

NOAA Technical Memorandum NMFS-NWFSC-58



Ecosystem Recovery Planning for Listed Salmon:

An Integrated Assessment Approach
for Salmon Habitat

December 2003

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service

NOAA Technical Memorandum NMFS Series

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This document should be cited as follows:

Beechie, T.J., E.A. Steel, P. Roni, and E. Quimby (editors). 2003. Ecosystem recovery planning for listed salmon: an integrated assessment approach for salmon habitat. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-58, 183 p.



Ecosystem Recovery Planning for Listed Salmon:

An Integrated Assessment Approach for Salmon Habitat

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December 2003

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EXECUTIVE SUMMARY

The Endangered Species Act (ESA) requires that a recovery plan be developed for all species listed as threatened or endangered. For Pacific salmon, this includes 26 evolutionarily significant units (ESUs) of six species—Chinook salmon (*Oncorhynchus tshawytscha*), chum salmon (*O. keta*), coho salmon (*O. kisutch*), pink salmon (*O. gorbuscha*), sockeye salmon (*O. nerka*), and steelhead (*O. mykiss*)—distributed among nine geographic areas along the West Coast. Several factors associated with harvest, hatchery, hydropower, and habitat influence the decline of salmon populations in the western United States, but the relative importance of each factor varies among ESUs. Each of these factors should be addressed in a successful recovery plan.

Previous documents have provided guidance for recovery planning (NMFS 1992, 2000, McElhany et al. 2000), but they do not have specific guidance on how to implement the habitat portion of a recovery plan. This technical memorandum supplements prior guidance documents with information specific to habitat recovery planning. It is not intended that existing habitat recovery planning efforts (e.g., at the local watershed level) should be abandoned in favor of methods discussed here. Rather these methods should help clarify the specific purposes and methods of assessment within the existing approaches. Audiences that may benefit from this document include Technical Recovery Teams (TRTs) assigned to each of the geographic planning areas, local watershed planning groups, and National Marine Fisheries Service (NOAA Fisheries) personnel.

After the introductory section, this report is divided into five main sections. The first, An Assessment Approach for Habitat Recovery Planning, presents a conceptual framework for understanding relationships among land uses, watershed functions, habitat conditions, and biota. The framework relies on principles of watershed and ecosystem management and organizes the habitat-related questions that each recovery plan should attempt to answer. The second, Analyses for Phase I Recovery Planning: Setting Recovery Goals, discusses assessments that help identify important habitat losses and set recovery goals. The third, Analyses for Phase II Recovery Planning: Identifying Ecosystem Restoration Actions, presents more detailed assessments to conduct within individual watersheds for identifying causes of habitat loss or degradation. How to use Phase I and Phase II information together to help prioritize actions is addressed in the next section, Prioritizing Potential Restoration Actions within Watersheds. Finally, Managing Uncertainty in Habitat Recovery Planning discusses how uncertainty can affect planning decisions and provides guidance and examples for identifying and quantifying types of uncertainty. This document also includes three appendices. The following is a summary of these sections.

An Assessment Approach for Habitat Recovery Planning

Our conceptual approach to habitat recovery planning is based on principles of watershed and ecosystem function. Salmon are adapted to local environmental conditions, including associated temporal and spatial variability. Those conditions vary in space and time due to

landscape processes and land use. Because landscape processes (e.g., sediment supply, wood recruitment to streams) create and sustain habitats over time, an approach to habitat recovery that focuses on preserving or restoring ecosystem processes should provide good quality salmon habitat over the long term. This general approach applies to all ecoregions, though the relative importance of various landscape processes differs by ecoregion.

For Phase I recovery planning, a suite of habitat analyses helps identify or clarify certain recovery goals (e.g., abundance goals) for ESUs or populations. The Phase I assessments can also identify where large habitat losses have occurred and may help identify which habitats limit recovery of populations. In Phase II planning, watershed process assessments are the basis for identifying causes of habitat loss or degradation as well as ecosystem recovery actions. Results from both assessments are used to prioritize restoration actions. New information gained from future assessments and management experiments is used to update the recovery plan.

Analyses for Phase I Recovery Planning: Setting Recovery Goals

The first phase of habitat recovery planning addresses how habitat changes might have altered the abundance, survival, population growth rate, spatial structure, and life history diversity of ESUs or individual populations. This question can be addressed by assessments and analyses conducted at several levels of resolution. First, ESU-wide analyses can provide an overall understanding of broad-scale patterns of land use and habitat conditions and relate these to the recovery goals (salmon abundance, population growth rate, spatial structure, and diversity). Second, watershed-level analyses can elucidate such patterns specific to each watershed. Results of these analyses can be used to set biological delisting criteria for each of the salmon ESUs and their constituent populations.

The ESU-level analyses are meant to provide information about a broad geographic area in a relatively short period of time using existing data. Consistent methodologies applied across an entire ESU enable comparisons of results among populations or watersheds. Correlation analyses using existing geospatial data can identify relationships among natural landscape attributes, land uses, and salmon populations (e.g., the Salmonid Watershed Analysis Model or SWAM). Comparisons between current and historical habitat conditions can help assess potential productivities and capacities of salmon populations, identify where large habitat losses have occurred, and help identify which habitat losses might have large effects on ESU viability.

At the watershed level, similar analyses can be conducted to ascertain relationships among landscape attributes, land uses, and salmon viability. Existing tools include the simplified limiting factors model, the ecosystem diagnosis and treatment (EDT) model, and the dynamic life cycle model. All three approaches compare current and historical habitat conditions, but differ in their data requirements and representation of the salmon life cycle. The EDT model is complex and greatly relies on expert opinion for input data, whereas the other approaches are simpler models based primarily on measured data. The simplified limiting factors model has the least complete representation of the salmon life cycle, allowing only life stage capacities to change. The EDT model allows both life stage capacities and survivals to change. The dynamic life cycle model allows life stage capacities and survivals to change and can examine population

growth rates over time in response to habitat actions. These assessments elucidate patterns of habitat alteration and highlight areas where such change may have most affected salmon viability. Results can be used to identify criteria required to sustain viable populations and identify critical uncertainties in our predictions of how populations will respond to habitat restoration.

Analyses for Phase II Recovery Planning: Identifying Ecosystem Restoration Actions

Phase II assessments are primarily intended to identify causes of habitat loss or degradation and identify ecosystem restoration actions. Specific inventories and assessments to identify altered ecosystem processes can be grouped into distributed processes (i.e., widespread non-point such as sediment supply inventories), reach-level processes (e.g., floodplain and riparian characterization), and other ecosystem functions not easily described by rates or levels (e.g., barrier and flow-diversion inventories). Assessments that identify impaired biological integrity (e.g., Benthic Index of Biological Integrity or B-IBI, multivariate model analyses) can identify locations where habitat degradation may be altering biological communities as well as which ecosystem processes have been disrupted. All these analyses aim to identify the natural landscape processes active in a watershed, the effects of land use on natural processes, and the causal relationships between land use and habitat conditions. Specific results include locations of impaired stream segments, reaches, or subwatersheds and causes of impairment. From these assessments, a list of habitat restoration actions can be prepared for each watershed of an entire ESU.

Prioritizing Potential Restoration Actions within Watersheds

The recovery plan should include a prioritized list of ecosystem restoration actions. Many factors influence the prioritization of restoration actions in recovery planning and there are many philosophical approaches to recovery of ecosystems and listed species. When little is known about habitats that limit recovery of listed ESUs or the causes of habitat degradation, an interim prioritization approach based on effectiveness of different types of actions can be used. This hierarchical strategy gives priority to actions that have high probability of success, low variability among projects (i.e., consistency of results), relatively quick response time, and long duration of results. If more is known about habitat limitations and causes of habitat loss, Phase I and Phase II information can be combined to prioritize restoration actions necessary for more efficient recovery of single species. Cost and time required to implement actions as well as immediate management needs may also be considered during prioritization. Where more than one species is of concern or where habitat recovery goals are more broadly defined, alternative strategies that consider multiple species, protection of refugia, and other factors may be used.

Managing Uncertainty in Habitat Recovery Planning

Acknowledging, describing, and estimating uncertainty associated with assessments and analyses can increase the effectiveness of recovery planning. This process elucidates the full range of possible outcomes and the probability of seeing each of these outcomes. Knowing where uncertainties exist allows resource managers to develop plans with acceptable risk (i.e., plans where the benefits of an action outweigh its costs).

By recognizing where uncertainty exists, areas that need further clarification (e.g., more data, additional expert opinion, better model performance) can be identified. To do this, estimates of the magnitude of uncertainty in each of five types of uncertainties—prediction, parameter, model, measurement, and natural stochastic variation—must be generated. Identification of which types of uncertainty are likely to have the largest effect on predictions can suggest areas where improvements in information will be most beneficial.

Often, decisions need to be made before adequate data are available. Provided that uncertainties are identified, several established methods can be used to make decisions based on the best available information. These methods aid prioritization of actions and are preferred over methods that rely on guesswork, biased data, or data collected at inappropriate scales. Final outcomes chosen must be robust to each type of uncertainty identified. These decision strategies should assist in creating sound plans in the interim and can be reevaluated as new information is obtained.

Appendices

Three appendices follow in this guidance document. Appendix A, *Issues of Scale in Habitat Recovery Planning*, examines the concept of scale with particular emphasis on analyses to help set recovery goals. It demonstrates how the effects of habitat change on the four components of population viability can be examined over multiple scales and includes examples from the literature to illustrate the types of information obtained at each scale. Appendix B, *Estimating Chinook Salmon Spawner Capacity of the Stillaguamish River*, is an example analysis for Phase I recovery planning. This case study estimates the river's current and historical capacity for adult Chinook salmon based on habitat data at the unit scale (e.g., pool, riffle, and glide), then extrapolates to the watershed scale to estimate the maximum number of adult Chinook that the river historically produced and the system's potential for production today. Appendix C, *Restoration of Habitat-Forming Processes: An Applied Restoration Strategy for the Skagit River*, is an example analysis for Phase II recovery planning. It briefly describes the Skagit Watershed Council's habitat protection and restoration strategy, directed at restoring the disturbed habitat-forming processes instead of attempting to build specific habitat conditions, as well as applications of the methods and preliminary results.

ACKNOWLEDGMENTS

The editors thank the following people for providing valuable reviews and comments on an earlier draft of this document: the members of the Willamette/Lower Columbia and Puget Sound Technical Recovery Teams; Jim Karr, University of Washington, College of Ocean and Fishery Sciences; Susan Bolton, University of Washington, Center for Water and Watershed Studies; Pete Bisson, U.S. Forest Service, Pacific Northwest Research Station; Bruce Rieman, Jason Dunham, Russ Thurow, and Dan Isaak, U.S. Forest Service, Rocky Mountain Research Station; Derek Poon, Gretchen Hayslip, Michael Rhylo, Lillian Herger, Krista Mendelman, and Tom Connor, U.S. Environmental Protection Agency, Region 10; Dudley Reiser, R2 Resource Consultants, Inc., Redmond, Washington; David Jensen, Frank Orth & Associates, Kirkland, Washington; Dale McCullough, Columbia River Inter-Tribal Fish Commission; Brad Johnson, Asotin County Conservation District, Clarkston, Washington; Lloyd Moody, State of Washington Governor's Salmon Recovery Office Salmon Team; Kelly Moore, Oregon Watershed Enhancement Board; Barry Thom, Spencer Hovekamp, and Tom Cooney, National Marine Fisheries Service; Michelle McClure, Mary Ruckelshaus, and Robin Waples, Northwest Fisheries Science Center; Tommy Williams, Eric Bjorkstedt, David Boughton, Steve Lindley, and Brian Spence, Southwest Fisheries Science Center; and John Kocik, Northeast Fisheries Science Center. The editors also thank Karrie Hanson, independent contractor, and Aimee Fullerton, Northwest Fisheries Science Center, for administrative and editorial support.

In addition, the authors of Appendix C, Restoration of Habitat-Forming Processes, thank the Environmental Systems Research Institute, Redlands, California, for providing a substantial grant enabling the acquisition of Geographic Information System software for that project and the U.S. Forest Service for providing road inventory data for the identification of landslide hazard areas.

INTRODUCTION

One of the main purposes of the Endangered Species Act is “to provide a means whereby the ecosystems upon which endangered species and threatened species depend may be conserved” (ESA 1973). The ESA consequently requires the development and implementation of recovery plans in order to realize the conservation of listed species. Details that recovery plans must include are:

- 1) a description of such site-specific actions as may be necessary to achieve the plan’s goal for conservation and survival of the species,
- 2) objective, measurable criteria which, when met, would result in a determination that the species be removed from the list, and
- 3) estimates of the time and cost required to carry out those measures needed to achieve the plan’s goal and take the intermediate steps toward that goal.

For ESA-listed salmon in the western United States, this requirement is no small task, as salmon habitat is ubiquitous and actions that protect or restore the ecosystems on which salmon depend are in conflict with many land uses in the region.

The ESA provides little guidance concerning the content of recovery plans for individual species. Therefore, the National Marine Fisheries Service (NOAA Fisheries) provides additional scientific guidance on setting recovery goals for evolutionarily significant units (ESUs) of salmon and the populations within them (McElhany et al. 2000), based on the concept of viable salmonid populations (VSPs). An ESU, equivalent to a “distinct population segment” under the ESA, is “a population or group of populations that are 1) substantially reproductively isolated from other populations and 2) contribute substantially to the ecological or genetic diversity of the biological species” (Waples 1995, Myers et al. 1998). For each ESU, recovery goals generally are concerned with identifying how many and which independent populations are necessary for ESU viability (McElhany et al. 2000). McElhany et al. (2000) identify four categories of recovery goals that must be met for each population within an ESU of listed salmon: population abundance (size), population growth rate (and related parameters), spatial structure (within a population or group of populations), and diversity (i.e., the distribution of traits within and among populations). However, the VSP guidance does not address how to identify specific restoration actions for harvest, hydropower, hatcheries, or habitat that are necessary to achieve ESU or population viability.

In addition to the VSP guidance, NOAA Fisheries provides guidance to the Technical Recovery Teams (TRTs), which are tasked with developing the technical aspects of a recovery plan for each ESU of listed salmon (NMFS 2000). Known as the TRT Guidance Document, that guidance has two phases of recovery planning: Phase I identifies the recovery goals (i.e., criteria that must be met for delisting) and Phase II identifies restoration actions necessary for recovery. However, there is considerable overlap in habitat analyses used for Phase I and Phase II planning. The habitat elements of the TRT work program, mainly included in Phase II planning, are: 1) describe fish and habitat relationships, 2) identify factors causing decline and limiting factors, and 3) identify actions for recovery. The TRT Guidance Document goes on to indicate that characterizing habitat/fish relationships includes assessing the spatial distribution of fish abundance for each population in the ESU, associating fish abundance with habitat

characteristics, and identifying human factors that have the greatest impact on key freshwater and marine habitats. However, it does not specify appropriate spatial scales or resolution levels of data analyses. Moreover, it does not clearly elucidate the questions that such analyses are intended to answer, especially with respect to population goals for diversity and spatial structure. The TRT Guidance Document also stops short of specific questions for identifying limiting factors and identifying habitat restoration actions. As neither the VSP guidance nor TRT Guidance Document address how to identify specific habitat actions that would support salmon recovery, the Watershed Program of the Environmental Conservation Division at the Northwest Fisheries Science Center was asked to develop guidance for the habitat restoration elements of salmon recovery plans. In response to that request, this technical memorandum describes an approach to developing the habitat elements of a recovery plan for salmon listed under the ESA.

Purpose and Scope

The purpose of this document is to help both TRTs and local watershed groups list specific recovery planning questions, assemble appropriate methods for answering those questions, and utilize that assessment information to identify and prioritize ecosystem restoration actions. We focus on analyses that can help identify the restoration actions necessary to recover ecosystems that support salmon and help set population recovery goals. However, we do not address many other aspects of recovery planning here. These include the Columbia River hydropower system, harvest and hatchery practices, exotic species impacts, and the specifics of certain regulatory statutes that may be considered programmatic elements of a recovery plan. Regulations such as water quality standards, forest practices rules, the Northwest Forest Plan, and local growth management ordinances should serve as ecosystem protection actions at a minimum, and may serve as passive recovery actions in the best case (e.g., where substantial riparian buffers allow natural recovery of riparian processes and functions).

Here we provide guidance for two main audiences, TRTs and local watershed groups (e.g., watershed councils, lead entities) that identify and conduct restoration actions. In general, we expect TRTs to focus largely on analyses for Phase I recovery planning (with some overlap into Phase II) and local watershed groups to focus mainly on analyses for Phase II recovery planning. We recognize that many existing assessment methodologies already incorporate aspects of the guidance provided here (e.g., Moore 1997, Quigley and Arbelbide 1997, SWC 1998, OWEB 1999a, JNRC 2001), and we support existing approaches that favor restoration of ecosystem processes and functions. We do not intend that existing methods be abandoned in favor of a redesigned assessment, but we believe this guidance will be useful to existing TRTs and local watershed groups in clarifying the specific purposes and methods of assessment within their existing approaches. In addition, there are many TRTs yet to be formed and many local watershed groups that have not yet formulated an approach and methodology for recovery planning.

Overview

This document provides guidance for choosing and conducting analyses to assist in both Phase I and Phase II recovery planning for listed salmon. In the next section, An Assessment Approach for Habitat Recovery Planning, we present a conceptual framework for understanding relationships among land uses, watershed functions, habitat conditions, and biota. The framework relies on principles of watershed and ecosystem management and organizes the habitat-related questions that each recovery plan should attempt to answer. These questions first address how habitat changes might have affected abundance, survival, population growth rate, spatial structure, and diversity of salmon populations within an ESU (questions relevant to Phase I recovery planning or setting recovery goals). A second group of questions addresses causes of habitat change. The answers provide the basis for identifying actions that are necessary to restore the ecosystem upon which salmon depend (Phase II recovery planning).

After listing the important questions, we provide a brief overview of methodologies that are appropriate for answering each question. In the Analyses for Phase I Recovery Planning: Setting Recovery Goals section, we discuss assessments that create a broad understanding of habitat issues affecting salmon populations across an ESU and help set recovery goals. In the Analyses for Phase II Recovery Planning: Identifying Ecosystem Restoration Actions section, we describe more detailed assessments to conduct within individual watersheds for identifying causes of habitat loss or degradation. How to use Phase I and Phase II information together to help prioritize restoration actions is addressed in the next section, Prioritizing Potential Restoration Actions within Watersheds. Then in Managing Uncertainty in Habitat Recovery Planning, we discuss how uncertainty may affect planning decisions and provide guidance and examples for identifying and quantifying types of uncertainty. Finally, this technical memorandum includes three appendices. Appendix A, Issues of Scale in Habitat Recovery Planning, examines the concept of scale in recovery planning with particular emphasis on analyses to help set recovery goals. Appendix B, Estimating Chinook Salmon Spawner Capacity of the Stillaguamish River, is an example analysis for Phase I recovery planning. Appendix C, Restoration of Habitat-forming Processes: An Applied Restoration Strategy for the Skagit River, is an example analysis for Phase II recovery planning.

Notes on Terminology

Because salmon recovery planning draws on many scientific disciplines, there is considerable variation in the use of some terminology (e.g., the term productivity has different meanings depending on the discipline in which it is used). To help minimize confusion surrounding specific terms and clarify their meanings in our usage, we have included a glossary, which also defines specialized acronyms. In addition, to help avoid misinterpretation of our guidance, we discuss here five terms commonly used in salmon recovery planning—habitat, ecosystem, recovery, restoration, and productivity.

The first two terms, habitat and ecosystem, are often used interchangeably, which creates some confusion about their meanings. For the purposes of this document, the term habitat refers to the aquatic environment that fish experience and not those landscape processes or attributes

outside streams that alter habitat conditions. In general use, the term ecosystem refers to the dynamic and holistic system of all the living and dead organisms in an area and the physical and climatic features that are interrelated in the transfer of energy and material. In this document, the ecosystem is the aquatic environment and biota, physical and biological processes active in that environment, and the landscape processes and land uses that form and sustain the aquatic environment and biota. In general, recovery planning will aim to restore habitat attributes that support salmon by restoring ecosystem processes that form and sustain those habitats.

The third term, recovery, in the context of listed populations, means attaining specified goals for viable populations and ESUs (abundance, population growth rate, spatial structure, and diversity). For watershed processes and habitats, recovery means returning from a disturbed state to some prior condition, not necessarily pristine.

Restoration, the fourth term, in its strictest definition is returning a site to some predisturbed condition (Gore 1985, NRC 1996). Some practitioners call this full restoration. It is generally more holistic or systemic than habitat creation, reclamation, rehabilitation, or enhancement, and not accomplished through manipulation of individual ecosystem or watershed elements. In contrast, habitat enhancement is the improvement of habitat from its existing or previous condition. It does not necessarily seek to restore conditions to some predisturbed state or restore disrupted watershed or ecosystem processes and functions such as delivery of water, wood, and sediment. Some practitioners call this (and related terminology) partial restoration. Here we use the term restoration generically to mean both restoration and enhancement, but we distinguish between those activities that restore watershed or ecosystem processes and those that enhance habitat.

The fifth problematic term is productivity. In salmon management and research it has four meanings: population growth rate (e.g., McElhaney et al. 2000), number of adult returns per spawner (e.g., Moussalli and Hilborn 1986), stage-to-stage survival rate at low population size or density-independent survival (e.g., Moussalli and Hilborn 1986, Lestelle et al. 1996), and plant and algae biomass produced per unit area per year (e.g., Begon et al. 1986). To reduce the potential for misunderstanding, we do not use the term productivity and instead use more specific terms as appropriate.

AN ASSESSMENT APPROACH FOR HABITAT RECOVERY PLANNING

In this section we briefly describe an approach to understanding ecosystem functions and habitat change, as well as the scientific and practical reasons for choosing it. Our approach is based on a simple conceptual framework for understanding relationships among ecosystem processes, land uses, habitat conditions, and biota. Using this conceptual framework, we organize a series of questions that must be answered in developing a recovery plan, identify the purpose of each assessment method, and illustrate the relationships among different assessments. We also suggest a sequence for the assessments and describe the importance of management experiments and monitoring in updating the recovery plan.

Restoring Ecosystems to Support Recovery of Listed Salmon

Over the past decade, many scientists have pointed out that the listing of salmon and other species as threatened or endangered is largely a result of trying to manage individual species and habitat characteristics rather than managing whole ecosystems (e.g., Doppelt et al. 1993, Frissell et al. 1997). Scientists and resource managers alike have recognized that restoration that carefully considers the watershed or ecosystem context is more likely to be successful at restoring individual or multiple species and preventing the demise of others (Nehlsen et al. 1991, Doppelt et al. 1993, FEMAT 1993, Lichatowich et al. 1995, Reeves et al. 1995, Beechie et al. 1996, Moore 1997). This conclusion suggests that habitat recovery planning will require assessments of disruptions to ecosystem functions and biological integrity, which have reduced the productive capacity of Pacific Northwest river systems and are partly responsible for declines in salmon abundance. The goal of such assessments is to identify alterations of key processes that affect stream habitats and specify the management actions required to restore processes that sustain aquatic habitats and support biological integrity (e.g., FEMAT 1993, Moore 1997, Quigley and Arbelbide 1997, Beechie and Bolton 1999). In this approach, restoring specific salmon populations is subordinate to the goal of restoring the ecosystem that supports multiple salmon species. In addition, information on habitat changes or conditions that limit specific salmon populations can be useful for identifying actions that may have the greatest effect on salmon recovery (e.g., Reeves et al. 1991) or for helping to set population and ESU recovery goals.

In this technical memorandum, the ecosystem approach to salmon recovery planning includes two main assessment elements: analysis of landscape and habitat factors to help set recovery goals, and analysis of disrupted ecosystem processes to identify watershed and aquatic habitat restoration actions. Each element relies on a conceptual framework describing general relationships among land uses, landscape characteristics, aquatic habitat, and biological responses (Figure 1). This framework illustrates that landscape processes and land uses alter aquatic habitats, which in turn alter aquatic communities or populations. Therefore, aquatic habitat conditions can be viewed as the link between landscapes and fish populations. Making these relationships explicit allows us to organize analyses of ecosystem processes and functions in a way that brings greater clarity of purpose to each analysis, as well as a better understanding

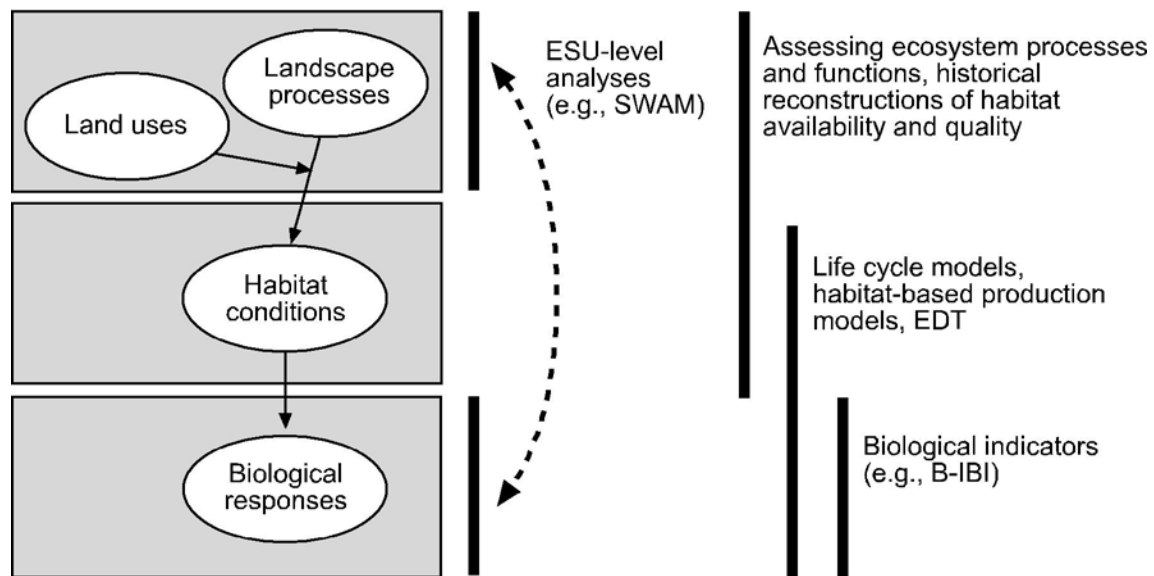


Figure 1. Schematic diagram of linkages among landscape processes, land uses, habitat changes, and biological responses. (Adapted from Beechie et al. 2003.)

of how the results of each analysis will be used in recovery planning. Four classes of analyses are useful in recovery planning. First, for ESU-wide analyses of land use effects on salmon populations, landscape and land use factors can be correlated with indicators of population performance (e.g., correlation analyses) to indicate where populations have been impacted by various land uses. Second, population-level analyses that assess biological responses directly (e.g., using a biological indicator) can help identify where ecosystem functions have been impaired within watersheds. Third, assessments of habitat loss and resultant salmon population declines can be conducted by relating current and historical habitat abundance and condition to salmon utilization and survival. Finally, assessing disrupted ecosystem functions and processes within watersheds can identify causes of habitat change that result in diminished biological integrity and declines in salmon populations.

Scientific Basis for an Ecosystem Approach

The scientific basis for this approach can be summarized in two important characteristics of salmon and their habitats:

1. Salmonid stocks are adapted to local environmental conditions (Miller and Brannon 1982, Healey 1991).
2. Spatial and temporal variations in landscape processes create a dynamic mosaic of habitat conditions in a river network (e.g., Naiman et al. 1992, Reeves et al. 1995).

These statements imply that salmonid species or populations are adapted to spatially and temporally variable habitats (Beechie et al. 1996), and may further imply that such environmental variability is important to the long-term survival of populations (Reeves et al. 1995). Perhaps most importantly, each salmon population (even one located close to another) is adapted to the spatial and temporal sequences of habitat conditions found in its watershed, which influences life history diversity across an ESU.

Because salmonids are adapted to spatially and temporally varied habitat conditions, it does not make sense to manage for the same conditions in all locations or expect conditions to remain constant in any single location. This has been recognized in scientific critiques of many management issues in the past decade, including “one-size-fits-all” habitat standards (Bisson et al. 1997), not managing for spatial or temporal variation in habitats (Reeves et al. 1995, Bisson et al. 1997), and addressing symptoms of a disrupted ecosystem rather than causes (Frissell and Nawa 1992, Spence et al. 1996). Those approaches generally do not consider that local populations are adapted to the natural potential habitat conditions within their range and that those conditions vary in space and time. By contrast, identifying the root causes of degradation (i.e., impaired ecosystem processes and functions) focuses restoration on those processes that form and sustain habitats. This focus allows each part of the river network to express its natural potential habitat and helps conserve and restore the natural spatial and temporal variation of habitats to which salmon are adapted.

We stress that identifying the root causes of ecosystem degradation is important for two main reasons. First, scientists and resource managers do not understand most of the linkages between landscapes, habitats, and salmon populations with any great certainty, and we cannot predict exactly how land uses alter habitat conditions or how those habitat changes alter salmon populations. In fact, one can argue that even now we are not yet aware of all the aspects of

aquatic ecosystems that significantly affect salmon populations. This lack of knowledge has led to significant habitat degradation—such as in the widespread removal of wood debris from Pacific Northwest rivers. While the practice began over 150 years ago to improve navigation (Sedell and Luchessa 1982, Collins et al. 2002), the degradation was exacerbated as recently as the 1980s when fish biologists recommended wood removal to help adult salmon migrate upriver. Only when they learned of its significant role in rearing habitat formation did biologists stop the practice. Had they rather chosen to assume that salmon are adapted to local habitat conditions, they could have avoided a significant proportion of the recent habitat losses by choosing management actions that preserved riparian forest processes and natural wood functions in channels, even without understanding the value of wood in aquatic ecosystems.

The second reason for identifying root causes is that traditional restoration actions (e.g., bank protection, spawning gravel placement) attempt to build habitats that do not move in space or time, whereas natural habitats are often created by movement of river channels, wood debris, and sediment. Many such restoration actions fail to restore habitats because they do not recognize the integrated nature of physical and ecological processes in watersheds (Frissell and Nawa 1992, Beechie et al. 1996). This lack of knowledge leads to two main types of failure: 1) site-prescribed engineering solutions can be overwhelmed by altered watershed processes that are far removed from degraded habitats (e.g., increased sediment supply from upslope sources can bury engineered structures and pools), or 2) such measures can prevent habitat formation that would otherwise naturally occur (e.g., bank protection prevents formation of new off-channel habitats). Avoiding these types of project failures requires that we focus on restoring ecosystem processes and functions that form and sustain salmonid habitats rather than on the habitats themselves.

Many organizations have recently adopted approaches to salmon habitat restoration that have a watershed or process-based approach (e.g., Moore 1997, SWC 1998, OWEB 1999a, JNRC 2001), which should help avoid some of the mistakes just described. However, many local groups continue to identify restoration projects in an opportunistic fashion, without assembling a broader understanding of habitat degradation and decline of listed species. Without this larger context, proposed projects are often disconnected from each other and fail to address the most important habitat losses. Continued development of holistic assessment approaches at the watershed level (e.g., SWC 1998, OWEB 1999a) should help resource managers more effectively utilize funding and resources allocated for salmon recovery.

Practical Considerations

Systematic watershed assessments can address several parts of a salmon recovery plan. Three types of watershed assessments address tasks that are listed in the TRT Guidance Document:

1. Correlation analyses help set population recovery goals (Phase I planning) and identify fish and habitat relationships (Phase II planning).
2. Assessments of current and historical habitat abundance and quality help identify recovery goals (Phase I planning) or factors causing decline and limiting factors (Phase II planning).

3. Assessments of altered habitat-forming processes help identify causes of habitat loss or degradation and actions for ecosystem and habitat recovery (Phase II planning).

In combination, these assessments provide a broad understanding of actions that are likely to improve population performance of listed salmon and form the basis of both regional and site-specific plans for ecosystem restoration. Beyond the TRT guidance tasks, systematic watershed assessments provide agencies a watershed-level understanding of habitat restoration needs, which they can use for evaluating habitat conservation plans, programmatic actions, and proposed habitat restoration projects.

These assessments can also help agencies address the Clean Water Act (CWA 1972) by identifying causes of various water quality problems, especially those associated with non-point pollution sources. The assessments are consistent with more holistic management approaches such as watershed management (e.g., Swanson 1981), ecosystem management (e.g., Johnson et al. 1985), and managing for biodiversity or biological integrity (e.g., McNeely et al. 1990, Karr 1991), and can simultaneously help accomplish the habitat-related purposes of the ESA and the CWA. The stated purposes of the congressional acts are to “provide a means whereby the ecosystems upon which endangered species and threatened species depend may be conserved” (ESA 1973), and “restore and maintain the chemical, physical, and biological integrity of the nation’s waters” (CWA 1972). The common thread is that management of landscapes and ecosystems is a single approach that will produce sustainable clean water and support salmon recovery.

Several watershed assessment approaches recently adopted by a variety of salmon recovery groups in the Pacific Northwest (e.g., FEMAT 1993, WDNR 1995, SWC 1998, OWEB 1999a, JNRC 2001) focus on restoring ecosystems and watershed processes, and should help address the parallel goals of the ESA and CWA more efficiently. These watershed assessment processes support an ecosystem approach or at least include certain process-based components of an ecosystem approach. While some of these assessments were not specifically designed to help develop Pacific salmon recovery plans, they provide data that are relevant to understanding disruptions to watershed or ecosystem processes. To the extent that these assessments answer specific questions relevant to habitat recovery planning, their results can be used within the context of the approach described in this report.

Key Assessments for Habitat Recovery Planning

Developing the habitat elements of a salmon recovery plan requires understanding how land uses have altered landscape processes that form and sustain salmon habitats and how those habitat changes might have affected salmon populations. We describe two groups of questions that must be answered to develop a habitat recovery plan (Table 1). The set of important questions for Phase I recovery planning concentrates on how habitats have changed since presettlement times and how those habitat changes have affected salmon and other biota. These questions motivate historical reconstructions of habitat types and abundance as well as assessments of relationships between habitat and salmon population characteristics. The set of important questions for Phase II recovery planning focuses on identifying disruptions to ecosystem function and the types of habitat restoration necessary for ecosystem recovery. These

Table 1. Primary questions to answer in developing a habitat recovery plan.

Question	Analysis area	Data type
<i>Phase I questions: Assessing changes in habitat availability and potential impacts on population characteristics</i>		
How might habitat changes have altered the abundance of individual populations?	ESU or watershed	ESU: mainly remote sensing Watershed: mainly field
How might habitat changes have altered the population growth rate of individual populations?	ESU or watershed	ESU: mainly remote sensing Watershed: mainly field
How might habitat changes have altered the diversity of life history patterns?	ESU or watershed	ESU: mainly remote sensing Watershed: mainly field
How might habitat changes have altered the spatial structure of populations?	ESU or watershed	ESU: mainly remote sensing Watershed: mainly field
<i>Phase II questions: Assessing disruptions to ecosystem functions and biological integrity</i>		
Where has biological integrity been degraded?	Watershed	Field
Where have watershed processes and ecosystem functions been impaired?	Watershed	Field/remote sensing

questions also motivate assessments that identify where the biological integrity of ecosystems has been degraded and where specific ecosystem processes or functions are disrupted.

For organizational purposes, it is useful to diagram the relationships among habitat assessments that can be used in recovery planning (Figure 1). The Phase I assessments (those regarding changes in habitat and salmon populations) fall into two groups: 1) assessments that quantify habitat change and then use habitat-based models to estimate changes in fish populations (e.g., limiting factors analysis, life cycle models, and the ecosystem diagnosis and treatment or EDT model), and 2) correlation analyses that relate landscape and land use characteristics to fish population performance without directly quantifying changes to habitat (e.g., the Salmon Watershed Analysis Model or SWAM). Note that neither of these assessments directly identifies causes of habitat degradation or specific restoration actions. However, these assessments have three important uses in setting recovery goals for the ESU and each population within it (i.e., Phase I recovery planning). First, they provide habitat-based estimates of potential population size for comparison to estimates from population viability analyses (see McElhany et al. 2000 for background on use of population viability analyses in describing VSPs). Second, they provide insights into potential changes in life history diversity by identifying losses of important habitat types. And third, the ESU-wide correlation analyses can help identify which populations are most constrained by habitat loss and therefore may be most difficult to recover.

The Phase II assessments (those regarding ecosystem functions and biological integrity) can be separated into two components: 1) screening assessments to identify areas where ecosystem processes and functions are most impaired, and 2) specific field inventories to diagnose causes of ecosystem impairment (see Appendix C, page 157, for examples). Assessments that correlate landscape and land use characteristics with population attributes (e.g., SWAM) can indicate which habitat changes are most likely responsible for declines in salmon populations, and therefore which broad categories of restoration actions are most likely to result in increased salmon populations. Direct assessments of ecosystem processes that form salmon habitats (e.g., barrier inventories, riparian condition inventories) identify causes of degradation as well as restoration actions that are required to recover ecosystem functions and biological integrity.

It is important to note that, while there are relatively few differences in Phase I assessment procedures across the Pacific Northwest, Phase II assessment procedures can vary substantially. Pacific Northwest environments have been classified as a nested set of ecoregions (CEC 1997) (Figure 2). At the coarsest levels (Levels I and II), these ecoregions denote three main areas within which climate, lithology, topography, and ecosystems are generally similar: marine northwestern Coastal Forests, drier northwestern Forested Mountains, and semiarid to arid Western Deserts (CEC 1997, USEPA 2000). Basic differences in watershed processes among ecoregions are shown in Table 2 (see also OWEB 1999a). In general, the same categories of assessments must be conducted regardless of ecoregion (e.g., sediment supply, riparian functions, isolated habitats), but the specific processes or mechanisms addressed may vary from one ecoregion to another. For example, sediment supply to the stream network should be evaluated in any watershed, but certain processes of sediment supply may be emphasized depending on location. Sediment supply is dominated by landsliding in most watersheds of the coastal range and Cascade Mountains (e.g., Sidle et al. 1985), so understanding land use effects on landslide rates and sediment volumes is critical to identifying restoration actions such as road

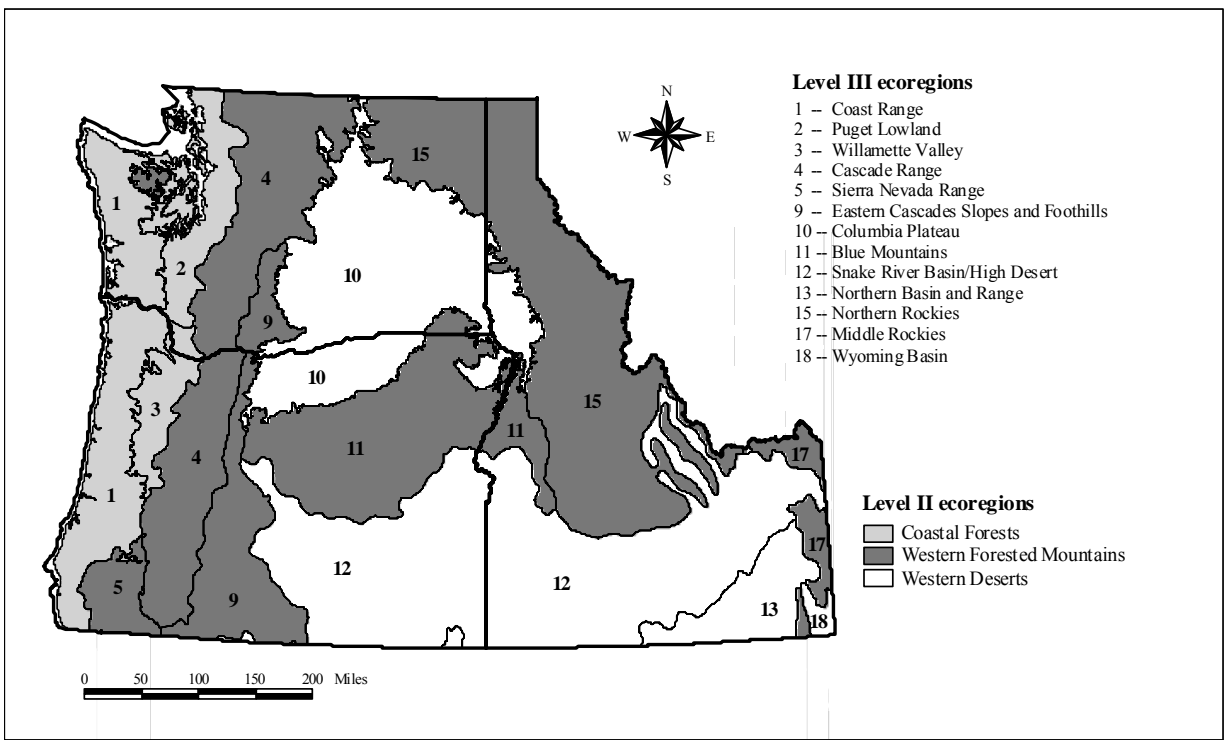
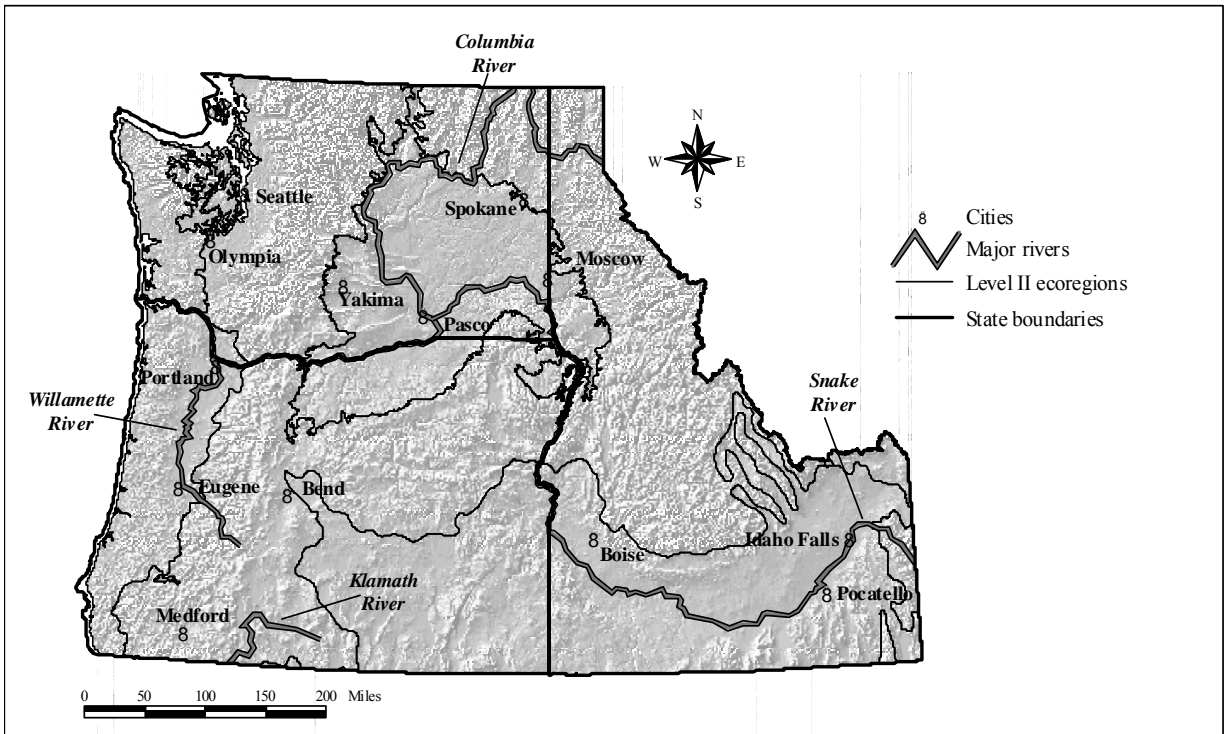


Figure 2. Locations of major rivers and cities of the Pacific Northwest (upper panel) and Level II and Level III ecoregions (lower panel).

Table 2. Regional differences in dominant ecosystem processes or functions in the Pacific Northwest. This table is intended to illustrate that different processes and assessments should be emphasized in different ecoregions. Important ecosystem processes vary within ecoregions and watershed-level assessments should target those processes that are locally important within each watershed. (Note that the Columbia River estuary is in the Coastal Forests ecoregion, but also affects Columbia River stocks in the Western Deserts and Western Forested Mountains ecoregions.)

