causing fish to frequently hold below weirs for extended periods. After holding, fish can redistribute their spawning activity to less suitable areas downstream of the weir site. By delaying the migration, weirs are less useful to fishery managers than counting towers or other techniques that do not alter migratory timing.

Counting towers

Counting towers are elevated structures on the shoreline or in the river that allow observers to count the number of salmon migrating upstream and downstream. Counting efficiency typically increases with increasing water clarity, decreasing stream size, and decreased surface disturbance. Counting accuracy decreases as fish group size and the number of species increase. Viewing can be improved by wearing polarized glasses, by attaching high-contrast materials to the river bottom, and by illuminating the stream with floodlights at night. Counts are usually made at set times for a predetermined duration (e.g., every hour for ten minutes), then extrapolated to estimate interim fish passage.

An advantage of counting towers over weirs is that they do not alter migratory timing and behavior of salmon. As a result, data from counting towers are often more useful than weirs to fishery managers, who use run timing to determine the magnitude of the run in-season than count useful data than weirs. A disadvantage of counting towers is that they are dependent on clear water to enumerate salmon. Because water visibility conditions are governed by factors such as river surface disturbance and suspended particles that usually differ among years, estimates from tower counts are usually less accurate and precise than estimates from weirs.

Aerial surveys

Aerial surveys entail counting fish in estuaries or rivers while flying at low altitude in helicopters or fixed-wing airplanes. Indices of abundance can be generated from a single survey per season. Estimates of abundance must be generated from multiple surveys and the use of various statistical methods (e.g., area under the curve computations). Indices and abundance estimates are both improved by surveying the salmon run as close to its peak as possible. Aerial surveys often work well for sockeye, pink, and chum salmon because these species tend to spawn in large aggregations and are easily recognized from the air. Efficiency of aerial surveys increases with compression of the spawning run, decreased riparian canopy, and fish contrast with background. Because count efficiency usually varies among observers and river systems, replicate observers and ground truth exercises are needed to provide defensible escapement estimates from this technique.

Similar to foot and float surveys, aerial surveys can be very effective in the right situations. Fishery managers in Alaska rely heavily on aerial surveys for in-season monitoring of abundance in hundreds of systems, but long-term research programs based entirely on aerial survey data are less common.

Float/foot surveys

These forms of visual surveys entail counting fish while either walking along the stream or floating down it. Streams are usually surveyed multiple times, and abundance indices can be estimated from peak counts of live fish or from peak live plus total dead counts. Estimates of actual abundance can be derived from multiple surveys using various statistical methods. A common approach is to survey a group of smaller streams, such as headwater tributaries, then to use these counts to index escapement in larger rivers that are too difficult to survey on foot. Count accuracy is generally dependent on the same factors described for aerial surveys above. Foot surveys are most effective when observers wade in the stream, less effective when observers survey from the shoreline, and least effective when observers survey from the stream bank.

In suitable river systems, foot and float surveys can be a very cost effective method to monitor adult salmon abundance. However, there is a wide variation in the precision and accuracy of estimates obtained from these methods and the successes are usually limited to small streams with favorable flow regimes (clear water, low variability in discharge, etc.).

Mark-recapture experiments

Estimating salmon abundance with mark-recapture techniques involves capture and tagging of a portion of the run and then re-sampling the run later in space or time to estimate the proportion of the run that was initially tagged. Abundance estimates can be generated using several different statistical techniques, nearly all of which are variations of the well-established Petersen method. The Petersen method estimates the number of individuals (N) at the original sampling point based on the original number of marked fish (M), the number of marked fish re-captured (R) at a recovery station, and the total number of fish examined for marks (C) at the recovery station. Fish must usually be captured at one point on the river and recaptured at a second, but different capture methods can be used at capture and recapture sites. Recovering tags from carcasses on the spawning grounds is a common recapture method. Mark-recapture studies are most effective when carried out close enough to the migration terminus to minimize effects of straying and tag loss, yet far enough away to allow adequate mixing of marked and unmarked fish after the initial capture event. Capture locations, sampling effort, and mark rate need to be carefully selected based on the objectives of the study.

Mark-recapture techniques can be used to estimate population sizes under conditions that prohibit use of many other methods, such as in large or turbid rivers where the fish cannot be seen. Mark-recapture experiments are more labor intensive and therefore more expensive than most visual survey methods. However, an important goal of most escapement monitoring is obtaining basic biological information from the fish runs (size, age, condition, etc.) and, unlike most other survey methods, this sampling can easily be incorporated into mark-recapture programs because fish capture is key part of the experiment. Mark-recapture experiments are designed to detect when important assumptions have been violated and this detection can be used to either correct or discard escapement estimates. With sampling-based techniques such as acoustics, it is sometimes very difficult to detect when something critical has gone wrong in the study by examining the data alone.