Watershed process or function	Level II ecoregion		
	Western Deserts	Western Forested Mountains	Coastal Forests
Sediment	Gullyng and surface erosion (especially in agricultural areas)	Mass wasting and gullyng	Mass wasting (surface erosion in agricultural lowlands)
Flood hydrology	Snowmelt dominated flood regime	Snowmelt dominated flood regime	Rain and rain-on-snow flood regime
Low flow hydrology	Diversions and dams common	Diversions and dams common	Diversions and dams less common
Riparian functions	Grasses and some forest; sediment retention a dominant function	Sparse forests, shade a dominant function	Dense forests, wood recruitment a dominant function
Habitat connectivity	Culverts, dams, and dikes common; incision and floodplain abandonment common	Culverts, dams, and dikes common	Culverts, dams, and dikes common
Estuary function	Not applicable (Columbia River estuary should be assessed in relation to freshwater habitats)	Not applicable (Columbia River estuary should be assessed in relation to freshwater habitats)	Severe impacts in agricultural and urban areas
Biological integrity	Especially important in urban and agricultural areas	Especially important in urban and agricultural areas	Especially important in urban and agricultural areas

decommissioning or reconstruction. By contrast, sediment supply in dry rangelands of the Columbia Plateau is more a function of surface erosion and gullying (e.g., Kaiser 1967, Peacock 1994), especially where soils are bare for some portion of the year due to agricultural practices. In these areas, assessing sediment impacts will focus more on changes in surface erosion rates and volumes in order to identify where modification of agricultural practices may reduce sediment supplies. These and other analyses of watershed processes are described in more detail in the Analyses for Phase II Recovery Planning: Identifying Ecosystem Restoration Actions section of this document, page 40, and the Prioritizing Potential Restoration Actions within Watersheds section, page 60.

Sequencing the Assessments

The typical sequence of assessments (illustrated in Figure 3) is:

1. Phase I, identify recovery goals for populations and ESUs, including goals for abundance, population growth rate (and related parameters), spatial structure, and diversity.
2. Phase II, evaluate ecosystem processes and functions to identify the suite of possible habitat restoration actions.
3. Integrate Phase I and Phase II information into a recovery plan.

Phase I assessments indicate where the greatest habitat losses have been, what types of habitat losses have occurred, and which habitats are likely having the greatest affect on individual salmon populations. They are not ecosystem assessments and focus on individual species in order to establish the four categories of recovery goals. Phase I assessments are typically conducted at two levels of resolution: 1) ESU-wide correlations among landscape attributes and fish population characteristics (e.g., abundance, life history patterns) using low-resolution geospatial data, and 2) more detailed watershed-level assessments of habitat availability for different life history stages. The former provides information that is useful in setting goals for recovery of the entire ESU, whereas the latter is focused on setting more specific recovery goals for individual populations. Typically an ESU-wide assessment will be completed first because it is conducted with existing data. These assessments can indicate where the most important habitat losses have been and provide some insight into which habitats may be limiting individual populations. With reference to Figure 1, these assessments will relate landscape attributes and land use practices directly to fish abundance or survival, and ignore causal mechanisms that link landscape processes and land uses to habitat change or habitat change to fish population response. These ESU-wide assessments can indicate general patterns of population declines resulting from different land uses, but the data are generally too coarse to allow detailed analyses of habitat change and its effects on fish populations (e.g., Lunetta et al. 1997, Pess et al. 1999a, Feist et al. 2003). More detailed assessments for watersheds and individual populations involve collection of information on current and historical habitat abundance and quality, and therefore take more time to complete. These assessments can provide more detail on the types of habitat losses that have occurred and which life stages might be most impacted for individual species or populations.

Phase II assessments identify where ecosystem processes or functions have been impaired and therefore where ecosystem rehabilitation or restoration actions are needed. They

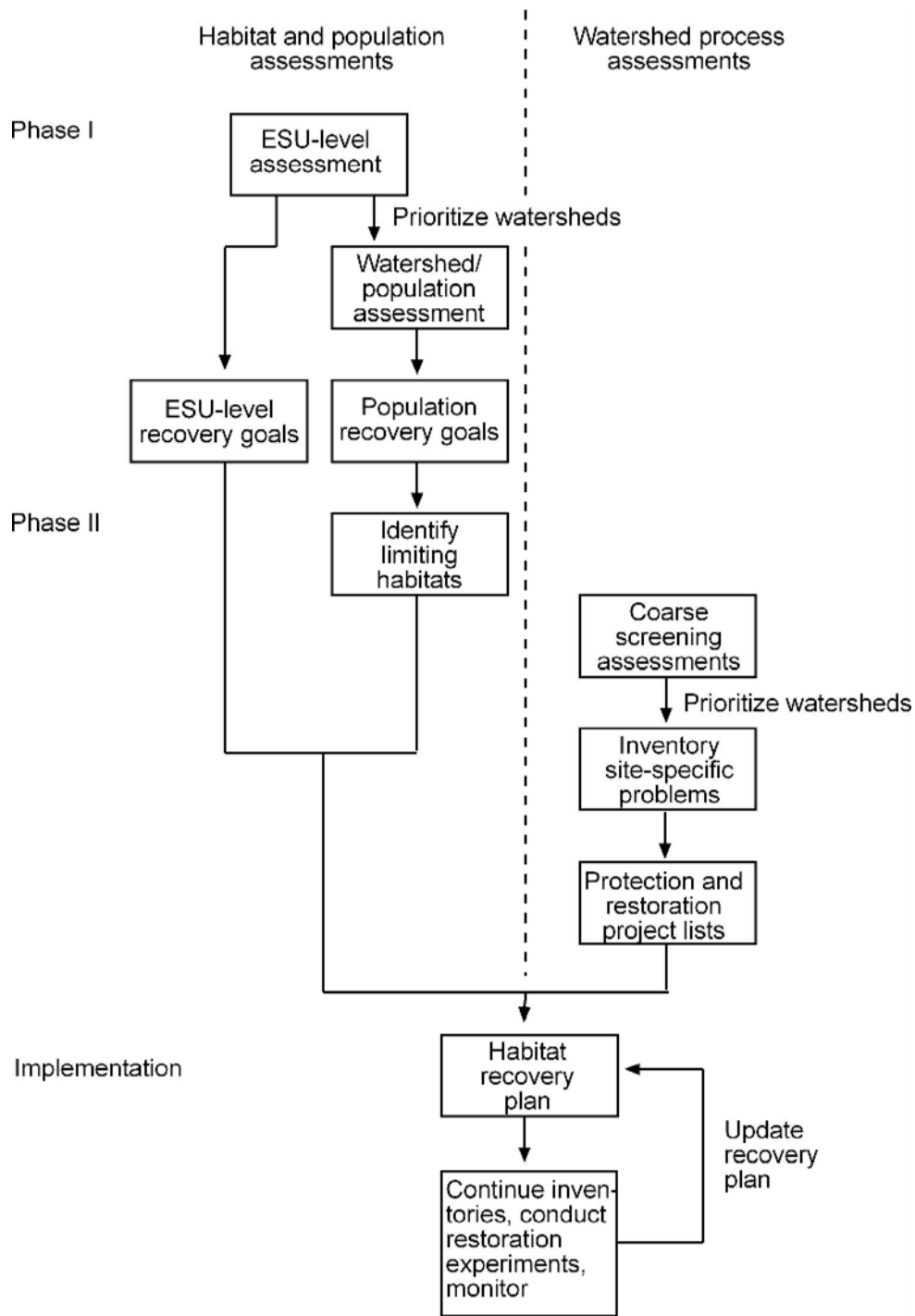


Figure 3. Generalized sequence for Phase I and Phase II assessments, integration of Phase I and Phase II information into the recovery plan, and plan updates based on continued inventories and monitoring.

do not focus on individual listed species, but focus on ecosystem attributes and processes that support multiple salmon species. ESU-wide correlation analyses of impaired processes and salmon populations are typically part of the Phase I coarse-resolution assessment described above, and may require little additional work beyond reinterpretation of outputs from the Phase I analysis. However, some additional analysis of landscape or land use variables may be required to provide results that more specifically address changes in ecosystem processes. Watershed-level assessments in Phase II are more detailed and time consuming, and resource managers should expect such that such inventories and assessments will take several years to complete. These watershed-level assessments have two essential components: 1) a screening component to identify where in the watershed each ecosystem process or function is most impaired, and 2) a field inventory component to identify specific actions that are needed to restore those processes. The screening assessments are primarily intended to help focus field inventories where they are most needed, but can also provide a general sense of where different types of restoration actions are likely to be focused and how much those actions might cost.

In recovery domains where a single species is listed, the restoration actions identified in Phase II assessments can later be prioritized using the life cycle information from Phase I. In such cases, life cycle models indicate which habitats are likely most limiting, and therefore where and what types of restoration actions are likely to improve population performance. This approach alters the sequence of ecosystem restoration actions, but all actions remain focused on restoring landscape processes and functions that sustain salmon habitats over the long term (e.g., Beechie and Bolton 1999). The main risk inherent in this approach is that life cycle models provide only a “best guess” about which actions will most improve a population. Errors in the model may lead managers to focus too heavily on restoration actions that are not in fact limiting recovery of a population (see the Managing Uncertainty in Habitat Recovery Planning section, page 74). Therefore, it is important to emphasize a number of ecosystem restoration actions simultaneously, even where a single species is the focus of a recovery strategy. Where it is not appropriate to focus on any single species for recovery planning, other schemes for prioritizing actions should be employed (see the Prioritizing Potential Restoration Actions within Watersheds section, page 60).

Implementing Habitat Actions and Updating the Recovery Plan

The assessments described in this document are part of a larger sequence of steps needed to enact long-term strategies for salmon recovery. For most groups, completing all Phase II inventories will take many years and reliably predicting most population responses to habitat actions is not currently possible. Thus it is important to have a strategy for implementing interim actions, learning how populations respond to those actions, and updating the recovery plan as new information becomes available. Recognizing the long-term nature of inventories, restoration experiments, and salmon recovery allows the tasks to be logically sequenced for implementation. In essence the steps are:

1. Identify restoration goals and objectives.
2. List assessments needed to identify appropriate habitat restoration actions (i.e., the assessments needed to complete Phase I and Phase II planning).
3. Identify and compile existing assessments to identify initial restoration actions.

4. Implement preliminary restoration actions as experiments, conduct remaining assessments and inventories to fill in the data gaps, and revise the plan and actions as new information becomes available.

Step 1 describes the overall restoration strategy and types of information required to implement it. To some extent, the goals of restoration strategies for salmon recovery are constrained by the purposes of the ESA (i.e., conserve the ecosystems upon which listed species depend) and the CWA (i.e., protect the biological integrity of aquatic systems). Consistency with the purposes of these two acts will simplify the assessments needed to identify habitat protection and restoration actions and help avoid conflicting restoration priorities that arise from differing habitat requirements among species. Examples of restoration goals are to “protect and restore the processes that form and sustain habitats to which salmonid stocks are adapted” (SWC 1998), “restoration and protection of habitat conditions and processes upon which the fish depend” (LCFRB 2001), or “to have a diversity of habitats and natural processes necessary to sustain healthy populations of native species” (WRS 2001). Along with these habitat restoration goals, strategies should also have clearly stated near-term and long-term objectives. Near-term objectives should incorporate those actions that we already know are consistent with conservation of ecosystems that support salmon (e.g., removal of migration blockages, habitat protection through easements or acquisitions). Longer term objectives should include management experiments to clarify which actions are most beneficial to aquatic ecosystems and listed species, as well as implementing larger restoration projects that require changes in infrastructure or land uses (e.g., modifying levee systems to reopen access to estuary habitats). In essence, strategies should describe how different actions will be identified and prioritized, how long-term inventories can be incorporated into the recovery plan, and how monitoring information will feed back into updates of the recovery plan.

Step 2 should explicitly list the types of assessments required to implement a recovery strategy. The complete recovery plan will include assessments for all of the Hs (habitat, hydropower, hatcheries, and harvest). This document provides guidance on assessments that will be useful in Phase I and Phase II planning for habitat actions (only one of the Hs).

Step 3 examines the list of assessments needed to identify information that already exists as well as those assessments that remain to be conducted. At this stage information can be compiled to identify interim habitat restoration actions. Some examples of this stage of assessment can be found in the Oregon Watershed Enhancement Board assessments (online at <http://www.oweb.state.or.us/publications/index.shtml>) or the Washington Conservation Commission habitat limiting factors reports (online at <http://salmon.scc.wa.gov/reports/index.html>).

Step 4 includes two main components: 1) completing inventories that identify specific habitat restoration actions (e.g., barrier inventories or riparian condition inventories), and 2) conducting restoration experiments to improve our understanding of which types of actions will most benefit salmon in each recovery domain or ESU. Inventory data can be directly incorporated into a recovery plan to expand the list of actions necessary to restore ecosystem processes and functions that support salmon recovery. Monitoring of management experiments improves our ability to predict the outcome of restoration actions and can be used to adjust priorities in the recovery plan.

ANALYSES FOR PHASE I RECOVERY PLANNING: SETTING RECOVERY GOALS

Recovery goals for salmon ESUs and populations might include numerical fish population targets, numerical population trend targets, qualitative or quantitative targets for spatial distribution of populations and population diversity, habitat quality standards, or management outcome targets (McElhany et al. 2000). In this section, we consider how habitat analyses at the ESU and watershed scales can inform the development of viability goals for salmon populations and ESUs. These analyses also inform Phase II recovery planning by identifying fish-habitat relationships and factors causing decline. ESU-level analyses are used to examine the quantity and quality of habitat across numerous populations within ESUs, whereas watershed-level analyses focus on questions specific to individual populations.

As ESU and population viability goals are set, we must simultaneously evaluate whether current, historical, or “restored” habitat might be sufficient to support populations of the desired size, as well as whether the type and distribution of available habitats can support the desired spatial structure and diversity of salmon populations. Where current habitats cannot support the desired populations, we must identify and prioritize ecosystem restoration actions that will help achieve the recovery goals (see the Analyses for Phase II Recovery Planning section, page 40, and the Prioritizing Potential Restoration Actions within Watersheds section, page 60). For any of these analyses, it is critical to select habitat measures that can be linked to population performance and are sensitive to land use changes or restoration actions. Habitat measures (physical, chemical, or biological) that meet these criteria facilitate an understanding of how land uses or restoration actions change habitats and how those habitat changes in turn create population responses in salmon (see Figure 1). This is true whether the analysis is conducted with coarse-resolution or fine-resolution data available over entire ESUs or only in certain watersheds.

Because habitats and biota are hierarchically structured, it is also important to view habitat data in the context of a hierarchical classification system such as illustrated in Table 3 (see also Appendix A, page 127, for further discussion of scale issues in Phase I recovery planning). With such a classification of habitats, results of analyses across entire ESUs can be linked to fine-resolution analyses within individual watersheds. Moreover, this hierarchical structure allows one to construct simple predictive models for estimating abundance and distribution of fine-resolution habitats based on available coarse-resolution data (e.g., Lunetta et al. 1997).

ESU-Level Analyses for Abundance and Survival Goals

ESU-level analyses differ from watershed-level analyses in that they ask questions and analyze data that span the area of entire ESUs. The area of existing ESUs ranges from 7,200 to 38,600 km². The number of independent salmon populations within each ESU varies from as few as one to more than 30 (see Northwest Salmon Recovery Planning, online at <http://www.nwfsc.noaa.gov/trt/>). Because these analyses encompass large geographic areas and often

Table 3. Habitat types used for the two types of watershed assessments described in this report. Coarser scale habitat types are mapped from topographic maps, aerial photography, and satellite imagery. Finer scale habitat types are mapped using a combination of aerial photography (for larger units) and field measurements. (Adapted from Beechie et al. 2003.)

Coarser scale	Habitat type		Finer scale
Large main stem (>50m bankfull width) by channel type based on gradient and confinement	<ul style="list-style-type: none"> • Mid-channel • Edge 	<ul style="list-style-type: none"> • Mid-channel pool • Mid-channel glide • Mid-channel riffle <ul style="list-style-type: none"> Boulder/cobble Cobble/gravel • Bar edge • Bank edge <ul style="list-style-type: none"> Natural Hardened • Backwater (alcove) 	
Small main stem (10–50 m bankfull width) and tributaries (<10 m bankfull width) by channel type based on gradient and confinement	<ul style="list-style-type: none"> • Pool • Riffle 	<ul style="list-style-type: none"> • Pool <ul style="list-style-type: none"> Scour Plunge Trench Backwater • Glide • Run • Rapid • Riffle 	
Off-channel habitat within large main-channel floodplains	<ul style="list-style-type: none"> • Channel-like 		
Impoundment	<ul style="list-style-type: none"> • Pond-like 	<ul style="list-style-type: none"> • Pond < 500 m² • Pond > 500 m² and < 5 ha • Lake > 5 ha 	
Palustrine wetland	<ul style="list-style-type: none"> • Forested • Scrub/shrub 	Open water area by season	
Riverine tidal wetland	<ul style="list-style-type: none"> • Forested • Scrub/shrub 	Open water area by season and tidal stage	
Tidal delta wetland	<ul style="list-style-type: none"> • Scrub/shrub • Emergent 	Open water area by season and tidal stage	
Tidal delta channel	<ul style="list-style-type: none"> • Main stem • Blind • Distributary 		

more than one salmon population, the goals and data needs are inherently different from efforts directed at watershed, stream, or reach scales.

The goal of an ESU-level analysis is to identify how habitat changes might have altered the abundance, population growth rate, spatial structure, and diversity of individual populations and ESUs. The nature of this question combined with the geographic scale of analyses means that ESU analyses will typically correlate landscape characteristics (e.g., land use and land form) to characteristics of habitat and fish (Figure 1) in order to describe large-scale patterns of habitat change (Table 4). In general, fine-resolution data (e.g., habitat typing, barrier inventories) used in watershed-level assessments are not comprehensively available across the large geographic areas these analyses must cover. Therefore, ESU-scale analyses use currently available data (usually at coarse resolution) to rapidly address questions that span large geographic areas (see Table 4 and Table 5).

Here we describe two approaches to assessing how land uses might be related to salmon abundance or survival rates. The first uses simple correlations among landscape/land use variables and salmon abundance to evaluate the relative quality of different stream reaches within a large study area (e.g., Pess et al. 2002, Feist et al. 2003). The second uses coarse-resolution data to estimate current and historical habitat abundance within an ESU. Analyses for addressing changes in density-independent survival rates (either for single life stages or for returning adults per spawner) will be similar to those for abundance, except that survival measures will be used as the response variable rather than abundance.

Correlation Analyses

Correlation studies link patterns of land cover and land use to fish abundance, fish survival, or instream habitat quality and help identify ESU-level relationships between salmonid populations and the physical, chemical, and biological components of their habitat. Correlation analyses can utilize a broad range of metrics for population performance (e.g., genetic diversity, juvenile abundance, adult abundance, population growth rate, life-stage specific survivals), landscape characteristics (e.g., road density, geology, land use), or habitat attributes (e.g., percent pools, water temperature, number or concentration of contaminants). These studies can be used to make predictions about where habitat conditions might limit or enhance salmon populations, generate initial prioritizations of habitat action types and locations, generate hypotheses for further testing, and suggest important factors to control when setting up small-scale experiments, monitoring projects, or large management experiments (Figure 4). However, they cannot identify cause and effect relationships because of correlations among habitat descriptors, correlations among landforms and land uses, and the potential for unmeasured variables to explain existing patterns.

One example of this type of analysis is the Salmonid Watershed Analysis Model (SWAM), a series of spatial and statistical analyses that relate salmonid population metrics in a basin to landscape and land use characteristics derived from existing geospatial data layers. SWAM has been used in the Salmon River basin in Idaho (Feist et al. 2003), the Snohomish River basin in Washington (Pess et al. 2002), and the Willamette River basin in Oregon (Steel et al. in prep.). In these basins, SWAM linked indices of adult fish abundance (redd counts or adult

Table 4. List of analyses that address questions pertaining to the four categories of recovery goals for salmon.

Recovery goal	Example of analysis	Reference
Population abundance and growth rate	Quantification of current vs. historical habitats	McIntosh et al. 2000 Thompson and Lee 2000 Thurow et al. 2000
	Effects of irrigation diversions in the Salmon River basin	McClure et al. in press
	Land use impacts on salmon	Bradford and Irvine 2000 Thompson and Lee 2000 Paulsen and Fisher 2001
Spatial structure and diversity	Quantification of current vs. historical habitats	Thurow et al. 2000
	Regional patterns in fish diversity	Frissell 1993b Waples et al. 2001
	Associations between fish assemblages and habitat	Waite and Carpenter 2000
	Presence/absence mapping	Quigley and Arbelbide 1997

Table 5. General description of potential analytical approaches for rapidly estimating current and historical habitat abundance at the ESU level. Note that methods are not readily available for estimating historical conditions for most habitat types. Thus ESU-scale analyses most commonly focus on direct loss of important habitat types.

Type of habitat change	Possible analysis method
Tributary and mainstem blockages	Utilize digital information on known barriers and historical ranges (e.g., Quigley and Arbelbide 1997). May also model historical ranges based on channel slopes and stream size.
Channel type (e.g., based on Montgomery and Buffington 1997)	Estimate from vegetation information, hydrography, and digital elevation models (Lunetta et al. 1997).
Off-channel, wetland, or beaver pond areas	No remote sensing method available (historical data lacking).
Lakes	No remote sensing method available (historical data lacking).
Estuaries	No remote sensing method available (historical data lacking). Use existing information where possible (e.g., Bortleson et al. 1980).

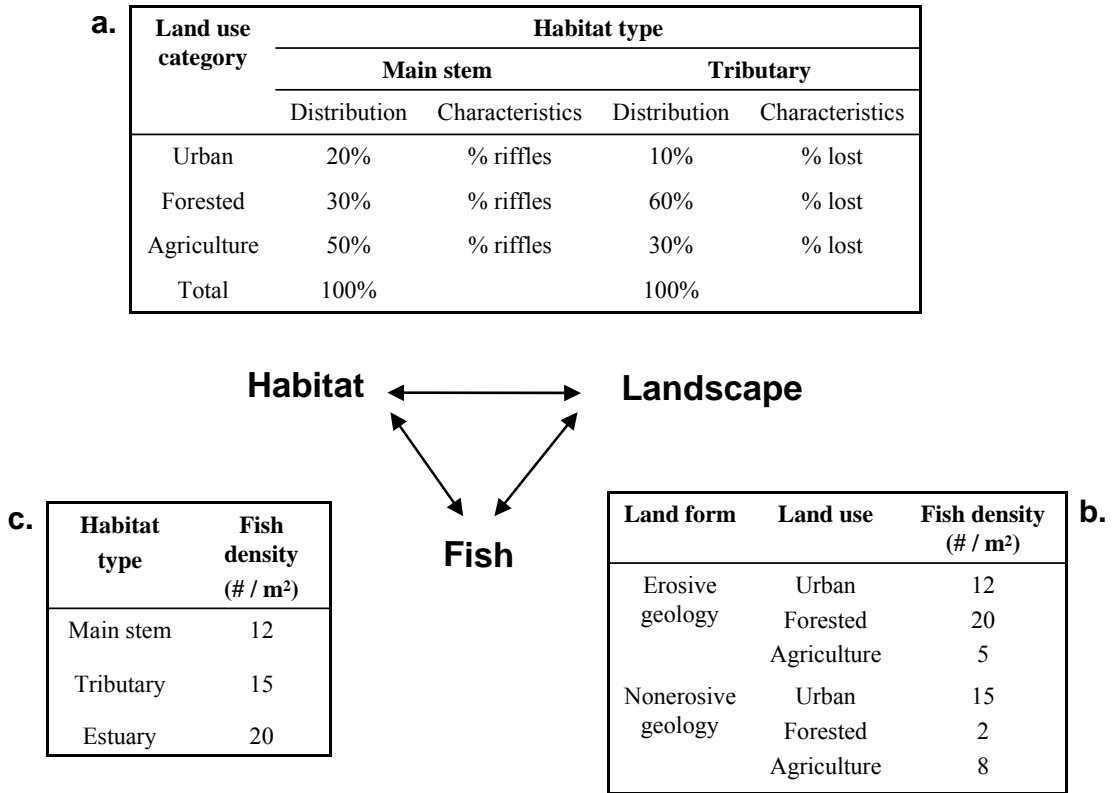


Figure 4. Illustration of the kinds of relationships between habitat, landscape, and fish that broad-scale analyses can examine: Table A illustrates how habitat quantity and characteristics are distributed across different land uses, Table B illustrates how fish density in three land use categories differs in erosive vs. nonerosive geologic settings, and Table C describes how fish density differs across habitat types. The numbers in the tables are fictitious and for illustrative purposes only.

fish counts at index sites) to multiple descriptors of landscape conditions across the entire watershed draining to the index reach, as well as to conditions in the riparian area directly associated with the index reach. Alternate population metrics such as juvenile abundances or life-stage specific survivals are possible wherever adequate data exists.

The spatial and statistical analyses involved in the SWAM approach are comprised of five steps. First, conceptual, mechanistic relationships between landscape features and population abundance during all freshwater life stages are identified from the literature and by local habitat biologists. These conceptual relationships define the habitat data layers to use as potential predictor variables. Second, spatial heterogeneity in the salmonid population data is examined to determine if certain areas in the basin consistently exhibit better population performance than other areas. Third, landscape data layers are overlaid with the georeferenced fish abundance data (e.g., redds counts). Fourth, a statistical model is developed to describe annually consistent relationships between landscape characteristics and fish abundance. And finally, the statistical model is used to extrapolate relationships to the entire basin of interest or specific locations within the basin (Figure 4). Many combinations of population and landscape metrics can be used in this type of analysis and the best choice for a particular basin will be driven by available data.

SWAM or SWAM-like analyses provide broad-brush estimates of current or potential fish occupancy within a basin and factors affecting abundance. In the Willamette River basin, SWAM is used to estimate potential fish occupancy behind barriers, then prioritize barrier removal projects. Correlative models relating fish population performance to habitat conditions may also help identify the best remaining reaches or subwatersheds in a particular basin or identify areas that were historically productive. Ecological insights developed from these analyses may suggest likely habitat factors limiting population performance. Experience from these studies can be used to identify habitat characteristics to control when setting up experiments or monitoring and evaluation programs. Predictions of areas likely to support strong populations can suggest areas where detailed watershed assessments and habitat inventories should be conducted (see the Analyses for Phase II Recovery Planning section, page 40).

Current and Historical Potential Habitat

A second approach for evaluating the ability of multiple watersheds to support viable salmon populations is to examine the distribution and quantity of current and historical habitat across multiple watersheds and populations (e.g., comparing 20 populations). These analyses use limited habitat survey or historical distribution information supplemented by ancillary topographic and hydrologic data. In addition, these analyses rely heavily on geospatial data sets such as digital terrain models, Landsat imagery, and regional hydrography to predict physical stream features (e.g., Lunetta et al. 1997). The widespread availability of corresponding spatial datasets (remotely sensed imagery, Geographic Information System or GIS data, and spatially explicit modeling methods) permits the derivation of representative reach-level geomorphic and hydrologic information for multiple watersheds (Table 5). This information can be used in conjunction with field-based mapping data, such as of anthropogenic modifications (e.g., Bortleson et al. 1980), to refine estimates of currently and historically available habitat for

different species. Subsequently, methods to refine historical habitat estimates can be used to estimate possible levels of historical fish abundance across the watershed.

A specific example of this type of assessment is an inventory of currently and historically available stream reaches and the amount of habitat blocked by migration barriers such as dams, diversions, and culverts (e.g., Steel and Sheer in prep.). Where inventories of migration barriers are available, they can be used to address several questions for ESUs and their constituent populations:

1. How many kilometers of stream habitat are unavailable or unreachable to fish due to anthropogenic barriers?
2. What proportion of historical habitats is currently usable for juvenile and adult salmonids?
3. Is current habitat sufficient to support VSPs?

In Phase II recovery planning for identifying and prioritizing actions, these same analyses can provide additional information toward developing a list of actions (e.g., which barrier removals might provide the greatest habitat and population benefits).

The first step of the analysis includes stream network acquisition or generation and barrier identification. Modeled stream networks can be used to achieve the appropriate data resolution and multiple barrier data layers will likely need to be examined for accuracy and combined. By comparing historically available habitats to those currently available below migration barriers, these analyses describe the type and degree of habitat loss for each population. For example, mapping 2,600 barriers in the Willamette/Lower Columbia (WLC) ESU and the amount of stream blocked by each shows that certain populations have been more strongly influenced by manmade barriers than other populations (Figure 5).

The second step, using a classification of more detailed information about reach-level stream characteristics (e.g., stream gradient, drainage area, or channel width), assesses whether accessible or inaccessible stream habitats are or might be useful to fish. The classification scheme can be based on existing models, published literature, or interviews with local biologists, and reach attributes from field data, aerial photos, or models. In the WLC, stream reaches in specific gradient ranges were identified as possible or prime spawning and rearing habitat for winter steelhead (*Oncorhynchus mykiss*), summer steelhead, Chinook salmon (*O. tshawytscha*), and chum salmon (*O. keta*) based on a survey of local biologists, and these gradients were modeled for the WLC domain using a procedure Miller (2003) developed that employs a digital elevation model to generate stream reach information (e.g., Figure 6).

The third step is evaluating whether the amount of usable habitat is sufficient to support VSPs across the ESU. In the Puget Sound and WLC ESUs, demographic models were used to generate preliminary goals for individual populations (see Northwest Salmon Recovery Planning, online at <http://www.nwfsc.noaa.gov/trt/>). The amount of usable habitat calculated as described above was used to verify whether target numbers are realistic given the actual proportion of stream kilometers likely to be used by salmon, either currently or historically. Fish densities implied by a range of population abundance goals (goals divided by total number of prime or possible stream kilometers) can be estimated and evaluated (see Steel and Sheer in prep. for additional details). Because the inventory approach is based on multiple GIS data layers,

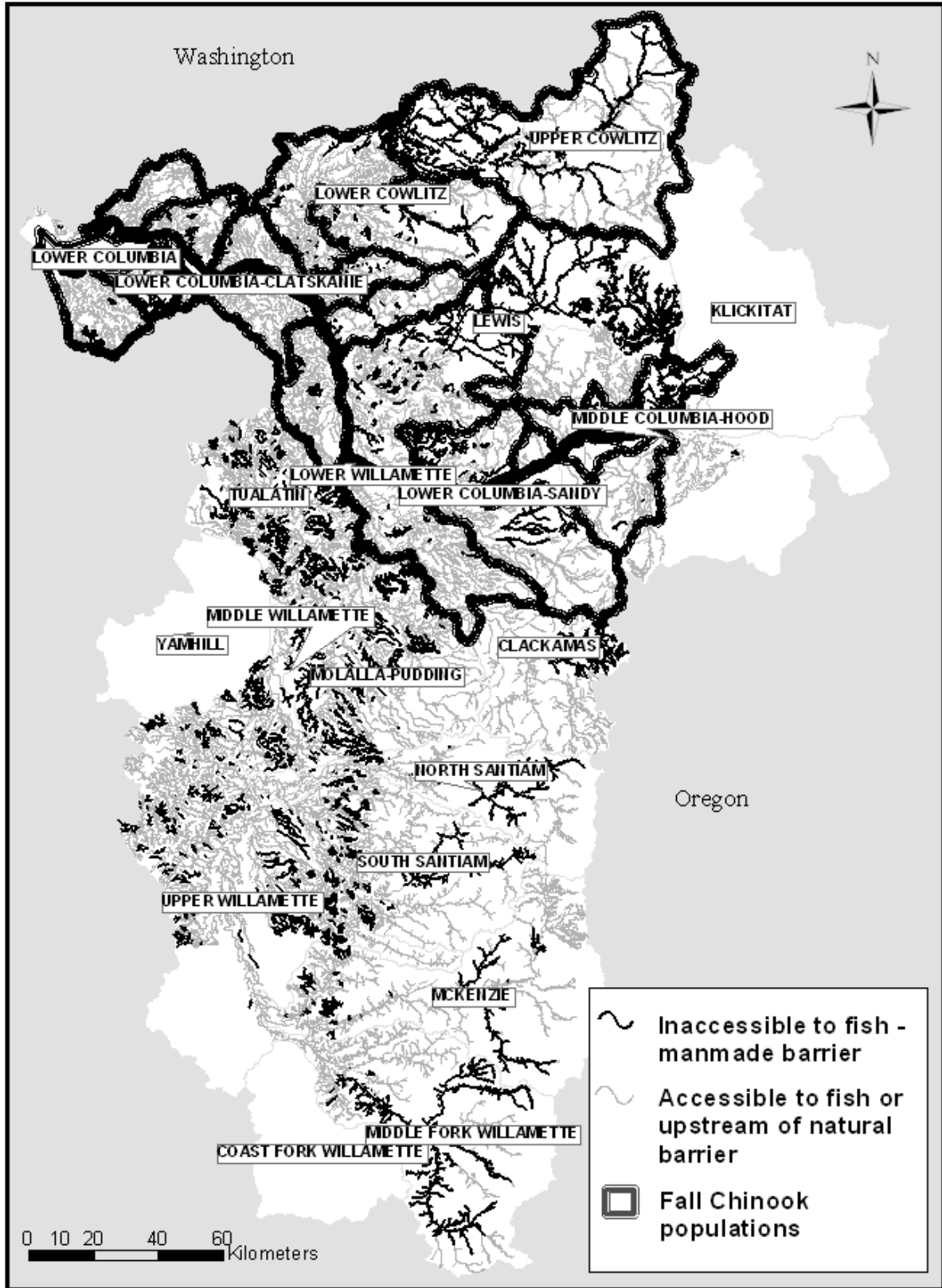


Figure 5. Stream accessibility for all streams considered in the WLC analysis. Labels indicate the 4th field hydrologic basin.

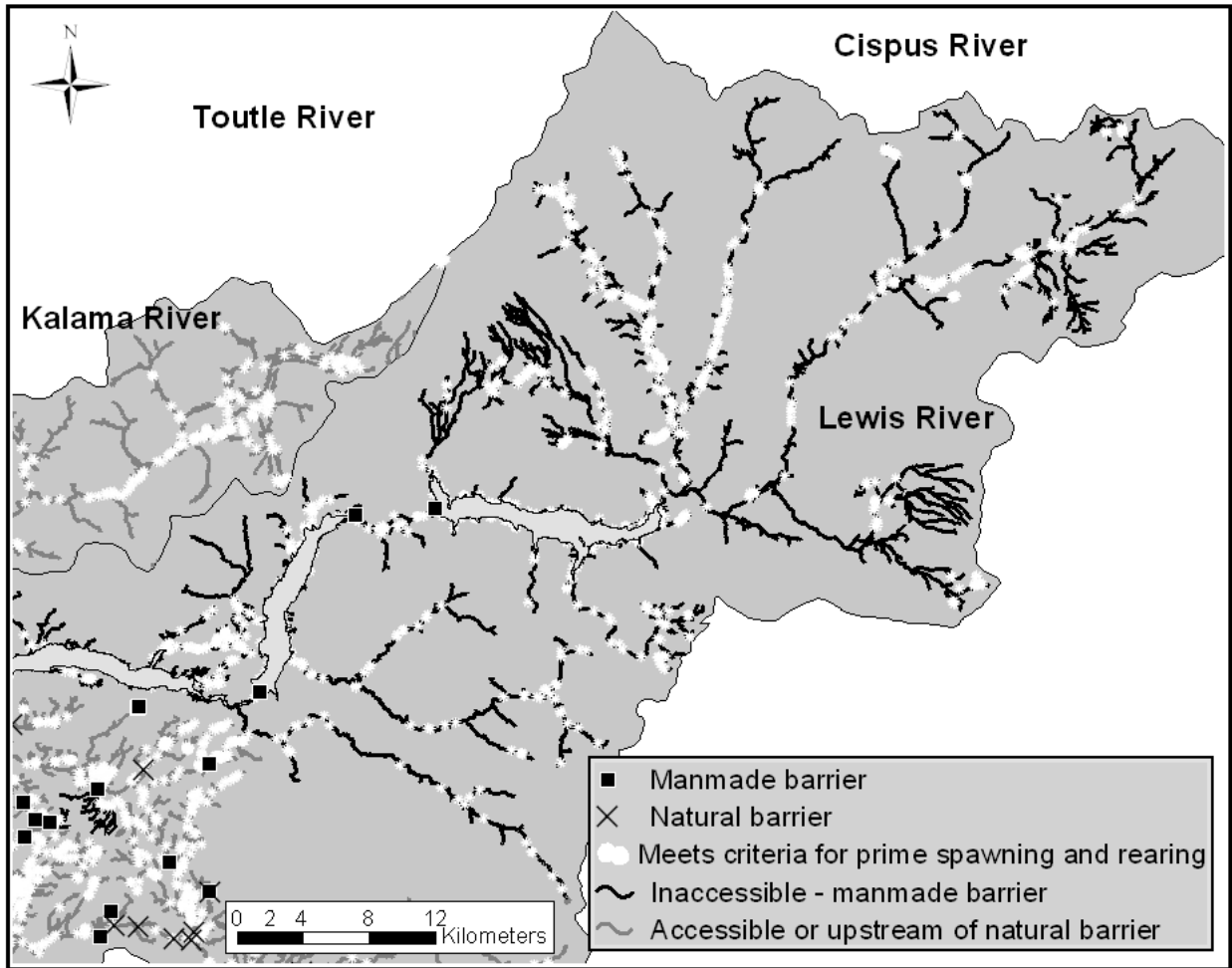


Figure 6. Example of the identification of potential spawning habitat that is isolated above dams and classification of prime habitat for Chinook rearing or spawning in the Lewis River based on gradient thresholds.

each with variable precision and accuracy, as well as an estimated classification system, the precision and accuracy of the resulting estimates should be assessed (e.g., by comparing predictions to field measures as in Lunetta et al. 1997). Continued work on this topic will make the inventory approach more useful for decision making.

Watershed-Level Analyses for Abundance, Survival, and Population Growth Rate Goals

For Phase I recovery planning, watershed-level analyses are designed primarily to assist in setting abundance goals for recovery, although they can also shed light on goals for density-independent survival rates, population growth rates, life history diversity, and spatial structure. These watershed-scale analyses provide greater detail on how habitat changes might have altered salmon populations than do ESU-level analyses. This additional detail is important in salmon recovery planning for several reasons. First, landscape, land use, and habitat differences among watersheds prevent generalizations about limiting factors, potential abundance, and habitat capacity. Second, populations are locally adapted to watershed-level conditions, so habitat needs of salmon populations vary among watersheds. Third, the types of habitat changes that cause changes in salmon fitness and survival differ among watersheds. Finally, watershed-level analyses answer questions that require fine-scale field data that is only available for particular watersheds.

In conducting these analyses, considering how different analysis approaches represent the salmon life cycle is important. In a generalized salmon life cycle model (Figure 7), the number of surviving fish at the beginning of each life stage is a function of capacity and density-independent survival in the previous stage. Both capacity and density-independent survival are affected by habitat quantity and quality, and the number of smolts per spawner represents the combined life stage transitions from spawning to saltwater entrance. Habitat analyses at the watershed-level are conducted using one of three life-stage specific approaches: 1) simplified limiting factor models, 2) complex expert system models such as the EDT model for evaluating limiting habitat conditions, and 3) dynamic life cycle models to estimate population responses over time. All approaches are based on the salmon life cycle, and all assess current and historical habitat conditions in a watershed to estimate how habitat changes may have altered salmon abundance or survival at different life stages. However, the approaches differ in two main respects.

First, each approach emphasizes different aspects of the life cycle and different parameters driving stage-to-stage survivorship. Limiting factors models such as the coho salmon (*O. kisutch*) limiting factors model (Reeves et al. 1989) focus on changes in capacity at each freshwater life stage and treat density-independent stage-to-stage survivals as constants. The EDT model allows both capacity and density-independent survival to change at each life stage, but does not estimate population response over time. Therefore, both of these approaches can help set abundance goals, but the EDT model can also help assess goals for life stage survivals or returning adults per spawner at low population sizes. The dynamic life cycle model allows both capacity and survival to vary at each life stage, and also explicitly evaluates population growth or

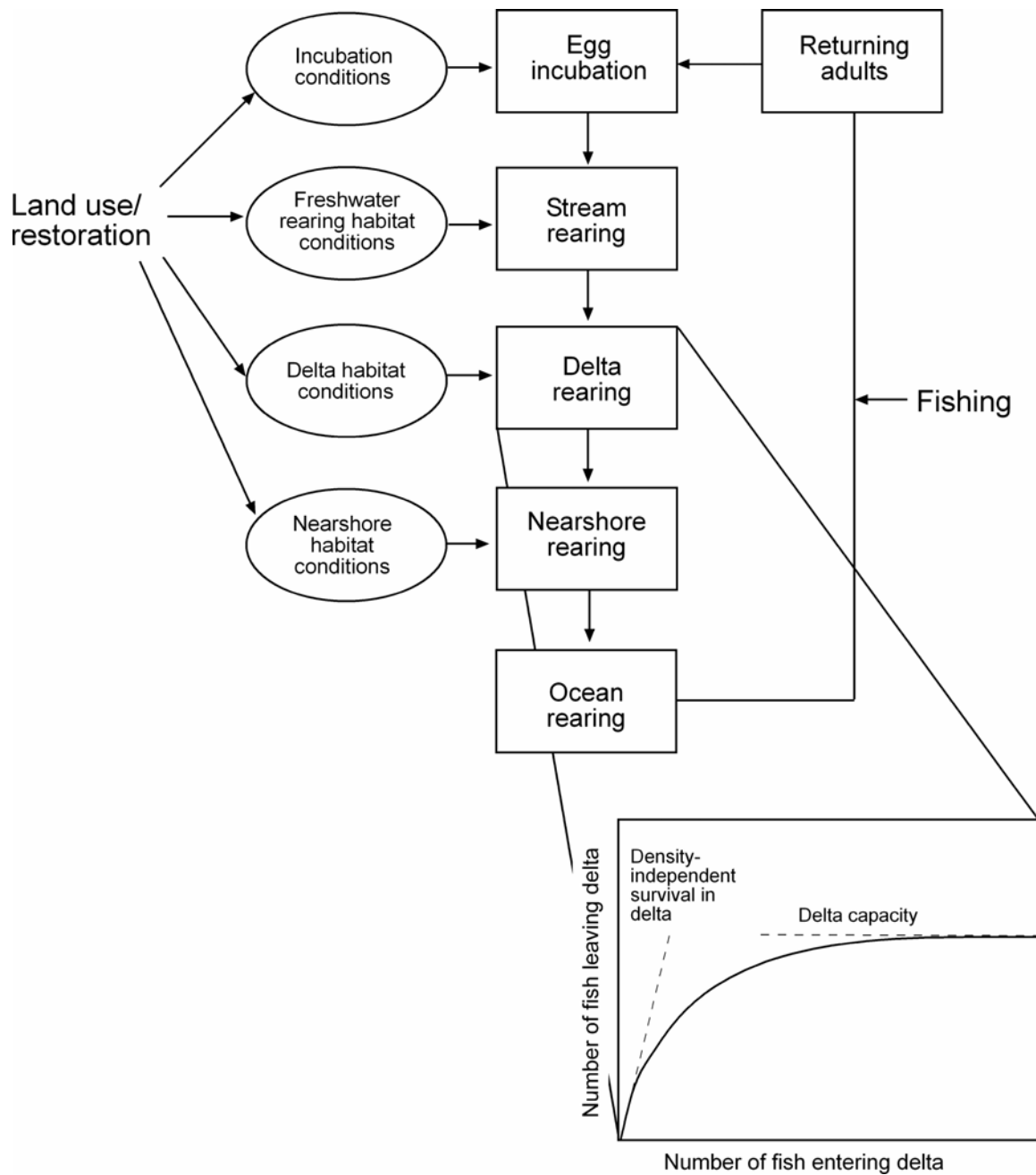


Figure 7. Generalized life cycle model illustrating linkages among life stage transitions (boxes), habitat conditions affecting those transitions (ovals), and human actions altering habitat conditions or survival. Expanded panel illustrates a typical density-dependent relationship for one life stage, with density-independent mortality at low population size and increasing density dependence as population size approaches habitat capacity. (Note however that all life stages may not be regulated by density-dependent mechanisms.)

decline over time. Thus it can help evaluate population growth rate goals in addition to abundance and survival goals.

The second main difference among the approaches is in data requirements. The EDT model is a relatively rapid assessment technique that relies on expert judgments of current and historical habitat conditions for more than 40 individual habitat variables, requiring inputs for each reach and each month of the year as well as estimated relationships between habitat and fish survival. The empirical limiting factors and life cycle approaches focus on fewer parameters measured or estimated from empirical relationships and require longer implementation time due to the time required to gather habitat data.

We review the three approaches to Phase I analyses at the watershed-level in the context of setting abundance goals for recovery. For this discussion, we group the limiting factors model and dynamic life cycle model together because they both rely on similar reconstructions of historical habitat availability. The EDT model is considered separately because of its reliance on expert judgment for most of its habitat input data.

Limiting Factors Model and Life Cycle Model

The simplest approach to estimating how habitat changes have altered fish abundance at the watershed level is to use a simplified limiting factors model to assess current and historical habitat availability and production potential (Reeves et al. 1989, Beechie et al. 1994). Many studies have quantified juvenile and adult fish use of particular habitat types (e.g., Bisson et al. 1988, Groot and Margolis 1991, Lichatowich 1999, Montgomery et al. 1999) and general patterns of habitat use by different species are largely consistent among studies (Figure 8, Pess et al. 2003). Therefore, developing new fish-use relationships for each watershed should not be necessary and limited field data should be sufficient to confirm that existing data from nearby streams can be used.

Unlike associations among fish densities and habitat types, habitat data are not transferable across watersheds. The natural potential of stream networks and the effects of land use on habitat condition vary by watershed (Frissell et al. 1986, Lunetta et al. 1997, Beechie et al. 2001, Collins and Montgomery 2001). Therefore, habitat inventories must be conducted separately in each river basin or planning area. Assessments for estimating current and historical habitat in a particular watershed are conducted in two steps: 1) estimate current and historical abundance of habitat types and 2) estimate population responses (simplified limiting factors model or dynamic life cycle model).

Assessing changes in habitat availability

A habitat classification system suitable for estimating current and historical habitat and potential fish production must have two main attributes. First, analysts must be able to associate fish abundance and survival with each habitat type. Second, to estimate changes in potential production over time, it must be possible to quantify both current and historical areas of each habitat type. We recommend a suite of habitat types at two hierarchical scales similar to that shown in Table 3. The coarser resolution of habitat types can be mapped from remotely sensed data at the reach scale (e.g., topographic maps, aerial photography, or satellite information),

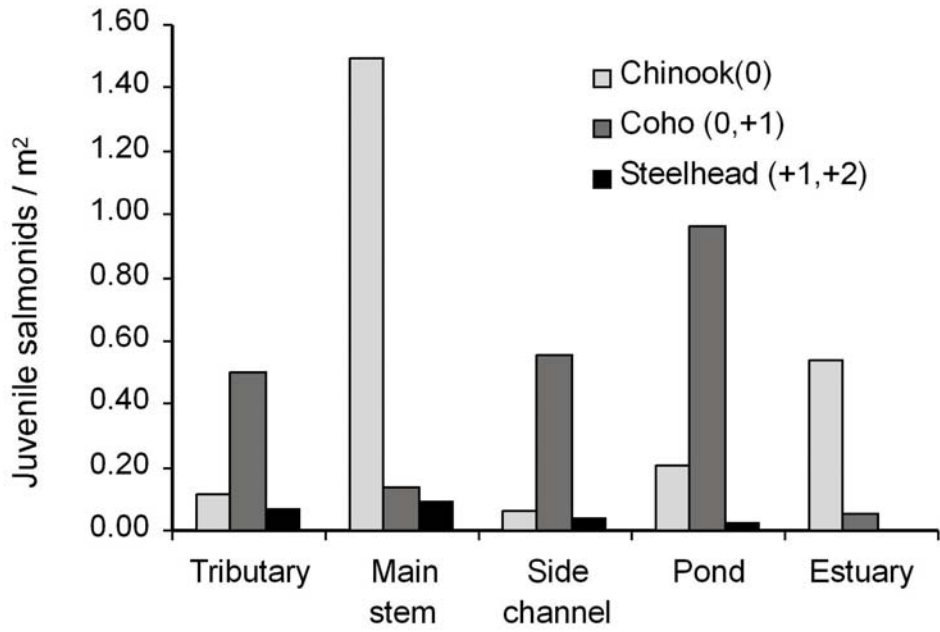


Figure 8. General juvenile salmonid use at the habitat scale. (Compilation of over 60 references.)

whereas the finer resolution of habitat types must be identified in the field at the habitat-unit scale (sometimes with the aid of aerial photography). Because these typing systems are nested, all reaches within a watershed can be stratified by landscape and land use factors using the remotely sensed coarse-resolution data, and reaches within each stratum can be subsampled to develop distributions of habitat types within each reach type. This hierarchical system enables extrapolation of habitat conditions for unsampled reaches within the watershed. Stratification of reach types may include several landscape and land use factors, although a relatively small number of strata are desirable to reduce the complexity and number of assumptions and calculations. For example, tributary reaches may be stratified simply by slope and land use in order to identify changes in pool area as a result of land uses (Beechie et al. 2001). However, the same slope classes are not particularly relevant for large rivers, where some combination of slope and discharge may be more useful in predicting natural channel patterns (e.g., Leopold et al. 1964).

Methods for estimating current and historical habitat abundance differ among habitat types. Therefore, describing a single methodology for assessing changes is not possible. Instead, we provide an overview of different approaches for assessing a habitat's present and historical conditions with references for greater detail on specific methods (Table 6).

Assessing population responses

Once habitat changes have been quantified, changes in potential population sizes can be estimated for specific life stages using a simplified limiting factors analysis (e.g., Reeves et al. 1989) or a dynamic life cycle model (e.g., Emlen 1995, Botsford and Brittnacher 1997, Ratner et al. 1997). As described earlier, the limiting factors approach focuses only on juvenile life stages and allows habitat capacity to vary while treating survival parameters as constants. By contrast, the dynamic life cycle model can incorporate changes in capacity or survival and evaluates population responses over long time frames.

Simplified limiting factors analysis—As described in Reeves et al. (1989), smolt production potential from a given habitat type or area is calculated as:

$$\text{habitat area} \times \text{average fish density} \times \text{survival to smolt} \quad (1)$$

Comparing the impacts of habitat alterations on smolt production potential requires separate estimates for each habitat type. Thus the production potential of a habitat for each life stage (e.g., spawning, egg to fry, summer rearing, winter rearing) can be expressed mathematically as:

$$N = \left(\sum_{i=1}^k \left(\left(\sum_{j=1}^n A_{ij} \right) \times d_i \right) \right) \quad (2)$$

where N is the population estimate, $\sum A_{ij}$ is the sum of areas of all habitat units ($j=1$ through n) of type i , and d_i is the density of fish in habitat type i (Beechie et al. 2003). To compare capacities among life stages and identify which habitats may be limiting smolt production, the population estimate for each life stage in a given habitat is multiplied by density-independent survival to smolt stage so the capacities can be compared in terms of number of smolts ultimately produced

Table 6. General description of analysis approaches for estimating current and historical habitat abundance at the watershed level. References provide more detail on methods.

Habitat type	Analysis method	Reference
Reduced off-channel or wetland areas	Historical habitat areas estimated from historical maps, notes, and photos and often field verified by residual evidence of prior locations. Present-day areas can be measured from aerial photographs and in the field.	Beechie et al. 1994 Collins and Montgomery 2001
Lakes	Changes to lake areas measured directly from current and historical maps and typically indicate where rivers have been dammed for hydropower or water supplies.	Beechie et al. 1994
Beaver ponds	Presettlement beaver pond areas estimated based on frequencies of beaver ponds in relatively pristine areas or predictive methods using stream and valley characteristics. Present-day pond areas within the study area measured using field surveys and aerial photography.	Naiman et al. 1988 Pollock and Pess 1998
Tributary and mainstem blockages	Portions of tributaries no longer accessible to salmon mapped using inventories of habitat upstream of migration barriers. Natural barriers to salmon migration must first be identified to delineate the assessment area. Habitat areas upstream of each manmade barrier must be surveyed to determine how much habitat is inaccessible.	Beechie et al. 1994 WDFW 1998 OWEB 1999a Pess et al. 1999b
Altered pool abundance	Based primarily on data from reference sites within the study area, but may also use historical information where available.	Beechie et al. 1994 WDFW 1998 OWEB 1999a Nickelson and Lawson 1998 Collins and Montgomery 2001

(Reeves et al. 1989). Equation 2 can also be used to estimate historical spawner capacity (or potential population size at other life stages) based on estimates of historical habitat availability (Appendix B, page 137). Both spawning and rearing capacities can then be used to develop or assess population viability abundance goals and can be incorporated into assessments of factors that limit population size.

Dynamic life cycle model—This second tool for evaluating how habitat changes affect salmon abundance and population trends (growth or decline) uses the same current and historical habitat data as above. A typical form of habitat-based life cycle model is the Leslie matrix (e.g., Emlen 1995, Botsford and Brittnacher 1997, Ratner et al. 1997), which can consider how fish move from one habitat to another and employ density-dependent or density-independent relationships to describe transitions between stages (Greene and Beechie in prep.). Thus each life stage transition within this model can be governed by capacity, survival, or movement parameters.

As with the preceding approaches, there are few estimates of stage-to-stage survivals for use in such models and few data to describe the form of relationships among habitat and life stages (e.g., density-independent mortality, density-dependent mortality, or density-dependent movements to less favorable habitats). However, this approach forces analysts to specify how mortality and movements are governed between life stages and address uncertainties stemming from lack of data. Therefore, one important use of such models is to begin evaluating which assumptions and data most strongly affect model outputs so recovery goals can be set with appropriate caution.

In one example of this approach, Greene and Beechie (in prep.) found that predicted improvements in Puget Sound Chinook salmon population growth rate or escapement strongly depend upon habitat-specific survival and residency estimates, as well as knowledge of density-dependent mechanisms. Both population growth rate and escapement showed the greatest sensitivity to nearshore and ocean survival regardless of the existence and mechanism of density dependence (Figure 9). However, simply altering the density-dependence assumptions while holding all habitat variables the same altered predicted abundance of Chinook salmon by more than a factor of four (Figure 10).

Such findings have direct implications for setting recovery goals, as well as for identifying habitats that may limit recovery of populations. First, these models point out that model assumptions and parameters can dramatically alter our predictions of population responses to habitat changes, and therefore that abundance goals should be set with these uncertainties in mind. Second, such models can identify parameter and model uncertainties (see the Managing Uncertainty in Habitat Recovery Planning section, page 74) that substantially alter our conclusions about which habitats limit recovery, and therefore shift the focus of restoration efforts. Finally, such models can indicate that certain life stage survivals (e.g., nearshore for ocean-type Chinook salmon populations) may be most sensitive to habitat change regardless of the assumptions about density dependence. However, a sensitivity analysis simply begs the questions whether significant habitat changes have occurred and whether restoration is feasible. Therefore, such analyses also motivate efforts to characterize poorly understood habitats, their effects on salmon abundance and survival, and the extent to which they have been modified.

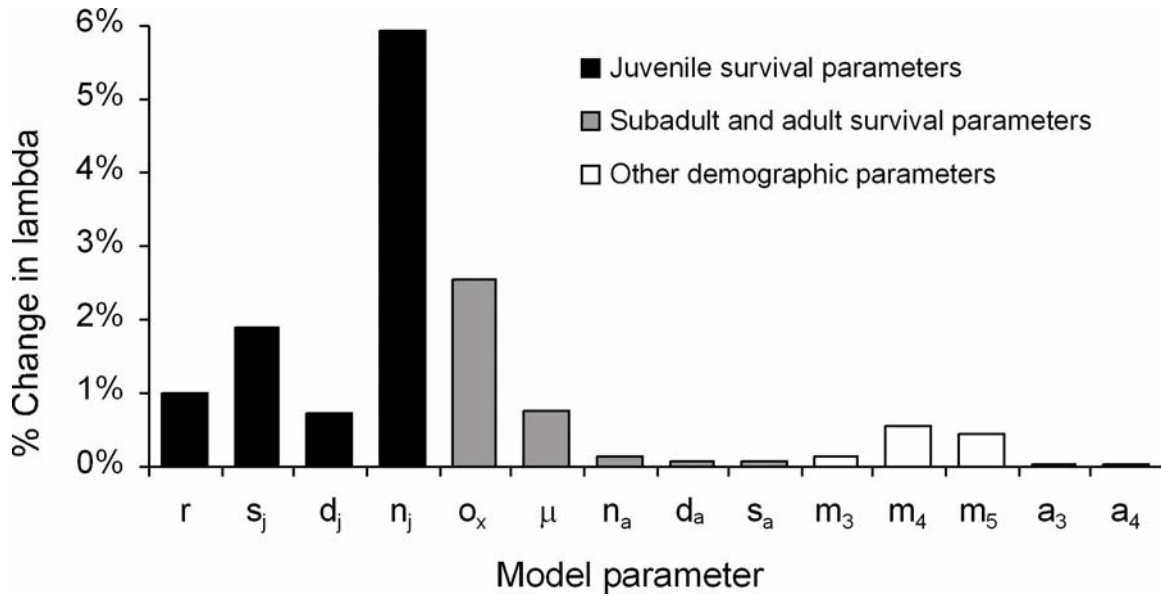


Figure 9. Sensitivity of lambda (λ) to changes in model parameters when population dynamics of Puget Sound ocean-type Chinook salmon are density independent. Each bar represents a percentage change in λ resulting from a 5% change in each particular model parameter. Parameters are: r = redd survival, s_j = juvenile stream survival, d_j = tidal delta survival, n_j = nearshore survival, o_x = annual ocean survival, μ = survival through harvest, n_a = adult survival back through the near shore, d_a = adult survival back through the tidal delta, s_a = adult survival back through the stream, m_x = age-specific fecundity, and a_x = age-specific breeding propensity. (From Greene and Beechie in prep.)

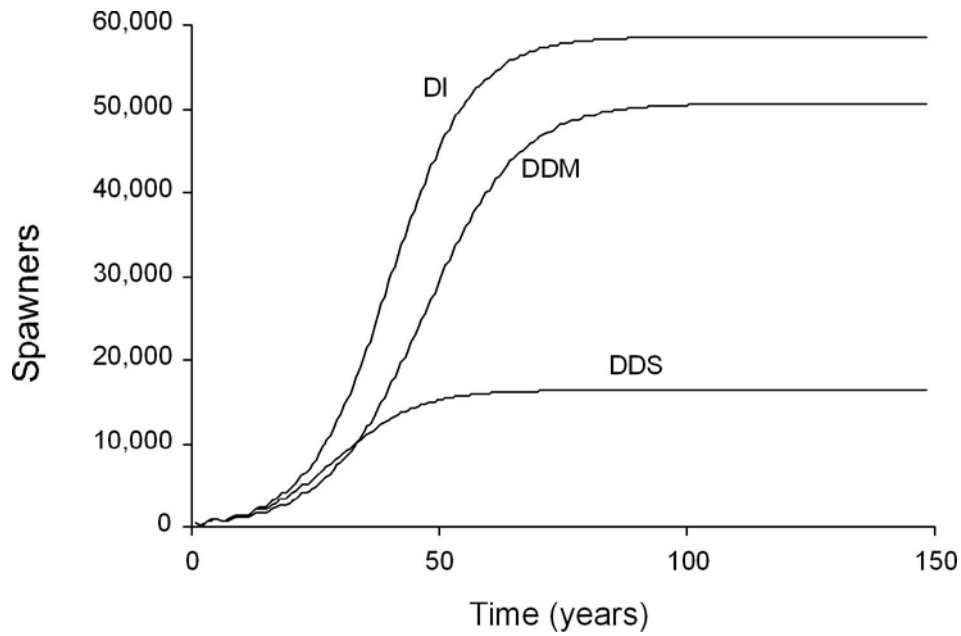


Figure 10. Predicted Puget Sound ocean-type Chinook salmon escapement as a function of time for density-independent survival (DI), density-dependent survival (DDS), and density-dependent movement (DDM) scenarios with a spawning capacity of 60,000. (From Greene and Beechie in prep.)

Ecosystem Diagnosis and Treatment

EDT, an example of the third approach to watershed-level analyses, is a complex salmon production model that has been used throughout the Pacific Northwest for salmon recovery planning. The conceptual basis for the EDT model is described in Lichatowich et al. (1995) and Mobrand et al. (1997). Details of its structure and use are found in Lestelle et al. (1996). EDT is a habitat-based model that relies primarily on expert opinion (best professional judgment) as environmental input data. It organizes environmental inputs, estimates habitat condition, and predicts fish population performance based on estimated life-stage specific stock-recruit functions. Fish population performance is characterized using a “survival landscape,” which is created by multiplying the life stage functions together. The survival landscape is typically created for environmental states corresponding to two points in time, current and historical, but may also be created for other states. The spatial unit of analysis is a reach (e.g., one river mile to several river miles).

There are three levels of information in an EDT analysis. Level 1, the input data, includes 45 environmental variables (or some subset thereof), including empirical data (e.g., data measured in the field), derived data (e.g., estimated from coarse-scale data), and anecdotal information (e.g., best professional judgment). Level 2 is the set of biological rules that drive the model. Biological rules are working hypotheses about how a salmonid species at a given life stage will respond to a specific environmental variable. The shape of each biological rule is estimated from published literature and expert judgment. The level of proof behind each rule is ranked based on the information underlying it. The sum of the functions results in a combined estimate of the survival of fish throughout the life cycle. Level 3 is the translation of the rules into 17 biological performance attributes (variables) that give relative survival or performance by life stage. Each attribute is used to modify an idealized or optimum condition that is the “historical template.” Survival and performance by life stage are the sum of the 17 biological attributes and always a fraction that ranges between 0 and 1.

EDT has been used to estimate habitat capacity under current, historical, and restored conditions. It can help organize existing expert opinion and empirical data to create hypotheses about linkages among certain habitat conditions and fish abundance. However, because the underlying data and functional relationships are largely untested, the accuracy of any EDT outcome is unknown. As noted in Mobrand et al. (1997), this performance measure is an indicator of how favorable the environment is or might become for salmon to persist and abound, not a predictor of how many will return and when. Currently, the EDT model does not provide estimates of the uncertainty (or precision) of the output estimates. Output from EDT will be more useful for decision making if estimates of both accuracy and precision can be generated.

Analyses for Spatial Structure and Diversity Goals

Both coarse-scale and fine-scale (see Table 3) comparisons of current and historical habitat within a watershed can indicate whether the diversity of habitat types available to salmonids today are vastly different from the past, whether connectivity between habitat types has been altered, and consequently whether spatial structure or life history diversity have been

altered. While changes in distribution and diversity of habitats can be identified through these analyses, more detailed work is needed to address patch size and natural dynamics within individual systems. In this subsection, we describe existing approaches that relate habitat conditions to spatial structure and diversity at multiple scales and suggest how this type of information might be used to inform the development of recovery goals.

ESU-Level Analyses

Few studies have tried to determine how changes in habitat may have altered the spatial structure and diversity of salmon populations and ESUs (Table 4). However, several studies have examined genotypic and phenotypic diversity at a variety of scales, and from these studies, Healey and Prince (1995) concluded that the majority of genotypic diversity is contained within stocks while most phenotypic diversity is greater across populations and landscapes. This suggests that ESU-level analyses may find stronger relationships among habitat variables and diversity than will watershed-level analyses.

Several completed large-scale analyses for salmon indicate that habitat changes have radically altered spatial structure and population diversity in some ESUs. For example, the Interior Columbia Basin Ecosystem Management Project characterized the distribution of individual fish species, patterns in fish species diversity and status, and their relationships to landscape characteristics (Quigley and Arbelbide 1997). The analyses indicate major declines in the number and distribution of salmonid species located in Columbia River subwatersheds. Anadromous fish species have been largely extirpated from large portions of their range, and the consequences of this for ESU viability need to be addressed.

In another example of large-scale analysis, Waples et al. (2001) characterized patterns of intraspecific diversity for Pacific Northwest salmon species along three major axes: ecology, life history, and biochemical genetics. The ecology axis included characteristics of freshwater habitats that are of known importance to salmon (i.e., hydrography, temperature, vegetation, geology, etc.), and results indicated that diversity within a species was significantly related to the ecological diversity experienced by that species. For example, diversity measures were lower for pink salmon (*O. gorbuscha*) and chum salmon, which are limited in distribution to areas directly affected by Pleistocene glaciation. In contrast, Chinook salmon and steelhead were broadly distributed and exhibited the greatest degree of diversity. Results such as these indicate that reductions in species ranges will likely alter spatial structure and diversity within ESUs, and may ultimately constrain recovery of some ESUs under certain management scenarios.

Frissell (1993b) mapped region-wide patterns of extinction and endangerment of native fishes in the Pacific Northwest and California using data compiled for inland fishes (Williams et al. 1989) and anadromous stocks (Nehlsen et al. 1991). Mapping units were based on a drainage basin size of 50–2,000 km² and basins were categorized according to the number of species (0–1, 2–3, 4–5, or 6–8) classified as extinct, endangered, or threatened. Isopleths were then fitted between the categories. Results indicated a general increase in endangerment from north to south and identified basins in Idaho, Puget Sound, and northern California in which population declines were mainly due to large-scale dams and irrigation projects. Dams, logging roads, and floods have also damaged habitats and severely threatened faunal diversity in other basins in southern Oregon and northern California.

Watershed-Level Analyses

Smaller scale analyses of the spatial structure and diversity of fish populations are rare. One that attempts to bridge this gap is an analysis of bull trout (*Salvelinus confluentus*) by Dunham and Rieman (1999) within the Boise River. Their results indicate that the large-scale geometry of catchments can influence the distribution of aquatic species. Bull trout populations in larger, less isolated, less disturbed patches are more likely to persist. They conclude that disturbance within these habitats should be minimized and speculate that conservation and restoration opportunities might best be centered within those patches of intermediate size or isolation.

Conclusions

Habitat analyses at multiple scales can help set goals for abundance, population growth rate, spatial structure, and diversity. These large-scale and small-scale analyses compare current and historical habitats to evaluate whether current habitat is sufficient to support VSPs and ESUs. ESU-scale analyses apply consistent techniques to examine questions over large spatial scales and often rely on remotely sensed information and coarser resolution habitat data. Watershed-scale analyses focus on questions relevant to individual populations.

The analyses discussed in this section are designed to answer questions necessary to set biological recovery goals (Phase I). As these goals are set, the next phase of recovery planning must address how to reach them. The data and information collected for the analyses can also contribute to identification of factors causing decline, quantification of fish-habitat relationships, and efforts to prioritize actions for ESUs and watersheds. The next two sections address questions pertinent to Phase II recovery planning and prioritizing restoration actions.

ANALYSES FOR PHASE II RECOVERY PLANNING: IDENTIFYING ECOSYSTEM RESTORATION ACTIONS

In this section we describe assessments and inventories that develop site-specific lists of ecosystem protection and restoration actions within watersheds during Phase II of recovery planning. These assessments focus on how land uses have disrupted ecosystem processes and functions that support salmon and identify specific actions needed to correct those problems. At the ESU-level, analyses described under Phase I identify broad habitat types that are most impaired within each watershed (e.g., estuary, main stem, tributary), as well as broad categories of habitat recovery actions (e.g., barrier removals). We do not repeat discussion of those assessments here.

Within individual watersheds, two types of assessments can be used during Phase II recovery planning. The first type includes screening assessments to focus inventories on areas where they are most needed. The second type includes field inventories that identify specific locations where habitat protection or restoration actions are needed (see also Figure 3). Screening assessments can largely rely on existing data (e.g., geospatial coverages, hydrologic data, existing inventories) to map impaired processes, but may also include field assessments of biological integrity to help identify potential ecosystem disturbances where causes of habitat degradation are more complex (e.g., urban areas). In contrast, specific projects such as fixing a culvert barrier or fencing a riparian area can only be identified with field data. Both types of assessments are relevant in all ecoregions, although specifics of the assessments and inventories may vary depending on which ecosystem processes are most important in the given ecoregion.

Earlier we presented a conceptual diagram illustrating how natural landscape processes and land uses form habitat conditions (Figure 1). Here we expand the conceptual diagram to explain linkages among ultimate controls, proximate controls, habitat-forming processes, habitat conditions, and biological responses (Figure 11). Ultimate controls are independent of land management over the long term (centuries to millennia), act over large areas ($>1 \text{ km}^2$), and shape the range of possible processes and habitat conditions in a watershed (Naiman et al. 1992, Beechie and Bolton 1999). Proximate controls are affected by land management over the short term (i.e., years to decades), act over smaller areas, and determine habitat conditions expressed at any point in time (Naiman et al. 1992).

For organizational purposes, we group ecosystem processes and functions into three categories: 1) distributed watershed processes (similar to non-point sources, such as supplies of sediment and water), 2) reach-level processes that primarily affect the adjacent reach (e.g., riparian processes), and 3) other ecosystem functions (e.g., habitat connectivity). Ecosystem processes are typically measured as rates and characterize what ecosystems or components of ecosystems do (SWC 1998). For example, sediment or hydrologic processes in a watershed may be characterized by the rates (volume/area/time) at which sediment or water is supplied to and transported through specific locations of a watershed. Certain riparian functions such as wood recruitment to streams can be viewed similarly. In contrast, other ecosystem functions or attributes such as habitat connectivity are not well described as processes. Rather, migration barriers reduce the habitat capacity of a system and flow diversions may divert or pump fish into

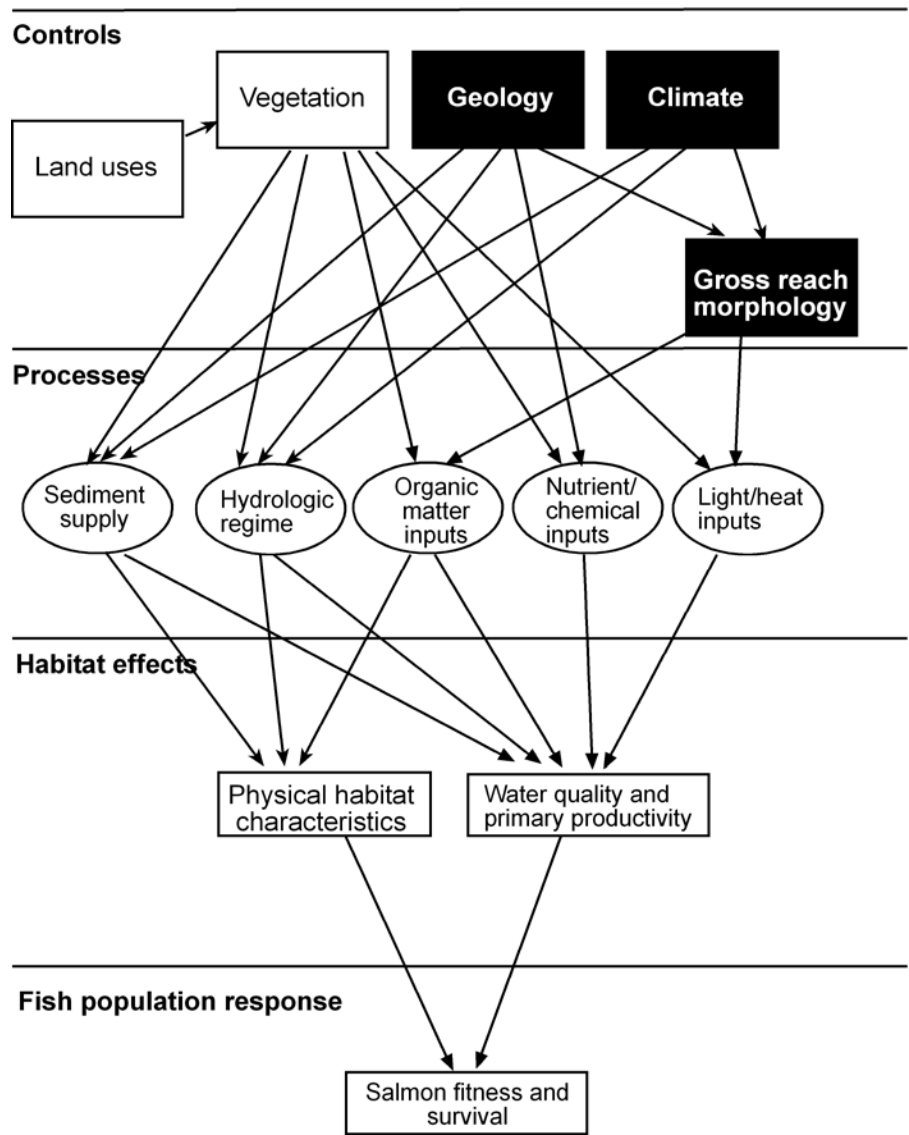


Figure 11. Schematic diagram of relationships between controls on watershed processes, effects on habitat conditions, and salmon survival and fitness (adapted from Beechie and Bolton 1999). Dark boxes in upper row are ultimate controls and light boxes are proximate controls.

irrigation systems. Because neither fits neatly into the categories of watershed-level or reach-level processes, each is considered separately.

Watershed-Level Analyses

The purpose of watershed-level assessments is to identify: 1) the natural landscape processes and functions in a watershed, 2) the effects of land use on natural processes, and 3) the causal relationships between land use and changes to habitat conditions. Ecosystem protection and restoration actions resulting from these assessments are directed at protecting and restoring beneficial habitat-forming processes rather than attempting to build specific habitat conditions (FEMAT 1993, Spence et al. 1996, Moore 1997, Beechie and Bolton 1999). As described earlier, the watershed-level assessments systematically identify land use disruptions to habitat-forming processes at two levels of resolution. First, screening assessments locate disturbed habitat-forming processes using existing GIS data and limited field measurements for ground-truthing (e.g., Lunetta et al. 1997, Quigley and Arbelbide 1997, our Appendix C). These assessments identify where processes are most disrupted and focus field inventories on areas most in need of restoration. Second, field-based inventories identify specific alterations to flow regimes, sediment supply, riparian conditions, habitat connectivity, water quality, and channel and floodplain interactions (e.g., OWEB 1999a, our Appendix C). This more detailed assessment relies solely on field-based inventories and identifies specific protection or restoration actions that are required for recovery.

Assessing Degradation of Ecosystem Processes and Functions

Ecosystem processes and functions to inventory at a minimum should include hydrology, sediment supply, riparian functions, channel-floodplain interactions, habitat isolated from salmon access, and water quality (Table 7). This suite of inventories is based on current scientific knowledge of their effects on salmonid habitat and survival of salmon in freshwater, as well as knowledge of how various land use practices affect the processes and functions. The list may not include all impacts to salmon in a watershed, but does include those that are clearly supported by scientific literature (e.g., Meehan 1991, WDNR 1995, OWEB 1999a) and appear to be responsible for a significant proportion of the total loss in salmon production from Pacific Northwest river basins. As described earlier in this report, dominant watershed controls and natural landscape processes vary by ecoregion, leading to differences in the assessments to be conducted for identifying restoration actions (Table 2).

Watershed-level processes

Watershed-level processes are those that have multiple, widely distributed sources, including sediment supply, hydrology, and inputs of nutrients or pesticides (Table 7). Describing how these processes have been disrupted and what restoration actions are required for their recovery requires two kinds of assessments. First, process assessments identify the degree to which process has been altered by land use and where in each watershed these changes have occurred. Second, inventories identify where specific restoration actions must be taken in order for recovery to occur.

Table 7. Examples of methods for rating individual landscape processes.

Distributed watershed processes

Hydrology—disruption of peak flows, low flows, and channel-forming flows

A change in the magnitude, frequency, duration, and rate of minimum, mean, and maximum flows can be examined using the indicators of hydrologic alteration (IHA), which assess the difference in 32 biologically significant hydrologic parameters of pre- and post-anthropogenic activities such as dam operations, flow diversion, groundwater pumping, or intensive land use (Ritcher et al. 1997).

Hydrology—increases in peak flows

Lowland basins: Hydrologic impairment in lowland basins can be rated based on planned effective impervious area (EIA), which is the weighted average EIA upstream of the stream reach under fully developed conditions. EIA \leq 3% is considered “functioning,” EIA between 3% and 10% is “moderately impaired,” and EIA $>$ 10% is “impaired” (based on Booth and Jackson 1997, and see example in our Appendix C).

Mountain basins: Peak flow ratings for mountain subbasins can be developed based on empirical correlations between land use and elevated peak flow in forested basins (Jones and Grant 1996, and see example in our Appendix C).

Sediment supply

Estimating impairment of sediment supply: Changes in average sediment supply for forested subbasins within a watershed can be estimated based on present-day sediment supply rates from unlogged, clear-cut, and roaded portions of the watershed (Dietrich and Dunne 1978, Paulson 1997, Montgomery et al. 1998).

Surface erosion on croplands and rangelands: Changes in average sediment supply for croplands within a watershed can be estimated on crop practices, soil type, rainfall, slope, and other factors (Dunne and Leopold 1978).

Routing estimates: In-channel sediment storage assessments identify sediment movement rates and can help estimate recovery time of habitats (Madej and Ozaki 1996).

Inventory—identify sediment reduction projects: Inventories must focus on factors that influence sediment supply, identification of landslide hazard areas so forest practices can be avoided or modified in sensitive areas (e.g., Montgomery et al. 1998), such as risk of road-related landslides (e.g., Renison 1998), crop management practices that increase surface erosion (Wischmeier and Smith 1965), or grazing practices that alter sediment supply.

Reach-level processes

Riparian function

Remote sensing assessment: Use remote sensing classifications of vegetation to assess riparian buffer width and type in order to help determine how much and where riparian buffer impairment has occurred on a reach or river basin scale. Identify historical conditions using reference locations and historical documentation. Compare historical condition to current riparian condition in order to determine degree of change.

Field inventory: In addition to documenting forested buffer width, field inventories also classify stand types by species mix and seral stage, which gives sufficient information to prescribe generalized management regimes for each segment of riparian forest (Collins et al. 1994). Inventories also identify areas of livestock access and potential fencing projects.

Riparian alteration due to grazing: Use similar methods but include indicators such as stubble height measurements as indicator of disturbance (Clary and Lenninger 2000, Turner and Clary 2001).

Table 7 continued. Examples of methods for rating individual landscape processes.

Reach-level processes (continued)

Channel and floodplain interactions

Floodplain areas can be delineated using 100-year floodplain maps from the Federal Emergency Management Agency or U. S. Geological Survey 7.5-minute quadrangles and aerial photographs.

Habitat connectivity—anthropogenic blockages

Manmade barriers to anadromous fish habitat are identified through a systematic field inventory of channel crossing structures (culverts, tide gates, bridges, dams, and other manmade structures). The inventory identifies the type and physical dimensions of structures as well as physical attributes necessary for modeling water flow conditions and comparing results to passage criteria for salmonids (e.g., WDFW 1998).

Disrupted water quality

Contaminants

Association of fish assemblage structure and environmental variables: Compare fish assemblage composition to chemical and physical environment (Waite and Carpenter 2000).

Identifying altered sediment supply—Sediment supply to streams is altered by many processes including changes in mass wasting due to logging and road building (e.g., Sidle et al. 1985), increased surface erosion after prescribed burns (e.g., Megahan et al. 1995), increased surface erosion from unpaved road surfaces (e.g., Bilby et al. 1989), and surface erosion and gully erosion after grazing (Platts 1991, Elmore 1992, Johnson 1992, Trimble and Mendel 1995). We present two main approaches to understanding disruptions to these sediment supply processes: 1) budgeting and 2) landscape indicators based on known relationships of certain water and land uses to the parameter in question. The budgeting approach is often used for sediment supply, but can also be used for inputs of nutrients or pesticides to water bodies. The general budget can be stated in equation form:

$$\Delta S = I - O \quad (3)$$

where ΔS is change in storage, I is input, and O is output (e.g., Reid and Dunne 1996). In essence, S is the stream condition for any parameter (e.g., the amount of sediment or of a pesticide in the stream), and quantifying changes in inputs or outputs indicates how land uses have altered the stream ecosystem. In many cases, it may only be necessary to quantify how inputs have been altered by land uses, which is called a partial budget. That is, where changes to outputs are negligible, an increased input is approximately equal to the change in storage and to the altered stream condition. Therefore, it may not be necessary to understand output processes in detail (e.g., sediment transport) in order to calculate change in storage and understand how the stream ecosystem has been altered.

We illustrate the partial budget approach by describing how one might approach two different altered sediment inputs to streams due to land use: 1) extrapolation of limited empirical data for estimating increased fine sediment supply from tilled croplands in the Blue Mountain Level III ecoregion, and 2) an empirical approach to estimating changes in landslide rates due to forestry activities in the North Cascades Level III ecoregion. Both approaches focus on identifying where sediment supplies to streams have been significantly altered and can help focus restoration efforts on areas that contribute large amounts of sediment. Note that these approaches do not identify the exact locations of restoration actions, which require specific inventories of croplands where eroded sediments are delivered directly to streams or road segments with high risk of landsliding. For efficiency, these inventories can initially target those areas of high sediment supply identified by the partial sediment budgets.

In the first example, the partial sediment budget for croplands makes use of measured erosion rates from soils with and without cover crop. Soils without cover crop erode at rates as much as 10 times higher than soils with cover crop (see complete overview of processes and rates in Dunne and Leopold 1978). The rate varies with soil type, rainfall, slope, cover type, and other factors. Local erosion rates for different soils and cover crops have been measured in many areas by researchers and land management agencies. Examples for different soils and cover crops can be found in Dunne and Leopold (1978). From known rates, a simple cumulative model for basins can be expressed as:

$$I_c = (A_c \times E_c) + (A_{nc} \times E_{nc}) \quad (4)$$

where I_c is the current total estimated sediment input to the selected reach, A_c is the area of land

with cover crop or other natural vegetation, E_c is the erosion rate per unit area with cover crop, A_{nc} is the area of land with no cover crop, and E_{nc} is the erosion rate per unit area without cover crop. (Additional parameters may be added for other cover types as needed.) A natural background rate of sediment supply from surface erosion can be estimated by applying the natural erosion rate (I_n) to the entire basin:

$$I_n = (A_c + A_{nc}) \times E_c \quad (5)$$

Calculations of I_c/I_n for various subwatersheds within a region can then be compared to identify those areas where tilling is likely to have significantly altered sediment supply to streams. Where soil erosion rates have not been measured, it may be necessary to use predictive equations such as the Universal Soil Loss Equation (Wischmeier and Smith 1965, 1978) or Revised Universal Soil Loss Equation (Renard et al. 1991, 1997). Dunne and Leopold (1978) provide a good overview of the equation and its application, along with charts and tables for estimating parameters in the equation, and the original handbooks can be consulted for greater detail on the methods. Estimates of local soil parameters are generally available from local USDA Natural Resources Conservation Service offices.

In the second example, a partial budget for sediment supply in coastal forests is constructed by conducting landslide inventories from historical aerial photographs and estimating contributions of fine sediments from road surface erosion (e.g., Paulson 1997). The general approach is similar to that for the cropland erosion example, where the final product of the partial sediment budget is I_c/I_n and comparisons among basins indicate areas where sediment supplies have been significantly altered. In these inventories, landslides are enumerated and measured on each aerial photograph and volume of each landslide is calculated based on a relationship of photo-measured area to field-measured volume for a subset of the recent landslides. Land use association is also recorded for each landslide (e.g., clear-cut, road, or mature forest), allowing estimation of the aggregate impact of land use on the sediment input, as well as identification of the land uses most responsible for changes in sediment supply. Surface erosion estimates can be based on characteristics of road surfaces, cut and fill slopes, and precipitation (e.g., WDNR 1995). Calculation of I_n typically assumes there is no surface erosion (overland flow is rare in the Coastal Forest ecoregion) and the landslide sediment production rate for mature forests can be applied to the entire basin. These sediment budgets can then be compared to identify areas where sediment supplies have been most altered and where modified timber harvest practices or road modifications have the greatest impact on ecosystem recovery.

Landscape and land use indicators of altered sediment supplies can be developed from such sediment budgets (or field studies of erosion) in order to more rapidly screen large areas for disrupted sediment supply. For example, GIS maps of geology, soils, and hillslope angles can identify areas that are prone to landsliding (e.g., Montgomery and Dietrich 1994, our Appendix C), and overlays of land cover and roads can identify where landsliding has likely increased (Appendix C). Results of such screening analyses can then identify areas where inventories of potential restoration actions should be focused.

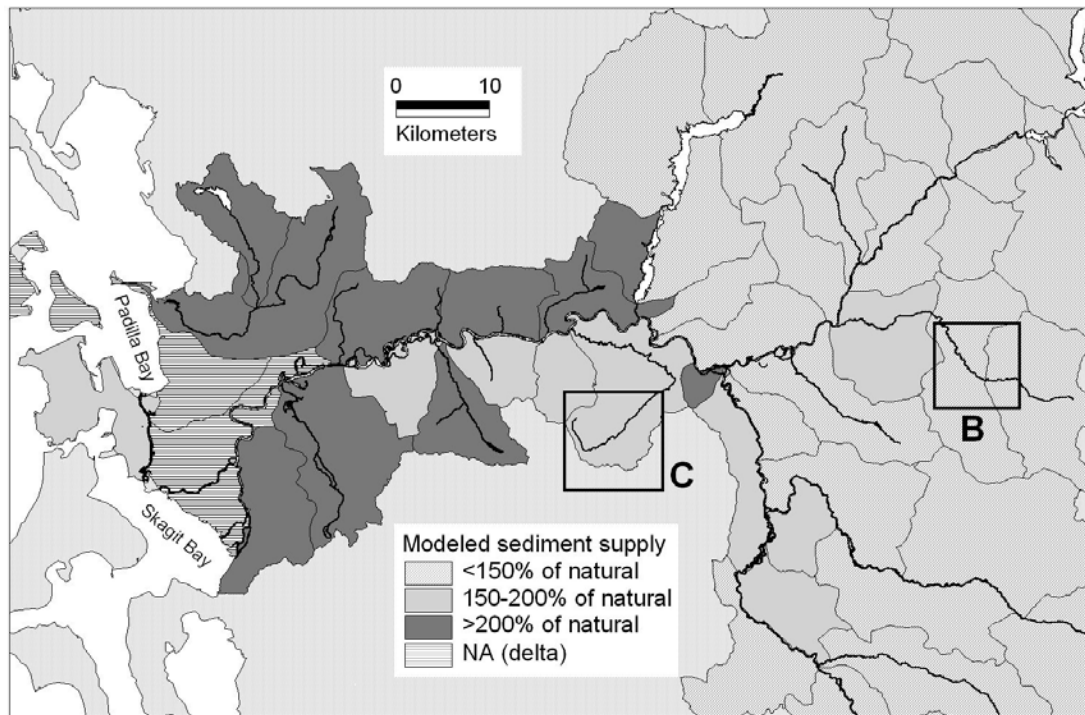
In general, remote sensing methods and mapping of landscape indicators identify areas for passive restoration, but field inventories are required to identify active restoration projects. For areas dominated by mass wasting, mapping identifies areas particularly prone to landslide

hazard and sensitive to land uses such as clear-cut logging or road building (Figure 12). Such maps identify passive restoration actions (e.g., areas to avoid for future logging), which allow recovery of sediment supply rates by preventing or modifying land uses within hazard areas. Road landslide hazard inventories identify specific areas for active restoration (e.g., removal of hazardous roads). Road inventories should identify road segments at risk of failure (e.g., Renison 1998) as well as specific stream crossings, cross drains, or fills likely to fail. Each potential failure site can be itemized on project lists for restoration action. These actions can then be prioritized based on protection of refugia, potential impact to stream habitat, smolt production, cost, and other factors.