Video recording

Adult salmon passage has been monitored using video cameras and recorders. Recording and analyzing fish passage with time-lapse video can be substantially cheaper and faster than using people stationed at fixed points, especially at remote or multiple sites. Underwater and aerial video is particularly effective where migrating fish are channeled into a constriction, such as at a weir or fish ladder. In addition, video recording allows managers to retain a permanent record of numbers, sizes, and species of migrating fish, and can be used with computers to enhance images and analyze large amounts of data. Technique efficacy increases with water clarity, decreased stream channel size, and increased concentration of fish.

Initial set up and ground truth of video methods is required to properly configure the system and allow for the development of defensible escapement estimates. However, once developed, this method offers one of the most accurate and cost effective methods available today to monitor salmon abundance in small and medium-sized river systems. Like counting towers, a valuable feature of video monitoring is that it doesn't hinder fish migration or alter behavior.

Resistivity counters

Resistivity counters are passive sensors that detect the difference in water conductivity when fish are present and absent. Conductivity sensors (three cables running perpendicular to the stream current) can be arranged in a mat on the stream floor, or in a tunnel through which fish must swim. Fish that enter the detection zone cause an increase in conductivity because fish body fluids are more conductive than the surrounding water. These body fluids are less conductive than salt or brackish water, so resistivity counters are only effective in freshwater. Tunnel counters require the construction of a full weir and some species of salmon are very reluctant to use the narrow tunnels. Sub-sampling (e.g., test netting, visual counts) is usually necessary to apportion counts from mixed-species migrations because resistivity counters cannot differentiate between fish species. The signal data from the counter can be used to estimate individual fish lengths and this can be used to distinguish between species if there are adequate differences in size among species. Resistivity counters require fish to travel near the sensors and therefore cables are usually installed in an elevated substrate lying on the streambed. Because of this need to have fish travel close to the sensors, counters are effective at weirs, fishways, or in shallow streams.

Like video, resistivity counters require that time and money be invested to develop and ground truth the technique on each river system. Once developed, resistivity counters offer a non-intrusive and inexpensive method of counting fish while not altering fish migration and behavior. Unlike video, resistivity counters can continue to function during periods when turbidity precludes visual enumeration. However, when multiple species are present in a river system, resistivity-based estimates require regular ground-truth observations using video methods or from direct human observation at the site.

Acoustics

Monitoring adult salmon abundance in rivers with acoustics is a particularly challenging branch of fisheries acoustics. Unlike many marine mobile survey applications, riverine acoustics use stationary transducers with acoustic beams aimed in a relatively small water volume, surrounded by the acoustically reflective boundaries of the river surface and bottom. These boundaries can make it difficult to distinguishing fish targets from acoustic noise. In addition, river bottom bathymetry and variable flow regimes requires relatively sophisticated equipment and careful deployment, calibration, and testing. Finally, current riverine acoustic systems cannot distinguish among salmon species, so expensive sampling programs are required to obtain estimates of species composition in situations where two or more species are present.

Factors that affect the efficacy of acoustic systems include: site bathymetry and substrate, hardware configuration and fish behavior. Transducers are typically mounted near shore and aimed horizontally into the river, perpendicular to flow, monitoring migrating fish in side-aspect. A bottom substrate of low acoustic reflectivity (e.g., sand, small rocks) enables the acoustic beam to be aimed close to the bottom. Migrating salmon often migrate close to shore and close to the bottom where water velocities are slowest. Acoustic sites are best where fish are actively migrating in a predictable area in the water column and not holding or milling. In addition to escapement counts, modern acoustic data can provide information on the size and behavior (direction of travel, ground speed, etc.) of salmon. With success heavily dependent on site characteristics and fish behavior, it usually requires several years of research and development at a given site to arrive at an acoustic monitoring technique than can be used to provide high quality escapement estimates.

Hydroacoustic techniques have been used since the 1960s to estimate adult salmon escapement in several rivers in Alaska. The early systems used single-beam acoustic techniques, with dual-beam techniques introduced in the mid 1980s. In the early 1990s, a split-beam acoustic system was developed. Split beam acoustics improved the ability to locate fish in three dimensions in contrast to earlier acoustic systems and this has enabled "tracking" of individual fish. This tracking allows more refined measurements of fish behavior (upstream and downstream movement, location in the water column, distinguishing multiple targets, etc.) and, therefore, it has provided an improvement to monitoring escapement and fish behavior at several experimental acoustic sites. Despite these recent advances in technology, long-term acoustic monitoring of salmon in Alaska still relies heavily on 1980s acoustic technology. The Alaska Department of Fish and Game (ADF&G) is in the midst of an intensive and multi-year transition from older to newer acoustic technology. In addition to improving escapement monitoring, this research and development effort by ADF&G will substantially increase knowledge and understanding in this field over the next five years.