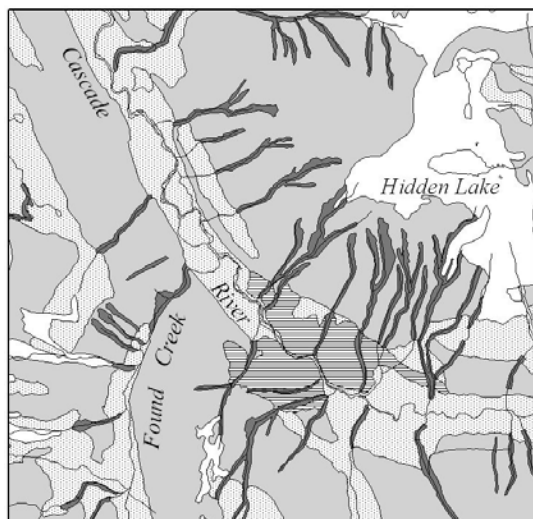
Where surface erosion and gulying are dominant processes, terrain and soil conditions that lead to severe erosion can also identify areas where modified agricultural practices can reduce erosion and sediment supply to streams. Modeling of altered sediment yields by various conservation practices can help identify the types of agricultural practices that are greatest contributors to erosion (Williamson et al. 1998) as well as those restoration actions that are most likely to be successful (Ebbert and Roe 1998). Actions can also be itemized and prioritized based on a number of factors including the magnitude of reduced erosion and costs.

Identifying altered hydrologic regime—Hydrologic processes can be altered by land uses in a variety of ways, including increased peak flows from impervious surfaces (e.g., Booth and Jackson 1997), livestock compaction (Trimble and Mendel 1995), increased peak flows from increased snow accumulation and melt (e.g., Zeimer 1981, Harr 1986, Beschta et al. 2000), and decreased peak flows or low flows from dams and withdrawals (e.g., Ritcher et al. 1996, Donato 1998, Spinazola 1998). Assessments of increased peak flows typically utilize landscape indicators of changes to watershed processes based on known functional relationships between land cover and peak flows (e.g., Booth and Jackson 1997, Beschta et al. 2000, our Appendix C), and may include detailed models that project changes in peak flow hydrographs as a result of land cover changes (e.g., Booth and Jackson 1997). Assessments of low flow changes typically include inventories of total withdrawals and calculation of the proportion of stream flow removed (e.g., Donato 1998, Spinazola 1998), as well as indirect estimates based on power consumption at pumping stations (e.g., Maupin 1999).

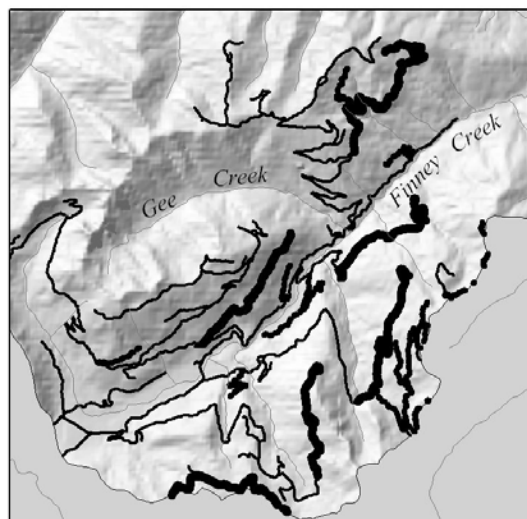
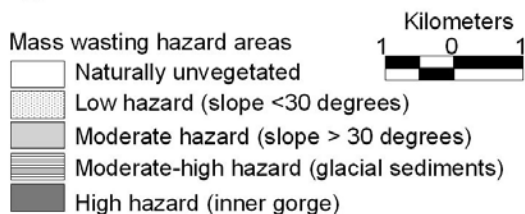
Known relationships among zoning, impervious surface area, and changes in hydrologic processes and biota have been used to indicate changes in hydrologic regime in urban areas (see Appendix C). Where impervious surface areas are less than 3% of the watershed area, hydrologic regime is not significantly different from one with no impervious surfaces (Booth and Jackson 1997). However, where impervious surfaces are more than 10% of the watershed area, hydrologic regime has likely been altered to the point where changes in biota are severe (Lucchetti and Furstenberg 1992, Moscrip and Montgomery 1997, May et al. 1997). Similar analyses can be developed for other watershed processes such as contaminant runoff from agricultural or urban areas, where high concentrations of compounds that are toxic to salmon alter their behavior in ways that could reduce survival (Scholz et al. 2000). More general landscape indicators such as percent of a watershed in urban land cover may be greater predictors of biological condition, because they are more inclusive measures of anthropogenic disturbance and not just a change in one specific watershed process such as hydrologic regime or water quality (Karr and Chu 2000, Morley and Karr 2002). Examples of use of land cover indices for peak flow changes from rain-on-snow are also included in Appendix C.



A



B



C



Figure 12. A is map of areas in the Skagit River basin where sediment supply has likely increased due to land use, based on extrapolation of data from sediment budgets. B is landslide hazard map for a portion of the upper Cascade River basin. C is hazard map of U.S. Forest Service roads classified by risk of failure.

Indicators of hydrologic alteration (IHA) can also be used to assess the degree of hydrologic alteration within a watershed (Ritcher et al. 1996). The method summarizes complex hydrologic variation using 32 stream flow parameters that have biologically relevant attributes (Ritcher et al. 1996). The hydrologic data is from known sources such as stream gages and wells. Each parameter is separated into pre- and post-impact time frames, and the central tendency (defined as the mean and median) and dispersion (defined as the variance and coefficient of variation) are compared to assess degree of hydrologic perturbation (Ritcher et al. 1996). Perturbation can include activities such as dam operations, flow diversion, groundwater pumping, or intensive land use (Ritcher et al. 1997). The tool is used with other ecosystem metrics (e.g., biological integrity indices) and can help set stream flow restoration targets, identify areas of hydrologic alteration, and measure progress toward quantified conservation goals (Ritcher et al. 1996, 1997, 1998). The tool is not meant to predict biological response to hydrologic alteration (Ritcher et al. 1996).

Low-flow impairments can be identified through inventories of diversions and quantification of water withdrawals. Data availability varies between large dams and small, private irrigation or water supply diversions (Spence et al. 1996, Quigley and Arbelbide 1997). For large dams (>2 m high), inventory data are available for regional characterization of water withdrawals and cumulative withdrawals can be calculated (e.g., Quigley and Arbelbide 1997). However, data for smaller diversions and their effect on stream flows are less readily available (Spence et al. 1996), and inventories of low flow changes are needed to systematically identify stream reaches where low flows are at issue within individual watersheds.

The existing 303d database from the U.S. Environmental Protection Agency (EPA) identifies more than 13,000 km of flow-impaired stream reaches in the interior Columbia River basin (Quigley and Arbelbide 1997) as well as additional streams in western Oregon and Washington. This database can be used as a preliminary inventory of withdrawals and low-flow impairments. More detailed field inventories of withdrawals can be conducted within watersheds to list all small dams, diversions, and pump stations that withdraw water from streams and assess the degree to which stream flows are reduced. State water rights databases (e.g., Washington Department of Ecology, Oregon Water Resources Department) provide a starting point for such assessments, although field inventories of actual withdrawals are often needed to confirm which water rights are currently in use. In general, ranking the proportion of stream flow withdrawn in various reaches indicates which reaches deviate most significantly from natural stream flows and are most likely in need of increased stream flows. Methods available to identify specific locations where water withdrawals impact stream flows include source metering using stream flow gauges or other measurement devices (e.g., Donato 1998), direct assessment of flow change (e.g., Ritcher et al. 1996), and estimates of water withdrawal based on power consumption at pumping stations (e.g., Maupin 1999).

In areas where hydrologic regime approximates the natural regime, ecosystem management should focus on protecting current hydrologic processes. These actions might include avoiding additional hydrologic changes by preventing new impervious surfaces and forestry impacts to peak flows. By contrast, where hydrologic regime deviates significantly from the natural regime, restoration actions should be identified. For alterations to peak flows, identification of restoration actions may include actions to alleviate impervious surfaces (Holz et al. 1998, Maryland DER 2000) and impacts of clear-cuts and roads on peak flow responses. For

low flow impairment, Instream Flow Incremental Methodology (IFIM) or variations of it can help identify how much stream flow is necessary to support aquatic ecosystems at both low-flow and high-flow periods (Jowett 1997).

Identifying altered water quality—Water quality parameters can also indicate areas with a high likelihood of disruption, especially with regard to temperature and nutrient or pesticide inputs. Again, the EPA 303d list provides a useful starting point for identifying disruptions to water quality. Many streams throughout the West are listed as water quality impaired, which indicates that some type of restoration may be necessary. In general, further field inventories are necessary to clarify the exact nature of the problem and identify corrective actions.

Water quality assessments may include direct measures of water quality parameters and relationships among parameters and biotic assemblages may help identify where disruptions are most important (Waite and Carpenter 2000). For example, multivariate classification and ordination were used to examine patterns in chemical and physical variables in association with relative fish abundance in the Willamette River basin (Waite and Carpenter 2000). Patterns of fish assemblages were primarily related to water temperature, dissolved oxygen, and stream channel gradient at the ecoregion scale. However, chemical concentrations of pesticides and total phosphorus were more important than physical habitat features in low gradient floodplain regions such as the Willamette Valley (Waite and Carpenter 2000). Water quality restoration actions may thus need to be a priority in such areas. (Additional biological indicators are discussed later in this section.)

Reach-level processes

Reach-level processes are those processes that directly affect the adjacent reach (Table 7), such as riparian functions and floodplain-channel interactions. An extensive body of literature describes linkages between riparian forest functions and stream habitat, which in turn affect the survival and abundance of salmonids. Riparian functions include supply of wood and leaf litter to streams (Naiman et al. 1992), shading (Beschta et al. 1987), and root reinforcement of streambanks and floodplain soils (Platts 1991, Elmore 1992). Dominant functions vary by ecoregion, though many streams even in the driest ecoregions have or had a forested riparian corridor (Platts 1991). Channel and floodplain interactions form a wide array of habitats that salmonids historically occupied (Sedell and Luchessa 1982, Peterson and Reid 1984, Collins et al. 2002). Many of these habitats are now either destroyed or inaccessible to salmon due to the effects of levees, dams, channel incision, or other land uses (Sedell and Luchessa 1982, Beechie et al. 1994, Peacock 1994, Shafroth 1999, Pohl 1999, Beechie et al. 2001, Collins et al. 2002).

Identifying disrupted riparian processes—The level of wood input or other riparian functions increases with increasing width of forest buffer on streams (Figure 13), and the proportion of function occurring within a given distance of the channel edge varies by function (e.g., Sedell et al. 1997). These types of relationships can be used to evaluate the current status of functional interaction between a stream reach and riparian area and indicate whether existing levels of riparian protection are sufficient to ensure continued function. A similar assessment approach can be applied to other types of riparian systems and for different riparian functions.

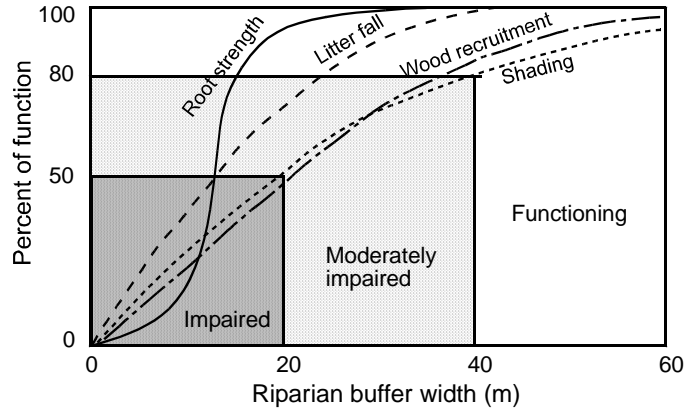


Figure 13. Illustration of change in riparian function with distance from channel (curves adapted from Sedell et al. 1997) and the Skagit Watershed Council's classification of impaired, moderately impaired, and functioning riparian forests.

Two types of assessments are required for reach-level processes. First a coarse-resolution assessment identifies where reach-level processes have been disrupted, providing a general sense of the change in riparian function from historical conditions (e.g., Lunetta et al. 1997, OWEB 1999a). Subwatersheds where the current distribution of riparian conditions deviates markedly from that expected under a natural disturbance regime are general locations where riparian restoration efforts may be appropriate. The same data can also help resource managers understand how land use practices differ in degree of impact on riparian functions, which can then help assess the potential impacts of large-scale land use policies on salmon habitat recovery (e.g., evaluating potential effects of growth management legislation).

Second, field inventories of riparian sites must be used to identify specific restoration actions (Clary and Leninger 2000, see our Appendix C). Field inventories may consist of initial measurements and classification from aerial photography combined with field confirmation of the riparian vegetation conditions for each stream reach. Newly developed, multispectral technologies may also identify riparian conditions with sufficient detail for site-scale planning purposes. At a minimum, they should classify riparian conditions by buffer width, stand type, and age of vegetation. From the data, managers can identify impaired or moderately impaired stream segments in order to determine the likely cause of that impairment and identify required restoration actions. In general, impairment is defined with respect to a natural reference condition, which is usually based on historical information (e.g., OWEB 1999a, Collins and Montgomery 2001, our Appendix C). However, in grazed riparian areas where the natural riparian vegetation is not forested, identification of disrupted riparian function may rely on other measures to indicate levels of disturbance (Clary and Leninger 2000, Turner and Clary 2001).

Regardless of current condition of riparian areas, establishing protected areas along the channel where natural riparian vegetation can develop through time and interact with the stream is a necessary component of passive riparian restoration. Active restoration efforts may include exclusion of livestock in drier riparian systems with less woody vegetation (Clary et al. 1996, Clary 1999), as well as planting desired riparian plant species or manipulating existing vegetation to accelerate tree growth and the development of desired stand structural characteristics (Berg et al. 1996, Beechie et al. 2000).

Channel-floodplain interactions—Disruptions to floodplain and channel interactions may also dramatically reduce abundance of wood, pools, and off-channel habitats in larger river systems. These disruptions may result from altered sediment and wood supplies (e.g., downstream of dams, Pohl 1999, Shafroth 1999), installation of dikes and riprap to control channel movement (e.g., Beechie et al. 1994, Collins et al. 2002), and channel incision that isolates a channel from its floodplain (e.g., Peacock 1994). Inventories that can help identify these disruptions include measurement of channels no longer accessible to salmon (Sedell and Luchessa 1982, Beechie et al. 1994), mapping of dikes, riprap, and disconnected floodplain surfaces (Appendix C), aerial photograph inventories of channel and habitat changes downstream of dams (Pohl 1999, Shafroth 1999), and inventories of incised channel segments.

Stream channel classification systems can also help identify disruptions in channel-floodplain interactions. Stream classification systems use a suite of variables such as geology, valley floor constraint, and channel slope to determine stream channel type and response of channels to changes in inputs such as water, wood, sediment, and energy over an entire

watershed (Table 8). Stream channel classification systems reduce the number of variables and measurements needed to differentiate site response to channel-floodplain disruption by controlling for some of the site-to-site variation in landscape characteristics. The features used to classify channel reaches and valley segments are often relevant for the development of channel-floodplain restoration plans, as stream reaches that have similar physical characteristics will respond to restoration actions similarly. These classification systems should be used in conjunction with the preceding inventory methods.

Habitat connectivity—impaired fish passage

Assessing isolated habitats is one of the simplest inventories to conduct, because criteria for fish migration blockages are relatively clear and identifying the amount of habitat affected involves little subjectivity. The Northwest states developed fish passage criteria for juvenile and adult salmonids to use as the basis for identifying fish blockages (WDFW 1998, ODFW 2001). Private landowners, watershed groups, and local, state, and federal agencies subsequently developed systematic methods to restore habitats through barrier inventory, assessment, and allocation of funds to correct the fish passage problems identified (ODFW 2001, WDFW 2001). Combining these inventory results with cost estimates for restoration actions allows resource managers to rank the cost-effectiveness of individual projects in order to more effectively direct the expenditure of limited restoration funds. For example, cost-effectiveness of reconnection projects can be estimated based on the habitat area upstream of the project multiplied by the average life span of a blockage (≈ 50 years) and divided by the cost of the project (Pess et al. 2003). These results allowed natural resource agencies to identify the most cost-effective projects for reconnecting blocked tributary habitats based on benefits to multiple salmonid species, as well as costs of reconstructing individual stream crossings (Pess et al. 2003).

Water diversions can also impair fish passage and have been a recognized problem for salmonids in the Northwest. There are almost 76,000 permitted water diversions in Oregon alone, however, many do not affect ESA-listed salmonids (OPSW 2001). NOAA Fisheries, California, Idaho, Oregon, and Washington have all developed criteria to exclude both juvenile and adult salmonids from being entrained in water diverted without being impinged on diversion screens (NMFS 1995, CDFG 2000, ODFW 2001, WDFW 2001). The criteria developed by state and federal agencies allow for the development of inventories because it involves less subjectivity. Again, combining these inventory results with cost estimates for restoration actions allows managers to rank the cost-effectiveness of individual projects in order to more effectively direct the expenditure of limited restoration funds.

Assessing Biological Integrity

A key component of salmon habitat is the stream biota itself. Invertebrates, amphibians, diatoms, and other stream organisms are integral parts of the aquatic food web upon which threatened and endangered fish species depend. These assemblages are also sensitive to a variety of watershed disturbances expressed over multiple spatial scales, and therefore excellent indicators of stream condition. Unlike anadromous fishes that are subject to varied disturbances in both the marine and freshwater environments (e.g., migration blockages, interaction with hatchery fish, damaged estuarine habitats, or overharvest), less migratory stream organisms often

Table 8. Summary of contemporary spatial scale classifications. (Adapted from Bauer and Ralph 1999.)

Classification system reference	Spatial scale addressed by classification system						
	Eco-region	River basin	Water-shed	Sub-watershed	Valley segment	Stream reach	Habitat unit
Bisson et al. 1982							X
Frissell et al. 1986			X	X	X	X	X
Seaber et al. 1987		X	X	X			
Paustian 1992				X	X	X	
Maxwell et al. 1995	X	X	X	X	X	X	
Rosgen 1994					X	X	
Montgomery and Buffington 1997						X	
Omernik and Bailey 1997	X	X	X				

provide a more accurate reflection of site condition. Much research in the field of biological assessment (measuring and evaluating biota directly) has focused on benthic invertebrates as indicator organisms (Rosenburg and Resh 1993, Merritt and Cummins 1996). Over the past century, bioassessment techniques using invertebrates and other assemblages have ranged from saprobien indexes (Hilsenhoff 1982) to toxicity testing (Buikema and Voshell 1993), indicator species abundance (Farwell et al. 1999), diversity indexes (Wilhm and Dorris 1966), and more recently to multivariate models (Wright et al. 2000) and multimetric indexes (Davis and Simon 1995).

In the context of ecosystem recovery planning, these bioassessment tools can identify high quality areas in need of protection and degraded reaches in need of restoration, and assist in identifying the specific stressors causing biological impairment (such as factors discussed in the preceding subsections of this section). This type of information will help focus assessments of disrupted ecosystem processes on those impacts that are most biologically important (Beechie and Bolton 1999). Of late, many studies incorporating specific bioassessment tools have evaluated the relationships between these measures of instream biological condition and land uses/land cover patterns over multiple spatial scales (Steedman 1988, Richards et al. 1996, Allan et al. 1997, Wang et al. 1997, Morley and Karr 2002). Some applications of this research include linking specific land use impacts and current condition of stream reaches, and setting realistic recovery goals given current land use patterns in particular river basins. We anticipate that these biological assessments will be most valuable in urban and agricultural areas where multiple impacts are likely to have occurred and the array of necessary process assessments may be prohibitively expensive without information to help prioritize them.

Multivariate models

In this approach a predictive model is developed based on a large (≈ 200 sites) data set of reference (minimally disturbed) sites (Reynoldson et al. 2001). Using multivariate statistical analyses, reference sites are matched to a set of habitat descriptors (e.g., stream order, elevation, geology, etc.) and classified into groups. Level of impairment at a given sample site is then determined by comparison to the appropriate reference group. This approach has been most widely applied with the development of RIVPACS (River Invertebrate Prediction and Classification System) in England, AUSRIVAS (Australian River Assessment Scheme) in Australia, and BEAST (Benthic Assessment of Sediment) in Canada (Wright et al. 2000). In the Pacific Northwest, multivariate models have been developed for the Fraser River basin in British Columbia (Reynoldson et al. 2001) and with the BORIS (Benthic Evaluation of Oregon Rivers) model in Oregon (Canale 1999). Based on benthic invertebrates, BORIS scores a site from 0 (severe impairment) to 100 (comparable to reference condition). A RIVPACS-type predictive model applicable to wadeable streams throughout Oregon, Washington, and Idaho is currently being developed (Hawkins and Ostermiller 2001, G. Hayslip¹).

Multimetric indexes

Multimetric indexes, such as an Index of Biological Integrity (IBI), integrate empirically tested metrics of stream biota (Karr and Chu 1999). This approach was first developed using

¹ G. Hayslip, U.S. EPA, Region 10, 1200 Sixth Ave., Seattle, WA 98101. Pers. commun., March 2002.

fish communities in the midwestern United States (Karr et al. 1986), but has since been modified for a variety of assemblages—most commonly fish (Simon 1998), invertebrates (Kerans and Karr 1994), and algae (Hill et al. 2000). As with multivariate models, IBIs and other multimetric indexes are regionally calibrated based on ecoregion designations and local reference conditions. In the Pacific Northwest, an IBI using benthic macroinvertebrates was developed and calibrated with data from both Oregon and Washington (Kleindl 1995, Fore et al. 1996, Morley 2000, Adams 2001). This index, known as the Benthic Index of Biological Integrity or B-IBI (Karr and Chu 1999), is composed of 10 measures of taxa richness, population structure, disturbance tolerance, and feeding ecology (Table 9). When scores from these metrics are summed, the B-IBI provides a numeric synthesis of site condition that ranges from 10 (poor) to 50 (excellent) and can determine five categories of resource condition (Doberstein et al. 2000). Multimetric indexes developed in other states differ somewhat in field methods and metrics (Hayslip in press).

Applications

While many of the current bioassessment protocols in use across the nation were developed largely in response to legal mandates under the CWA, these monitoring tools have much application to recovery planning under the ESA. In response to the CWA's legal mandate "to restore and maintain the chemical, physical, and biological integrity of the nation's waters" (CWA 1972) and under EPA guidance (Plafkin et al. 1989, Barbour et al. 1999), states developed assessment protocols and water quality standards to determine if their water bodies are supporting beneficial uses such as recreation, domestic water supply, and—most pertinent to recovery planning efforts—aquatic life attainment. Although these assessment protocols and water quality standards were traditionally focused primarily on physical and chemical criteria, over the last decade there has been increasing incorporation of biological indicators that directly measure aquatic life and the maintenance of "biological integrity."

Biological integrity has been defined in many ways. Here we use it as defined by Karr (1991): "the capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of the natural habitat of the regions." States and other public and private entities use information collected under the CWA reporting requirements in much the same way that it could be applied to ESA recovery planning, for examples: in watershed assessments that inventory biological condition across large areas and quantify level of impairment; as a screening tool for identifying areas in need of further biological, physical, or chemical evaluation; in risk assessments, pollution permitting, and evaluation of proposed habitat modifications; and in prioritizing areas in need of protection and restoration, then evaluating these conservation actions (Yoder and Rankin 1998, Karr and Chu 1999, Morley and Karr 2002). In the following paragraphs, we describe biological assessment protocols currently in development or in place in the western United States.

State environmental agencies apply both multimetric and multivariate techniques to assess and report on the biological integrity of surface waters. The Idaho Department of Environmental Quality has developed an ecological assessment framework for wadeable streams and larger rivers that is composed of four multimetric indexes based on invertebrates, fish, diatoms, and physiochemical parameters (Grafe 2000a, 2000b). The California Department of

Table 9. The 10 metrics of the B-IBI and their predicted responses to increasing human disturbance.

Metric	Description	Response
<i>Taxa richness and composition</i>		
Total taxa	Richness	Decrease
Mayfly taxa	Richness	Decrease
Stonefly taxa	Richness	Decrease
Caddisfly taxa	Richness	Decrease
<i>Population structure</i>		
Dominance by top 3 taxa	Relative abundance	Increase
Long-lived taxa	Richness	Decrease
<i>Tolerance and intolerance</i>		
Intolerant taxa	Richness	Decrease
Tolerant taxa	Relative abundance	Increase
<i>Feeding and other habits</i>		
Clinger taxa	Richness	Decrease
Predators	Relative abundance	Decrease

Fish and Game uses a 19-metric invertebrate stream bioassessment procedure modified from the EPA's national Rapid Bioassessment Protocols (Barbour et al. 1999). The University of Alaska at Anchorage, working in conjunction with the state's Department of Environmental Conservation, is developing an invertebrate multimetric stream condition index for three stream types defined by gradient and substrate (Major et al. 2001). The Washington Department of Ecology and Oregon Department of Environmental Quality currently apply a combination of multimetric and multivariate approaches to assess the condition of streams and rivers (Mochan and Mrazik 2000, Plotnikoff and Wiseman 2001). All the states discussed above include narrative biological criteria in their water quality standards; taking this a step further, Oregon will soon incorporate numeric biocriteria in its standards (Hayslip footnote 1).

Although the state environmental agencies are largely responsible for defining, evaluating, and protecting designated uses of water bodies under the CWA, federal, tribal, and local regulatory agencies, volunteer, nonprofit, and private organizations, and academic institutions also conduct bioassessments to varying degrees. At a regional level, monitoring work conducted under the Northwest Forest Plan includes bioassessment of invertebrates, periphyton, and fishes (Reeves et al. 2002). In the Puget Sound region, the B-IBI has been applied by city and county agencies (King County 1996, Thornburgh and Williams 2000), university scientists (May et al. 1997, Larson et al. 2001, Morley and Karr 2002), and volunteers (Fore et al. 2001) to track the health of streams over time, screen watersheds for further physical or chemical monitoring, and evaluate various restoration and conservation strategies. For example, two studies recently conducted in Washington used the B-IBI and other invertebrate metrics to evaluate the biological effectiveness of wood placement in forested (O'Neal et al. 1999) and urban (Larson et al. 2001) basins.

Tuning restoration efforts to site-specific needs is enhanced by using biology to aid detection of primary causes of degradation. Both multimetric indexes and multivariate analyses provide a numeric synthesis of the biological dimensions of site condition, but they can also be broken down to derive descriptive and potentially diagnostic information from each of the component metrics. For instance, in the case of aquatic invertebrates, there are hundreds of species throughout the Western states—each with specific life history requirements and varying tolerance to specific forms of disturbance (Rosenberg and Resh 1993, Merritt and Cummins 1996). The groundwork has already been laid for research on biological response signatures: “biological community characteristics that aid in distinguishing one impact type over another” (Yoder 1991, Yoder and Rankin 1995). What remains for future research is to better link biological response variables with physical and chemical manifestations of human disturbance. In addition to bioassessment for lotic waters, protocols are being developed for lake (Gerritsen et al. 1998), wetland (Adamus et al. 2001), and estuarine environments (Gibson et al. 2000). This evolving body of work will enable resource managers to better track ecological health over a larger portion of the salmon landscape.

Conclusions

Assessments of current and historical conditions of a watershed can greatly improve our efforts to plan, implement, and monitor ecosystem restoration for the recovery of Pacific salmon.

Systematically collected habitat data, a more thorough understanding of fish responses to habitat change, and a greater understanding of stream biota will allow refinement of the modeling tools used to predict fish and other biological response from application of different restoration strategies. These refinements will improve estimates of rates and pathways of recovery for many salmonid species in any river and assist in prioritizing restoration actions. However, many of these refinements are still many years from completion.

In the interim, systematic inventories of disrupted habitat-forming processes and blockages to salmon migration should be conducted to provide a complete river basin overview of necessary restoration actions that can be logically prioritized. A minimum set of inventories for any river basin should include barrier inventories, erosion inventories, floodplain and riparian characterization, channel and valley type classification, flow reduction or peak flow increase inventories, water quality inventories, and biological indicator inventories. Some of these data are already available for parts of many watersheds. These data provide the basis for identifying restoration actions, which can be prioritized by cost-effectiveness, influence on particular species, adjacency to existing population centers or centers of biological diversity (commonly called refugia, biological hot spots, source watersheds, core areas, key habitat), or other strategies.

There are many sources of uncertainty in these assessments. Uncertainties in assessments stem from natural variability in habitat-forming processes, habitat characteristics, and fish populations, as well as from errors in assumptions and limitations of data or knowledge. Our ability to characterize these types of uncertainty is limited by availability of data on watershed processes, habitat conditions, and fish populations over long periods of time. Lack of knowledge about current habitat conditions or responses of fish populations to changing habitat conditions introduces uncertainty into predictions of fish responses to watershed and habitat restoration. Improving the quality of the data reduces uncertainty related to knowledge gaps and improves our ability to address the uncertainty related to natural variability in fish response to habitat conditions.

Recovery plans designed to protect and recover processes that create and sustain riverine habitats are more likely to recover salmon of all species. Using a comprehensive assessment process and developing restoration plans focused on the reestablishment of habitat-forming processes minimizes conflicts that can arise with species-centric restoration approaches. Restoration of habitat-forming processes targets restoration of the natural array of habitat types and conditions within a watershed, which is consistent with the concepts of watershed and ecosystem management supported by the scientific community. This approach focuses on the natural potential of each watershed, and therefore is most likely to restore the diversity and abundance of stocks appropriate to each watershed in Puget Sound.

PRIORITIZING POTENTIAL RESTORATION ACTIONS WITHIN WATERSHEDS

Previous sections outlined habitat analyses for setting recovery goals (Phase I planning) and identifying ecosystem restoration actions (Phase II planning). The next step is to incorporate Phase I and Phase II information into a recovery plan and develop a prioritized list of ecosystem restoration actions within watersheds (Beechie and Bolton 1999, OWEB 2001, Roni et al. 2002). If models could accurately link changes in watershed processes to habitat changes and population responses, this would be a simple matter of running the models to see which restoration actions most efficiently attain the recovery goals. Because such models do not exist, we must rely on a longer term approach to recovery that develops initial hypotheses about which actions will be most effective, conducts management experiments to test these hypotheses, and monitors effectiveness of different actions to adjust the recovery plan in the future. In this section we describe a range of prioritization approaches for recovery planning as well as the need for management experiments and monitoring.

What Do We Know about Restoration?

The term restoration has been used to describe a suite of stream, watershed, and estuarine habitat manipulations and improvements. As we said in the Introduction section of this technical memorandum, restoration in its strictest definition is returning a site to some predisturbed condition (Gore 1985, NRC 1996). Generally it is more holistic or systemic than habitat creation, reclamation, rehabilitation, or enhancement, and not accomplished through manipulation of individual ecosystem or watershed elements (NRC 1996, Frissell and Ralph 1998). In contrast, habitat enhancement is the improvement of habitat from an existing or previous condition. It does not necessarily seek to restore conditions to some predisturbed state or to restore disrupted watershed or ecosystem processes and functions such as delivery of water, wood, and sediment. Restoration can also be further classified as passive or active (Kauffman et al. 1997). Passive techniques seek to restore processes by halting detrimental land uses, protecting areas, and setting up conditions that will allow recovery of the stream (e.g., exclusion of cattle from a riparian area). Active restoration generally seeks to create relatively rapid habitat changes (within a few months or years) in watershed processes or habitat conditions. Active techniques, which may include habitat enhancement, are those that seek to directly manipulate and improve watershed processes or habitat, such as thinning riparian areas, removing migration barriers, or placing logs in a stream channel to create pools. Here, as we said earlier, we use the term restoration generically to mean both restoration and enhancement (and related terminology), but distinguish between those activities that restore watershed or ecosystem processes and those that enhance habitat (Figure 14).

Most restoration techniques fall into five general categories—habitat reconnection, road improvement, riparian habitat, instream habitat, and nutrient enrichment. Gore (1985), Reeves et al. (1991), Slaney and Zaldokas (1997), Cowx and Welcome (1998), OWEB (1999b), and others provide descriptions of restoration techniques and information on designing and implementing them. Gore (1985), Reeves et al. (1991), and Roni et al. (2002) have reviewed common

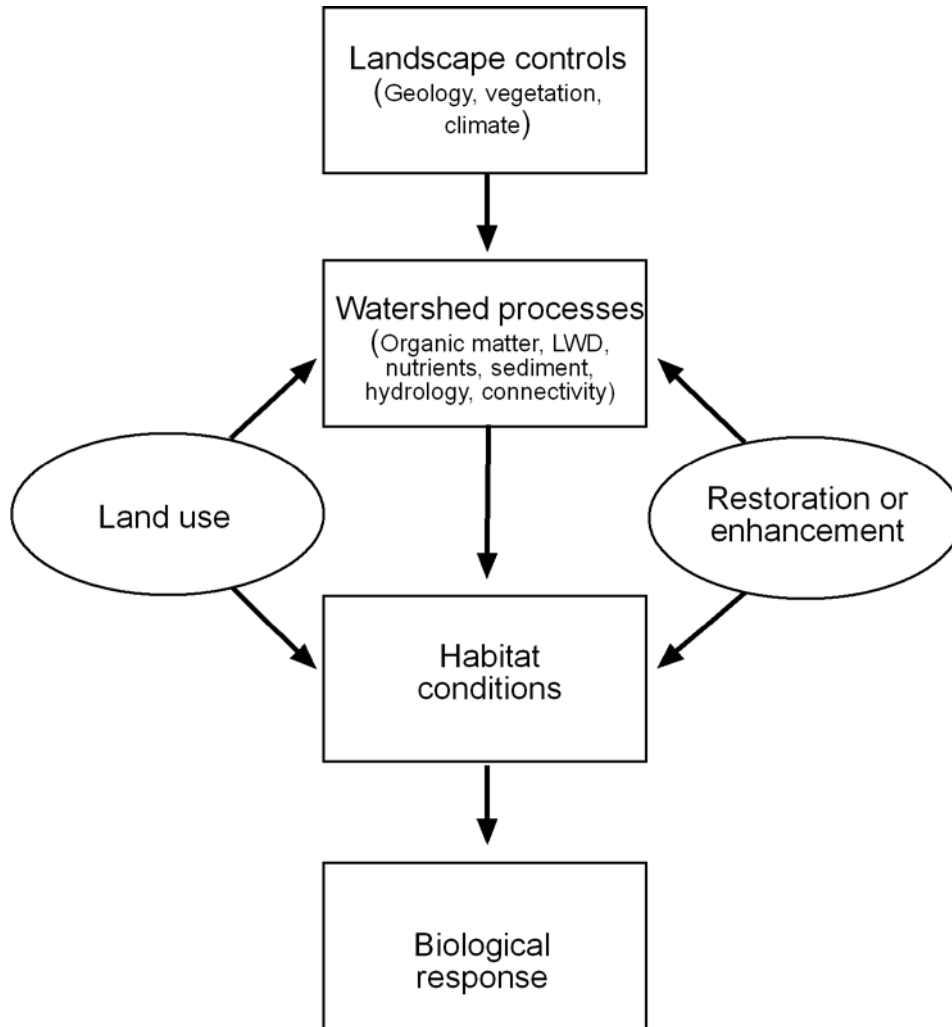


Figure 14. Simplified model of landscape controls and watershed processes, and how land use and restoration or enhancement can influence habitat and biota.

restoration techniques, their effectiveness, longevity, and whether they restore processes or are short-term habitat enhancement (Table 10). Although many authors have discussed the need to restore processes and prioritize restoration (Beechie et al. 1996, Minns et al. 1996, Jones and Moore 2000, Rieman et al. 2000, Luce et al. 2001, JNRC 2002), specific guidance on which techniques to use and how to prioritize restoration is rather limited. The lack of guidance on the appropriateness of techniques and how to prioritize restoration actions stems in part from limited information on the biological effectiveness of various techniques (Reeves et al. 1991, Chapman 1996, Roni et al. 2002, 2003). The responses of fishes to watershed and stream habitat restoration techniques have not been thoroughly evaluated, and there is considerable debate within the scientific community about the effectiveness of these techniques (Reeves et al. 1991, Kondolf 1995, Kauffman et al. 1997, Roni et al. 2002).

Most monitoring has focused on the physical response to instream restoration techniques with inadequate monitoring of fish, invertebrates, and other biota. However, the biological response to restoration techniques is often the ultimate measure of effectiveness. Monitoring juvenile and adult salmonid abundance often requires more than 10 years to detect a response to restoration, due to high interannual variability (Bisson et al. 1997, Reeves et al. 1997, Maxell 1999, Ham and Pearsons 2000, Roni et al. 2003). Moreover, some techniques such as wood and boulder placement in streams yield highly variable results (Chapman 1986) and how the results of reach-level studies can be interpreted for population level responses remains unclear. Therefore, drawing conclusions about the biological effectiveness of various techniques has been difficult and that difficulty has hampered efforts to provide scientific guidance on restoration activities.

In the 1990s the notion became widely accepted that restoring watershed processes is the key to restoring watershed health and improving fish habitat throughout western North America and elsewhere. Beechie et al. (1996), Kauffman et al. (1997), Beechie and Bolton (1999), Roni et al. (2002), and others have described restoration and recovery strategies that emphasize restoring physical and biological processes that create healthy watersheds and high-quality habitats. Yet activities that restore processes (e.g., road removal and improvement, culvert removal, and riparian and upslope restoration) are often conducted at the site or reach level. Prioritization of restoration actions needs to place site-specific restoration within a watershed context.

Strategies for Prioritizing Actions

Watershed and stream restoration are key components of many land management plans and should be an important component of most recovery plans for threatened and endangered species. Yet how site-specific actions might fit into a larger context of watershed restoration and salmon recovery often remains unclear, and many approaches to prioritizing restoration actions are available. Deciding which approach best suits a specific watershed or population may depend on many factors including how much is known about habitats that limit recovery of populations, the causes of habitat degradation in a watershed, or even the number of listed species within a watershed. Therefore, describing a single prioritization scheme applicable to all watersheds is difficult.

Table 10. Typical response time, duration, variability of success, and probability of success for common restoration techniques. (Modified from Roni et al. 2002.)

Restoration type^a	Specific action	Years to achieve response	Longevity of action (years)	Variability of success among projects	Probability of success
Reconnect habitats	Culverts	1–5	10–50+	Low	High
	Off channel	1–5	10–50+	Low	High
	Estuarine	5–20	10–50+	Moderate	Moderate to high
	Instream flows	1–5	10–50+	Low	High
Roads and land use	Road removal	5–20	Decades to centuries	Low	High
	Road alteration	5–20	Decades to centuries	Moderate	Moderate to high
	Change in land use	10+	Decades to centuries	Unknown	Unknown
Riparian restoration	Fencing	5–20	10–50+	Low	Moderate to high
	Riparian replanting	5–20	10–50+	Low	Moderate to high
	Rest-rotation or grazing strategy	5–20	10–50+	Moderate	Moderate
	Conifer conversion	10–100	Centuries	High	Low to moderate
Instream habitat restoration	Artificial log structures	1–5	5–20	High	Low to high ^b
	Natural LWD placement	1–5	5–20	High	Low to high ^b
	Artificial log jams	1–5	10–50+	Moderate	Low to high ^b
	Boulder placement	1–5	5–20	Moderate	Low to high ^b
	Gabions	1–5	10	Moderate	Low to high ^b
Nutrient enrichment	Carcass placement	1–5	Unknown	Low	Moderate to high
	Stream fertilization	1–5	Unknown	Moderate	Moderate to high
Habitat creation	Off channel	1–5	10–50+	High	Moderate
	Estuarine	5–10	10–50+	High	Low
	Instream	See various instream restoration techniques above			

^a The first three categories of restoration (reconnect isolated habitats, roads and land use, and riparian restoration) are considered process-based or passive restoration; the last three (instream, nutrient enrichment, and habitat creation) are considered enhancement or active restoration.

^b Depends on species and project design.

Here we describe several strategies to prioritize restoration actions, beginning with an interim approach to prioritizing site-specific restoration activities in a watershed context. This interim approach, based primarily on the effectiveness and longevity of specific types of restoration actions, does not require detailed information about which habitats limit population recovery. We then describe a second approach for watersheds where only one species is listed and priorities may be directed toward those actions that are most likely to benefit the listed species. Finally, we compare several alternative approaches (including refugia and multispecies approaches) to illustrate how priorities might differ under different prioritization schemes. We focus on those activities that occur within an individual watershed (U.S. Geological Survey 5th or 6th field hydrologic unit or HUC). Other large-scale restoration efforts that may occur at the basin or ESU scale, and thus may influence many watersheds, should be prioritized within a basin or ESU. We do not discuss such broad-scale priorities here.

An Interim Approach

In the absence of detailed knowledge of factors limiting recovery, an interim prioritization scheme can serve to logically sequence different types of restoration actions based on their probability and variability of success, response time, and longevity (Table 10). All else being equal (e.g., costs, listed species concerns), those techniques that have a high probability of success, low variability among projects, and relatively quick response time should be implemented before other techniques. For example, reconnecting isolated off-channel habitats or blocked tributaries provides a quick biological response, is likely to last many decades, and has a high likelihood of success. By contrast, riparian restoration or road improvement may not produce results for many years or even decades for some functions, yet improvements will be long lasting. Other techniques such as instream large woody debris (LWD) placement are generally effective at increasing coho salmon densities (but less effective for other species), and have relatively short longevity.

Using information summarized in Table 10, Roni et al. (2002) developed a hierarchical flow chart that can be used to help guide the selection and prioritization of restoration projects based on understanding watershed processes and known effectiveness of techniques (Figure 15). Protection of high-quality habitat should be given priority over habitat restoration, as maintaining good habitat is typically far easier and more successful than trying to recreate or restore degraded habitat. Among restoration options, reconnection of high-quality habitat should be undertaken before methods that produce less consistent results. Watershed process restoration is typically the next highest priority, and instream actions such as LWD placement should be undertaken either after or in conjunction with reconnection of isolated habitats and other efforts to restore watershed processes. Manipulation of instream habitat may also be appropriate where short-term increases in fish production are needed for a threatened or endangered species (Beechie and Bolton 1999).

While most techniques fit well into this hierarchy, estuarine restoration, carcass placement, and nutrient enhancement are relatively new techniques whose places in this hierarchy are uncertain. Although comparatively little is known about the effectiveness of estuarine restoration, reconnecting isolated estuarine habitats such as distributary sloughs is similar to reconnecting isolated off-channel habitats, which has shown to be effective (Table 10).

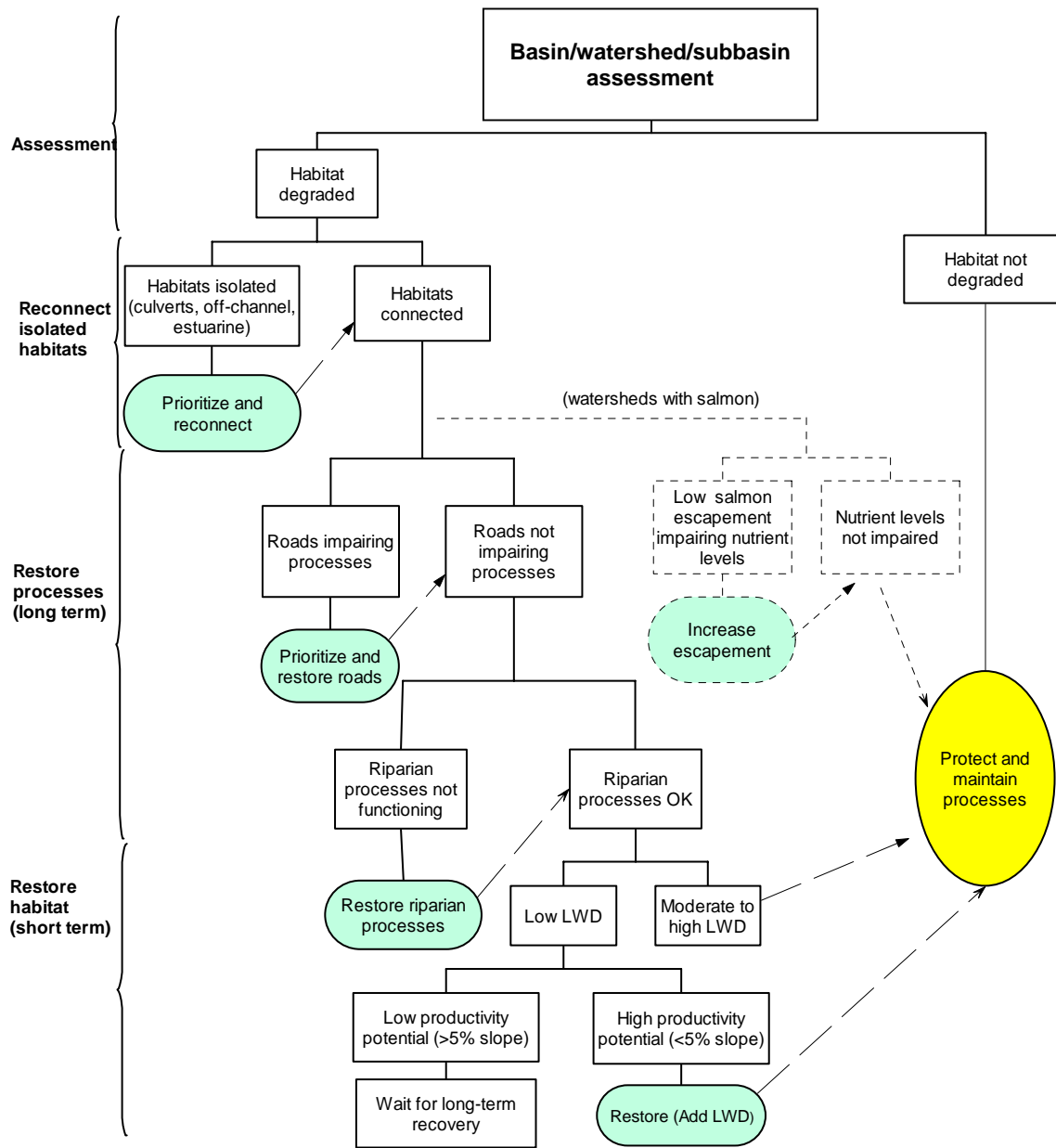


Figure 15. Flow chart depicting hierarchical strategy for prioritizing specific restoration activities (modified from Roni et al. 2002). Shaded boxes indicate where restoration actions should take place. Addition of salmon carcasses or nutrients may be appropriate at various stages following reconnection of isolated habitats.

Given the importance of estuaries to anadromous fishes and the success of reconnecting isolated off-channel habitats, it is likely that reconnecting estuarine habitat would be effective and should be considered at the same time as reconnecting other isolated habitats. The placement of salmon carcasses or other nutrients into streams, which may increase fish condition and production in the short term, is a form of habitat enhancement that can occur at any stage in the watershed restoration process. However, because it does not restore but rather mitigates for a deficient process, we suggest that it be considered at the same point in the hierarchy as instream habitat manipulation. Similarly, the creation of new estuarine or off-channel habitats does not restore a process and the effectiveness of these efforts is unclear.

A common restoration technique not covered in Roni et al. (2002) is restoration of instream flows or natural hydrology either from water withdrawal projects or below large water storage projects. Water withdrawal or flow manipulation disrupts hydrologic processes, including delivery and routing of sediment and nutrients, and can dramatically impact habitat formation, connectivity, and quality (Bednarek 2001). We consider restoring instream flows and natural hydrologic patterns part of restoring watershed processes, and therefore do not have a separate category for this technique. Upslope activities and land use can also have dramatic effects on stream hydrology, sediment delivery, water chemistry, and water quality. Altering land use and other upslope restoration techniques not explicitly discussed in Roni et al. (2002) also can be included with restoring watershed processes.

Within the broad restoration categories in Table 10, some techniques are more effective than others or more applicable in some provinces than others. For example, we include riparian silviculture (e.g., replanting, conifer conversion), fencing, and reduced grazing under riparian restoration. Livestock exclusion is a form of riparian protection that has been shown to be effective on range and agricultural lands (Platts 1991), while the long-term effectiveness of riparian replanting and conversion in forested watersheds is largely unknown. Priorities for various types of riparian restoration will differ by region and watershed, as will other specific restoration techniques that fall into these broad categories. However, a watershed assessment is the important first step to determine the most effective type of restoration within a given restoration category for the watershed in question (Beechie et al. 2003).

The principles outlined above were designed primarily for forest, range, and other moderately modified rural lands. However, they are still useful in urban and agricultural lands, even though other factors such as large infrastructure (e.g., highways and buildings) may constrain certain restoration opportunities. In urban areas, hydrologic and sediment processes in streams are highly altered (e.g., increased high flows and channel downcutting). Areas with intensive agriculture often have severe water quality problems. Stream channels in both urban and agricultural areas are often highly channelized and lack adequate riparian vegetation. Thus the framework we outline may need to be modified for use in these highly altered systems where some processes cannot be reliably restored, or where water quality or hydrologic changes may compromise the effectiveness of many of the common restoration techniques.

Single Species Approaches

In watersheds where most Phase I and Phase II analyses have been completed, a more detailed prioritization of actions is possible. For this one should know:

1. Which habitats are most impaired or most likely inhibiting recovery of populations (from Phase I assessments)?
2. Which impaired ecosystem processes prevent recovery of the limiting habitats (from Phase II assessments)?

The information from Phase I assessments can be used to identify high priority areas for salmon recovery. Because habitat use varies by species and life history pattern, the same list of habitat recovery areas might be prioritized differently depending on the species of interest (e.g., Beechie and Bolton 1999, Figure 16). In general, habitat areas should be classified at a relatively coarse level of resolution (e.g., estuary, main stem, overwintering habitats), because the information available for evaluating which habitats limit salmon recovery is very sparse and the certainty of the answers is very low (see also the Managing Uncertainty in Habitat Recovery Planning section, page 74). While EDT analyses have a finer spatial resolution, their results should be used only in the most general terms because of the large number of uncertainties inherent in 1) the collection of information, 2) the models used to estimate fish responses, and 3) the lack of model validation.

Once specific habitat areas have been prioritized, the results of Phase II assessments can be examined to determine which restoration actions are required for recovery of the high-priority habitat areas. The Phase II assessments identify the causes of habitat degradation by evaluating where ecosystem processes have been disrupted and inventorying specific causes of habitat loss (e.g., barrier inventory, road sediment reduction inventory, riparian inventory). Thus if Phase I assessments identify a specific habitat area as a likely limiting habitat (e.g., the estuary or tributaries for early rearing), then Phase II assessments identify the causes of degradation within that area (see also Appendix C, page 157, for examples).

It is critical to bear in mind that the prioritization of actions does not alter the types of actions that are needed to restore ecosystems that support salmon (Beechie and Bolton 1999). Rather the Phase II assessments identify the suite of actions needed to restore ecosystem processes and functions, and prioritization alters the sequence in which those actions are taken (Figure 16). This of course implies that restoration of ecosystems to support salmon will include a wide range of actions affecting the entire life cycles of multiple species. However, where a single species is listed, altering the sequence of those actions for most rapid recovery of the listed species may be prudent.

Alternative Prioritization Schemes

Alternative strategies for prioritizing restoration that incorporate economic, ecological, and biological factors have been proposed or used, especially where there are multiple listed species and attempting to prioritize actions based on the needs of individual species would lead to conflicting priorities. In such cases other approaches to prioritization may be more appropriate, such as the refugia approach (Sedell et al. 1990) or a multispecies, cost-effectiveness approach (e.g., SWC 1998). Where at least one species appears to be at high risk of extinction, the refugia approach may be most appropriate to make sure that individual populations are preserved first. By contrast, watersheds with relatively stable populations might embark on a longer term, process-based approach to ecosystem recovery. It is likely that most recovery plans will incorporate different strategies for different watersheds or populations.

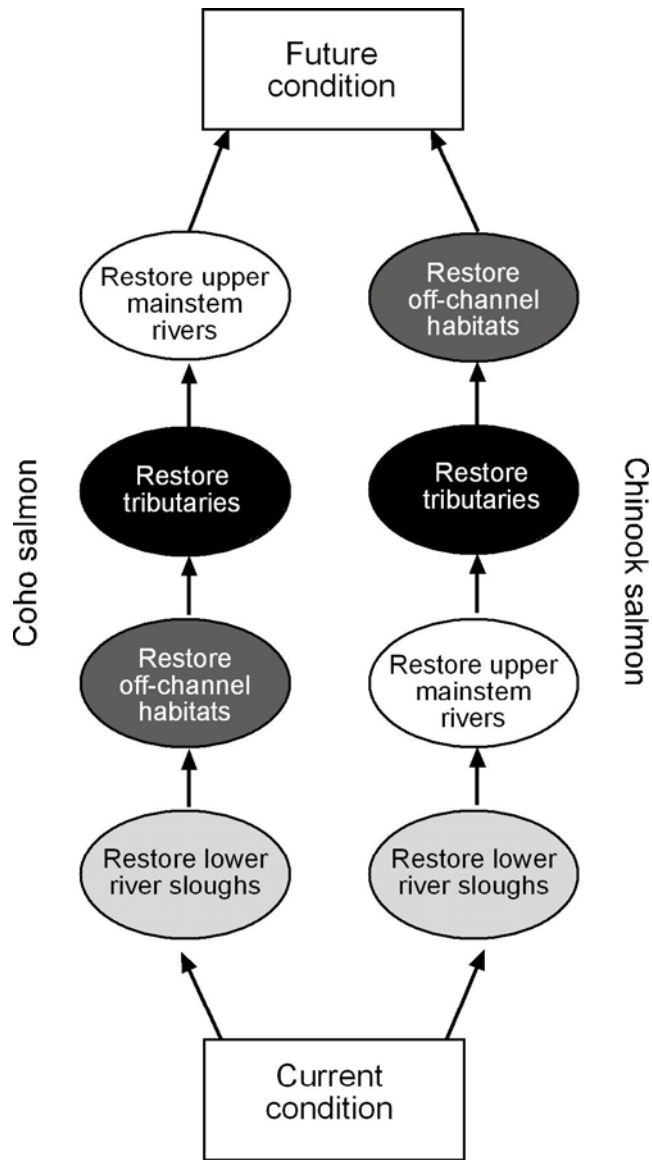


Figure 16. Prioritization sequence for habitat restoration based on species of interest. (Modified from Beechie and Bolton 1999.)

Sedell et al. (1990), Wasserman et al. (1995), Beechie et al. (1996), Frissell (1993a), Frissell and Bayles (1996), and others have outlined restoration strategies that focus on providing refugia and protecting high quality habitats. Beechie et al. (1996) outlined a prioritization strategy that focused on providing refugia for a depressed steelhead stock in Deer Creek, Washington. Other strategies might prioritize actions on potential increase in fish numbers, total cost, cost per fish, aquatic diversity, metapopulation attributes, or scoring based on a suite of these and other factors (e.g., Beechie et al. 1996, Frissell and Bayles 1996, Doyle 1997, SRSRC 2002, LCFRB 2002). Some states such as Oregon have developed sequential methodologies for conducting assessments and prioritizing and implementing restoration activities (Figure 17). These various strategies incorporate management goals beyond simply restoring watershed or ecosystem processes and habitat. Thus the sequencing of restoration actions under different prioritization strategies will vary.

We demonstrate how priorities might vary with prioritization schemes by developing a hypothetical list of potential restoration actions (Table 11) and ranking those actions using different prioritization schemes (Table 12). This analysis indicates that if actions were prioritized based on Roni et al. (2002), impassable culverts and reconnection of habitats would occur first, followed by road, riparian, and LWD placement. If actions were prioritized by whether they were in refugia for an ESA-listed species, instream flow and LWD placement would be first, simply because they are in a high priority area. Similarly, different cost, cost/fish, and total fish production all produced slightly different prioritization scenarios. This simple example illustrates how priorities might differ based on the method, information used, and management objectives. In the next section, *Managing Uncertainty in Salmon Habitat Recovery Planning*, we also discuss accounting for uncertainty in prioritizing restoration actions toward incorporating the risks and likelihoods of success and failure (physical, biological, or financial) into the planning process.

The appropriate method for prioritizing restoration activities within a watershed will depend on numerous factors. Our intent here is to discuss how one prioritizes site-specific restoration actions within a watershed. However, all else being equal or if limited information is available, we recommend a strategy similar to that outlined in Roni et al. (2002, see Figure 15) that focuses on reconnecting isolated habitats and restoring watershed processes before or alongside habitat manipulations or enhancement.

Need for Monitoring and Management Experiments

Reviews of various restoration techniques (e.g., Roni et al. 2002) indicate that knowledge about the effectiveness of most techniques is incomplete and comprehensive research and monitoring are needed. Even techniques that appear to be well studied such as instream LWD placement need more thorough evaluation and long-term monitoring. This emphasizes the need for comprehensive monitoring and evaluation of both individual and multiple restoration actions at multiple scales. Many restoration actions should be treated as management experiments and accompanied by research and monitoring to determine both physical and biological responses. These results, crucial for adaptive management, can then be used to guide future restoration actions and more accurately quantify the potential increase in fish production for habitat

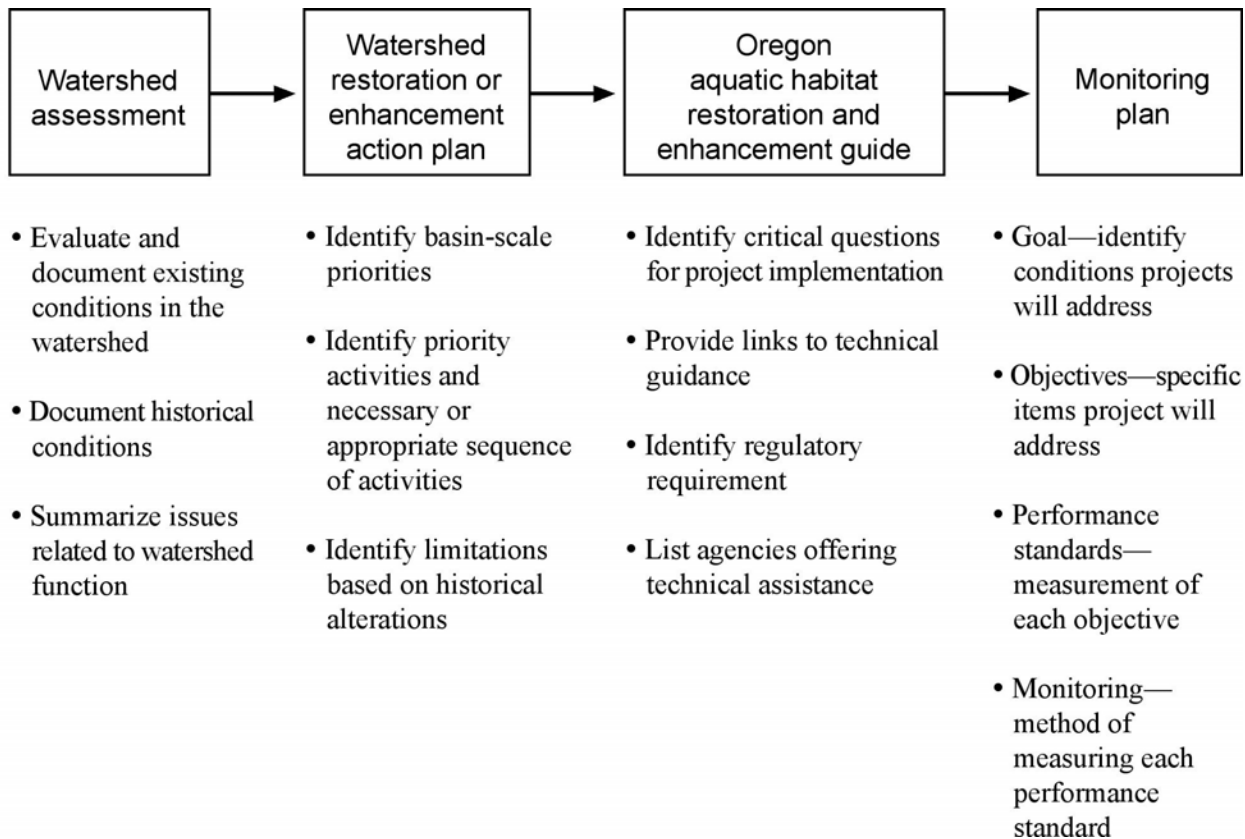


Figure 17. Process for restoration planning, prioritization, and implementation used by the Oregon Watershed Enhancement Board, Oregon Department of Fish and Wildlife, and State of Oregon. (Based on figure in OWEB 1999b.)

Table 11. Example of list of potential restoration actions within a watershed. All stream names and numbers are fictitious and for demonstration purposes only.

Site ID	Site name	Action	Refugia ^a	Km treated	M ² treated	Coho smolts ^b	Chinook smolts ^b	Total cost	\$/coho
A	Clark Creek	LWD placement	2	3	15,000	3,750	750	50,000	13.30
B	Upper Simpson Creek	LWD placement	1	2	10,000	2,500	500	32,000	12.80
C	Lower Simpson Creek	LWD placement	1	2	14,000	3,500	700	35,000	10.00
D	Check Creek	Fencing/cattle exclusion	1	5	60,000	6,000	3,000	20,000	3.30
E	Dry Creek	Increase instream flows	2	20	200,000	20,000	10,000	500,000	25.00
F	Big River	Reconnect estuarine tidal channel (e.g., dike removal)	3	1	100,000	10,000	50,000	350,000	35.00
G	Big River	Excavate new estuarine slough	3	2	200,000	20,000	100,000	750,000	37.50
H	Clark Creek	Culvert replacement/fish passage	2	3	15,000	3,750	0	150,000	40.00
I	Simpson Creek	Road decommissioning	1	20	200,000	20,000	10,000	1,500,000	75.00
J	Clark Creek	Road resurfacing/sediment reduction	2	10	50,000	5,000	2500	750,000	150.00
K	Big River Slough	Reconnect isolated oxbow slough	3	4	800,000	400,000	40,000	75,000	0.19

^a Refugia numbers, based on Beechie et al. 1996, are: 1 = refugia (areas where recovery is relatively predictable); 2 = key habitat areas or areas that provide for the largest long-term recovery of species of interest, but are sensitive to disturbance and more difficult to restore; and 3 = key habitat areas or areas expected to provide the smallest gain for species of interest.

^b Numbers represent expected annual increase in smolt production.

Table 12. Example of different order of priorities based on different prioritization methods using information in Table 11. Two of the methods of prioritization, Roni et al. (2002), based on the project sequence in Figure 15, and refugia, do not distinguish between projects of the same type. Hence there are only four levels and three levels for the two methods, respectively.

Site ID	Potential restoration action	Roni et al.	Refugia	Total cost	Cost/coho	Total fish
A	LWD placement	4	2	4	5	8
B	LWD placement	4	1	2	4	11
C	LWD placement	4	1	3	3	9
D	Fencing/cattle exclusion	3	1	1	2	6
E	Increase instream flows	1	2	8	6	4
F	Reconnect estuarine tidal channel (e.g., dike removal)	1	3	7	7	3
G	Excavate new estuarine slough	4	3	10	8	2
H	Culvert replacement/fish passage	1	2	6	9	10
I	Road decommissioning	2	1	11	10	5
J	Road resurfacing/sediment reduction	2	2	9	11	7
K	Reconnect isolated oxbow slough	1	3	5	1	1

manipulations. Ultimately, monitoring and evaluating these actions will help us prioritize restoration opportunities and wisely spend limited restoration and recovery funds for salmon.

MANAGING UNCERTAINTY IN HABITAT RECOVERY PLANNING

The salmon ecosystem recovery planning approach proposed in this guidance document requires a complex series of decisions about habitat actions despite large amounts of uncertainty in the available information from many sources. This uncertainty can result in risks to habitats and populations from inappropriate management advice (Fogarty et al. 1996). Past failures of management plans to prevent population declines and collapse are due in part to the failure to recognize uncertainty in available information and a lack of procedures for including uncertainty in the decision-making process (Wade 2001). Inevitably, decisions will be based on a tapestry of models, estimates, expert opinions, myths, predictions, and data. By identifying, quantifying, and acknowledging the uncertainty in information used for recovery planning, we can increase the likelihood that recovery plans will be successful. The benefits of explicitly accounting for uncertainty include capturing all the available information regarding uncertain factors, providing the full range of possible outcomes and the probability of observing each, and identifying the key drivers of overall uncertainty in model projections (Mishra 2001). In this section we provide guidance via quantitative and qualitative examples for managing uncertainties inherent in habitat recovery planning.

A brief example illustrates how identifying and quantifying uncertainty can help a resource manager make explicit trade-offs between potential positive outcomes and acceptable risks. In choosing between two possible culverts for restoring fish passage, one might be given information that removal of culvert A is predicted to increase fish capacity by 120 fish while removal of culvert B is predicted to increase fish capacity by 100 fish. With no estimates of uncertainty, the manager would choose culvert A because it has the highest expected increase in fish capacity. However, more complete information might indicate that replacement of culvert A would open habitat that was less certain to be occupied (120 ± 70), while replacement of culvert B would open wetland habitat with a high degree of certainty (100 ± 10) to be quickly colonized. With the additional information, decision makers could then explicitly choose between a higher but less likely increase in fish capacity and a lower but more certain increase in fish capacity. In this example, neither action is likely to cause harm (a negative change in fish capacity). In other situations, actions with a high potential payoff may also contain some risk of being detrimental to fish, for example, when deciding whether to use chemical herbicides to remove nonnative vegetation from riparian areas. Without an estimate of the magnitude of uncertainty in the information on which decisions must be made, decision makers cannot make informed decisions.

The importance of clearly communicating uncertainty has been repeatedly emphasized in the fisheries literature (Francis and Shotton 1997):

- “Understanding the risk or uncertainty associated with choices could help fisheries managers select management strategies, decide which types of risks and uncertainty inhibit the effectiveness of management techniques, and finally, recognize which types of uncertainty must inevitably remain” (Peterson and Smith 1982).
- “Point estimates should be accompanied by variance estimates” (USCTC 1997).
- “The managers’ task may be made easier if uncertainty in a fishery assessment were expressed” (Francis 1992).

- “Scientific advice to fishery managers needs to be expressed in probabilistic terms to convey the uncertainty about the consequences of alternative harvesting policies” (McAllister et al. 1994).
- “Clearly, when management decisions are to be based on quantitative estimates from fishery assessment models, it is desirable that the uncertainty be quantified and used to calculate the probability of achieving the desired target and/or risk of incurring undesirable events” (Caddy and Mahon 1995).

Such reporting of uncertainty in data and predictions has become common in harvest management (Rosenberg and Restrepo 1994). However, uncertainty is not often incorporated into salmon habitat recovery planning despite broad consensus that considering uncertainty is important and necessary in the conservation and management of species (Mangel et al. 1996, Flaaten et al. 1998, Akcakaya et al. 2000, Ralls and Taylor 2000, Wade 2001).

In this section, we first describe five types of uncertainty embedded in predictions of habitat capacity. We follow this with two examples of uncertainty in habitat management issues related to recovery planning. In each example, we describe how management decisions might be improved by acknowledging, quantifying, and reducing uncertainty in the decision-making process. The first example describes qualitative strategies for reducing uncertainties regarding chemical contaminants and making structured decisions in the face of limited empirical data. The second example describes the use of decision tables for making decisions that incorporate uncertainty. The final subsection describes strategies for making decisions when empirical data are lacking. Here we distinguish between variability, which is characterized by differences in a variable’s value over time, space, or populations, and uncertainty, which is lack of knowledge about a true and constant value of a quantity (Morgan et al. 1990, Cullen and Frey 1999). Our discussion of methods for reducing uncertainty is purposefully simplified throughout, but references are provided for each example so that interested readers can locate more detailed information. By omitting site-specific and mathematical details, we intend to express a general framework for incorporating uncertainty into decisions.

Types of Uncertainty

Precise and accurate predictions are a fundamental goal in the aquatic sciences. Improved management of aquatic resources will result from a predictive science that can forecast the consequences, costs, and benefits of management actions (Pace 2001). A prediction might be a value (e.g., habitat capacity estimate, extinction risk, or survival rate) or a relationship between a habitat action and a biological response (e.g., effects of high flows on egg survival, effects of a particular restoration technique on fish survival, or projected population trajectories under different climate scenarios). Population viability and habitat goals (Phase I recovery planning) as well as prioritized project lists and watershed plans (Phase II recovery planning) must be developed from these types of predicted values and relationships. Informed plans and decisions will be based on both the predictions and the uncertainty surrounding them.

The five types of uncertainty found in predictions of habitat capacity are predictive uncertainty, parameter uncertainty, model uncertainty, measurement uncertainty, and natural stochastic variation (Table 13). Evaluating the relative magnitudes of the five types of

Table 13. Tools and methods for quantifying and reducing uncertainty.

Class of uncertainty	Brief definition	Habitat example	Method for quantifying	Possibility for reducing
Prediction uncertainty	Difference between modeled response and true response.	Uncertainty of predicting habitat capacity of a given watershed after instream restoration.	Leave-one-out estimates of prediction error rates. Simulation studies comparing conditions where model was built to those in which it is being applied.	Collect data for conditions in which predictions are required. Do not extrapolate beyond conditions under which model was developed.
Parameter uncertainty	Difference between true parameter (such as an average or a regression coefficient) and parameter as estimated from the data.	Uncertainty of parameters describing change in capacity as a function of changes in watershed condition.	Statistical theory for model coefficients derived from data. Sensitivity analysis for model coefficients estimated from other sources.	Collect more data or more accurate data. Collect data over a wider variety of conditions.
Model uncertainty	Difference between natural system and the mathematical equation used to describe it. Includes model form and set of predictors.	Uncertainty in relationship between habitat conditions and fish capacity. Uncertainty in which habitat descriptors are best predictors of fish capacity.	Statistical descriptions of model fit: Akaike's information criteria (AIC), Bayesian information criteria (BIC), likelihood ratios, F-statistics.	Consider wide variety of models. Conduct sensitivity analyses.
Measurement uncertainty	Difference between true value and the recorded value.	Uncertainty in measurements of data used to build the predictive model, i.e., fish or redd density under differing habitat conditions.	Test accuracy of measurement technique against standard method or known values.	Improve measurement techniques. Increase number of replicates. Calibrate biased measurement techniques.
Natural stochastic variation (process uncertainty)	Inherent random variability.	Natural fluctuations in population size, habitat selection, or habitat conditions.	Variance of the observed data. Variance of the observed data for different sets of conditions.	Collect more replicates for conditions of interest. Stratify data collection.

uncertainty embedded in a particular prediction is valuable because it tells us where to be skeptical. More formally, we may pursue value of information (VOI) analysis to establish which additional information is most likely to improve our decision-making position (Raiffa and Schlaifer 1961, Raiffa 1997). VOI techniques seek to identify situations in which the cost of reducing uncertainty is outweighed by the benefit of the reduction. In some cases, the predictive uncertainty turns out prohibitively large and the available empirical data therefore provides little guidance for decision making. In such cases, other decision-making processes that do not require quantitative predictions can be used (see Using Decision Rules When Empirical Data Are Inadequate subsection, page 86).

To a great degree, the five types of uncertainty are nested: prediction uncertainty includes parameter and model uncertainty, which each includes measurement error and natural variability. Here we start with prediction uncertainty, the broadest form of uncertainty, and work down to the underlying natural variation. We provide examples of how each type of uncertainty arises, how it might be quantified, and how it might be reduced (Table 13). We conclude each subsection with a summary of how decision making can be improved by quantifying and acknowledging each class of uncertainty. A series of questions to ask of any prediction is in Table 14.

Prediction Uncertainty

Predictions include uncertainty from natural stochastic variation of the system being modeled, measurement uncertainty of the data used to build the model, uncertainty surrounding the form of the model, and parameter uncertainty (components addressed in the following subsections). In addition, predictions can include uncertainty that results from applying a model to a new situation. For example, a capacity estimate for Watershed X might predict future capacity based on current and past data for the same watershed or an estimate of current capacity for Watershed X might be based on data collected in other watersheds. Both cases involve extrapolating from conditions under which data were collected to new conditions. Uncertainty associated with these or similar extrapolations, say from the laboratory to the field, is difficult or impossible to quantify but must be considered and described.

Prediction uncertainty can be evaluated by ground-truthing (i.e., field measurement of specific attributes), prediction confidence intervals, and cross-validation simulation studies. Ground-truthing will help quantify the accuracy and precision of past predictions about current conditions, but can only suggest how well the model may perform under future conditions. Prediction confidence intervals can be computed in situations for which the manager does not need to extrapolate beyond the original data (Zar 1984). Where there is more than one predictor variable, caution should be used in defining the joint sample space beyond which one is extrapolating. In cross-validation simulations, the model is constructed and parameterized using a subset of the data (Stone 1974). The model is then assessed by how well it predicts that subset of data excluded from model construction. Cross-validation simulations do not include uncertainty associated with extrapolating from measured to unmeasured conditions. To assess how well a model may predict unmeasured conditions requires careful consideration of those model components that may be sensitive to expected differences between measured and unmeasured conditions (i.e., current vs. future conditions). Models can be compared in their

Table 14. Questions to guide the evaluation of predictions.

Prediction uncertainty

How similar are the conditions under which the original information was gathered to those for which the prediction is being made? How sensitive is the model (data, mechanism, and parameter estimates) to site-specific details?

Parameter uncertainty

Is the prediction sensitive to small changes in parameter estimates? If so, how precise are the estimates of those parameters?

Model uncertainty

What are the assumptions on which the prediction is based? How sensitive is the prediction to these assumptions?

Measurement uncertainty

Could any of the information on which the prediction is based be biased? How precise and how accurate are the data?

Natural stochastic variation (process uncertainty)

Can measurements be stratified across conditions to reduce the effects of natural variability?

relative sensitivity to changing conditions. Models that rely on predictors only correlated with the causal factors are particularly likely to have high levels of prediction uncertainty, because in new situations the correlations on which the model is based may no longer be coincident with the causal mechanism.

Parameter Uncertainty

Model parameters are necessarily estimated with uncertainty. A statement of the uncertainty of these parameter estimates is critical for making informed management decisions. Parameters that have biological meaning provide a context for interpreting the associated uncertainty. For example, imagine one had created a regression model to estimate smolt density as a function of the number of pieces of wood in the stream. The model would include a parameter, for example 12.3, that estimated the increase in smolt density for each piece of wood. The conclusion from such a model without parameter uncertainty estimates might be to embark on a widespread wood placement plan. However, if the parameter estimate had been more completely expressed as 12.3 ± 15.1 , we might diversify the types of restoration actions used or choose a different restoration action with a smaller but more certain fish response and little or no risk of an adverse affect. For statistical models, parameter estimates are developed from the data and the uncertainty associated with these estimates is relatively easy to compute. For mechanistic models, parameters may be estimated from data, from similar models of other phenomena, or by expert opinion. When parameters are not estimated from data, the uncertainty surrounding them can be difficult or impossible to quantify. If estimates from such models are used, the potential uncertainties should be described; the direction and magnitude of the potential errors can often be estimated qualitatively.

Sensitivity analyses can be used to estimate the effect of parameter uncertainty. Nominal range or local sensitivity analysis computes the effect on model outputs of systematically varying each parameter in the model across its range of plausible values while holding the other inputs at their nominal values. Where small changes in parameter values lead to large changes in model predictions, the uncertainty of those parameters should be carefully evaluated. Models that are extremely sensitive to changes in parameter estimates and have highly uncertain estimates of those parameters will yield predictions with large uncertainty. Even where models produce highly uncertain predictions, they may be useful for quantifying the uncertainty in predictions and determining the type and quality of information that would be required to produce predictions with acceptable levels of certainty. The sensitivity analysis tells the managers that predictions are sensitive to particular conditions and that they will either have to increase precision of parameter estimates or ensure that management plans are robust to expected uncertainty. Increased precision of parameter estimates can be achieved by collecting more data, data over a wider range of values, or better data (data with less measurement uncertainty).

Model Uncertainty

Nearly all estimates and predictions used in management are explicitly or implicitly based on an underlying model. Uncertainty exists about both the model form (e.g., a linear relationship vs. a Ricker curve) and which predictor variables to include. Model uncertainty results from an incomplete understanding and a simplified representation of ecological systems

and functions (Fogarty et al. 1996). For example, we might have a model that predicts habitat capacity as a linear function of several habitat parameters: wood density, pool density, gradient, adjacent land use, and water temperature. The default assumption may be to use a simple linear regression model. However, we may be uncertain whether the effects of these five habitat descriptors are additive or have a linear relationship to habitat capacity, and we may also be unsure if these five habitat descriptors are the best set of predictors or if an alternate set might perform just as well. Many statistical tools (adjusted R-squared, Akaike's information criteria or AIC, Bayesian information criteria or BIC, F-tests, likelihood ratio tests, cross-validation metrics) are available for choosing between models (Burnham and Anderson 1998). In general these techniques balance the degree to which the model fits or predicts the data with the complexity of the model, usually expressed as the number of parameters.

Models that fail to describe the ecological process accurately or to include an important predictor can have enormous management implications. Model predictions can be of the wrong magnitude or even the wrong direction. Resource managers and ecologists have often erred significantly by failing to consider model uncertainty. For example, the prevailing model of habitat effects on fish survival once assumed that fish survival decreases with increasing amounts of instream wood, and as a result, large amounts of wood were removed from streams and rivers (Maser et al. 1988). Thus habitat degradation in the Pacific Northwest can in part be attributed to a failure to assess the possibility that this model was incorrect (Beechie et al. 1996).

Model uncertainty is very difficult to quantify because there are an infinite number of possible models; none is exactly correct. Simulation studies generate data using a particular model, then ask questions about the behavior of those data (Morgan et al. 1990). They can quantify the degree to which the structure of the model influences the model's predictions. Averaging predictions from a suite of models can reduce the impact of model uncertainty on management predictions (Burnham and Anderson 1998, Cullen and Frey 1999). Beyond these tools, reducing model uncertainty is extremely difficult. Schnute and Richards (2001) suggest that model uncertainty be managed by keeping an open mind, identifying all assumptions, and testing those assumptions continuously.

Measurement Uncertainty

Measurement uncertainty or observation error is simply the difference between a true value and our recorded observation of it. It results from measurement, sampling, and data processing errors (Francis and Shotton 1997). All observations carry some degree of measurement uncertainty. This uncertainty may be large and problematic or small and of negligible consequence. Some phenomena such as the survival of fish in different habitats are inherently difficult to measure. Consequently, the variables associated with these phenomena have a high degree of measurement uncertainty. Other phenomena such as stream discharge can be measured quite accurately. Uncertainty resulting from sampling error occurs when the measured samples are not representative of the population for which inference is being made. The incorporation of measurement and sampling errors can obscure or create relationships between variables (Ludwig and Walters 1981, Walters and Ludwig 1981). Measurement error as defined here can also occur during data processing and storage.

Measurement uncertainty is directly related to both the accuracy and the precision of the measurement technique. Accuracy in a measurement technique, the inverse of uncertainty, describes the average distance between the measured value and the truth. The precision of a measurement describes the variability around that average. Therefore, a measurement tool can be highly precise (low variance across repeated measurements) and yet inaccurate (the average of repeated measurements is far from the true value). In other words, it is quite possible for a measurement to be characterized by little variability but a large degree of uncertainty. While there have been many attempts to estimate measurement uncertainty in, for example, habitat surveys (Pleus 1995, Roper and Scarnecchia 1995, Poole et al. 1997) or redd surveys (Jones et al. 1998, Dunham et al. 2001), the known uncertainty in these types of data is rarely included in the uncertainty of predictions from models that are based on these types of data.

Measurement uncertainty can result in systematic error or bias. Bias is a directional error that results from measurement using a systematically inaccurate tool. Biased or potentially biased measurements might include subjective assessments or incomplete records. A less visible form of bias occurs when a measurement technique tends to overestimate in certain conditions and underestimate in other conditions. A simple example is helicopter redd surveys. Redds are easier to identify where there are fewer trees; therefore the accuracy or uncertainty of the measurement may depend on whether there are riparian buffers. If the bias is not corrected, the data might erroneously predict increases in redd density with removal of riparian trees.

Measurement uncertainty can be reduced but not eliminated. Replication is the best way to reduce the uncertainty, though it will not remove bias resulting from the use of inaccurate measurement tools. Bias can be corrected using unbiased measurements. Measurement uncertainty in expert opinion or subjective assessments can be very difficult to assess because no actual data exists. Although it may be possible to determine how well experts agree with one another (precision), it is impossible to assess or quantify accuracy when there are no accurately measured data available for comparison. In such cases, sensitivity analyses (as just described in the Parameter Uncertainty subsection) can provide an assessment of the degree to which small amounts of measurement uncertainty or bias in the input data might affect predictions (Morgan et al. 1990). Measurement uncertainty may also be quantified using repeated measurements or by computer-intensive techniques such as resampling or bootstrap methods (Efron and Tibshirani 1991, 1993). By quantifying measurement uncertainty, the value of collecting more data with the same measurement or sampling technique versus a more expensive technique can be weighed.

Natural Stochastic Variation

Natural stochastic variation is the inherent random variability in ecological systems, such as temperature or population fluctuations. It also incorporates the underlying stochastic nature of population dynamics (Rosenberg and Restrepo 1994). It contributes to our inability to make precise predictions. Increased amounts of natural stochastic variation, often called process uncertainty, require increased numbers of observations (either more sites or more replications or both) to make estimates of a given precision (Shea and Mangel 2001). Very high levels of natural variation can mean that estimates of the required precision are simply impossible to obtain (Korman and Higgins 1997).

Identifying and quantifying natural stochastic variation helps us to distinguish between situations in which small amounts of additional data should dramatically increase our ability to make good decisions and situations in which additional data are unlikely to provide significant increases in the accuracy of predictions. This is the heart of VOI analysis discussed earlier. In some cases, stratifying the data or redefining the question can reduce the effects of natural stochastic variation. For example, we might make separate estimates of in-river survival for wet versus dry years. Resource managers would then be able to make more informed decisions about the value of habitat restoration plans that potentially have different effects in wet versus dry years. Because stochastic variation is a natural phenomenon, it cannot be reduced to increase the precision of our predictions. Where it can no longer be reduced by stratification, quantifying and acknowledging stochastic variation is the best way to manage it.

In summary, an informed management decision requires information about the uncertainty of the predictions on which that decision will be based (Pace 2001, Regan et al. 2002). Evaluating the uncertainty in each prediction requires the dissection of that uncertainty into its classes. Each class as well as methods for quantifying and reducing uncertainty are summarized in Table 13. By asking the questions in Table 14, we can identify critical knowledge gaps, improve predictions, and reduce the chances of making poor or uninformed decisions because of poor predictions.

Example 1: Creating a Prioritized List of Restoration Projects

Once we have a series of predictions with their associated uncertainties, we must combine them into an action plan (see *Prioritizing Potential Restoration Actions within Watersheds* section, page 60). In this example, we demonstrate one method of setting up a decision table for using predictions and their confidence intervals to develop a project list for a habitat recovery plan. Developing a project list is difficult because of uncertainty about how fish may respond to changes in the environment. For instance, we may have a list of potential actions, each of which is expected to increase pool habitat. There are uncertainties in estimating the increase in pool area and about the density of fish that can be supported by a given amount of pool habitat. By explicitly including the uncertainty in a decision table, we can identify the actions with the highest expected final fish density and determine the potential value of reducing the uncertainty. Analogous examples have been worked out in the harvest literature (Hilborn and Walters 1992).

The first task in setting up a decision table is to describe the “alternative states of nature” and ascribe probabilities to these states. In this example, the alternative states of nature are the alternative hypotheses about how many juveniles are supported by a given area of pool habitat. Table 15 presents sample hypotheses and associated probabilities. The probabilities associated with each hypothesis may be generated in a number of ways. One method that can combine multiple types of information is meta-analysis, which pulls together information from multiple sources (Liermann and Hilborn 1997, Myers et al. 2001). Other Bayesian analysis techniques can also be used to combine disparate sources of information. A trademark of Bayesian analysis is the assignment of probabilities to alternative states of nature (Wade 2000). Strengths and weaknesses of the Bayesian approach are described by Dixon and Ellison (1996). If only limited

Table 15. Input information and results of decision analysis for prioritizing restoration actions. Example alternative hypotheses about the states of nature (i.e., density of fish per m² of pool habitat) and the relative probability that the hypothesis is true are in the first two rows. All probabilities must sum to one. Expected outcomes for potential habitat actions (total fish) as a function of each hypothesized fish density are displayed below the hypothesis probabilities. Overall expected outcomes (increase in total number of fish) of each potential action, given all potential states of nature, are in last column.

Hypothesized fish density per pool		5	10	15	20	Overall expected outcome
Hypothesis probability		0.1	0.3	0.5	0.1	
Potential action	Remove culvert A	2,744	4,892	5,248	5,786	4,945
	Remove culvert B	2,844	3,400	3,858	6,457	3,879
	Remove riprap	2,012	4,172	4,260	4,340	4,017
	Add wood	1,568	3,410	5,963	6,230	4,784

or ambiguous data are available, expert opinion can be solicited to assign probabilities to the various hypotheses. Numerous texts describe the complexity of selecting a group of experts, combining their disparate judgments, and other challenges of this approach (Morgan et al. 1990, Cooke 1991). As noted earlier in the section, knowing if expert opinion is correct is impossible precisely because we use it in situations for which we have no data. If expert opinion is used to assign probabilities to a set of hypotheses, then the prioritized list that emerges from the decision-analysis process will be a formalization of those opinions.

The next step in setting up a decision table is to associate an outcome with each potential action, assuming each of the alternative hypotheses about the state of nature is true. For example, if the hypothesis that pools can support five juvenile fish per m² is true, then the number of fish expected from the removal of culvert A might be 2,744 fish. In this example the outcome is number of fish, but other appropriate outcome units such as fish per dollar may be of interest. This outcome is calculated based on an assessment of the number of pools that would be made available after removal of the culvert. More realistic and detailed decision tables might include additional information such as the number of riffles, types of pools, depths of pools, or quality of expected pool habitat. Table 15 shows potential outcomes in total fish for a number of management actions as a function of fish density in pools.

Finally, we calculate the final expected outcome of each potential action, given the probabilities of the states of nature (Table 15). The expected outcome of each action is calculated by summing the expected outcome for each state of nature multiplied by the probability that the state of nature is true. For example, the expected outcome for removal of culvert A is $(2744 \times 0.1) + (4892 \times 0.3) + (5248 \times 0.5) + (5786 \times 0.1) = 4945$. Table 15 shows the expected outcome for each of the four potential actions. The largest expected increase in total number of fish is associated with removal of culvert A.

This is an extremely simple example. Hypotheses about the states of nature will often involve more than a single dimension (e.g., more than pool density). Many types of information can be included in the analysis, but there will often be only one or two critical uncertainties that drive a decision. Decision tables provide a structured method for including and communicating uncertainties and can easily be constructed for many of the examples in this document. For example, the methods described in the Prioritizing Potential Restoration Actions within Watersheds section, page 60, could be modified to include uncertainty about fish response, restoration costs, or habitat quality by using the decision table methodology described here. Another tool for making decisions is a logic tree, which models the impact of uncertainties in states of nature and in the occurrence of future conditions on possible outcomes (Kessler and McGuire 1999). Logic trees are particularly useful when only subjective probabilities about the states of nature exist.

Example 2: Water Quality and Habitat Recovery Planning

Uncertainty in habitat planning can result from the omission of a key habitat variable, such as water quality. The quantity and quality of salmon habitat are both important determinants of salmon population viability. Stream temperatures, sedimentation, and water

pollution are all examples of measures of habitat quality. However, empirical data for the various forms of water pollution are rarely incorporated into habitat models. Consequently, the complex impacts of urbanization, agricultural land uses, and industrial activities on the chemical condition of salmon habitat may lead to large levels of uncertainty in habitat recovery planning. In this example, we suggest ways to improve habitat decision making by incorporating water quality data. We provide nonquantitative solutions to reducing uncertainties that result from the omission of key habitat variables.

Environmental monitoring studies have consistently detected a wide array of metals, pesticides, and other toxic substances in the surface water and sediment of salmon habitats, and also in the tissues of salmon themselves. These contaminants may affect salmon abundance and survival via immediate lethal effects on individual fish. However, such effects are rare compared to the vast array of potential sublethal effects that may reduce individual fitness and population performance and potential indirect effects such as reductions in the abundance of key prey taxa. Despite documented exposure conditions (Wentz et al. 1998, Ebbert and Embrey 2002), the impact of environmental contaminants on salmon health or on the biological integrity of aquatic systems is poorly understood and habitat-based models for salmon recovery rarely capture the biological significance of water and sediment quality. Predictions of salmon population viability are likely to have high levels of model and prediction uncertainty if water and sediment quality are not included in model development.