The disadvantages of acoustics to monitor salmon escapement include its high capital cost, the often-high operating cost (highly skilled staff, intensive sampling programs for species composition) and the need for significant development time (multi-year) to adequately test equipment and ground truth counts. Advantages include the ability to count fish in turbid water, sample large volumes of water and not alter fish behavior.

Monitoring Methods for Juvenile Salmon

Weirs

Weirs have been used to capture and enumerate juvenile salmon on small streams throughout the region for decades. Many of the juvenile weir applications were developed as part of long-term coded-wire tagging programs where a significant portion of the outmigrating smolt population needed to be captured, sampled and tagged. A juvenile salmon weir (or fence) is usually made of wood or aluminum panels lined with fine wire mesh. The panels are arranged into V- or W-shaped fences with the crotch or base of the V (or W) at the downstream end of the weir. Downstream migrating salmon are funneled through the fence into downstream holding boxes where fish can be held until a crew comes to sample and tag them. Streams suitable for juvenile salmon weirs must have relatively low discharge and debris load because the fine-meshed weirs are prone to blockage and washout. Regular maintenance of the weir and handling of the entire fish run makes weirs a relatively expensive form of monitoring juvenile abundance.

When 100 percent efficiency of the weir is not feasible, mark-recapture techniques are usually employed to estimate the total outmigration. Fish are marked by fin clipping, streamer tags, or marker dyes and then re-released to be resampled at a second downstream weir or are carried upstream of the initial weir and released. Given the non-random and variable distribution of migrating fish within the stream, expanding catches based on cross-sectional area of the stream covered with the weir or trap is inappropriate.

Traps

Various forms of traps have been developed to capture and assess the abundance of downstream-migrating juvenile salmon. Inclined-plane traps, rotary-screw traps and fyke nets are all variations of the same theme of a funnel-shaped, mesh-lined cone staked in the stream bed or suspended between two pontoons and positioned in the stream. These traps “filter” fish from the water and deposit them into holding tanks. Baited minnow traps are small cylindrical wire mesh tubes with funnel entrances. Similar to incomplete weirs, virtually all these methods rely on mark-recapture procedures to develop abundance estimates. Trap efficiencies usually vary over time, making study design and rigor of paramount importance for obtaining meaningful estimates from these techniques.

Electrofishing

Electrofishing captures fish by exposing them to an electrical field that either stuns the fish (electronarcossis) or forces them to swim towards the source of the field (electrotaxis). Electrofishing is used to capture both juvenile and adult salmon. It is only effective in freshwater because fish body fluids must be more conductive than the surrounding medium for the electrical field to have any effect. Some freshwater systems, however, have conductivities too low to carry an electrical pulse and are thus unsuitable for electrofishing. Salmonids are particularly sensitive to electrical fields and numerous electrofishing techniques have thus been developed to capture salmonids in lakes, rivers, and streams. However, electrofishing is usually effective for juvenile salmonids in small streams, where substantial portions of the habitat can be exposed to the electrical field at a time. Such streams are usually electrofished using a relatively small, portable device, such as one carried in a backpack. Population estimates are typically generated using mark-recapture or multiple-pass removal techniques, whereas abundance indices can be generated by monitoring abundance at fixed sites at equal intervals.

Electrofishing is an active sampling technique and can be preferable to passive sampling techniques in certain situations. Electrofishing can capture non-migratory juvenile salmon still rearing in their natal stream whereas passive techniques such as weirs only catch migrating fish. Confined spaces, such as brushy stream banks often preferred by juvenile salmon, are also easier to sample with lightweight, mobile electrofishing gear than with heavier, more cumbersome equipment such as traps. Electrofishing equipment is also not as size selective as many passive capture techniques. Finally, monitoring populations by electrofishing can often be less expensive than weirs or traps and requires less total labor over the course of a season.

The drawbacks to electrofishing are that it can kill or injure fish and can affect the behavior of those fish that are uninjured. Electrofishing effectiveness also varies with conditions and habitat types, usually requiring that estimates be stratified by habitat type. It is also effective only in clear streams because fish must be seen to be captured by workers. It is also limited to small and moderate-sized streams where it is possible to retrieve temporarily stunned fish.

Acoustics

The most successful application of using sonar for monitoring juvenile salmon has been with acoustic surveys of lakes to estimate sockeye salmon abundance. Unlike side-aspect riverine acoustics, vertical-aspect or downward-looking acoustics is a well-developed and effective sampling technique. Downward-looking transducers are attached to boats and specific or random transects are made over the lake, usually during darkness when fish are well distributed in the water column. Replication is possible across temporal and spatial scales (depth, lake basin, etc.) allowing for relatively robust and precise estimates. Acoustics have been used on dozens of sockeye salmon nursery lakes in British Columbia and Alaska as part of short-term research programs and to a lesser extent, as part of long-term monitoring programs.