There are several reasons why the specific determinants of chemical habitat quality are often excluded from habitat models. First, chemical habitat quality can be difficult and expensive to measure. Second, there is a general absence of toxicological data for most of the chemicals that have been detected in salmon habitat. Third, many conventional endpoints or biomarkers of chemical exposure have no clear or consistent relationship to the survival or reproductive success of the exposed animal. Consequently, there is often a disconnect between the biological scale at which toxicological studies are conducted and the data requirements for current habitat recovery models (Hansen and Johnson 1999a, 1999b).

Recovery plans that capture broad spatial and temporal patterns of chemical habitat degradation, despite incomplete empirical data, will minimize uncertainties around predicted outcomes of restoration actions and therefore reduce risks to salmon populations. Contaminants occur in complex mixtures whose composition varies in time and space. Salmon habitat conditions may reflect current land use activities or activities that were restricted or banned many years ago (e.g., persistent chemicals such as DDT). Moreover, water quality at a specific point within a watershed may be determined by land use activities that are far removed from the focus of restoration efforts. Acknowledging the large spatial and temporal scales at which contaminants can affect fish helps identify some of the uncertainty associated with predicting the effects of restoration actions. We can surmise, for example, that the uncertainty of predicted increases in habitat capacity for a given restoration action is likely higher in areas with high levels of past or present on-site or upstream chemical contamination. Likewise, we might expect inaccuracy and prediction uncertainty in survival estimates that are extrapolated from a stock within a pristine watershed to a stock that migrates through a highly contaminated estuary.

In many cases, we do have data on chemical contamination but we do not know how to incorporate it into habitat recovery planning. A limited number of studies have specifically

addressed the impacts of environmental contaminants on biological processes in Pacific salmon that are clearly linked to survival, migratory success, or reproductive success (Kruzynski and Birtwell 1994, Arkoosh et al. 1998, Hansen et al. 1999, Heintz et al. 2000, Scholz et al. 2000, Rice et al. 2001, Meador et al. 2002). The challenge in estimating the effects of toxic chemicals on salmon health is to identify which contaminants are known or suspected to occur in particular habitats and pathways of toxicity for these chemicals that have significance for the survival, migratory success, or reproductive success of wild salmon.

Planners or researchers should utilize the primary toxicological literature in the development of recovery plans. Answers to the following questions can often be found in the toxicological literature and will enable more accurate and precise predictions about the effects of specific chemical contaminants on predicted salmon population performance.

1. What is the evidence that a contaminant or class of contaminants is present in salmon habitat?
2. What are the expected environmental concentrations?
3. How long will exposures last?
4. What life history stages of salmon are likely to be affected?
5. What are the primary possibilities for sublethal toxicity in fish?

From this information it may be possible to estimate the chances that the contaminant is currently or may in the future be a significant limiting factor in salmon population viability within the geographic area of concern.

Incorporating toxicological data can improve decisions about the prioritization of water quality improvements versus physical habitat restoration. For example, in watersheds where insecticides occur (primarily in agricultural and urban areas), it should be possible to estimate the potential loss of invertebrate prey, the subsequent reduction in the growth of juvenile fish, and the likelihood that salmon from contaminated habitats will have a lower rate of marine survival. If environmental monitoring data are unavailable, recovery planners might extrapolate potential chemical concentrations from other (monitored) basins with similar agricultural or urban land use. Even simple comparisons between reported environmental concentrations and toxicity thresholds for aquatic invertebrates can reduce the scientific uncertainty surrounding the potential effects of contaminants on salmon population viability. This in turn would improve restoration prioritization and watershed management plans.

For water quality and other habitat characteristics about which less is known, it is clearly better to acknowledge the uncertainties and incorporate the available information, no matter how limited. In the example of water quality, we can estimate and incorporate the direction of the effect even when we are not yet able to quantify the magnitude of that effect. We can also seek empirical data from nontraditional sources. Moreover, identifying key uncertainties will help establish priorities for ongoing and future research.

Using Decision Rules When Empirical Data Are Inadequate

A careful and honest examination of uncertainty in data, predictions, and models will inevitably lead to the identification of situations in which adequate empirical data for making a

decision are simply not available. Uncertainty should not lead to inaction. Methods are being developed to allow quantitative analysis of the sensitivity of decisions to uncertainties in the data. For example, sensitivity analyses were used to demonstrate that the best management decision for Hector's dolphin (*Cephalorhynchus hectori*) was robust to model uncertainties, and thereby removed uncertainty in the scientific data as an excuse for inaction (Slooten et al. 2000). In the face of large amounts of uncertainty in empirical relationships, simulation models and decision analysis were used to evaluate management actions for listed salmonids in the Snake River basin (Peters and Marmorek 2001, Peters et al. 2001). Where empirical data are inadequate, we strongly discourage basing decisions on biased or imprecise predictions, prioritization systems for which guesswork must be substituted for data, or information that becomes inaccurate or imprecise at the scale for which the decision must apply. Instead, we suggest that resource managers provide an explicit rationale for the decision that requires minimal data.

The most important characteristics of a decision rule are that it can be documented and is robust. Documentation is important because future managers will need to understand the basis for the decision. This requirement prevents arbitrary decisions in the face of inadequate data. Decision rules that are robust to uncertainties in the information help prevent risky management decisions (Schnute and Richards 2001). Decision rules presented in the literature include the following two examples.

The Precautionary Principle can be stated as, "When an activity raises threats of harm to public health or the environment, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically" (Raffensperger and Tickner 1999). Because this principle shifts the burden of proof to those who create risks and does not define which risks are most important (Hilborn et al. 2001), it has generated much controversy and confusion about its appropriate implementation. However, there are many examples of national and international policies that have been based on the Precautionary Principle. European environmental law is based on the Precautionary Principle through the 1992 Treaty on European Union, and the Rio Declaration from the United Nations Conference on Environment and Development binds the United States to implement the Precautionary Principle in environmental health protection (Raffensperger and Tickner 1999). While we are not advocating this particular decision making rule, we present it as an example of a relatively simple guiding principle for high-level decisions in the absence of definitive data.

Safe Minimum Standard (SMS) is another decision-making rule that has received considerable attention. The SMS approach is a collective choice process that prescribes protecting a given level of a renewable resource unless the social costs are excessive (Berrens 2001). This approach to making environmental decisions is usually invoked in settings involving considerable uncertainty and potentially irreversible losses. It prioritizes social costs over loss of renewable resources. We present this approach for comparison to emphasize the importance of carefully choosing the decision-making principle and documenting exactly what considerations should be involved. The choice of a guiding principle will dictate management decisions until improved information is available.

The choice of a decision-making rule need not be purely theoretical. The Assessment Approach for Habitat Recovery Planning section, page 5, discusses the importance of defining a

habitat strategy that includes gathering additional data and taking interim actions. This habitat strategy is an excellent example of how a guiding principle can be used for decision making until adequate data become available. The Prioritizing Potential Restoration Actions within Watersheds section, page 60, presents guidelines for selecting restoration actions before all of the habitat data are available. Again, this is a simple and effective method for dealing with incomplete information.

Another common approach to formalizing decision making without adequate empirical data or quantitative predictions is a scoring matrix. A scoring matrix can be used to prioritize potential actions, project proposals, potential action sites, or information gathering. The advantage of a scoring matrix is that ranks can be based on weighted priorities, for example, project longevity, proximity to other projects, or land ownership. The decision path can be clearly explained and is easily repeatable. As better information becomes available, the matrix can be adjusted. A disadvantage of the scoring matrix is that the weights assigned to each priority can dramatically alter the outcome and specifying a satisfactory weighting function in advance is often difficult. Examples of scoring matrices in current use include the Snake River Salmon Recovery Region Comprehensive Project Scoring Matrix (SRSRC 2002), the Lower Columbia Fish Recovery Board Interim Habitat Strategy Project Scoring Sheet (LCFRB 2001), and the Skagit System Cooperative methodology for rating individual landscape processes (Appendix C, page 157). The scoring matrix provided by the Lower Columbia Fish Recovery Board dedicates a section to “Certainty of Success,” explicitly including some metrics of uncertainty.

In each of the above examples, it is important to consider whether the decision strategy is robust to the types of uncertainties that exist. A strategy that would be beneficial under a scenario that has a 50% chance of representing reality but detrimental the rest of the time is not a robust choice. Strategies should be developed so that the outcome is acceptable given the range of possibilities for which there is uncertainty. Again the Hector’s dolphin management plan is an example of a strategy that is explicitly robust to the uncertainties in the data (Slooten et al. 2000).

Using decision-making strategies that require minimal data carries two obligations. First, we must evaluate whether improved information would produce a cost-effective improvement in decision making (VOI analysis). If so, then a strong attempt to reduce uncertainties by gathering more or better information is required. The analyses described in the Types of Uncertainty subsection above can identify critical information uncertainties and reduce their impact. Second, we must set a time frame for reevaluating the decision. In the best possible scenario, decision strategies requiring minimal data serve as interim measures until additional information is available.

In conclusion, we emphasize that estimates of uncertainty—quantitative where possible, qualitative for other situations—should be included with all information being considered in a decision-making framework. A systematic treatment of uncertainty should include:

- 1) identification of uncertain events, states of nature, relationships, and parameters,
- 2) determination of the likelihood associated with each potential state or value,
- 3) use of data or models to evaluate consequences of each potential state or value, and
- 4) examination of the relationship between uncertain inputs and potential outputs to identify key uncertainties (Mishra 2001).

Even where a formal analysis of uncertainty is not possible, describing sources and magnitudes of uncertainty is important in providing managers with enough information to weigh potential risks and benefits of possible actions (Rosenberg and Restrepo 1994).

A careful examination of the sources and causes of uncertainty will ensure informed decisions and make improvements in both precision and accuracy likely. Quantifications of uncertainty can be formally incorporated into decision making using decision tables. In other situations, simple strategies such as collecting data at multiple scales or incorporating data from other disciplines will provide for more informed decisions. However, a lack of empirical data need not prevent informed decisions from being made in a clear and formal manner. It is possible to implement strategies that require minimal data. Such strategies are preferable to using biased or imprecise predictions, guesswork disguised as data, or information that is inappropriate to the scale of the decision.

As we said earlier in this technical memorandum, our conceptual approach to habitat recovery planning is holistically focused on restoring or preserving watershed and ecosystem processes to provide good quality salmon habitat over the long term. This implies that restoration of ecosystems to support salmon will include a wide range of actions affecting the life cycles of multiple species. We began with a conceptual framework for understanding relationships among land uses, watershed functions, habitat conditions, and biota as a basis for organizing the habitat-related questions that each recovery plan should attempt to answer. We separated recovery planning into two phases—Phase I planning that identifies recovery goals and Phase II planning that identifies causes of habitat loss or degradation and necessary ecosystem restoration actions. Then we showed how results from both assessments can be used to prioritize restoration actions and how incorporating estimates of uncertainty into the decision-making process increases the likelihood of success in salmon habitat recovery planning. Finally, new information gained from assessments and management experiments should be used to update the recovery plan.

GLOSSARY

anadromous. Moving from the sea to freshwater for reproduction.

anthropogenic. Caused or produced by human action.

bankfull width. Channel width between the tops of banks on either side of a stream; tops of banks are the points at which water overflows its channel at bankfull discharge. *Compare wetted width.*

basin. *See watershed.*

benthic. Of, related to, or living in the soil-water interface of a lake or stream.

B-IBI. For *Benthic Index of Biological Integrity*. An overall assessment of invertebrate condition constructed from various biometrics and represented by a single number. *See also benthic, biological integrity, and IBI.*

biodiversity. Range of different species of plants and animals in an environment or during a specific period of time.

biological integrity. Defined in various ways, here it is the capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of the natural habitat of the regions (Karr 1991).

biota. Flora and fauna of a region.

catchment. *See watershed.*

culvert. Buried pipe or covered structure that allows a watercourse to pass under a road or underground.

CWA. For *Clean Water Act*. Passed by Congress, its purpose is to “restore and maintain the chemical, physical, and biological integrity of the nation’s waters” (CWA 1972).

density-dependent survival. Occurs when death rates in a population are dependent on the number of individuals in the population. *Compare density-independent survival.*

density-independent survival. Occurs when death rates in a population are not dependent on the number of individuals in the population. *Compare density-dependent survival.*

tributary. Branch of a river or stream that flows away from the main channel and does not rejoin it. Also called *tributary channel*.

disturbance. Introduction of an unwanted condition into a system or interference with a habitat’s normal or existing conditions.

- ecoregion.** Area determined by similar land surface form, potential natural vegetation, land use, and soil; it may contain few or many geological districts.
- ecosystem.** In general use, it is the dynamic and holistic system of all the living and dead organisms in an area and the physical and climatic features that are interrelated in the transfer of energy and material. In this document, it is the aquatic environment and biota, physical and biological processes active in that environment, and the landscape processes and land uses that form and sustain the aquatic environment and biota. *Compare* **habitat**.
- EDT.** For *ecosystem diagnosis and treatment*. The EDT model is an analytical tool for assessing relationships among stream habitat attributes and salmon population performance.
- EIA.** For *effective impervious area*. An impervious area with direct hydraulic connection to a stream. *See also* **impervious surface**.
- endangered species.** Species in danger of extinction throughout all or a significant portion of its range. *See also* **ESA** and **threatened species**.
- enhancement.** Improving watershed processes and habitat conditions from an existing state. It does not necessarily seek to restore processes or conditions to some predisturbed state. Some practitioners call this partial restoration. *Compare* **rehabilitation** and **restoration**.
- ESA.** For *U.S. Endangered Species Act*. Passed by Congress, its purpose is to “provide a means whereby the ecosystems upon which endangered species and threatened species depend may be conserved” (ESA 1973).
- estuary.** Semienclosed coastal body of water at the mouth of a river where the saltwater ocean tide meets the freshwater current.
- ESU.** For *evolutionarily significant unit*. A population or group of populations that are 1) substantially reproductively isolated from other populations, and 2) contribute substantially to the ecological or genetic diversity of the biological species (Myers et al. 1998). It is sometimes represented as the spatial area encompassing the population(s).
- floodplain.** Flat area adjoining a river channel constructed by the river in its present climate and overflow at times of high discharge.
- fry.** Brief transitional stage of recently hatched fish that spans from absorption of the yolk sac through several weeks of independent feeding.
- gabion.** Wire basket filled with stones, used for enhancing aquatic habitats or stabilizing streambanks.
- GIS.** For *Geographic Information System*. A computer system for assembling, storing, manipulating, and displaying geographically referenced information.
- glide.** Relatively slow and shallow stream section with moderate water velocities and little or no surface turbulence.

ground-truthing. Field measurement of specific attributes that have been predicted from models or remotely sensed data for the purpose of assessing accuracy and precision of predictions.

gullying. Erosion of soil by formation or extension of gullies from surface runoff.

habitat. In this document, the term refers to the aquatic environment that fish experience and not those landscape processes or attributes outside streams that alter habitat conditions.
Compare ecosystem.

habitat unit. Relatively homogenous area of the stream channel that differs from adjoining areas in depth, velocity, and substrate characteristics.

hydromodification. Alteration of streambanks or channel morphology by bank hardening (e.g., riprap), dredging, diking, or other mechanical means.

IBI. For *Index of Biological Integrity*. A synthesis of various biometrics that numerically assesses associations between human activities and biological attributes. *See also B-IBI and biological integrity.*

impervious surface. Defined in watershed management as a manmade surface such as asphalt or concrete paving that prohibits the movement of water from the land surface into the underlying soil.

impoundment. Body of water gathered or enclosed (such as in a reservoir) for irrigation, flood control, or similar purposes.

Landsat. Landsat satellites supply global land surface images and data.

LWD. For *large woody debris*. Large piece of woody material such as a log or stump that intrudes into a stream channel. LWD is typically defined as wood greater than 10 cm in diameter and 1 m in length, but other minimum size criteria are also used.

macroinvertebrate. Animal without a backbone living in one stage of its life cycle, usually the nymph or larval stage. Macroinvertebrates are visible without magnification and many are benthic organisms (see **benthic**).

main stem. Principle stream or channel of a stream network.

mass wasting. Downslope movement of earth materials under gravity, including such processes as rockfalls, landslides, and debris flows.

natural stochastic variation. Inherent random variability in ecological systems, such as temperature or population fluctuations. Also called *process uncertainty*.

outlier. In statistics, any data point exhibiting anomalous behavior.

parr. Young salmonid actively feeding in freshwater.

peak flow. Greatest stream discharge measured over a period of time, such as a season or year.

pool:riffle:glide ratio. Ratio of the respective surface areas or lengths of pools to riffles to glides in a given stream reach, often expressed as the relative percentage of each category.

population. Group of individuals of a species living in a certain area that maintain some degree of reproductive isolation.

reach. Section of stream between two defined points.

recovery. In the context of listed populations, attaining specified goals for viable populations and ESUs (population abundance, population growth rate, spatial structure, and diversity). For watershed processes and habitats, returning from a disturbed state to some prior condition, not necessarily pristine.

redd. Nest in gravel, dug by a fish for egg deposition, and associated gravel mounds.

reference site. Site in a relatively natural state, at which to measure natural or unmanaged conditions. May also refer to a site that serves as an experimental control, which has characteristics similar to a treatment site with the exception of the treatment itself.

refugia. Also commonly called biological hot spots, source watersheds, core areas, and key habitat, they are population centers or centers of biological diversity.

rehabilitation. Improving ecosystem conditions, or sometimes more specifically, returning ecosystem conditions to a defined level of health. Some practitioners call this partial restoration. *Compare restoration and enhancement.*

remotely sensed data. Data gathered from a remote station or platform, as in satellite or aerial photography.

restoration. In the strictest sense, returning the ecosystem to some predisturbed condition. Some practitioners call that full restoration. In this document, the term is used generically to mean both restoration and enhancement (and related terminology). *Compare rehabilitation and enhancement.*

riffle. Shallow section of a river or stream with rapid current and surface turbulence.

riparian. Part of the landscape that exerts a direct influence on stream channels or lake margins and the water or aquatic ecosystems.

riprap. Layer of large, durable materials used to protect a streambank from erosion; may also refer to the materials used, such as rocks or broken concrete.

salmonid. Fish of the family *Salmonidae*, including salmon, trout, and chars.

scale. In aquatic environment recovery planning, it can be viewed as a hierarchy of spatially nested systems. Each of these spatially nested systems can be thought of as an individual

spatial and temporal scale. The result is a system in which development and persistence occur at specific temporal scales within each level of the hierarchy such that conditions within smaller scale systems are constrained by the larger scale systems that contain them (Frissell et al. 1986, Urban et al. 1987).

sediment budget. Accounting of sediment sources and transfer processes in a watershed. The complete budget quantifies sediment sources, transport, and storage within a watershed, usually tracking each process of sediment production or movement separately.

sediment supply. Supply of sediment to a river system, where it is carried in suspension (suspended load and wash load) or on the bottom (bed load).

seral. Of, relating to, or constituting a sere (which is a series of ecological communities formed in ecological succession).

side channel. Flood channel or abandoned stream channel connected to a stream or river at periods of high flow. It serves juvenile fish as rearing habitat and refuge from floods.

smolt. Juvenile salmonid in its seaward migrant stage.

species. Category of biological classification ranking immediately below genus or subgenus, comprising related organisms or populations potentially capable of interbreeding. (Note that in the context of the ESA, “distinct population segments” of a species may be listed separately.)

stochastic. Of or relating to uncertainties or random variables. *See also natural stochastic variation.*

SWAM. For *Salmonid Watershed Analysis Model*. A large-scale landscape analysis for identifying high priority areas for salmon habitat restoration.

taxa. Plural of taxon, a taxonomic group or entity.

thalweg. Line defining the lowest points along the length of a riverbed or valley.

threatened species. Species not presently in danger of extinction but likely to become so in the foreseeable future. *See also endangered species and ESA.*

tributary. Stream or river that flows into another stream or river.

TRT. For *Technical Recovery Team*. The TRT establishes biologically based ESA recovery goals for listed salmonids within a given recovery domain. Members serve as science advisors to the recovery planning phase.

uncertainty. Lack of knowledge about the true value of a quantity or lack of knowledge about which of several alternative models best describes the mechanism of interest. Types of uncertainty include prediction uncertainty, parameter uncertainty, model uncertainty, measurement uncertainty, and **natural stochastic variation** (also called process uncertainty).

variability. Heterogeneity of values over time, space, or different members of a population.

VSP. For *viable salmonid population*. An independent population of any Pacific salmonid (genus *Oncorhynchus*) that has a negligible risk of extinction due to threats from demographic variation, local environmental variation, and genetic diversity changes over a long time frame (McElhany et al. 2000).

watershed. Entire land drainage area of a river. Also called *basin* or *catchment*.

wetted width. Width of the water surface within a channel. Compare **bankfull width**.

CITATIONS

- Abbe, T. B. 2000. Patterns, mechanics, and geomorphic effects of wood debris accumulations in a forest river system. Doctoral dissertation. Univ. Washington, Dept. Geological Sciences, Seattle.
- Abbe, T. B., and D. R. Montgomery. 1996. Large woody debris jams, channel hydraulics, and habitat formation in large rivers. *Regul. Rivers Res. Manag.* 12:201–221.
- Adams, J. W. 2001. Using aquatic macroinvertebrates to assess stream condition in the Clackamas River Basin, Oregon. Master's thesis. Univ. Washington, Seattle.
- Adamus, P., T. J. Danielson, and A. Gonyaw. 2001. Indicators for monitoring biological integrity of inland, freshwater wetlands: A survey of North American technical literature (1990–2000). EPA 843-R-01. U.S. Environmental Protection Agency, Office of Water, Washington, DC. Online at <http://www.epa.gov/owow/wetlands/bawwg/monindicators.pdf> [Accessed 5 Feb. 2003].
- Akcakaya, R. H., S. Ferson, M. A. Burgman, D. A. Keith, G. M. Mace, and C. R. Todd. 2000. Making consistent IUCN classifications under uncertainty. *Conserv. Biol.* 14:1001–1013.
- Allan, J. D. 1995. *Stream ecology: Structure and function of running waters*. Chapman & Hall, London.
- Allan, D. J., D. L. Erickson, and J. Fay. 1997. The Influence of catchment land use on stream integrity across multiple spatial scales. *Freshw. Biol.* 37:149–161.
- Arkoosh, M. R., E. Casillas, P. Huffman, E. Clemons, J. Evered, J. E. Stein, and U. Varanasi. 1998. Increased susceptibility of juvenile Chinook salmon from a contaminated estuary to *Vibrio anguillarum*. *Trans. Am. Fish. Soc.* 127:360–374.
- Baltz, D. M., B. Vondracek, L. R. Brown, and P. B. Moyle. 1991. Seasonal changes in microhabitat selection by rainbow trout in a small stream. *Trans. Am. Fish. Soc.* 120:166–176.
- Barbour, M. T., J. Gerritsen, B. D. Snyder, and J. B. Stribling. 1999. *Rapid bioassessment protocols for use in streams and wadeable rivers: Periphyton, benthic macroinvertebrates, and fish*. Second edition. EPA 841-B-99-002. U.S. Environmental Protection Agency, Office of Water, Washington, DC.
- Barila, T. Y., R. D. Williams, and J. R. Stauffer, Jr. 1981. The influence of stream order and selected stream bed parameters on fish diversity in Raystown Branch, Susquehanna River drainage, Pennsylvania. *J. Appl. Ecol.* 18:125–131.
- Bauer, S. B., and S. C. Ralph. 1999. *Aquatic habitat indicators and their applications to waters quality objectives within the Clean Water Act*. Tech. Rep. EPA-910-R-99-104. U.S. Environmental Protection Agency, Region 10, Seattle.
- Baxter, C. V., C. A. Frissell, and F. R. Hauer. 1999. Geomorphology, logging roads, and the distribution of bull trout spawning in a forested river basin: Implications for management and conservation. *Trans. Am. Fish. Soc.* 128:854–867.
- Baxter, C. V., and F. R. Hauer. 2000. Geomorphology, hyporheic exchange, and selection of spawning habitat by bull trout (*Salvelinus confluentus*). *Can. J. Fish. Aquat. Sci.* 57:1470–1481.

- Beamer, E., T. Beechie, B. Perkowski, and J. Klochak. 2000. Application of the Skagit Watershed Council's strategy: River basin analysis of the Skagit and Samish Basins—Tools for salmon habitat restoration and protection. Skagit Watershed Council, Mount Vernon, WA.
- Beamer, E. M., and R. A. Henderson. 1998. Juvenile salmonid use of natural and hydromodified stream bank habitat in the mainstem Skagit River, northwest Washington. Skagit System Cooperative, La Conner, WA.
- Beamer, E. M., and G. Pess. 1999. Effects of peak flows on Chinook (*Oncorhynchus tshawytscha*) spawning success in two Puget Sound river basins. In R. Sakrison and P. Sturtevant (eds.), Watershed management to protect declining species, p. 67–70. American Water Resources Association, Middleburg, VA.
- Bednarek, A. T. 2001. Undamming rivers: A review of the ecological impacts of dam removal. *Environ. Manag.* 27(6):803–814.
- Beechie T. J. 1992. Delineation of hydrologic regions in the Skagit River basin. Skagit System Cooperative, La Conner, WA.
- Beechie, T., E. Beamer, B. Collins, and L. Benda. 1996. Restoration of habitat-forming processes in Pacific Northwest watersheds: A locally adaptable approach to salmonid habitat restoration. In D. L. Peterson and C. V. Klimas (eds.), *The role of restoration in ecosystem management*, p. 48–67. Society for Ecological Restoration, Madison, WI.
- Beechie, T., E. Beamer, and L. Wasserman. 1994. Estimating coho salmon rearing habitat and smolt production losses in a large river basin, and implications for restoration. *N. Am. J. Fish. Manag.* 14:797–811.
- Beechie, T. J., and S. Bolton. 1999. An approach to restoring salmonid habitat-forming processes in Pacific Northwest watersheds. *Fisheries* 24(4):6–15.
- Beechie, T. J., B. D. Collins, and G. R. Pess. 2001. Holocene and recent geomorphic processes, land use, and salmonid habitat in two north Puget Sound river basins. In J. B. Dorava, D. R. Montgomery, F. A. Fitzpatrick, and B. B. Palcsak (eds.), *Geomorphic processes and riverine habitat: Water science and application*, Vol. 4, p. 37–54. American Geophysical Union, Washington, DC.
- Beechie, T. J., G. Pess, E. Beamer, G. Lucchetti, and R. E. Bilby. 2003. Role of watershed assessments in recovery planning for salmon. In D. R. Montgomery, S. Bolton, D. B. Booth, and L. Wall (eds.), *Restoration of Puget Sound rivers*, p. 194–225. University of Washington Press, Seattle.
- Beechie, T. J., G. Pess, P. Kennard, R. E. Bilby, and S. Bolton. 2000. Modeling recovery rates and pathways for woody debris recruitment in northwestern Washington streams. *N. Am. J. Fish. Manag.* 20:436–452.
- Beechie, T. J., and T. H. Sibley. 1997. Relationships between channel characteristics, woody debris, and fish habitat in northwestern Washington streams. *Trans. Am. Fish. Soc.* 126:217–229.
- Begon, M., J. L. Harper, and C. R. Townsend. 1986. *Ecology: Individuals, populations, and communities*. Sinauer and Associates, Inc., Sunderland, MA.
- Berg, D. R., T. K. Brown, and B. Blessing. 1996. Silvicultural systems design with emphasis on the forest canopy. *Northwest Sci.* 70:31–36.

- Berrens, R. P. 2001. The safe minimum standard of conservation and endangered species: A review. *Environ. Conserv.* 28:104–116.
- Beschta, R. L., R. E. Bilby, G. W. Brown, L. B. Holtby, and T. D. Hofstra. 1987. Stream temperature and aquatic habitat: Fisheries and forestry interactions. *In* E. O. Salo and T. W. Cundy (eds.), *Streamside management: Forestry and fishery interactions*, p. 191–232. University of Washington Press, Seattle.
- Beschta, R. L., M. R. Pyles, A. E. Skaugset, and C. G. Surfleet. 2000. Peakflow response to forest practices in the western Cascades of Oregon, USA. *J. Hydrol.* 233:102–120.
- Bilby, R. E., K. Sullivan, and S. H. Duncan. 1989. The generation and fate of road-surface sediment in forested watersheds of southwestern Washington. *For. Sci.* 35:453–468.
- Bilby, R. E., and J. W. Ward. 1991. Characteristics and function of large woody debris in streams draining old-growth, clear-cut, and 2nd-growth forest in southwestern Washington. *Can. J. Fish. Aquat. Sci.* 48: 2499–2508.
- Bisson, P. A., J. L. Nielsen, R. A. Palmason, and L. E. Grove. 1982. A system of naming habitat types in small streams, with examples of habitat utilization by salmonids during low stream flow. *In* Neil B. Armantrout (ed.), *Acquisition and utilization of aquatic habitat inventory information*, p. 62–73. American Fisheries Society, Bethesda, MD.
- Bisson, P. A., G. H. Reeves, R. E. Bilby, and R. J. Naiman. 1997. Watershed management and Pacific salmon: Desired future conditions. *In* D. J. Stouder, P. A. Bisson, and R. J. Naiman (eds.), *Pacific salmon and their ecosystems: Status and future options*, p. 447–474. Chapman & Hall, New York.
- Bisson, P. A., K. Sullivan, and J. L. Nielsen. 1988. Channel hydraulics, habitat use, and body form of juvenile coho salmon, steelhead, and cutthroat trout in streams. *Trans. Am. Fish. Soc.* 117: 262–273.
- Bjornn, T. C., and D. W. Reiser. 1991. Habitat requirements of salmonids in streams. *In* W. R. Meehan (ed.), *Influences of forest and rangeland management on salmonid fishes and their habitats*, p. 83–138. American Fisheries Society, Special Publication 19, Bethesda, MD.
- Booth, D. B., and C. R. Jackson. 1997. Urbanization of aquatic systems: Degradation thresholds, stormwater detention, and the limits of mitigation. *J. Am. Water Resour. Assoc.* 33(5):1077–1090.
- Bortleson, G. C., M. J. Chrzastowski, and A. K. Helgeson. 1980. Historical changes of shoreline and wetland at eleven major deltas in the Puget Sound region, Washington. USGS Hydrologic Investigations Atlas HA-617. U.S. Geological Survey, Washington, DC.
- Botsford, L. W., and J. G. Brittnacher. 1997. Viability of Sacramento winter-run Chinook salmon. *Conserv. Biol.* 12(1):65–79.
- Bozek, M. A., and F. J. Rahel. 1991. Assessing habitat requirements of young Colorado River cutthroat trout by use of macrohabitat and microhabitat analyses. *Trans. Am. Fish. Soc.* 120:571–581.

- Bozek, M. A., and F. J. Rahel. 1992. Generality of microhabitat suitability models for young Colorado River cutthroat trout (*Oncorhynchus clarki pleuriticus*) across sites and among years in Wyoming streams. *Can. J. Fish. Aquat. Sci.* 49:552–564.
- Bradford, M. J., and J. R. Irvine. 2000. Land use, fishing, climate change, and the decline of Thompson River, British Columbia, coho salmon. *Can. J. Fish. Aquat. Sci.* 57:13–16.
- Bradford, M. J., G. C. Taylor, and J. A. Allan. 1997. Empirical review of coho salmon smolt abundance and the prediction of smolt production at the regional level. *Trans. Am. Fish. Soc.* 126:49–64.
- Buikema, A. L., Jr., and J. R. Voshell, Jr. 1993. Toxicity studies using freshwater benthic macroinvertebrates. In D. M. Rosenberg and V. H. Resh (eds.), *Freshwater biomonitoring and benthic macroinvertebrates*, p. 344–398. Chapman & Hall, New York.
- Burner, C. J. 1951. Characteristics of spawning nests of Columbia River salmon. *Fish. Bull. Fish Wildl. Serv.* 61:97–110.
- Burnham, K. P., and D. R. Anderson. 1998. *Model selection and inference: An information-theoretic approach*. Springer-Verlag, New York.
- Bustard, D. R., and D. W. Narver. 1975. Preferences of juvenile coho salmon (*Oncorhynchus kisutch*) and cutthroat trout (*Salmo clarki*) relative to simulated alteration of winter habitat. *J. Fish. Res. Board Can.* 32:681–687.
- Caddy, J. F., and R. Mahon. 1995. Reference points for fisheries management. *FAO Fisheries Tech. Paper* 347. Food and Agriculture Organization of the United Nations, Rome.
- Campbell, C. A. 1999. Assessing large-scale patterns in the distribution, abundance, and size of juvenile Atlantic salmon in the Connecticut River. Master's thesis. Univ. Massachusetts, Amherst.
- Canale, G. A. 1999. BORIS: Benthic evaluation of Oregon rivers. Tech. Rep. BIO98-003. Oregon Dept. Environmental Quality, Laboratory Division, Biomonitoring Section, Portland.
- CDFG (California Dept. Fish and Game). 2000. Fish screening criteria DFG 2000. Online at <http://www.iep.water.ca.gov/cvffrt/DFGCriteria2.htm> [Accessed 27 Jan. 2003].
- CEC (Commission for Environmental Cooperation). 1997. *Ecological regions of North America: Toward a common perspective*. Commission for Environmental Cooperation, Montreal.
- Chapman, D. W. 1996. Efficacy of structural manipulations of instream habitat in the Columbia River basin. *Northwest Sci.* 5:279–293.
- Chapman, W. M. 1943. The spawning of Chinook salmon in the main Columbia River. *Copeia* 1943:168–170.
- Chapman, D. W., D. E. Weitcamp, T. L. Welsh, M. B. Dell, and T. H. Schadt. 1986. Effects of river flow on the distribution of Chinook salmon redds. *Trans. Am. Fish. Soc.* 115:537–547.
- Clary, W. P. 1999. Stream channel and vegetation responses to late spring cattle grazing. *J. Range Manag.* 52:218–226.
- Clary, W. P., and W. C. Leninger. 2000. Stubble height as a tool for management of riparian areas. *J. Range Manag.* 53:562–573.

- Clary, W. P., N. L. Shaw, J. G. Dudley, V. A. Saab, J. W. Kinney, and L. C. Smithman. 1996. Response of a depleted sagebrush steppe riparian system to grazing control and woody plantings. Research Paper INT-RP-492. U.S. Forest Service, Intermountain Research Station, Ogden, UT.
- Collins, B. D. 1998. Preliminary assessment of historic conditions of the Skagit River in the Fir Island area: Implications for salmonid habitat restoration. Skagit System Cooperative, La Conner, WA.
- Collins, B. D., T. J. Beechie, L. E. Benda, P. M. Kennard, C. N. Veldhuisen, V. S. Anderson, and D. R. Berg. 1994. Watershed assessment and salmonid habitat restoration strategy for Deer Creek, North Cascades of Washington. Report to Stillaguamish Tribe of Indians and Washington Department of Ecology. 10,000 Years Institute, Seattle.
- Collins, B. D., and D. R. Montgomery. 2001. Importance of archival and process studies to characterizing pre-settlement riverine geomorphic processes and habitat in the Puget Lowland. *In* J. M. Dorava, D. R. Montgomery, B. B. Palcsak, and F. A. Fitzpatrick (eds.), *Geomorphic processes and riverine habitat*. Water science and application series, Vol. 4, p. 227–243. American Geophysical Union, Washington, DC.
- Collins, B. D., D. R. Montgomery, and A. D. Haas. 2002. Historical changes in the distribution and functions of large wood in Puget Lowland rivers. *Can. J. Fish. Aquat. Sci.* 59:66–76.
- Congleton, J. L. 1978. Feeding patterns of juvenile chum in the Skagit River saltmarsh. *In* S. J. Lipovski and C. A. Simenstad (eds.), *Proceedings of the Second Pacific Northwest Technical Workshop of Fish Food Habit Studies*, p. 141–150. Washington Sea Grant, Univ. Washington, Seattle.
- Congleton, J. L., S. K. Davis, and S. R. Foley. 1981. Distribution, abundance, and outmigration timing of chum and Chinook salmon fry in the Skagit saltmarsh. *In* E. L. Brannon and E. O. Salo (eds.), *Proceedings of the Salmon and Trout Migratory Behavior Symposium, June 3–5, 1981*, p. 153–163. Univ. Washington, School of Fisheries, Seattle.
- Connolly, P. J., and J. D. Hall. 1999. Biomass of coastal cutthroat trout in unlogged and previously clear-cut basins in the central coast range of Oregon. *Trans. Am. Fish. Soc.* 128:890–899.
- Cooke, R. M. 1991. *Experts in uncertainty-opinion and subjective probability in science*. Oxford Press, New York.
- Cowx, I. G., and R. L. Welcomme. 1998. *Rehabilitation of rivers for fish*. Fishing News Books, Oxford.
- Cullen, A. C., and H. C. Frey. 1999. *Probabilistic techniques in exposure assessment: A handbook for dealing with variability and uncertainty in models and inputs*. Plenum Press, New York.
- Cunjak, R. A. 1988. Behaviour and microhabitat of young Atlantic salmon (*Salmo salar*) during winter. *Can. J. Fish. Aquat. Sci.* 45:2156–2160.
- Cunjak, R. A. 1996. Winter habitat of selected stream fishes and potential impacts from land-use activity. *Can. J. Fish. Aquat. Sci.* 53(Suppl. 1):267–282.
- Cunjak, R. A., R. A. Curry, and G. Power. 1987. Seasonal energy budget of brook trout in streams: Implications of a possible deficit in early winter. *Trans. Am. Fish. Soc.* 116:817–828.
- Cunjak, R. A., and G. Power. 1987. The feeding and energetics of stream-resident trout in winter. *J. Fish Biol.* 31:493–511.

- CWA (Clean Water Act). 1972. Title 33 U.S. Code, Section 1251.
- Dauble, D. D., and D. R. Geist. 2000. Comparison of mainstem spawning habitats for two populations of fall Chinook salmon in the Columbia River basin. *Regul. Rivers Res. Manag.* 16:345–361.
- Dauble, D. D., and D. G. Watson. 1997. Status of fall Chinook salmon populations in the mid-Columbia River, 1948–1992. *N. Am. J. Fish. Manag.* 17:283–300.
- Davis, W. S., and T. P. Simon (eds.). 1995. *Biological assessment and criteria: Tools for water resource planning and decision making.* Lewis Publishers, Boca Raton, FL.
- DeGraaf, D. A., and L. H. Bain. 1986. Habitat use by and preferences of juvenile Atlantic salmon in two Newfoundland rivers. *Trans. Am. Fish. Soc.* 115:671–681.
- Dietrich, W. E., and T. Dunne. 1978. Sediment budget for a small catchment in mountainous terrain. *Z. Geomorph.* 29(Suppl):191–206.
- Dietrich, W. E., J. W. Kirchner, H. Ikeda, and F. Iseya. 1989. Sediment supply and the development of the coarse surface layer in gravel bed rivers. *Nature* 340(6230):215–217.
- Dinicola, R. S. 1989. Characterization and simulation of rainfall runoff relations for headwater basins in western King and Snohomish Counties, Washington State. USGS Water Resources Investigation Rep. 89-4052. U.S. Geological Survey, Tacoma, WA.
- Dixon, P., and A. M. Ellison. 1996. Bayesian inference. *Ecol. Monogr.* 6:1034–1035.
- Doberstein, C. P., J. R. Karr, and L. L. Conquest. 2000. The effect of fixed-count subsampling on macroinvertebrate biomonitoring in small streams. *Freshw. Biol.* 44: 355–371.
- Donato, M. M. 1998. Surface-water/ground-water relations in the Lemhi River basin, east-central Idaho. USGS Water Resources Investigation Rep. 98-4185. U.S. Geological Survey, Washington, DC. Online at <http://wa.water.usgs.gov/ccpt/pubs/fs-069-98.html> [Accessed 24 Jan. 2003].
- Doppelt, B., M. Scurlock, C. Frissell, and J. Karr. 1993. *Entering the watershed.* Island Press, Covelo, CA.
- Doyle, E. G. 1997. The habitat restoration cost estimation model (HRCCEM): A cooperative tool for watershed management. Master's thesis. Univ. Washington, Seattle.
- Dunham, J. B., and B. E. Rieman. 1999. Metapopulation structure of bull trout: Influences of physical, biotic, and geometrical landscape characteristics. *Ecol. Appl.* 9:642–655.
- Dunham, J., B. Rieman, and K. Davis. 2001. Sources and magnitude of sampling error in redd counts for bull trout. *N. Am. J. Fish. Manag.* 21:343–352.
- Dunham, J. B., B. E. Rieman, and J. T. Peterson. 2002. Patch-based models of species occurrence: Lessons from salmonid fishes in streams. *In* J. M. Scott, P. J. Heglund, M. Morrison, M. Raphael, J. Haufler, and B. Wall (eds.), *Predicting species occurrences: Issues of scale and accuracy*, p. 327–334. Island Press, Covelo, CA.
- Dunham, J. B., and G. L. Vinyard. 1997. Incorporating stream level variability into analyses of site level fish habitat relationships: Some cautionary examples. *Trans. Am. Fish. Soc.* 126:323–329.

- Dunne, T., and L. B. Leopold. 1978. *Water in environmental planning*. W. H. Freeman and Co., San Francisco.
- Ebbert, J. C., and S. S. Embrey. 2002. Pesticides in surface water of the Yakima River basin, Washington, 1999–2000—Their occurrence and an assessment of factors affecting concentrations and loads. USGS Water Resources Investigation Rep. 01-4211. U.S. Geological Survey, Washington, DC.
- Ebbert, J. C., and D. R. Roe. 1998. Soil erosion in the Palouse River basin: Indication of improvement. USGS Fact Sheet FS-069-98. Online at <http://wa.water.usgs.gov/ccpt/pubs/fs-069-98.html> [Accessed 24 Jan. 2003].
- Efron, B., and R. Tibshirani. 1991. Statistical data analysis in the computer age. *Science* 253(5018):390–395.
- Efron, B., and R. Tibshirani. 1993. *An introduction to the bootstrap*. Chapman & Hall, New York.
- Elmore, W. 1992. Riparian responses to grazing practices. In R. J. Naiman, (ed.), *Watershed management: Balancing sustainability and environmental change*, p. 442–457. Springer-Verlag, New York.
- Emlen, J. M. 1995. Population viability of the Snake River Chinook salmon (*Oncorhynchus tshawytscha*). *Can. J. Fish. Aquat. Sci.* 52:1442–1448.
- ESA (Endangered Species Act). 1973. Title 16 U.S. Code, Section 1531.
- Farwell, M. K., R. E. Bailey, and J. A. Tadey. 1999. Enumeration of the 1996 Harrison River Chinook salmon escapements. Canadian Manuscript Rep. of Fisheries and Aquatic Sciences 2478. Dept. Fisheries and Oceans Canada, Kamloops, British Columbia.
- Fausch, K. D. 1993. Experimental analysis of microhabitat selection by juvenile steelhead (*Oncorhynchus mykiss*) and coho salmon (*O. kisutch*) in a British Columbia stream. *Can. J. Fish. Aquat. Sci.* 50:1198–207.
- Feist, B. E., E. A. Steel, G. R. Pess, and R. E. Bilby. 2003. The influence of scale on salmon habitat restoration priorities. *Anim. Conserv.* 6(3):271–282.
- FEMAT (Forest Ecosystem Management Assessment Team). 1993. *Forest ecosystem management: An ecological, economic, and social assessment*. U.S. Forest Service and collaborating agencies, Washington, DC.
- Flaaten, O., A. G. V. Salvanes, T. Schweder, and O. Ulltang. 1998. Fisheries management under uncertainty—an overview. *Fish. Res.* 37:1–6.
- Flebbe, P. A. 1993. Comment on Meisner (1990): Effect of climatic warming on the southern margins of the native range of brook trout, *Salvelinus fontinalis*. *Can. J. Fish. Aquat. Sci.* 50:883–884.
- Fogarty, M. J., R. K. Mayo, L. O'Brien, F. M. Serchuk, and A. A. Rosenberg. 1996. Assessing uncertainty and risk in exploited marine populations. *Reliab. Eng. Syst. Saf.* 54:183–195.
- Fore, L. S., J. R. Karr, and R. W. Wisseman. 1996. Assessing invertebrate responses to human activities: Evaluating alternative approaches. *J. North Am. Benthol. Soc.* 15:212–231.