Counting downstream-migrating juvenile salmon in rivers is even more difficult than counting upstream-migrating adults. Acoustic smolt counters were developed in Bristol Bay, Alaska, in the early 1970s to estimate sockeye salmon abundance in several rivers and the three current and remaining projects have been monitored for almost 25 consecutive years. Two or three arrays of 10 upward-looking transducers are positioned on the streambed. Fish are enumerated as they pass downstream over the arrays. The smolt abundance data has been used to prepare forecasts of returning adults and to assess spawning escapement goals (e.g., smolt production versus previous escapement of adults).

Float surveys

Float surveys are used to obtain estimates of the abundance or density of resident juvenile salmon from observers who count fish while floating down the stream. Count accuracy is generally dependent on the same factors as for counting adults (discussed above). Intensive float surveys are suitable for relatively short, clear-water streams. Stratification of estimates by habitat type and sub-sampling across reaches can lead to obtaining estimates across long systems. Float surveys can be a cost effective method to monitor abundance of resident juvenile salmon such as coho and chinook salmon. Other species, which migrate through streams over relatively short periods of time, are difficult to quantify with float surveys.

Video

Similar to its use for monitoring adult salmon, the technique of using video to enumerate juvenile salmon is early in its development. Several experimental programs have demonstrated the utility and the potential of video-based systems, but we know of no long-term juvenile salmon monitoring projects relying on video techniques. The primary use of video for juvenile salmon has been in counting fish that have been funneled through narrow openings in weirs or traps. This application relies on video as a less expensive means of counting fish that previously had to be done by people. Computer-assisted pattern recognition software has been used to automate the recognition and counting process. A second application or potential application of video is to use it as a sampling tool similar to the way acoustics are used. A video-based project originally developed in 1999 to verify acoustic smolt estimates in Bristol Bay, Alaska, has demonstrated that in clear water, arrays of video cameras may offer a more robust technique to estimating smolt abundance than acoustics. Decreasing costs of digital video cameras, pattern recognition software and data transmission will make such video-based sampling techniques much more feasible than they were just a few years ago.

Selected Examples of Successful Long-term Monitoring Projects

Tower counts in Bristol Bay, Alaska

Tower counts have been used to estimate annual escapement of adult sockeye salmon to Bristol Bay rivers since the 1950s. Towers are typically set up in pairs, one on each side of the river at the sampling site. Observers count salmon migrating past each tower for ten minutes each hour and then multiply the counts by 6 to estimate the hourly salmon migration past each tower. These ten-minute-per-hour counts are typically continued 24 hours per day throughout the sockeye run. Tower counts are preferable to weirs in Bristol Bay because the streams are too large to be sampled with weirs and because tower counts do not affect migratory timing of the fish. Towers also require fewer personnel and are less expensive to run than weirs, allowing a greater number of rivers to be sampled with fixed funding levels. Comparisons of weir and tower counts in selected Bristol Bay streams have yielded agreements within 10% of one another. Such agreement, however, probably vary with the stream and with the behavior of the migrating salmon. Estimating hourly passage from 10-minute count intervals has also proven to be relatively precise, yielding 95% confidence intervals within 10% of the abundance estimate.

Long-term sites have been established on eight rivers in Bristol Bay with up to 22 million sockeye salmon counted annually. The escapement estimates from the towers are used for inseason management of the terminal ocean fisheries and for providing annual escapement data. This escapement data is combined with harvest data to produce the most extensive salmon stock-and-recruit dataset in the world. These datasets have been used to review and set system-specific escapement goals, monitor long-term changes in freshwater and marine habitat capacity, and to prepare annual pre-season forecasts of abundance.

Long-term weir counts on the Chignik River, Alaska

The Chignik River, Alaska, is a large, stable river flowing three miles from Chignik Lake to the Pacific Ocean. A weir has been operated regularly since 1922 to provide inseason management information and post-season salmon escapement estimates. The weir is installed annually, using diesel-powered pile drivers and SCUBA divers to access areas up to 15 feet deep. Since 1995, salmon passing through two gates in the weir have been recorded on underwater video cameras that feed images into a shoreline viewing station. An observer counts fish passage for ten minutes every hour and then multiplies the counts by six to estimate hourly passage. Scales are taken daily from sub-samples of sockeye salmon to apportion daily escapement counts to early- and late-run stocks. This estimate is then used to manage the ocean commercial fishery to meet different target escapement goals for early- and late-run stocks.

Escapement estimates from the Chignik weir are used for in-season management of the terminal ocean fishery and for post-season preparation of stock and recruit data. Data are used to prepare preseason forecasts of adult returns and have also been used to detect and measure changes in ecosystem productivity as the bathymetry and limnology of a nursery lake in the Chignik drainage has recently undergone significant change. The Chignik weir counts contribute to the longest time series of stock-and-recruit data of any single Pacific salmon stock.

There are several other large-river weirs and fishways in Alaska, British Columbia and the Yukon similar to the Chignik weir, and upwards of 100 weirs operated on smaller rivers each year. These projects provide escapement estimates for all species of salmon.

Acoustic monitoring of sockeye salmon in Cook Inlet, Alaska

Many streams in the Cook Inlet region of Alaska are glacially occluded, making it impossible to visually estimate salmon escapement. Hydroacoustic sonar counts were begun in 1968 in the Kenai and Kasilof rivers to better understand sockeye salmon escapement to glacial streams and to the region as a whole. Additional sonar systems were installed in the Susitna River in 1978 and in the Crescent River in 1980. Because sonar cannot differentiate among salmon species in a mixed-species run, sub-samples of migrating fish are captured with fishwheel or gillnets near each sonar site to estimate the species composition and to provide age, size, and sex data on the populations. Although the sonar sites on Cook Inlet tributaries have changed over the years, each still functions in its original watershed and provides daily escapement estimates for in-season management of sport and commercial fisheries. In addition to providing an effective way to manage the fishery and meet escapement goals, sonar-based escapement estimates provide a 30- year escapement record that has allowed fishery scientists to critically evaluate escapement goals and management policies for sockeye salmon in the Cook Inlet region.

There are currently about 12 long-term sites in Alaska where acoustics are used to monitor adult salmon escapement, one site in British Columbia and none in the Yukon.

Aerial surveys in Prince William Sound

Aerial surveys are used to estimate escapement of pink salmon to Prince William Sound, Alaska. Approximately 200 creeks are surveyed annually to provide inseason abundance indices and post-season escapement estimates. Inseason indices historically used unadjusted survey counts, whereas post-season estimates were historically calculated using area-under-the-curve methods assuming a stream life of 17.5 days. Weirs were operated on ten creeks from 1990 to 1992 to compare escapement estimates from aerial surveys and weir counts. Aerial surveys that used a constant 17.5-day stream life on each stream and did not estimate observer efficiency underestimated weir counts by over 50%. Aerial surveys that estimated observer efficiency and salmon stream life for each stream yielded escapement estimates within 10% of the weir counts. The results indicate that aerial surveys can provide relatively accurate escapement estimates when adjusted for observer efficiency, salmon stream life, and when survey intervals are frequent. As a result, aerial surveys are the most efficient and effective method for estimating escapement in a system like Prince William Sound, which has millions of salmon return each year to at least a thousand individual freshwater systems.

Almost 1,000 systems in Alaska and several hundred in British Columbia and the Yukon are aerial surveyed annually.

Mark-recapture experiments for Fraser River sockeye salmon escapement

At least sixteen major sockeye salmon stocks (escapements greater than 100,000 fish) in the Fraser River drainage have been monitored continuously since the 1950s using mark-recapture methods. The Canadian Department of Fisheries and Oceans maintains permanent field camps at these sites. The program is relatively expensive, but easily justified due to the high value of this fishery. Typically fish are captured near the spawning grounds using beach seines and tagged with Petersen disc tags. Fish carcasses are later examined for tags through regular foot surveys of the spawning grounds. Sockeye salmon escapement estimates from the Fraser River contribute to the largest stock-and-recruit dataset in the world for a group of salmon stocks from a single drainage basin. These data are used to prepare preseason forecasts of returns and have been used for a wide range of research over the last 50 years.

Large river mark-recapture experiments using fishwheels

Mark-recapture is one of the few methods for monitoring salmon escapement to large river systems. Large rivers are also often turbid and have relatively abundant returns, thereby precluding most traditional escapement monitoring methods. For several large river systems in Alaska, British Columbia and the Yukon, a method has evolved that uses a mark-recapture design paired with fishwheels to capture (and sometimes recapture) fish. The technique was originally tested in the late 1950s on the Taku, Nass and Fraser rivers but research and management needs did not justify the expense and effort required by these projects to succeed. As the demand for salmon abundance information increased, several projects were initiated in the early 1980s. Today this study design is being used to generate relatively precise, long-term time series of escapement for several species of salmon in the Yukon, Tanana, Taku, Chilkat and Nass rivers. In the last couple years, the method has been tested and is in the early stages of development on the Kuskokwim (Alaska), Fraser (British Columbia), Roanoake (North Carolina) and Skagit (Washington) rivers. The Yukon and Taku projects began in the early 1980s while the projects on the Chilkat and Nass were developed in the late 1980s and early 1990s.