- Fore, L. S., K. Paulsen, and K. O’Laughlin. 2001. Assessing the performance of volunteers in monitoring streams. *Freshw. Biol.* 46:109–123.
- Francis, R. I. C. C. 1992. Use of risk analysis to assess fishery management strategies: A case study using orange roughy (*Hoplostethus atlanticus*) on the Chatham Rise, New Zealand. *Can. J. Fish. Aquat. Sci.* 49:922–930.
- Francis, R. I. C. C., and R. Shotton. 1997. “Risk” in fisheries management: A review. *Can. J. Fish. Aquat. Sci.* 54:1699–1715.
- Franklin, J. F., and C. T. Dyrness. 1973. Natural vegetation of Oregon and Washington. Gen. Tech. Rep. PNW-8. U.S. Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR.
- Fraser, N. H. C., N. B. Metcalfe, and J. E. Thorpe. 1993. Temperature-dependent switch between diurnal and nocturnal foraging in salmon. *Proc. R. Soc. Lond. Ser. B Biol. Sci.* 252:135–139.
- Frissell, C. A. 1993a. A strategy for watershed restoration and recovery of Pacific salmon in the Pacific Northwest. Prepared for the Pacific Rivers Council. (Available from the Pacific Rivers Council, Inc., P.O. Box 10798, Eugene, OR 97440.)
- Frissell, C. A. 1993b. Topology of extinction and endangerment of native fishes in the Pacific Northwest and California (USA). *Conserv. Biol.* 7(2):342–354.
- Frissell, C. A., and D. Bayles. 1996. Ecosystem management and the conservation of aquatic biodiversity and ecological integrity. *Water Resour. Bull.* 32:229–240.
- Frissell, C. A., W. J. Liss, R. E. Gresswell, R. K. Nawa, and L. Ebersole. 1997. A resource in crisis: Changing the measure of salmon management. In D. J. Stouder, P. A. Bisson, and R. J. Naiman (eds.), *Pacific salmon and their ecosystems: Status and future options*, p. 411–446. Chapman & Hall, New York.
- Frissell, C. A., W. J. Liss, C. E. Warren, and M. D. Hurley. 1986. A hierarchical framework for stream habitat classification: Viewing streams in a watershed context. *Environ. Manag.* 10:199–214.
- Frissell, C. A., and R. K. Nawa. 1992. Incidence and causes of physical failure of artificial habitat structures in streams of western Oregon and Washington. *N. Am. J. Fish. Manag.* 12:182–197.
- Frissell, C. A., and S. C. Ralph. 1998. Stream and watershed restoration. In R. J. Naiman and R. E. Bilby (eds.), *Ecology and management of streams and rivers in the Pacific Northwest coastal ecoregion*, p. 599–624. Springer-Verlag, New York.
- Geist, D. R., J. Jones, C. J. Murray, and D. D. Dauble. 2000. Suitability criteria analyzed at the spatial scale of redd clusters improved estimates of fall Chinook salmon (*Oncorhynchus tshawytscha*) spawning habitat use in the Hanford Reach, Columbia River. *Can. J. Fish. Aquat. Sci.* 57:1636–1646.
- Gerritsen, J., R. E. Carlson, D. L. Dycus, C. Faulkner, G. R. Gibson, J. Harcum, and S. A. Markowitz. 1998. Lake and reservoir bioassessment and biocriteria: Technical guidance document. EPA 841-B-98-007. U.S. Environmental Protection Agency, Office of Water, Washington, DC. Online at <http://www.epa.gov/owow/monitoring/tech/lakes.html> [Accessed 5 Feb. 2003].

- Gibson, G. R., M. L. Bowman, J. Gerritsen, and B. D. Snyder. 2000. Estuarine and coastal marine waters: Bioassessment and biocriteria technical guidance. EPA 822-B-00-024. U.S. Environmental Protection Agency, Office of Water, Washington, DC. Online at <http://www.epa.gov/ost/biocriteria/States/estuaries/estuaries1.html> [Accessed 5 Feb. 2003].
- Gore, J. A. 1985. The restoration of rivers and streams, theories and experience. Butterworth Publishers, Stoneham, MA.
- Gorman, O. T., and J. R. Karr. 1978. Habitat structure and stream fish communities. *Ecology* 59(3):507–515.
- Grafe, C. S. (ed.). 2000a. Idaho small stream ecological assessment framework: An integrated approach. Idaho Dept. Environmental Quality, Boise. Online at http://www.deq.state.id.us/water/surface_water/wbag/WBAG_AssessmentFramework.htm [Accessed 5 Feb. 2003].
- Grafe, C. S. (ed.). 2000b. Idaho river ecological assessment framework: An integrated approach. Idaho Dept. Environmental Quality, Boise. Online at http://www.deq.state.id.us/water/surface_water/wbag/WBAG_AssessmentFramework.htm [Accessed 5 Feb. 2003].
- Graham, W. D., J. E. Thorpe, and N. B. Metcalfe. 1996. Seasonal current holding performance of juvenile Atlantic salmon in relation to temperature and smolting. *Can. J. Fish. Aquat. Sci.* 53:80–86.
- Gray, D. H., and W. F. Megahan. 1981. Forest vegetation removal and slope stability in the Idaho Batholith. Research Paper INT-271. U.S. Forest Service, Ogden, UT.
- Greene, C. M., and T. J. Beechie. In prep. Habitat-specific population dynamics of ocean-type Chinook salmon (*Oncorhynchus tshawytscha*) in Puget Sound. (Available from C. M. Greene, NWFSC, 2725 Montlake Blvd. East, Seattle, WA 98112.)
- Gregory, S. V., F. J. Swanson, W. A. McKee, and K. W. Cummins. 1991. An ecosystem perspective of riparian zones. *Bioscience* 41:540–551.
- Gresswell, R. E., W. J. Liss, G. L. Larson, and P. J. Bartlein. 1997. Influence of basin-scale physical variables on life history characteristics of cutthroat trout in Yellowstone Lake. *N. Am. J. Fish. Manag.* 17:1046–1064.
- Groot, C., and L. Margolis. 1991. Pacific salmon life histories. University of British Columbia Press, Vancouver.
- Grossman, G. D., J. Hill, and J. T. Petty. 1995. Observations on habitat structure, population regulation, and habitat use with respect to evolutionarily significant units: A landscape perspective for lotic systems. In J. L. Nielson (ed.), *Evolution and the aquatic ecosystem: Defining unique units in population conservation*, p. 381–391. American Fisheries Society, Symposium 17, Bethesda, MD.
- Hahn, P., C. Kraemer, D. Hendrick, P. Castle, and L. Wood. 2001. Washington State Chinook salmon spawning escapement assessment in the Stillaguamish and Skagit Rivers, 1998. Completion report to the U.S. Chinook Technical Committee and National Marine Fisheries Service, April 6, 2001. Washington Dept. Fish and Wildlife, Olympia.

- Ham, K. D., and T. N. Pearsons. 2000. Can reduced salmonid population abundance be detected in time to limit management impacts? *Can. J. Fish. Aquat. Sci.* 57:17–24.
- Hansen, J. A., J. C. Marr, J. Lipton, D. Cacela, and H. L. Bergman. 1999. Differences in neurobehavioral responses of Chinook salmon (*Oncorhynchus tshawytscha*) and rainbow trout (*Oncorhynchus mykiss*) exposed to copper and cobalt: Behavioral avoidance. *Environ. Toxicol. Chem.* 18:1972–1978.
- Hansen, L. J., and M. L. Johnson. 1999a. Conservation and toxicology: Integrating the disciplines. *Conserv. Biol.* 13:1225–1227.
- Hansen, L. J., and M. L. Johnson. 1999b. Conservation and toxicology: The need to integrate the disciplines. *Environ. Toxicol. Chem.* 18:2121–2122.
- Harr, R. D. 1986. Effects of clearcutting on rain-on-snow runoff in western Oregon: A new look at old studies. *Water Resour. Res.* 22:1095–1100.
- Hartman, G. F., J. C. Scrivener, and M. J. Miles. 1996. Impacts of logging in Carnation Creek, a high-energy coastal stream in British Columbia, and their implication for restoring fish habitat. *Can. J. Fish. Aquat. Sci.* 53(Suppl. 1):237–251.
- Harvey, B. C., and R. J. Nakamoto. 1997. Habitat-dependent interactions between two size-classes of juvenile steelhead in a small stream. *Can. J. Fish. Aquat. Sci.* 54:27–31.
- Harvey, B. C., J. L. White, and R. J. Nakamoto. 2002. Habitat relationships and larval drift of native and nonindigenous fishes in neighboring tributaries of a coastal California river. *Trans. Am. Fish. Soc.* 131:159–170.
- Hawkins, C., and J. Ostermiller. 2001. Status of predictive model development and testing for western Oregon and Washington: General model performance. Presented at Northwest Biological Assessment Workgroup 12th Annual Meeting, Cannon Beach, OR. Abstract online at <http://www.epa.gov/r10earth/offices/oea/aqbioass.html> [Accessed 5 Feb. 2003].
- Hayman R., E. Beamer, and R. McClure. 1996. FY 1995 Skagit River Chinook research. Skagit System Cooperative Chinook restoration research progress report #1, NWIFC Contract #3311 for FY95. Skagit System Cooperative, La Conner, WA.
- Hayslip, G. In press. Biological assessment using benthic macroinvertebrates for wadeable streams in the Pacific Northwest. U. S. Environmental Protection Agency, Region 10, Office of Environmental Assessment, Seattle.
- Healey, M. C. 1991. Life history of Chinook salmon (*Oncorhynchus tshawytscha*). In C. Groot and L. Margolis (eds.), *Pacific salmon life histories*, p. 311–394. University of British Columbia Press, Vancouver.
- Healey, M. C., and A. Prince. 1995. Scales of variation in life history tactics of Pacific salmon and the conservation of phenotype and genotype. In J. L. Nielson (ed.), *Evolution and the aquatic ecosystem: Defining unique units in population conservation*, p. 176–185. American Fisheries Society, Symposium 17, Bethesda, MD.

- Hearn, W. E., and B. E. Kynard. 1986. Habitat utilization and behavioral interaction of juvenile Atlantic salmon (*Salmo salar*) and rainbow trout (*S. gairdneri*) in tributaries of the White River of Vermont. *Can. J. Fish. Aquat. Sci.* 43:1988–98.
- Heggenes, J., O. M. W. Krog, O. R. Lindås, J. G. Dokk, and T. Bremnes. 1993. Homeostatic behavioural responses in a changing environment: Brown trout (*Salmo trutta*) become nocturnal during winter. *J. Anim. Ecol.* 62:295–308.
- Heggenes, J., S. J. Saltveit, D. Bird, and R. Grew. 2002. Static habitat partitioning and dynamic selection by sympatric young Atlantic salmon and brown trout in southwest England streams. *J. Fish Biol.* 60:72–86.
- Heintz, R. A., S. D. Rice, A. C. Wertheimer, R. F. Bradshaw, F. P. Thrower, J. E. Joyce, and J. W. Short. 2000. Delayed effects on growth and marine survival of pink salmon *Oncorhynchus gorbuscha* after exposure to crude oil during embryonic development. *Mar. Ecol. Prog. Ser.* 208:205–216.
- Hendrick, D. Unpubl. data. Data from the Snohomish and Stillaguamish Rivers. (Available from D. Hendrick, WDFW, 111 Sherman St., P.O. Box 1100, La Connor, WA 98257.)
- Hicks, B. J., J. D. Hall, P. A. Bisson, and J. R. Sedell. 1991. Responses of salmonids to habitat change. *In* W. R. Meehan (ed.), *Influences of forest and rangeland management on salmonid fisheries and their habitats*, p. 483–518. American Fisheries Society, Special Publication 19, Bethesda, MD.
- Hilborn, R., J. J. Maguire, A. M. Parma, and A. A. Rosenberg. 2001. The precautionary approach and risk management: Can they increase the probability of successes in fishery management? *Can. J. Fish. Aquat. Sci.* 58:99–107.
- Hilborn, R., and C. J. Walters. 1992. *Quantitative fisheries stock assessment: Choice, dynamics, and uncertainty*. Chapman & Hall, New York.
- Hill, B. H., A. T. Herlihy, P. R. Kaufmann, R. J. Stevenson, F. H. McCormick, and C. B. Johnson. 2000. Use of periphyton assemblage data as an index of biotic integrity. *J. North Am. Benthol. Soc.* 19:50–67.
- Hilsenhoff, W. L. 1982. Using a biotic index to evaluate water quality in streams. *Tech. Bulletin 132*. Wisconsin Dept. Natural Resources, Madison.
- Holtby, L. B., and J. C. Scrivener. 1989. Observed and simulated effects of climate variability, clear-cut logging, and fishing on the numbers of chum salmon (*Oncorhynchus keta*) and coho salmon (*O. kisutch*) returning to Carnation Creek, British Columbia. *Can. Spec. Publ. Fish. Aquat. Sci.* 105:62–81.
- Holz T., T. Liptan, and T. Schueler. 1998. Beyond innovative development: Site design techniques to minimize impacts to salmon habitat. *In* Tom Holz (ed.), *Salmon in the city*, Mount Vernon, WA, May 20–21, 1998, p. 54–59. Washington State Univ., Pullman.
- House, R. 1995. Temporal variation in abundance of an isolated population of cutthroat trout in western Oregon, 1981–1991. *N. Am. J. Fish. Manag.* 15:33–41.
- Huntington, C., W. Nehlsen, and J. Bowers. 1996. A survey of healthy native stocks of anadromous salmonids in the Pacific Northwest and California. *Fisheries* 21(3):6–14.

- Imhof, J. G., J. Fitzgibbon, and W. K. Annable. 1996. A hierarchical evaluation for characterizing watershed ecosystems for fish habitat. *Can. J. Fish. Aquat. Sci.* 53(Suppl. 1):312–326.
- JNRC (Joint Natural Resources Cabinet). 2001. Guidance on watershed assessment for salmon. Governor's Salmon Recovery Office, Olympia, WA. Online at <http://www.governor.wa.gov/ggro/watershed/watershed.htm> [Accessed 23 Jan. 2003].
- JNRC (Joint Natural Resources Cabinet). 2002. Roadmap for salmon habitat conservation at the watershed level. Governor's Salmon Recovery Office, Olympia, WA. (Available from Governor's Salmon Recovery Office, P.O. Box 43135, Olympia, WA 98504.)
- Johnson, K. L. 1992. Management for water quality on rangelands through best management practice: The Idaho approach. *In* R. J. Naiman (ed.), *Watershed management: Balancing sustainability and environmental change*, p. 415–441. Springer-Verlag, New York.
- Johnson, R. R., C. D. Ziebell, D. R. Paton, P. F. Folliott, and R. H. Hamre. 1985. Riparian ecosystems and their management: Reconciling conflicting uses. Gen. Tech. Rep. U.S. Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.
- Jones, J. A., and G. E. Grant. 1996. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon. *Water Resour. Res.* 32:959–974.
- Jones III, E. L., T. J. Quinn II, and B. W. Van Alen. 1998. Observer accuracy and precision in aerial and foot survey counts of pink salmon in a Southeast Alaska stream. *N. Am. J. Fish. Manag.* 18:842–846.
- Jones, K. K., and K. M. S. Moore. 2000. Habitat assessment in coastal basins in Oregon: Implications for coho salmon production and habitat restoration. *In* E. E. Knudsen, C. R. Steward, D. D. MacDonald, J. E. Williams, and D. W. Reiser (eds.), *Sustainable fisheries management: Pacific salmon*, p. 329–340. Lewis Publishers, New York.
- Jowett, I. G. 1997. Instream flow methods: A comparison of approaches. *Regul. Rivers Res. Manag.* 13:115–127.
- Kaiser, V. G. 1967. Soil erosion and wheat yields in Whitman County, Washington. *Northwest Sci.* 41:86–91.
- Karr, J. R. 1991. Biological integrity: A long-neglected aspect of water resource management. *Ecol. Appl.* 1(1):66–84.
- Karr, J. R., and E. W. Chu. 1999. *Restoring life in running waters: Better biological monitoring*. Island Press, Washington, DC.
- Karr, J. R., and E. W. Chu. 2000. Sustaining living rivers. *Hydrobiologia* 442:1–14.
- Karr, J. R., K. D. Fausch, P. L. Angermeier, P. R. Yant, and I. J. Schlosser. 1986. Assessment of biological integrity in running waters: A method and its rationale. Special Publication 5. Illinois Natural History Survey, Champaign, IL.
- Kauffman, J. B., R. L. Beschta, N. Otting, and D. Lytjen. 1997. An ecological perspective of riparian and stream restoration in the western United States. *Fisheries* 22(5):12–24.

- Keleher, C. J., and F. J. Rahel. 1996. Thermal limits to salmonid distributions in the Rocky Mountain region and potential habitat loss due to global warming: A geographic information system (GIS) approach. *Trans. Am. Fish. Soc.* 125:1–13.
- Kennedy, G. J. A., and C. D. Strange. 1986. The effects of intra- and inter-specific competition on the survival and growth of stocked juvenile Atlantic salmon, *Salmo salar* L., and resident trout, *Salmo trutta* L., in an upland stream. *J. Fish Biol.* 28:479–489.
- Kerans, B. L., and J. R. Karr. 1994. A benthic index of biological integrity (B-IBI) for rivers of the Tennessee Valley. *Ecol. Appl.* 4:768–785.
- Kessler, J. H., and R. M. McGuire. 1999. Total system performance assessment using a logic tree approach. *Risk Anal.* 19:915–932.
- King County. 1996. King County benchmark report. Metropolitan King County Countywide Planning Policies Benchmark Program, Seattle.
- Kleindl, W. J. 1995. A benthic index of biotic integrity for Puget Sound lowland streams, Washington, USA. Master's thesis. Univ. Washington, Seattle.
- Kondolf, G. M. 1995. Five elements for effective evaluation of stream restoration. *Restor. Ecol.* 3:133–136.
- Korman, J., and P. S. Higgins. 1997. Utility of escapement time series data for monitoring the response of salmon populations to habitat alteration. *Can. J. Fish. Aquat. Sci.* 54:2058–2067.
- Kruse, C. G., W. A. Hubert, and F. J. Rahel. 1997. Geomorphic influences on the distribution of Yellowstone cutthroat trout in the Absaroka Mountains, Wyoming. *Trans. Am. Fish. Soc.* 126:418–427.
- Kruzynski, G. M., and I. K. Birtwell. 1994. A predation bioassay to quantify the ecological significance of sublethal responses of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) to the antisapstain fungicide TCMTB. *Can. J. Fish. Aquat. Sci.* 51:1780–1790.
- Labbe, T. R., and K. D. Fausch. 2000. Dynamics of intermittent stream habitat regulate persistence of a threatened fish at multiple scales. *Ecol. Appl.* 10:1774–1791.
- Lanka, R. P., W. A. Hubert, and T. A. Wesche. 1987. Relations of geomorphology to stream habitat and trout standing stock in small Rocky Mountain streams. *Trans. Am. Fish. Soc.* 116:21–28.
- Larson, M. G., D. B. Booth, and S. A. Morley. 2001. Effectiveness of large woody debris in stream rehabilitation projects in urban basins. *Ecol. Eng.* 18:211–226.
- LCFRB (Lower Columbia Fish Recovery Board). 2001. Lower Columbia Fish Recovery Board interim habitat strategy. (Available from Lower Columbia Fish Recovery Board, 2127 8th Ave., Longview, WA 98632.)
- LCFRB (Lower Columbia Fish Recovery Board). 2002. Lower Columbia Fish Recovery Board 3rd round project evaluation process. (Available from Lower Columbia Fish Recovery Board, 2127 8th Ave., Longview, WA 98632.)
- Leopold, L. B., M. G. Wolman, and J. P. Miller. 1964. Fluvial processes in geomorphology. W. H. Freeman and Co., San Francisco.

- Lestelle, L. C., L. E. Mobrand, J. A. Lichatowich, and T. S. Vogel. 1996. Applied ecosystem analysis—a primer, EDT: The ecosystem diagnosis and treatment method. Project No. 9404600. Bonneville Power Administration, Portland, OR.
- Levin, S. A. 1992. The problem of pattern and scale in ecology. *Ecology* 73:1943–67.
- Lewis, C. A., N. P. Lester, A. D. Bradshaw, J. E. Fitzgibbon, K. Fuller, L. Hakanson, and C. Richards. 1996. Considerations of scale in habitat conservation and restoration. *Can. J. Fish. Aquat. Sci.* 53(Suppl. 1):440–445.
- Lichatowich, J. 1999. *Salmon without rivers: A history of the Pacific salmon crisis*. Island Press, Covelo, CA.
- Lichatowich, J., L. Mobrand, L. Lestelle, and T. Vogel. 1995. An approach to the diagnosis and treatment of depleted Pacific salmon populations in Pacific Northwest watersheds. *Fisheries* 20(1):10–18.
- Liermann, M., and R. Hilborn. 1997. Depensation in fish stocks: A hierarchic Bayesian meta-analysis. *Can. J. Fish. Aquat. Sci.* 54:1976–1984.
- Lisle, T. E. 1982. Effects of aggradation and degradation on pool-riffle morphology in natural gravel channels, northwestern California. *Water Resour. Res.* 18:1643–1651.
- Lisle, T. E. 1989. Sediment transport and resulting deposition in spawning gravels, north coastal California. *Water Resour. Res.* 25:1303–1319.
- Lobón-Cerviá, J., and P. A. Rincón. 1998. Field assessment of the influence of temperature on growth rate in a brown trout population. *Trans. Am. Fish. Soc.* 127:718–728.
- Luce, C. H., B. E. Rieman, J. B. Dunham, J. L. Clayton, J. G. King, and T. A. Black. 2001. Incorporating aquatic ecology into decisions on prioritization of road decommissioning. *Water Resour. Impact* 3(3):8–14.
- Lucchetti, G., and R. Furstenberg. 1992. Management of coho salmon habitat in urbanizing landscapes of King County, Washington, USA. *In* L. Berg and P. W. Delaney (eds.), *Proceedings of the Coho Workshop*, Nanaimo, B.C., May 26–28, 1992, p. 308–317. Dept. Fisheries and Oceans Canada, Vancouver, British Columbia.
- Ludwig, D., and C. J. Walters. 1981. Measurement errors and uncertainty in parameter estimates for stock and recruitment. *Can. J. Fish. Aquat. Sci.* 38:711–720.
- Lunetta, R. S., B. Cosentino, D. R. Montgomery, E. M. Beamer, and T. J. Beechie. 1997. GIS-based evaluation of salmon habitat in the Pacific Northwest. *Photogramm. Eng. Remote Sensing* 63(10):1219–1229.
- Madej, M. A., and V. Ozaki. 1996. Channel response to sediment wave propagation and movement, Redwood Creek, California, USA. *Earth Surf. Processes Landforms* 21:911–927.
- Major, E. B., B. K. Jessup, A. Prussian, and D. Rinella. 2001. Alaska stream condition index: Biological index development for Cook Inlet, 1997–2000 summary. Alaska Dept. Environmental Conservation, Anchorage. Online at <http://www.uaa.alaska.edu/enri/bmap/index.html> [Accessed 27 Jan. 2003].

- Mangel, M., L. M. Talbot, G. K. Meffe, M. T. Agardy, D. L. Alverson, D. B. Botkin, G. Budowski, T. Clark, J. Cooke, R. H. Crozier, P. K. Dayton, D. L. Elder, C. W. Fowler, S. Funtowicz, J. Giske, R. J. Hofman, S. J. Holt, S. R. Kellert, L. A. Kimball, D. Ludwig, K. Magnusson, B. S. Malayang III, C. Mann, E. A. Norse, S. P. Northridge, W. F. Perrin, C. Perrings, R. M. Peterman, G. B. Rabb, H. A. Regier, J. E. Reynolds III, K. Sherman, M. P. Sissenwine, T. D. Smith, A. Starfield, R. J. Taylor, M. F. Tillman, C. Toft, J. R. Twiss, Jr., J. Wilen, and T. P. Young. 1996. Principles for the conservation of wild living resources. *Ecol. Appl.* 6:338–362.
- Maryland DER (Prince George’s County, Maryland Dept. Environmental Resources, Programs and Planning Division). 2000. Low-impact development: An integrated design approach. EPA 841-B-00-003. National Service Center for Environmental Publications, Cincinnati, OH.
- Maser, C., R. F. Tarrant, J. M. Trappe, and J. F. Franklin. 1988. From the forest to the sea: A story of fallen trees. Gen. Tech. Rep. PNW-GTR-229. U.S. Forest Service, Pacific Northwest Research Station, Corvallis, OR.
- Maupin, M. A. 1999. Methods to determine pumped irrigation-water withdrawals from the Snake River between Upper Salmon Falls and Swan Falls dams, Idaho, using electrical power data. USGS Water Resources Investigation Rep. 99-4175. U.S. Geological Survey, Boise, ID.
- Maxwell, B. A. 1999. A power analysis on the monitoring of bull trout stocks using redd counts. *N. Am. J. Fish. Manag.* 19:860–866.
- Maxwell, J. R., C. J. Edwards, M. E. Jensen, S. J. Paustian, H. Parrott, and D. M. Hill. 1995. A hierarchical framework of aquatic ecological units in North America (nearctic zone). Gen. Tech. Rep. NC-176. U.S. Forest Service, North Central Experiment Station, St. Paul, MN.
- May, C. W., R. R. Horner, J. R. Karr, B. W. Mar, and E. B. Welch. 1997. Effects of urbanization on small streams in the Puget Sound lowland ecoregion. *Watershed Prot. Tech.* 2:483–494.
- McAllister, M. K., E. K. Pritch, A. E. Punt, and R. Hilborn. 1994. Bayesian approach to stock assessment and harvest decisions using the sampling/importance resampling algorithm. *Can. J. Fish. Aquat. Sci.* 51:2673–2687.
- McClure, M., E. Holmes, B. Sanderson, and C. Jordan. In press. A large-scale, multi-species status assessment: Anadromous salmonids in the Columbia River basin. *Ecol. Appl.*
- McElhany, P., M. H. Ruckelshaus, M. J. Ford, T. C. Wainwright, and E. P. Bjorkstedt. 2000. Viable salmonid populations and the recovery of evolutionarily significant units. U.S. Dept. Commerce, NOAA Tech. Memo. NMFS-NWFSC-42, Seattle.
- McIntosh, B., J. Sedell, R. Thurow, S. Clarke, and G. Chandler. 2000. Historical changes in pool habitats in the Columbia River Basin. *Ecol. Appl.* 10:1478–1496.
- McMahon, T. E., and G. F. Hartman. 1989. Influence of cover complexity and current velocity on winter habitat use by juvenile coho salmon (*Oncorhynchus kisutch*). *Can. J. Fish. Aquat. Sci.* 46:1551–1557.
- McNeely, J. A., K. R. Miller, W. V. Reid, R. A. Mittermeier, and T. B. Werner. 1990. Strategies for conserving biodiversity. *Environment* 32:16–20.

- Meador, J. P., T. K. Collier, and J. E. Stein. 2002. Use of tissue and sediment-based threshold concentrations of polychlorinated biphenyls (PCBs) to protect juvenile salmonids listed under the U.S. Endangered Species Act. *Aquat. Conserv.* 12:493–516.
- Meehan, W. R. (ed.). 1991. Influences of forest and rangeland management on salmonid fishes and their habitats. American Fisheries Society, Special Publication 19, Bethesda, MD.
- Megahan, W. F., J. G. King, and K. A. Seyedbagheri. 1995. Hydrologic and erosional responses of a granitic watershed to helicopter logging and broadcast burning. *For. Sci.* 41:777–795.
- Meisner, J. D. 1990. Effect of climatic warming on the southern margins of the native range of brook trout, *Salvelinus fontinalis*. *Can. J. Fish. Aquat. Sci.* 47:1065–1070.
- Merritt, R. W., and K. W. Cummins (eds.) 1996. An introduction to the aquatic insects of North America. Kendall Hunt Publishing Company, Dubuque, IA.
- Miller, D. J. 2003. Programs for DEM analysis. *In* Landscape dynamics and forest management. Gen. Tech. Rep. RMRS-GTR-101CD (CD-ROM). U.S. Forest Service, Rocky Mountain Research Station, Fort Collins, CO.
- Miller, R. J., and E. L. Brannon. 1982. The origin and development of life history patterns in Pacific salmonids. *In* E. L. Brannon and E. O. Salo (eds.), Proceedings of the salmon and trout migratory behavior symposium, p. 296–306. Univ. Washington, School of Fisheries, Seattle.
- Minns, C. K., J. R. M. Kelso, and R. G. Randall. 1996. Detecting the response of fish to habitat alterations in freshwater ecosystems. *Can. J. Fish. Aquat. Sci.* 53:403–414.
- Mishra, S. 2001. Dealing with uncertainty in environmental model predictions. *EOS* 82:568.
- Mobrand, L. E., J. A. Lichatowich, L. C. Lestelle, and T. S. Vogel. 1997. An approach to describing ecosystem performance “through the eyes of salmon.” *Can. J. Fish. Aquat. Sci.* 54:2964–2973.
- Mochan, D. G., and S. Mrazik. 2000. A summary of chemistry, temperature, habitat, and macroinvertebrate data from the southeast Oregon ambient monitoring sites. Tech. Rep. BIO00-03. Oregon Dept. Environmental Quality, Laboratory Division, Biomonitoring Section, Portland.
- Montgomery, D. 1993. Road surface drainage, channel extension, and slope stability. Geomorphological watershed analysis project. Final report for the period from 10/1/91 to 6/3/93. Rep. TFW-SH01-93-001. Washington Dept. Natural Resources, Olympia.
- Montgomery, D. R., E. M. Beamer, G. R. Pess, and T. P. Quinn. 1999. Channel type and salmonid spawning distribution and abundance. *Can. J. Fish. Aquat. Sci.* 56:377–387.
- Montgomery, D. R., and J. M. Buffington. 1997. Channel-reach morphology in mountain drainage basins. *Geol. Soc. Am. Bull.* 109:596–611.
- Montgomery, D. R., J. M. Buffington, R. D. Smith, K. M. Schmidt, and G. Pess. 1995. Pool spacing in forest channels. *Water Resour. Res.* 31:1097–1105.
- Montgomery, D. R., and W. E. Dietrich. 1994. A physically based model for the topographic control on shallow landsliding. *Water Resour. Res.* 30(4):1153–1171.

- Montgomery, D. R., K. Sullivan, and H. M. Greenberg. 1998. Regional test of a model for shallow landsliding. *Hydrol. Process.* 12:943–955.
- Moore, K. M. 1997. Conceptual framework for habitat restoration. *In* J. Nicholas (ed.), Oregon plan for salmon and watersheds supplement-I steelhead, Chapter 5. State of Oregon, Salem.
- Morantz, D. L., R. K. Sweeney, C. S. Shirvell, and D. A. Longard. 1987. Selection of microhabitat in summer by juvenile Atlantic salmon (*Salmo salar*). *Can. J. Fish. Aquat. Sci.* 44:120–129.
- Morgan, M. G., M. Henrion, and M. Small. 1990. Uncertainty: A guide to dealing with uncertainty in quantitative risk and policy analysis. Cambridge University Press, Cambridge, England.
- Morley, S. A. 2000. Effects of urbanization on the biological integrity of Puget Sound lowland streams: Restoration with a biological focus. Master's thesis. Univ. Washington, Seattle.
- Morley, S. A., and J. R. Karr. 2002. Assessing and restoring the health of urban streams in the Puget Sound basin. *Conserv. Biol.* 16:1498–1509.
- Moscip, A. L., and D. R. Montgomery. 1997. Urbanization, flood frequency, and salmon abundance in Puget Lowland streams. *J. Am. Water Resour. Assoc.* 33(6):1289–1297.
- Moussalli, E., and R. Hilborn. 1986. Optimal stock size and harvest rate in multistage life history models. *Can. J. Fish. Aquat. Sci.* 43:135–141.
- Mueter, F. J., R. M. Peterman, and B. J. Pyper. 2002. Opposite effects of ocean temperature on survival rates of 120 stocks of Pacific salmon (*Oncorhynchus* spp.) in northern and southern areas. *Can. J. Fish. Aquat. Resour.* 59:456–463.
- Murphy, M. L., and K. V. Koski. 1989. Input and depletion of woody debris in Alaska streams and implications for streamside management. *N. Am. J. Fish. Manag.* 9:427–436.
- Murphy, M. L., K. V. Koski, J. Heifetz, S. W. Johnson, D. Kirchofer, and J. F. Thedinga. 1985. Role of large organic debris as winter habitat for juvenile salmonids in Alaska streams. *Proc. West. Assoc. Fish Wildl. Agencies* 1984:251–262.
- Myers, J. M., R. G. Kope, G. J. Bryant, D. Teel, L. J. Lierheimer, T. C. Wainwright, W. S. Grand, F. W. Waknitz, K. Neely, S. T. Lindley, and R. S. Waples. 1998. Status review of Chinook salmon from Washington, Idaho, Oregon, and California. U.S. Dept. Commerce, NOAA Tech. Memo. NMFS-NWFSC-35, Seattle.
- Myers, R. A., B. R. MacKenzie, K. G. Bowen, and N. J. Barrowman. 2001. What is the carrying capacity for fish in the ocean? A meta-analysis of population dynamics of North Atlantic cod. *Can. J. Fish. Aquat. Sci.* 58:1464–1476.
- Naiman, R. J., C. A. Johnston, and J. C. Kelly. 1988. Alteration of North American streams by beaver. *Bioscience* 38:753–762.
- Naiman, R. J., D. G. Lonzarich, T. J. Beechie, and S. C. Ralph. 1992. General principles of classification and the assessment of conservation potential in rivers. *In* P. J. Boon, P. Calow, and G. E. Petts (eds.), *River conservation and management*, p. 93–124. John Wiley & Sons, New York.
- Nakamoto, R. J. 1994. Characteristics of pools used by adult summer steelhead overwintering in the New River, California. *Trans. Am. Fish. Soc.* 123:757–765.

- Nehlsen, W., J. E. Williams, and J. A. Lichatowich. 1991. Pacific salmon at the crossroads: Stocks at risk from California, Oregon, Idaho, and Washington. *Fisheries* 16(2):4–21.
- Neilson, J. D., and C. E. Banford. 1983. Chinook salmon (*Oncorhynchus tshawytscha*) spawner characteristics in relation to redd physical features. *Can. J. Zool.* 61:1524–1531.
- Nelson, R. L., W. S. Platts, D. P. Larsen, and S. E. Jensen. 1992. Trout distribution and habitat in relation to geology and geomorphology in the North Fork Humboldt River drainage, northeast Nevada. *Trans. Am. Fish. Soc.* 121:405–426.
- Nickelson, T. E., and P. W. Lawson. 1998. Population viability of coho salmon, *Oncorhynchus kisutch*, in Oregon coastal basins: Application of a habitat-based life cycle model. *Can. J. Fish. Aquat. Sci.* 55:2383–2392.
- Nickelson, T. E., J. D. Rodgers, S. L. Johnson, and M. F. Solazzi. 1992. Seasonal changes in habitat use by juvenile coho salmon (*Oncorhynchus kisutch*) in Oregon coastal streams. *Can. J. Fish. Aquat. Sci.* 49:783–789.
- Nielsen, J. L., T. E. Lisle, and V. Ozaki. 1994. Thermally stratified pools and their use by steelhead in northern California streams. *Trans. Am. Fish. Soc.* 123:613–626.
- NMFS (National Marine Fisheries Service). 1992. Recovery planning guidelines. National Marine Fisheries Service, Office of Protected Resources, Washington, DC.
- NMFS (National Marine Fisheries Service). 1995. Juvenile fish screen criteria. Environmental and Technical Services Division. Online at <http://www.iep.water.ca.gov/cvffrt/DFGCriteria2.htm> [Accessed 27 Jan. 2003].
- NMFS (National Marine Fisheries Service). 2000. Recovery planning guidance for Technical Recovery Teams. Sept. 1, 2000 draft. National Marine Fisheries Service, Portland, OR. Online at <http://www.nwfsc.noaa.gov/trt/guidanc9.pdf> [Accessed 12 Nov. 2003].
- NRC (National Research Council). 1996. *Upstream: Salmon and society in the Pacific Northwest*. National Academy Press, Washington, DC.
- ODFW (Oregon Department of Fish and Wildlife). 2001. Guidelines and criteria for stream-road crossings. Online at http://www.dfw.state.or.us/ODFWhtml/InfoCntrFish/Management/stream_road.htm [Accessed 27 Jan. 2003].
- Omernik, J. M., and R. G. Bailey. 1997. Distinguishing between watershed and ecoregions. *J. Am. Water Resour. Assoc.* 33:935–948.
- O’Neal, J. S., A. Watts, S. Bolton, and T. Sibley. 1999. Hydraulic and biological effects of large woody debris and an engineered wood alternative for stream channel rehabilitation projects. *In* R. Sakrison and P. Sturtevant (eds.), *Watershed management to protect declining species*, p. 405–408. American Water Resources Association, Middleburg, VA.
- OPSW (Oregon Plan for Salmon and Watersheds). 2001. Progress report. Oregon Governor’s Natural Resource Office, Salem, OR. Online at <http://www.oregon-plan.org> [Accessed 24 Jan. 2003].
- OWEB (Oregon Watershed Enhancement Board). 1999a. Oregon watershed assessment manual. (Available from Oregon Watershed Enhancement Board, 775 Summer St. NE, Suite 360, Salem, OR 97301.)

- OWEB (Oregon Watershed Enhancement Board). 1999b. Oregon aquatic habitat plan: Restoration enhancement guide. (Available from Oregon Watershed Enhancement Board, 775 Summer St. NE, Suite 360, Salem, OR 97301.)
- OWEB (Oregon Watershed Enhancement Board). 2001. A strategy for achieving healthy watersheds in Oregon. (Available from Oregon Watershed Enhancement Board, 775 Summer St. NE, Suite 360, Salem, OR 97301.)
- Pace, M. L. 2001. Prediction and the aquatic sciences. *Can. J. Fish. Aquat. Sci.* 58:63–72.
- Paulsen, C. M., and T. R. Fisher. 2001. Statistical relationship between parr-to-smolt survival of Snake River spring-summer Chinook salmon and indices of land use. *Trans. Am. Fish. Soc.* 130:347–358.
- Paulson, K. 1997. Estimating changes in sediment supply due to forest practices: A sediment budget approach applied to the Skagit River basin in northwestern Washington. Master's thesis. Univ. Washington, Seattle.
- Paustian, S. J. (ed.). 1992. A channel type users guide for the Tongas National Forest, Southeast Alaska. R10 Tech. Paper 26. U.S. Forest Service, Alaska Region, Juneau, AK.
- Peacock, K. A. 1994. Valley fill and channel incision in Meyer's Canyon, northcentral Oregon. Master's thesis. Oregon State Univ., Corvallis.
- Pess, G. R., T. J. Beechie, J. E. Williams, D. R. Whittall, J. L. Lange, and J. R. Klochak. 2003. Watershed assessment techniques and the success of aquatic restoration activities. *In* R.C. Wissmar and P.A. Bisson (eds.), *Strategies for restoring river ecosystems: Sources of variability and uncertainty in natural and managed systems*, p. 185–202. American Fisheries Society, Bethesda, MD.
- Pess, G. R., Bilby, R. E., and Montgomery, D. R. 1999a. Stream-reach and watershed-scale variables and salmonid spawning distribution and abundance in the Puget Sound region. *In* R. Sakrison and P. Sturtevant (eds.), *Watershed management to protect declining species*, p. 397–400. American Water Resources Association, Middleburg, VA.
- Pess, G. R., B. D. Collins, M. Pollock, T. J. Beechie, A. Haas, and S. Grigsby. 1999b. Historic and current factors that limit coho salmon (*Oncorhynchus kisutch*) production in the Stillaguamish River basin, Washington State: Implications for salmonid habitat protection and restoration. Consultant report to Snohomish County Dept. Public Works, Surface Water Management, Everett, WA, and the Stillaguamish Tribe of Indians, Arlington, WA.
- Pess, G. R., D. R. Montgomery, E. A. Steel, R. E. Bilby, B. E. Feist, and H. M. Greenberg. 2002. Landscape characteristics, land use, and coho salmon (*Oncorhynchus kisutch*) abundance, Snohomish River, Wash., U.S.A. *Can. J. Fish. Aquat. Sci.* 59:613–623.
- Peterman, R. M., B. J. Pyper, M. F. Lapointe, M. D. Adkison, and C. J. Walters. 1998. Patterns of covariation in survival rates of British Columbian and Alaskan sockeye salmon (*Oncorhynchus nerka*) stocks. *Can. J. Fish. Aquat. Resour.* 55:2503–2517.
- Peters, C. N., and D. R. Marmorek. 2001. Application of decision analysis to evaluate recovery actions for threatened Snake River spring and summer Chinook salmon (*Oncorhynchus tshawytscha*). *Can. J. Fish. Aquat. Sci.* 58:2431–2446.

- Peters, C. N., D. R. Marmorek, and R. B. Deriso. 2001. Application of decision analysis to evaluate recovery actions for threatened Snake River fall Chinook salmon (*Oncorhynchus tshawytscha*). *Can. J. Fish. Aquat. Sci.* 58:2447–2458.
- Peterson, N. P., A. Hendry, and T. Quinn. 1992. Assessment of cumulative effects on salmonid habitat: Some suggested parameters and target conditions. Rep. TAW-F3-92-001. Washington Dept. Natural Resources, Olympia.
- Peterson, N. P., and L. M. Reid. 1984. Wall-base channels: Their evolution, distribution, and use by juvenile coho salmon in the Clearwater River, Washington. In J. M. Walton and D. B. Houston (eds.), *Proceedings of the Olympic Wild Fish Conference, March 23–25, 1983*, p. 215–225. Peninsula College, Fisheries Technology Program, Port Angeles, WA.
- Peterson, S., and L. J. Smith. 1982. Risk reduction in fisheries management. *Ocean Manag.* 8:65–79.
- Phillips C., R. Cooper, and T. Quinn. 1981. Skagit River salmonid studies, 1977–1981. Washington Dept. Game and U.S. Fish and Wildlife Service, Olympia, WA.
- Phillips C., W. Freymond, D. Campton, and R. Cooper. 1980. Skagit River salmonid studies, 1977–1979. Washington Dept. Game, Olympia.
- Plafkin, J. L., M. T. Barbour, K. D. Porter, S. K. Gross, and R. M. Hughes. 1989. Rapid bioassessment protocols for use in streams and rivers: Benthic macroinvertebrates and fish. EPA 440-4-89-001. U.S. Environmental Protection Agency, Office of Water, Washington, DC.
- Platts, W. S. 1979. Relationships among stream order, fish populations, and aquatic geomorphology in an Idaho River drainage. *Fisheries* 4(2):5–9.
- Platts, W. S. 1991. Livestock grazing. In W. R. Meehan (ed.), *Influences of forest and rangeland management on salmonid fishes and their habitats*, p. 389–423. American Fisheries Society, Special Publication 19, Bethesda, MD.
- Pleus, A. E. 1995. Variability associated with salmon habitat identification and water surface area measurements. Master's thesis. Evergreen State College, Olympia, WA.
- Plotnikoff, R., and C. Wiseman. 2001. Benthic macroinvertebrate biological monitoring protocols for rivers and streams: 2001 revision. Publication 01-03-028. Washington State Dept. Ecology, Freshwater Ambient Biological Assessment Program, Olympia.
- Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegard, B. D. Richter, R. E. Sparks, and J. C. Stromberg. 1997. The natural flow regime. *Bioscience* 47:769–784.
- Pohl, M. M. 1999. The dams of the Elwha River, Washington: Downstream impacts and policy implications. Doctoral dissertation. Arizona State Univ., Tempe.
- Pollock, M. M., and G. R. Pess. 1998. The current and historical influence of beaver (*Castor canadensis*) on coho (*Oncorhynchus kisutch*) smolt production in the Stillaguamish River basin. Report for the Stillaguamish Tribe of Indians, Natural Resources Dept., Arlington, WA.
- Poole, G. C., C. A. Frissell, and S. C. Ralph. 1997. Instream habitat unit classification: Inadequacies for monitoring and some consequences for management. *J. Am. Water Resour. Assoc.* 33:879–896.