Mark-recapture studies entail capturing and tagging returning adult salmon from fishwheels well downstream of the spawning areas. Fish are sampled, marked or tagged, and released alive. To obtain estimates of the tagged proportion of the population (and ultimately, the escapement estimate), the population is re-sampled farther upstream using a variety of techniques. Fish are re-captured upstream with any of several sampling devices, such as additional fishwheels, in-river fisheries, fishways, fish weirs and carcass surveys. There are some important statistical issues to address with mark-recapture estimates; these issues are mostly related to unequal vulnerability of fish to capture through time or as a function of body size. The most significant source of error in the estimates arises from the uncertainty in the post-tagging behavior and survival rate of fish released from the tagging fishwheels. Radio telemetry is often used to assess this behavior and mortality rate early in the river-specific development of projects. The more successful projects in this category capture and mark from 5 to 10% of the population and re-examine 3 to 10% of the population at a later point in time and space, generating estimates with standard errors in the range of 5 to 10% of the point estimate.

Several large-river mark-recapture projects have been operated for 15 or more years and the success of this study design has led to secure, long-term funding arrangements for several projects. In addition, researchers are beginning to develop long time series of stock and recruitment (escapement and catch, and subsequent returns), which have generated estimates of survival rates and have improved preseason forecasts. These stock and recruit data are also being used to determine and modify escapement goals to several important salmon producing systems. Mark-capture techniques are ubiquitous and often combined with other research methods and therefore it is difficult to estimate the number of projects currently relying on this method. However, there are at least a few hundred escapement estimates derived annually from mark-recapture methods in Alaska, British Columbia and the Yukon.

Resistivity counters

Although not widely used here in North America, about 100 resistivity-based counting systems have been used to count Atlantic salmon and other species of fish on rivers in Great Britain for the last two decades. These counters are usually installed at water control structures and fishways to count anadromous and resident fish. A research group located at the University of British Columbia has largely been responsible for the deployment of resistivity counters on the Pacific Coast. The *Logie* fish counter has been used at the Keogh and Deadman rivers (British Columbia) for several years to count several species of salmon, including steelhead. Resistivity counters have replaced expensive weirs on both these rivers, providing accurate escapement counts at a very small fraction of the cost of the former weir projects. Success of these projects has resulted in a dramatic increase in the interest among researchers to use these systems to monitor salmon escapement and we expect an exponential growth in their use over the next five years.

Monitoring juvenile coho salmon abundance in British Columbia and Alaska

There are about 15 wild coho salmon stocks in British Columbia and Alaska where researchers have been closely monitoring juvenile (and adult) salmon abundance for 15-20 years. These projects are designed to provide long time series of freshwater and marine survival rates, as well as information on the magnitude and distribution of stock-specific harvests. They are termed “indicator stocks” because they are designed to provide an indication of the abundance and productivity of coho from a much wider area (e.g., Northcoast of British Columbia, Vancouver Island, southern Southeast Alaska, etc.). Juvenile fish are usually captured with weirs but baited minnow traps, inclined-plane traps and rotary screw traps are also used. Very small (1mm) coded-wire tags are implanted in the nose cartilage of the fish and the vestigal adipose fin is removed to identify the tagged fish later in the catch and escapement. Sampling ocean catches occurs at boat docks and fish plants along the entire coast and fish heads are collected from adipose-fin-clipped fish. The number of returning adults is determined by weir counts, mark-recapture experiments and, occasionally, by intensive aerial surveys.

These long-term research programs have allowed researchers to understand and tease apart the many confounding factors affecting salmon abundance. These programs have documented changes in fishing patterns, ocean productivity and freshwater survival. Results like regional co-variation of survival rates has allowed researchers to obtain a much better understanding of the extent and effects of climate change on salmon abundance.

Concluding Remarks and Future Directions

Monitoring salmon abundance is an essential component of salmon management in British Columbia, Alaska and the Yukon. Both adult and juvenile monitoring programs are so integral to management that it is difficult to imagine a salmon fisheries management model without them. Significant interannual and interdecadal variation in the productivity of salmon stocks within and among drainages makes abundance-based management appear necessary to sustain salmon and salmon fisheries.

A prerequisite to determining if monitoring abundance will have the power to detect cause-and-effect relationships will be quantifying the accuracy and precision of estimation techniques. Salmon abundance estimates have historically been treated as point estimates, often obtained to provide fishery managers with a rough measure of their performance with respect to meeting target escapement goals. As demands on these abundance data have grown, the need to understand the uncertainty of these estimates has increased. Biologists and statisticians within the Alaska Department of Fish and Game have been at the forefront of effort to estimate the uncertainty of routinely gathered abundance data. Confidence intervals and other statistics are now routinely reported with escapement and juvenile abundance estimates. Many of these statistics are possible because of recent research conducted to empirically quantify the among-observer differences in aerial surveyors, the effects of environmental variability on escapement estimation techniques and other sources of errors for a variety of techniques. Additional research on the accuracy and precision of estimates derived from different salmon monitoring techniques will be needed to assist with the development of cost-effective and rigorous validation monitoring programs.

There is a need for a greater synthesis of existing literature and knowledge in the area of monitoring salmon abundance. A thorough review of current monitoring techniques and their quantitative limits will help to identify future research needed to improve these techniques while identifying the most suitable methods for rigorous validation monitoring programs. It has been nearly 20 years since the last thorough review of salmon escapement estimation techniques (Cousens et al. 1982) and there has been an enormous amount of work done since then. Much of this information and knowledge is either in a mass of largely inaccessible gray literature or is altogether unreported.

In our first-hand professional experience over the last 20 years, we have often noticed stark differences in favored escapement monitoring techniques among regions. Obviously, some of this is due to differences in local conditions and there are economies to sticking with a particular technique once it has been refined for a particular region (limited local expertise, capital investment, etc.). However, this inertia in favored techniques has begun to dissipate over the last decade, in part because increased funding levels in many areas have removed the barriers of limited staff. In addition, international funding initiatives have resulted in cross-fertilization of ideas and expertise among regions. For example, the Pacific Salmon Commission has several funding initiatives that are directed by joint, international technical committees with representatives from all regions. In addition to directed funding, greater communication and sharing of first-hand experience within these organizations has dramatically increased the spread of successful salmon monitoring techniques.

Funding to monitor escapement has increased significantly over the last decade and we foresee that this trend will continue. We predict that this increase in resources, combined with recent technological developments, will result in the following:

- An increase in the number of salmon populations monitored;
- Significant improvements and refinements of the most-promising, but least-tested techniques discussed here (video, resistivity and acoustics);
- Improvements to video storage, transmission and analysis will decrease costs and result in exponential growth of this technique to monitor fish populations;
- With more empirical data available, there will be further development of quantitative techniques to strengthen inferences based on escapement data;
- There will be a decrease in the differences among regions of favored monitoring techniques.

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APPENDIX 2

THE EXTENT OF SALMONID ENUMERATION IN WASHINGTON STATE

A major goal of this report is to present a scientific basis for counting salmon as a means to determine the effects of practices intended to benefit the status of salmon. This appendix is included to demonstrate the extent of effort in counting salmon throughout the freshwaters of Washington State. Although not fully comprehensive, the depth of this list illustrates that fish counting is feasible and commonly done, although rarely as a part of validation monitoring efforts. Organizations included are directly involved in projects that are enumerating salmonids, or financially supporting such projects within the last five years.

Non-governmental Organizations

Carkeek Watershed Community Action Project
Chehalis River Basin Fisheries Task Force
Chums of Maxwelton Salmon Adventures
Hood Canal Salmon Enhancement Group
Lake Washington Forum
Long Live the Kings
Nisqually River Council
Nooksack Salmon Enhancement Association
North Olympic Salmon Coalition
Olympia Stream Team
Pacific Coast Salmon Coalition
Sea Resources
Skagit Fisheries Enhancement Group
South Puget Sound Salmon Enhancement Group
Washington Trout

Native American Tribes

Chehalis
Colville Confederated Tribes
Jamestown S'Klallam
Kalispell
Lower Elwha S'Klallam
Lummi
Makah
Muckleshoot
Nisqually
Quileute
Quinault
Sauk-Suiattle
Skagit System Cooperative
Skokomish
Spokane
Squaxin Island
Stilliguamish
Swinomish

Nooksack
Port Gamble S'Klallam
Puyallup
Tulalip
Yakima

Local Governments

Bellevue Stream Team
Chelan County Public Utilities District
City of Bothell, Salmonwater program
City of Issaquah , Salmonwatcher Program
City of Kirkland, Salmonwatcher Program
City of Renton, Salmonwatcher Program
City of Woodinville, Salmonwatcher Program
City of Seattle – Environment and Safety Division
City of Seattle – Seattle City Lights
City of Seattle – Seattle Public Utilities
Douglas County Public Utility District
Grant County Public Utilities District
King County Department of Natural Resources
King County Land and Water Division
King County Road Maintenance Environmental Unit
Pacific County Conservation District
Pierce County Conservation District
Redmond Stream Team
Skagit County Public Works
Snohomish County Surface Water Management
Underwood County Conservation District
Wahkiakum County Conservation District
Whatcom County Conservation District

State Government

Department of Natural Resources – Olympic Region
Washington Department of Fish and Wildlife
- Eastern Washington Office - Region 1
- North Central Office - Region 2
- South Central Office - Region 3
- North Puget Sound - Region 4
- Southwest Washington Office - Region 5
- Coastal Washington Office - Region 6

Federal Governments

US Army Corps of Engineers – see the Dams section
National Park Service – Mt. Rainier National Park
National Park Service – North Cascades National Park
National Park Service – Olympic National Park
USDA Forest Service – Colville National Forest
USDA Forest Service – Gifford Pinchot National Forest
- Cowlitz Valley Ranger District
- Headquarters Office
- Mt. Adams Ranger District
- Mt. Saint Helen's National Volcanic Monument

USDA Forest Service – Mt. Baker - Snoqualmie National Forest
- Mt. Baker Ranger District
- Skykomish Ranger District
- Darrington Ranger District

USDA Forest Service – Okanogan and Wenatchee National Forest
- Okanogan Valley Office
- Chelan Ranger District
- Entiat Ranger District
- Lake Wenatchee Ranger District
- Leavenworth Ranger District
- Naches Ranger District
- Tonasket Ranger District

USDA Forest Service – Olympic National Forest
- Pacific Ranger District
- Hood Canal Ranger District

USDA Forest Service – Umatilla National Forest
- Pomeroy Ranger District
- Walla Walla Ranger District

US Fish and Wildlife Service
- Carson National Fish Hatchery
- Columbia River Fisheries Program Office
- Entiat National Fish Hatchery
- Leavenworth National Fish Hatchery
- Little White Salmon National Fish Hatchery
- Makah National Fish Hatchery
- Mid Columbia Fisheries Resource Office
- Quilcene National Fish Hatchery
- Quinalt National Fish Hatchery

Spring Creek National Fish Hatchery
Tucannon River Hatchery
Upper Columbia River Fish and Wildlife Office
Western Washington Fish and Wildlife Office
Winthrop National Fish Hatchery
US Geological Survey – Biological Resources Division

Dams

US Army Corps of Engineers/Washington Department of Fish and Wildlife

Bonneville
The Dalles
Ice Harbour
John Day
Little Goose
Lower Monumental
Lower Granite
McNary
Priest Rapids
Rock Island
Rocky Reach
Wells

US Army Corps of Engineers

Mud Mountain
Hiram M Chittenden Locks

Washington Department of Fish and Wildlife Hatcheries

Arlington Hatchery
Barnaby Slough Pond Hatchery
Bellingham Hatchery
Bogachiel Hatchery
Chambers Creek Hatchery
Columbia Basin Hatchery
Coulter Creek Hatchery
Cowlitz Trout Hatchery
Eastbank Hatchery
Elochoman Hatchery
Fallert Creek Hatchery
Forks Creek Hatchery
Garrison Hatchery
Goldendale Hatchery
Hoodsport Hatchery
Hupp Springs Hatchery
Issaquah Hatchery
Kendall Creek Hatchery
Baker Lake Spawn Beach Hatchery
Beaver Creek Hatchery
Bingham Creek Hatchery
Cedar River Hatchery
Chelan Hatchery
Colville Hatchery
Cowlitz Salmon Hatchery
Dungeness Hatchery
Eells Springs Hatchery
Elwha Channel Hatchery
Ford Hatchery
Fox Island Pens Hatchery
George Adams Hatchery
Grays River Hatchery
Humptulips Hatchery
Hurd Creek Hatchery
Kalama Falls Hatchery
Klickitat Hatchery

Lake Aberdeen Hatchery
Lake Wenatchee / Chiwawa Hatchery
Lake Whatcom Hatchery
Lakewood Hatchery
Lewis River Hatchery
Lyons Ferry Hatchery
Marblemount Hatchery
McAllister Hatchery

Washington Department of Fish and Wildlife Hatcheries Continued

McKernan Hatchery
Merwin Hatchery
Methow Hatchery
Minter Creek Hatchery
Mossyrock Hatchery
Naches Hatchery
Naselle Hatchery
Nemah Hatchery
North Toutle Hatchery
Omak Hatchery
Palmer Ponds Hatchery
Priest Rapids Hatchery
Puyallup Hatchery
Reiter Ponds Hatchery
Ringold Springs Hatchery
Samish Hatchery
Satsop Springs Hatchery
Shale Creek Hatchery
Sherman Creek
Similkameen Pond Hatchery
Skamania Hatchery
Skookumchuck Hatchery
Sol Duc Hatchery
Soos Creek Hatchery
Speelyai Hatchery
Spokane Hatchery
Tokul Creek Hatchery
Tucannon River Hatchery
Tumwater Falls Hatchery
Turtle Rock Hatchery
Vancouver Hatchery
Voights Creek Hatchery
Wallace River Hatchery
Washougal Hatchery
Wells Hatchery
Whitehorse Pond Hatchery