- PSSRG (Puget Sound Stock Review Group). 1997. Puget Sound Salmon Stock Review Group report, 1997: An assessment of the status of Puget Sound Chinook and Strait of Juan De Fuca coho stocks as required under the Salmon Fishery Management Plan. Pacific Fishery Management Council, Portland, OR.
- Quigley, T. M., and S. J. Arbelvide (eds.). 1997. An assessment of ecosystems components in the interior Columbia Basin and portions of the Klamath and Great Basins: Volume III. Gen. Tech. Rep. PNW-GTR-405. U.S. Forest Service, Portland, OR.
- Rabeni, C. F. 1992. Habitat evaluation in a watershed context. *In* R. H. Stroud (ed.), Fisheries management and watershed development, p. 57–67. American Fisheries Society, Symposium 13, Bethesda, MD.
- Raffensperger, C., and J. A. Tickner. 1999. Introduction: To foresee and forestall. *In* C. Raffensperger and J. A. Tickner (eds.), Protecting public health and the environment: Implementing the Precautionary Principle, p. 1–11. Island Press, Washington, DC.
- Raiffa, H. 1997. Decision analysis: Introductory lectures on choices under uncertainty. McGraw-Hill, New York.
- Raiffa, H., and R. O. Schlaifer. 1961. Applied statistical decision theory. Harvard University Press, Cambridge, MA.
- Ralls, K., and B. L. Taylor. 2000. Better policy and management decision through explicit analysis of uncertainty: New approaches from marine conservation. *Conserv. Biol.* 14:1240–1242.
- Ratner, S., R. Lande, and B. B. Roper. 1997. Population viability analysis of spring Chinook salmon in the South Umpqua River, Oregon. *Conserv. Biol.* 11:879–889.
- Raymond, H. L. 1979. Effects of dams and impoundments on migrations of juvenile Chinook salmon and steelhead from the Snake River, 1966–1975. *Trans. Am. Fish. Soc.* 108:505–529.
- Reeves, G. H., L. E. Benda, K. M. Burnett, P. A. Bisson, and J. R. Sedell. 1995. A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionarily significant units of anadromous salmonids in the Pacific Northwest. *In* J. L. Nielsen (ed.), Evolution and the aquatic ecosystem: Defining unique units in population conservation, p. 334–349. American Fisheries Society, Symposium 17, Bethesda, MD.
- Reeves, G. H., F. H. Everest, and T. E. Nickelson. 1989. Identification of physical habitats limiting the production of coho salmon in western Oregon and Washington. Gen. Tech. Rep. PNW-245. U.S. Forest Service, Pacific Northwest Research Station, Corvallis, Oregon.
- Reeves, G. H., J. D. Hall, T. D. Roelofs, T. L. Hickman, and C. O. Baker. 1991. Rehabilitating and modifying stream habitats. *In* W. R. Meehan (ed.), Influences of forest and rangeland management on salmonid fishes and their habitats, p. 519–557. American Fisheries Society, Special Publication 19, Bethesda, MD.
- Reeves, G. H., D. B. Hohler, B. E. Hansen, F. H. Everest, J. R. Sedell, T. L. Hickman, and D. Shively. 1997. Fish habitat restoration in the Pacific Northwest: Fish Creek of Oregon. *In* J. E. Williams, C. A. Wood, and M. P. Dombeck (eds.), Watershed restoration: Principles and practices, p. 335–359. American Fisheries Society, Bethesda, MD.

- Reeves, G. H., D. B. Hohler, D. P. Larsen, D. E. Busch, K. Kratz, K. Reynolds, K. F. Stein, T. Atzet, P. Hays, and M. Tehan. 2002. Aquatic and riparian effectiveness monitoring plan for the Northwest Forest Plan. Regional Ecosystem Office, Portland, OR. Online at <http://www.reo.gov/monitoring/watershed/cover-aremp-report.htm> [Accessed 24 Jan. 2003].
- Regan, H. M., M. Colyvan, and M. A. Burgman. 2002. A taxonomy and treatment of uncertainty for ecology and conservation biology. *Ecol. Appl.* 12:618–628.
- Reid, L. M., and T. Dunne. 1996. Rapid evaluation of sediment budgets. Catena Verlag, Reiskirchen, Germany.
- Renard, K. G., G. R. Foster, G. A. Weesies, D. K. McCool, and D. C. Yoder. 1997. Predicting soil erosion by water: A guide to conservation planning with the revised universal soil loss equation (RUSLE). U.S. Dept. Agriculture, Washington, DC.
- Renard, K. G., G. R. Foster, G. A. Weesies, and J. P. Porter. 1991. RUSLE: Revised universal soil loss equation. *J. Soil Water Conserv.* 46(1):30–33.
- Renison, B. 1998. Risky business. *Engineering Field Notes* 30:7–20. U.S. Forest Service, Washington, DC.
- Reynoldson, T. B., D. M. Rosenberg, and V. H. Resh. 2001. A comparison of models predicting invertebrate assemblages for biomonitoring in the Fraser River catchment, British Columbia. *Can. J. Fish. Aquat. Sci.* 58:1395–1410.
- Rice, S. D., R. E. Thomas, G. Carls, R. A. Heintz, A. C. Wertheimer, M. L. Murphy, J. W. Short, and A. Moles. 2001. Impacts to pink salmon following the Exxon Valdez oil spill: Persistence, toxicity, sensitivity, and controversy. *Rev. Fish. Sci.* 9:165–211.
- Richards, C., L. B. Johnson, and G. H. Host. 1996. Landscape-scale influences on stream habitats and biota. *Can. J. Fish. Aquat. Sci.* 53(Suppl. 1):295–311.
- Rieman, B. E., J. D. Dunham, and J. T. Peterson. 1999. Development of a database to support a multi-scale analysis of the distribution of westslope cutthroat trout. Final report to U.S. Geological Survey, Reston, Virginia 20192. Agreement number: 1445-HQ-PG-01026. U.S. Forest Service, Rocky Mountain Research Station, Boise, ID.
- Rieman, B. E., P. F. Hessburg, D. C. Lee, R. F. Thurow, and J. R. Sedell. 2000. Toward an integrated classification of ecosystems: Defining opportunities for managing fish and forest health. *Environ. Manag.* 25:425–444.
- Rieman, B. E., D. C. Lee, and R. F. Thurow. 1997. Distribution, status, and likely future trends of bull trout within the Columbia River and Klamath River basins. *N. Am. J. Fish. Manag.* 17:1111–1125.
- Rieman, B. E., and J. D. McIntyre. 1995. Occurrence of bull trout in naturally fragmented habitat patches of varied size. *Trans. Am. Fish. Soc.* 124:285–296.
- Rieman, B. E., and J. D. McIntyre. 1996. Spatial and temporal variability in bull trout redd counts. *N. Am. J. Fish. Manag.* 16:132–141.
- Rieman, B. E., and D. L. Myers. 1997. Use of redd counts to detect trends in bull trout (*Salvelinus confluentus*) populations. *Conserv. Biol.* 11(4):1015–1018.

- Rimmer, D. M., U. Paim, and R. L. Saunders. 1983. Autumnal habitat shift of juvenile Atlantic salmon (*Salmo salar*) in a small river. *Can. J. Fish. Aquat. Sci.* 40:671–680.
- Rimmer, D. M., U. Paim, and R. L. Saunders. 1984. Changes in the selection of microhabitat by juvenile Atlantic salmon (*Salmo salar*) at the summer-autumn transition in a small river. *Can. J. Fish. Aquat. Sci.* 41:469–475.
- Rimmer, D. M., R. L. Saunders, and U. Paim. 1985. Effects of temperature and season on the position holding performance of juvenile Atlantic salmon (*Salmo salar*). *Can. J. Zool.* 63:92–96.
- Ritcher, B. D., J. V. Baumgartner, D. Braun, and J. Powell. 1998. A spatial assessment of hydrologic alteration within a river network. *Regul. Rivers* 14:329–340.
- Ritcher, B. D., J. V. Baumgartner, J. Powell, and D. Braun. 1996. A method for assessing hydrologic alteration with ecosystems. *Conserv. Biol.* 10:1163–1174.
- Ritcher, B. D., J. V. Baumgartner, R. Wigington, and D. Braun. 1997. How much water does a river need? *Freshw. Biol.* 37:231–249.
- Roni, P., T. J. Beechie, R. E. Bilby, F. E. Leonetti, M. M. Pollock, and G. P. Pess. 2002. A review of stream restoration techniques and a hierarchical strategy for prioritizing restoration in Pacific Northwest watersheds. *N. Am. J. Fish. Manag.* 22(1):1–20.
- Roni, P., M. Liermann, and A. Steel. 2003. Monitoring and evaluating responses of salmonids and other fishes to instream restoration. *In* D. R. Montgomery, S. Bolton, and D. B. Booth (eds.), *Restoration of Puget Sound rivers*, p. 318–329. University of Washington Press, Seattle.
- Roper, B. B., and D. L. Scarnecchia. 1995. Observer variability in classifying habitat types in stream surveys. *N. Am. J. Fish. Manag.* 15:49–53.
- Rosenberg, D. M., and V. H. Resh (eds.). 1993. *Freshwater biomonitoring and benthic macroinvertebrates*. Chapman & Hall, New York.
- Rosenberg, A. A., and V. R. Restrepo. 1994. Uncertainty and risk evaluation in stock assessment advice for U.S. marine fisheries. *Can. J. Fish. Aquat. Sci.* 51:2715–2720.
- Rosgen, D. L. 1994. A classification of natural rivers. *Catena* 22:169–199.
- Russell, L. R., K. R. Conlin, O. K. Johansen, and U. Orr. 1983. Chinook salmon studies in the Nechako River: 1980, 1981, 1982. *Can. Manuscr. Rep. Fish. Aquat. Sci.* 1728.
- Schaller, H. A., C. E. Petrosky, and O. P. Langness. 1999. Contrasting patterns of productivity and survival rates for stream-type Chinook salmon (*Oncorhynchus tshawytscha*) populations of the Snake and Columbia Rivers. *Can. J. Fish. Aquat. Resour.* 56:1031–1045.
- Schnute, J. T., and L. J. Richards. 2001. Use and abuse of fishery models. *Can. J. Fish. Aquat. Sci.* 58:10–17.
- Scholz, N. L., N. K. Truelove, B. L. French, B. A. Berejikian, T. P. Quinn, E. Casillas, and T. K. Collier. 2000. Diazinon disrupts antipredator and homing behaviors in Chinook salmon (*Oncorhynchus tshawytscha*). *Can. J. Fish. Aquat. Sci.* 57:1911–1918.

- Seaber, P. R., F. P. Kapinos, and G. L. Knapp. 1987. Hydrologic unit maps. USGS Water Supply Paper 2294. U.S. Geological Survey, Corvallis, OR.
- Sedell, J. R., and K. J. Luchessa. 1982. Using the historical record as an aid to salmonid habitat enhancement. *In* N. B. Armantrout (ed.), Acquisition and utilization of aquatic habitat inventory information, proceedings, Oct. 28–30, 1981, p. 210–223. Western Div. American Fisheries Society, Portland, OR.
- Sedell, J. R., G. H. Reeves, and P. A. Bisson. 1997. Habitat policy for salmon in the Pacific Northwest. *In* D. J. Stouder, P. A. Bisson, and R. J. Naiman (eds.), Pacific salmon and their ecosystems, p. 375–388. Chapman & Hall, New York.
- Sedell, J. R., G.H. Reeves, F. R. Hauer, J. A. Stanford, C. P. Hawkins. 1990. Role of refugia in recovery from disturbances: Modern fragmented and disconnected river systems. *Environ. Manag.* 14:711–724.
- Sedell, J., J. Yuska, and R. Speaker. 1984. Habitats and salmonid distribution in pristine, sediment-rich river valley systems: S. Fork Hoh and Queets River, Olympic National Park. *In* Fish and wildlife relationships in old-growth forests: Proceedings of a symposium held April 1982, Juneau, Alaska, p. 33–46. American Institute of Fishery Research Biologists. (Available from J. W. Reintjes, Rt. 4, Box 85, Morehead City, NC 28557.)
- Shafroth, P. B. 1999. Downstream effects of dams on riparian vegetation: Bill Williams River, Arizona. Doctoral dissertation. Arizona State Univ., Tempe.
- Shea, K., and M. Mangel. 2001. Detection of population trends in threatened coho salmon (*Oncorhynchus kisutch*). *Can. J. Fish Aquat. Sci.* 58:375–385.
- Sidle, R. C., A. J. Pierce, and C. L. O’Loughlin. 1985. Hillslope stability and land use. Water resources monograph series, Vol. 11. American Geophysical Union, Washington, DC.
- Simenstad, C. 1983. The ecology of estuarine channels of the Pacific Northwest coast: A community profile. Rep. FWS/OBS-83/05. U.S. Fish and Wildlife Service, Washington, DC.
- Simon, T. P. (ed.). 1998. Assessing the sustainability and biological integrity of water resources using fish communities. Lewis Publishers, Boca Raton, FL.
- Slaney, P. A., and D. Zaldokas. 1997. Fish habitat rehabilitation procedures. British Columbia, Ministry of Environment, Lands, and Parks and Ministry of Forests, Vancouver.
- Slooten, E., D. Fletcher, and B. L. Taylor. 2000. Accounting for uncertainty in risk assessment: Case study of Hector's dolphin mortality due to gillnet entanglement. *Conserv. Biol.* 14:1264–1270.
- Smith, K., and M. E. Lavis. 1975. Environmental influences on the temperature of a small upland stream. *Oikos* 26:228–236.
- Solazzi, M. F., T. E. Nickelson, S. L. Johnson, and J. D. Rodgers. 2000. Effects of increasing winter rearing habitat on abundance of salmonids in two coastal Oregon streams. *Can. J. Fish. Aquat. Sci.* 57:906–914.
- Spence, B. C., G. A. Lomnicky, R. M. Hughes, and R. P. Novitzki. 1996. An ecosystem approach to salmonid conservation. Funded jointly by the U.S. EPA, U.S. Fish and Wildlife Service, and

- National Marine Fisheries Service. TR-4501-96-6057. Man Tech Environmental Research Services Corp., Corvallis, OR.
- Spinazola, J. 1998. A spreadsheet notebook method to calculate rate and volume of stream depletion by wells in the Lemhi River Valley upstream from Lemhi, Idaho. U.S. Bureau of Reclamation, Boise, ID.
- SRSRC (Snake River Salmon Recovery Committee). 2002. 2002 Snake River salmon recovery region strategy. Asotin County Conservation District, Clarkston, WA.
- Steedman, R. J. 1988. Modification and assessment of an index of biotic integrity to quantify stream quality in southern Ontario. *Can. J. Fish. Aquat. Sci.* 45:492–501.
- Steel, E. A., B. E. Feist, D. Jensen, G. R. Pess, M. Sheer, J. Brauner, and R. E. Bilby. In prep. Large-scale habitat models to understand steelhead (*Oncorhynchus mykiss*) distribution and prioritize barrier removals in the Willamette Basin, OR, U.S.A. (Available from E. A. Steel, NWFSC, 2725 Montlake Blvd. East, Seattle, WA 98112.)
- Steel, E. A., and M. B. Sheer. In prep. Broad-scale habitat analyses to estimate fish densities for viability criteria. In Willamette/Lower Columbia Pacific salmonid viability report, Willamette/Lower Columbia Technical Recovery Team, Appendix C. National Marine Fisheries Service, Northwest Fisheries Science Center, Seattle, WA. (Available from E. A. Steel, NWFSC, 2725 Montlake Blvd. East, Seattle, WA 98112.)
- Stone, M. 1974. Cross-validated choice and assessment of statistical predictions. *J. R. Stat. Soc.* 36:111–147.
- Sumioka, S. S., D. L. Kresch, and K. D. Kasnick. 1998. Magnitude and frequency of floods in Washington. Water Resources Investigation Rep. 97-4277. U.S. Geological Survey, Tacoma, WA.
- Swanson, F. J. 1981. Fire and geomorphic processes: Erosion, watershed management, sedimentation. Gen. Tech. Rep. 26. U.S. Forest Service, Washington, DC.
- SWC (Skagit Watershed Council). 1998. Habitat protection and restoration strategy. Skagit Watershed Council, Mount Vernon, WA.
- Symons, P. E. K., and M. Heland. 1978. Stream habitats and behavioral interactions of underyearling and yearling Atlantic salmon (*Salmo salar*). *J. Fish. Res. Board Can.* 35:175–183.
- Thompson, W. L., and D. C. Lee. 2000. Modeling relationships between landscape-level attributes and snorkel counts of Chinook salmon and steelhead parr in Idaho. *Can. J. Fish. Aquat. Sci.* 57:1834–1842.
- Thornburgh, K., and G. Williams. 2000. The state of the waters: Water quality in Snohomish County's rivers, streams, and lakes. Snohomish County Public Works, Surface Water Management, Everett, WA.
- Thurrow, R. F., D. C. Lee, and B. E. Rieman. 2000. Status and distribution of Chinook salmon and steelhead in the interior Columbia River basin and portions of the Klamath River basin. In E. E. Knudsen, C. R. Steward, D. D. MacDonald, J. E. Williams, and D. W. Reiser (eds.), Sustainable fisheries management Pacific salmon, p. 133–160. Lewis Publishers, New York.

- Thurrow, R. F., D. C. Lee, and B. E. Rieman. 1997. Distribution and status of seven native salmonids in the interior Columbia River basin and portions of the Klamath River and Great Basins. *N. Am. J. Fish. Manag.* 17:1094–1110.
- Torgersen, C. E., D. M. Price, H. W. Li, and B. A. McIntosh. 1999. Multiscale thermal refugia and stream habitat associations of Chinook salmon in northeastern Oregon. *Ecol. Appl.* 9:301–319.
- Trimble, S. W., and A. C. Mendel. 1995. The cow as a geomorphic agent: A critical review. *Geomorphology* 13:233–253.
- Tschaplinski, P. J., and G. F. Hartman. 1983. Winter distribution of juvenile coho salmon (*Oncorhynchus kisutch*) before and after logging in Carnation Creek, British Columbia, and some implications for overwinter survival. *Can. J. Fish. Aquat. Sci.* 40:452–461.
- Turner, D. L., and W. P. Clary. 2001. Sequential sampling protocol for monitoring pasture utilization using stubble height criteria. *J. Range Manag.* 54:132–137.
- Urban, D. L., R. V. O'Neill, and H. H. Shugart. 1987. Landscape ecology. *Bioscience* 37(2):119–27.
- USACE (U.S. Army Corps of Engineers). 1998. Deepwater slough section 1135 restoration project near Conway, Washington. Ecosystem restoration report/environmental assessment. Seattle District U.S. Army Corps of Engineers, Seattle.
- USCTC (United States Chinook Technical Committee). 1997. A review of stock assessment data and procedures for U.S. Chinook salmon stocks. USCTCCHINOOK(97)-1. Pacific Salmon Commission, Vancouver, British Columbia.
- USEPA (U.S. Environmental Protection Agency). 2000. Level III ecoregions of the continental United States (Map, revised 2000). U.S. Environmental Protection Agency, National Health and Environmental Effects Research Laboratory, Corvallis, OR.
- Vannote, R. L., G. W. Minshall, K. W. Cummins, J. R. Sedell, and C. E. Cushing. 1980. The river continuum concept. *Can. J. Fish. Aquat. Sci.* 37:130–37.
- Vronskiy, B. B. 1972. Reproductive biology of the Kamchatka River Chinook salmon (*Oncorhynchus tshawytscha*). *J. Ichthyol.* 12:259–273.
- Wade, P. R. 2000. Bayesian methods in conservation biology. *Conserv. Biol.* 14:1308–1316.
- Wade, P. R. 2001. The conservation of exploited species in an uncertain world: Novel methods and the failure of traditional techniques. In J. D. Reynolds, G. M. Mace, K. H. Redford, and J. G. Robinson (eds.), *Conservation of exploited species*, p. 110–143. Cambridge University Press, Cambridge, England.
- Waite, I. R., and K. D. Carpenter. 2000. Associations among fish assemblage structure and environmental variables in Willamette Basin streams, Oregon. *Trans. Am. Fish. Soc.* 129:754–770.
- Walters, C. J., and D. Ludwig. 1981. Effects of measurement errors on the assessment of stock-recruitment relationships. *Can. J. Fish. Aquat. Sci.* 38:704–710.
- Wang, L., J. Lyons, P. Kanehl, and R. Gatti. 1997. Influences of watershed land use on habitat quality and biotic integrity in Wisconsin streams. *Fisheries.* 22:6–12.

- Waples, R. S. 1995. Evolutionarily significant units and the conservation of biological diversity under the Endangered Species Act. *In* J. L. Nielsen (ed.), *Evolution and the aquatic ecosystem: Defining unique units in population conservation*, p. 8–27. American Fisheries Society, Symposium 17, Bethesda, MD.
- Waples, R. S., R. G. Gustafson, L. A. Weitkamp, J. M. Myers, O. W. Johnson, P. J. Busby, J. J. Hard, G. J. Bryant, F. W. Waknitz, K. Neely, D. Teel, W.S. Grant, G.A. Winans, S. Phelps, A. Marshall, and B.M. Baker. 2001. Characterizing diversity in salmon from the Pacific Northwest. *J. Fish Biol.* 59(Supplement A):1–41.
- Ward, J. V. 1998. Riverine landscapes: Biodiversity patterns, disturbance regimes, and aquatic conservation. *Biol. Conserv.* 83:269–278.
- Ward, J. V., and J. A. Stanford. 1995. Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. *Regul. Rivers Res. Manag.* 11:105–119.
- Wasserman, L., E. Beamer, and T. Beechie. 1995. Salmon habitat restoration strategy for the Skagit River, Washington. *In* M. Murphy and R. Kirschner (eds.), *Using ecological restoration to meet Clean Water Act goals, proceedings of a national symposium*, p. 17–22. Northeastern Illinois Planning Commission, Natural Resources Dept., Chicago.
- Waters, T. F. 1995. *Sediment in streams: Sources, biological effects, and control*. Monograph 7. American Fisheries Society, Bethesda, MD.
- Watson, G., and T. W. Hillman. 1997. Factors affecting the distribution and abundance of bull trout: An investigation at hierarchical scales. *N. Am. J. Fish. Manag.* 17:237–252.
- WDFW (Washington Dept. Fish and Wildlife). 1998. *Fish passage barrier and prioritization manual of Washington Department of Fish and Wildlife*. Washington Dept. Fish and Wildlife, Olympia.
- WDFW (Washington Dept. Fish and Wildlife). 2001. *Fish passage design at road culverts*. Washington Dept. Fish and Wildlife, Olympia. Online at <http://www.wa.gov/wdfw/hab/engineer/cm/culvertm.htm#h2> [Accessed 24 Jan. 2003].
- WDNR (Washington Dept. Natural Resources). 1995. *Standard methodology for conducting watershed analysis*. Washington Dept. Natural Resources, Olympia.
- Welch, D. W., A. I. Chigirinsky, and Y. Ishida. 1995. Upper thermal limits on the oceanic distribution of Pacific salmon (*Oncorhynchus* spp.) in the spring. *Can. J. Fish. Aquat. Sci.* 52:489–503.
- Welch, D. W., Y. Ishida, and K. Nagasawa. 1998. Thermal limits and ocean migrations of sockeye salmon (*Oncorhynchus nerka*): Long-term consequences of global warming. *Can. J. Fish. Aquat. Sci.* 55:937–948.
- Wentz, D. A., B. A. Bonn, K. D. Carpenter, S. R. Hinkle, M. L. Janet, F. A. Rinella, M. A. Uhrich, I. R. Waite, A. Laenen, and K. E. Bencala. 1998. *Water quality in the Willamette Basin, Oregon, 1991–95*. U.S. Geological Survey Circular 1161. Online at <http://water.usgs.gov/pubs/circ/circ1161/> [Accessed 5 Feb. 2003].
- WFPB (Washington Forest Practices Board). 1995. *Standard methodology for conducting watershed analysis under Chapter 222-22 WAC*. Version 3.0 module to evaluate hydrologic change, p. C1–C57. Washington Dept. Natural Resources, Olympia.

- Whalen, K. G., D. L. Parrish, and S. D. McCormick. 1999a. Migration timing of Atlantic salmon smolts relative to environmental and physiological factors. *Trans. Am. Fish. Soc.* 128:289–301.
- Whalen, K. G., D. L. Parrish, and M. E. Mather. 1999b. Effect of ice formation on selection of habitats and winter distribution of post-young-of-the-year Atlantic salmon parr. *Can. J. Fish. Aquat. Sci.* 56:87–96.
- Wiens, J. A. 1986. Overview: The importance of spatial and temporal scale in ecological investigations. *In* T. J. Case and J. Diamond (eds.), *Community ecology*, p. 145–53. Harper & Row, New York.
- Wilhm, J. L., and T. C. Dorris. 1966. Species diversity of benthic macroinvertebrates in a stream receiving domestic and oil refinery effluents. *Am. Midl. Nat.* 76:427–449.
- Williams, J. E., J. E. Johnson, D. A. Hendrickson, S. Contreras-Balderas, J. D. Williams, M. Navarro-Mendoza, D. E. McAllister, and J. E. Deacon. 1989. Fishes of North America endangered, threatened, or of special concern: 1989. *Fisheries* 14(6):2–20.
- Williams, J. R., H. E. Pearson, and J. D. Wilson. 1985. Streamflow statistics and drainage-basin characteristics for the Puget Sound region, Washington: Volume II. Eastern Puget Sound from Seattle to the Canadian border. Open File Rep. 84-144-B. U.S. Geological Survey, Tacoma, WA.
- Williamson, A. K., M. D. Munn, S. J. Ryker, R. J. Wagner, J. C. Ebbert, and A. M. Vanderpool. 1998. Water quality in the central Columbia Plateau, Washington and Idaho, 1992–95. USGS Circular 1144. U.S. Geological Survey, Washington, D.C. Online at <http://water.usgs.gov/pubs/circ/circ1144/> [Accessed 24 Jan. 2003].
- Wischmeier, W. H., and D. D. Smith. 1965. Predicting rainfall-erosion losses from cropland east of the Rocky Mountains. USDA Agriculture Handbook No. 282. U.S. Government Printing Office, Washington, DC.
- Wischmeier, W. H., and D. D. Smith. 1978. Predicting rainfall erosion losses—A guide to conservation planning. USDA Agriculture Handbook No. 357. U.S. Government Printing Office, Washington, DC.
- Wright, J. F., D. W. Sutcliffe, and M. T. Furse (eds.). 2000. Assessing the biological quality of fresh waters: RIVPACS and other techniques. Freshwater Biological Association, Ambleside, United Kingdom.
- WRS (Willamette Restoration Strategy). 2001. The Willamette restoration strategy: Recommendations for the Willamette Basin supplement to the Oregon plan for salmon and watersheds. Willamette Restoration Initiative, Salem, OR.
- Yoder, C. O. 1991. The integrated biosurvey as a tool for evaluation of aquatic life attainment and impairment in Ohio surface waters. *In* Proceedings of symposium: Biological criteria: Research and regulation, p. 110–122. EPA 440-5-91-005. U. S. Environmental Protection Agency, Office of Water, Washington, DC.
- Yoder, C. O., and E. T. Rankin. 1995. Biological response signatures and the area of degradation value: New tools for interpreting multimetric data. *In* W. S. Davis and T. P. Simon (eds.), *Biological assessment and criteria: Tools for water resource planning and decision making*, p. 263–286. Lewis Publishers, Boca Raton, FL.

- Yoder, C. O., and E. T. Rankin. 1998. The role of biological indicators in a state water quality management process. *Environ. Monit. Assess.* 51:61–88.
- Zar, J. H. 1984. *Biostatistical analysis*. Prentice-Hall, Inc., Englewood Cliffs, NJ.
- Zeimer, R. R. 1981. Storm flow response to road building and partial cutting in small streams of northern California. *Water Resour. Res.* 17:907–917.

APPENDIX A: ISSUES OF SCALE IN HABITAT RECOVERY PLANNING

The aquatic environment is complex and dynamic, changing continually across space and time. Inhabitants have evolved in response to these ever-changing conditions. However, anthropogenic alterations to the landscape have disrupted the natural processes within these systems and species are often forced to contend with altered or unnatural habitat conditions. These alterations can be large or small, influencing expansive areas or more local conditions, and the effects can occur immediately or years later. Thus a thorough knowledge of the processes structuring the aquatic environment and how these processes interact over multiple spatial and temporal scales is critical for understanding the effects of disturbance on aquatic systems and their inhabitants.

This appendix examines the concept of scale in recovery planning with particular emphasis on analyses to help set recovery goals. Similar concepts apply to analyses designed to identify ecosystem restoration actions (described in the Analyses for Phase II Recovery Planning: Identifying Ecosystem Restoration Actions section, page 40), but are not discussed. This appendix first describes the inherent hierarchical nature of aquatic systems, specifying the need to study both the processes and inhabitants of these systems in a similar, hierarchical manner. Next it provides examples of small-scale and large-scale studies that highlight difficulties in transferring information across scales. Then these concepts are incorporated into examinations of how habitat alterations might influence the four categories of recovery goals: population abundance, population growth rate, spatial structure, and diversity (McElhany et al. 2000). Examples from the literature illustrate the types of information obtained at each scale and demonstrate the value of combining studies across scales to provide information on impaired processes and recovery potential.

Hierarchical Nature of Stream Systems

The aquatic environment can be viewed as a hierarchy of spatially nested systems (Frissell et al. 1986, Urban et al. 1987). Implicit in this hierarchical model is the concept of scale. For example, reaches (10^1 m) are contained within watersheds (10^3 m) and physical conditions within reaches are driven largely by frequent (10^0 – 10^1 years), low magnitude geomorphic events such as floods (Frissell et al. 1986). By contrast, watershed attributes are influenced by infrequent (10^5 – 10^6 years), high magnitude geologic events (e.g., glaciation, tectonic movements). The result is a system in which habitat development and persistence occur at specific temporal scales within each level of the hierarchy, and conditions within smaller scale systems are constrained by the larger scale systems that contain them (Frissell et al. 1986, Urban et al. 1987).

In addition, longitudinal (upstream to downstream) and lateral (stream to terrestrial) linkages help shape biological and physical structure at each level, resulting in a predictable spatiotemporal gradient of physical and biological conditions from headwaters to mouth (Vannote et al. 1980, Frissell et al. 1986, Gregory et al. 1991). For example, stream width,

depth, discharge (Platts 1979, Leopold et al. 1964), temperature (Allan 1995), and biological diversity (Vannote et al. 1980, Barila et al. 1981) increase with stream size while gradient and substrate size decrease (Platts 1979, Leopold et al. 1964). There is often a decrease in terrestrial inputs and riparian shading coupled with an increase in organic transport from headwaters to estuary (Vannote et al. 1980). Moreover, these conditions are structured by the climate, geology, and anthropogenic activity of the specific watershed (Vannote et al. 1980, Frissell et al. 1986). As a result, each segment within the system contains a predictable array of habitat conditions dependent on the watershed. These habitats, however, are not homogenous—there is simply an order to their heterogeneity (Frissell et al. 1986).

Because habitats are heterogeneous, species distributions are not even across the landscape but instead occur in patches. The quality and quantity of each habitat is a product of both large-scale and small-scale processes, and quantifying this environmental variation helps to understand subsequent biotic responses (Cunjak 1996). For example, water temperature varies both spatially and temporally and influences salmonid distributions and life history patterns. Large-scale temperature patterns influence species ranges and distributions (Meisner 1990, Flebbe 1993, Welsh et al. 1995, Keleher and Rahel 1996, Welsh et al. 1998). At the watershed scale, elevation, latitude, aspect, and stream size interact to determine annual and seasonal temperature cycles. Thus the physical location of a stream within the river network influences population life history characteristics such as spawn timing (Gresswell et al. 1997), growth rate (Lobón-Cerviá and Rincón 1998, Campbell 1999), and the timing of smolt migration (Whalen et al. 1999a). At smaller reach or segment scales, the type and density of riparian vegetation and the degree of groundwater input influences the stability of seasonal and diel temperatures (Smith and Lavis 1975, Gregory et al. 1991, Allan 1995). These reach-level patterns can influence behavior (Fraser et al. 1993), food digestion and assimilation (Cunjak and Power 1987, Cunjak et al. 1987), ability to hold position against water current (Rimmer et al. 1985, Graham et al. 1996), and interspecific and intraspecific survival and distribution (Torgersen et al. 1999, Harvey et al. 2002). Finally, at the habitat-unit scale, cool-water inputs from tributaries, intergravel flow through river bars, and streamside subsurface sources can thermally stratify individual pools, providing cool-water refuges for individuals of multiple age classes (Nielsen et al. 1994). Thus species assemblages and distributions are structured by a combination of larger scale geomorphic and climatic conditions, as well as biotic and abiotic conditions of the local environment. Consequently, biological and physical conditions at any site should be viewed in the context of the larger geologic, climatic, and geomorphologic conditions of the system as a whole—a multiscale approach.

Transferability Across Scales

Smaller scale studies generally focus on identifying physical features used by individuals (Bustard and Narver 1975, Cunjak 1988, Nakamoto 1994), how this habitat use changes ontogenetically and temporally (Rimmer et al. 1983, 1984, Baltz et al. 1991, Heggenes et al. 1993, Whalen et al. 1999b), and how these habitat preferences differ by species (Bisson et al. 1988, Fausch 1993, Heggenes et al. 2002). These types of studies also have identified bottlenecks limiting the production of different salmonids (McMahon and Hartman 1989,

Tschaplinski and Hartman 1983, Solazzi et al. 2000), and contributed to our understanding of both intraspecific (Symons and Heland 1978, Kennedy and Strange 1986, Harvey and Nakamoto 1997) and interspecific (Hearn and Kynard 1986) competition. Smaller scale studies often generate models based on correlations between habitat use or availability and fish abundance, incorporating the concepts of optimal and suitable habitat. However, individuals are not always found in suitable habitat (Bozek and Rahel 1991) and not all recruits are necessarily produced from those habitats with the highest densities (Grossman et al. 1995). Moreover, some preferences (e.g., nose velocities) are transferable within systems (DeGraaf and Bain 1986, Morantz et al. 1987), whereas others (e.g., substrate and depth) vary across systems and partly depend on habitat availability (Bozek and Rahel 1992). These habitat-based models may have low predictive power across large areas because 1) biological factors such as abundance of prey, predators, or competitors are sometimes excluded (Grossman et al. 1995), 2) specific mechanisms responsible for the selection (and subsequent consequences on individual fitness) are not identified (Grossman et al. 1995), 3) stream level variability may not be incorporated (Dunham and Vinyard 1997), and 4) frequent stochastic disturbances common at smaller scales make these systems less predictable (Levin 1992).

Larger scale investigations generally address the shaping of aquatic systems and their inhabitants by climate variation (Meisner 1990, Keleher and Rahel 1996), geology and geomorphology (Platts 1979, Lanka et al. 1987, Nelson et al. 1992, Richards et al. 1996, Kruse et al. 1997), and land use and land cover (Connolly and Hall 1999, Bradford and Irvine 2000, Waite and Carpenter 2000, Paulsen and Fisher 2001). Examining larger spatial scales over longer time frames produces more generalized models; however, detail is sacrificed (Levin 1992). Such models can link species presence, absence, or composition to stream or watershed characteristics (e.g., stream size, geology, climate, land use), but often with mixed results. The omission of natural temporal variation in population abundance can obscure relationships (House 1995, Bradford et al. 1997), and study designs with limited spatial coverage (Baxter et al. 1999, Rieman and McIntyre 1996, Pess et al. 2002) or short sampling periods (Rieman and Myers 1997) may not reliably indicate population trends or associations with habitat or habitat change. Also, many larger scale analyses synthesize small-scale datasets created for other purposes. Merging such data sets often combines data with inconsistent sampling frequencies, efficiencies, and representativeness, and analyses can produce unreliable or inexplicable results (Rieman et al. 1999).

In summary, key information can be obtained at any scale of study; however, combining this knowledge across scales and disciplines has proven difficult (Levin 1992, Imhof et al. 1996). It is generally accepted that occupancy of a given habitat is determined by a combination of small-scale biotic and abiotic conditions experienced by an individual within the constraints set by the larger landscape. As a result, there has recently been a rise in multiscale investigations that seek to understand the larger scale variables structuring aquatic species and, within these larger variables, the specific habitat characteristic influencing populations (e.g., Watson and Hillman 1997, Baxter and Hauer 2000, Labbe and Fausch 2000, Pess et al. 2002). As this research continues, recovery planning should emphasize maintaining a high degree of habitat heterogeneity to ensure the availability of sufficient habitat combinations to sustain multiple populations and species (Ward 1998). The focus should be on maintaining proper ecosystem function rather than on managing for specific habitat criteria. This focus requires a thorough

understanding of the linkages between biological and physical processes within and across scales (Lewis et al. 1996).

Scale in Recovery Planning

Anthropogenic activities can limit viability and persistence of salmon populations by affecting the quantity or quality of stream, estuary, and nearshore habitats. For example, forestry practices can alter the volume and timing of runoff or sediment delivered to streams and reduce the volume of large woody debris, number of off-channel habitats, streambank stability, channel roughness, and water quality (Meehan 1991). Agricultural practices often reduce riparian vegetation and increase streambank instability, sedimentation, hydromodification, and levels of nutrients and pesticides (Waters 1995, Waite and Carpenter 2000). Urbanized areas experience increased sedimentation and pollution along with many of the problems associated with agriculture (Waters 1995, Waite and Carpenter 2000). Dams and other forms of hydromodification can alter natural flow regimes, isolating river channels from their floodplains and riparian systems and altering the natural processes of sediment erosion and deposition (Poff et al. 1997).

Individually and in combination, these anthropogenic impacts alter salmonid abundance and survival at various life stages and ultimately influence the maintenance and recovery of populations and evolutionarily significant units (ESUs). Anthropogenic activities generally reduce habitat and community complexity (Ward 1998, Gorman and Karr 1978), and species with more rigid habitat requirements are more susceptible to habitat degradation and displacement by other species (Nelson et al. 1992). Thus understanding how land use activities alter natural processes and conditions within stream systems is critical for recovery efforts. The following subsections discuss incorporating scale into assessments of habitat factors that prevent populations or their parent ESUs from meeting the four categories of recovery goals: population abundance, population growth rate, spatial structure, and diversity (McElhany et al. 2000).

Population Abundance

The extinction risk faced by a population is inversely related to abundance, making it possible to use abundance to define broad risk categories (McElhany et al. 2000). To address how habitat changes might have altered fish abundance (and thus population risk), determining how abundance changes with land use is necessary. Recent and historical trends in abundance can be identified through such measures as redd counts, dam and weir counts, spawner and carcass surveys, harvest estimates, and juvenile counts. Once population trends have been identified, they can be compared to trends in land use activities for possible correlations.

For example, Nehlsen et al. (1991) examined anadromous fish stocks in the Pacific Northwest and California to identify stocks with high or moderate risk of extinction. Recent escapement trends for seven anadromous salmonid species were utilized to assess stock risk. One finding was that the native upriver fall Chinook salmon (*Oncorhynchus tshawytscha*) population in the upper Columbia was strong within the Hanford Reach, Washington (Huntington et al. 1996 classify this as the farthest inland population in healthy condition), while

native, naturally spawning populations had declined to very low levels within the Snake River. Using fish passage counts at individual dams, Dauble and Watson (1997) estimated that fall Chinook salmon spawning in the Hanford Reach increased from 60% of the total run above McNary Dam in the 1960s to 80% of the run in late 1980s and early 1990s. In contrast, the proportion of the run entering the Snake River declined over this period from 40% to less than 5%. This decline in the mid 1960s and the 1970s was attributed to losses of juveniles passing through turbines and delays of migrations in Snake River reservoirs (Raymond 1979).

Once these population trends were identified, investigating how they might have been shaped by habitat changes was possible. Dauble and Geist (2000) examined the spawning habitat characteristics of the Hanford and Hells Canyon (Snake River) sites to assess how hydroelectric development had influenced spawning habitat availability. Redds were found across a greater range of depths and dominant substrate sizes in the Hanford Reach than in Hells Canyon. They concluded that the Hanford Reach population has remained viable largely due to a geologic template that is highly compatible with its life history requirements. In contrast, the Hells Canyon population must contend with poor habitat quality and quantity coupled with the elimination of upstream and downstream populations through migration blockage and habitat inundation associated with dam construction.

The focus of abundance examinations is to identify spatial or temporal trends in abundance and correlate these trends with landscape features or land use activity across or within watersheds. However, the resulting correlations cannot identify causation. Rather, they highlight more detailed investigations needed to uncover impaired processes and identify necessary recovery efforts.

Population Growth Rate

Investigations of population growth rate over broad spatial scales often involve identifying gross differences in the growth rate of multiple stocks and the role of climatic conditions or marine and freshwater processes in shaping these patterns. For example, Mueter et al. (2002) examined the effects of ocean temperature on survival rates of pink salmon (*O. gorbuscha*), chum salmon (*O. keta*), and sockeye salmon (*O. nerka*) from Washington to Alaska. The growth rate was quantified for each of the 120 wild stocks by computing a survival rate ($\log(R/S)$) from eggs to adult recruits (R) after accounting for density-dependent effects of spawner abundance (S). Temperature effects were estimated for each stock separately, using a generalized Ricker model, then the distributions of parameters from these single stock models were examined to identify geographic differences across stocks. The results suggested that temperature effects on survival rates are consistent within regions, but that northern and southern stocks respond in opposite ways to temperature variations. Similarly, Peterman et al. (1998) used a multiple stock approach to examine spatial and temporal characteristics of environmental processes influencing the growth rate of 29 sockeye salmon stocks from British Columbia and Alaska. Again population growth rate varied at the regional scale, with survival rates of Fraser River stocks being influenced by large, stock-specific, interannual variability, while Bristol Bay stocks were driven by stronger regional-scale processes acting at both interannual and decadal time scales. Thus these larger scale analyses tend to identify growth rate trends for multiple stocks spanning wide areas, but cannot link these patterns to specific causal factors.

Focusing investigations on specific populations can identify how growth rate responds to a specific anthropogenic activity, but again the causal mechanisms can only be suggested. Schaller et al. (1999) examined the response of stream-type Chinook salmon stocks within the upper (Snake River and upper Columbia River) and lower Columbia River regions to hydropower development. Spawners were estimated for each index area based on expanded ground and aerial redd counts or live fish and carcass counts, and age-structured spawners were expanded into recruitment. For each index stock, spawner and recruit data were classified into two time periods: 1) pre-1970 brood years prior to the completion of the last two Snake River dams and 2) post-1974 brood years marking the initiation of mass transportation of smolts around the Snake River dams and passage improvements. While all three regions showed a general decline in growth rate and survival between the two time periods, the declines in upriver stocks (which were most affected by hydropower development) were more severe. Thus differences in the growth rate and survival rates between upriver and downriver stocks coincided in space and time with the development and operation of the hydropower system. However, more detailed analyses are needed to examine potential causal mechanisms for these findings.

Analyses of stage-specific growth rate (i.e., realized over some discrete portion of the life cycle) can also be important information sources, particularly where the dynamics of one life stage dominate the dynamics of the entire life cycle (McElhany et al. 2000). For example, Nickelson et al. (1992) estimated coho salmon (*O. kisutch*) smolt production for coastal Oregon basins using juvenile density estimates by habitat type for different seasons. Fully seeded streams were sampled each season and habitat was classified using a modified version of the habitat classification scheme described by Bisson et al. (1982). Results indicated that production of smolts in Oregon coastal streams can be limited by the availability of winter habitat. Once such bottlenecks are identified, they can guide the recovery planning process toward measuring the quantity of critical habitats available in nonimpacted versus impacted sites. Also, historical reconstructions can be conducted to quantify the actual losses of these critical habitats in impacted areas. For example, Beechie et al. (1994) estimated the magnitude of lost rearing habitat and the subsequent loss in coho salmon smolt production by habitat type and form of impact within the Skagit River basin. Using a combination of field surveys, maps, and orthophotos to estimate current and historical habitat, as well as survival to smoltification rates from Reeves et al. (1989), they found a 34% decrease in smolt production capacity of winter rearing habitats from historical production. Hydromodification, largely due to diking, accounted for 91% of the total smolt production losses for winter rearing areas. This type of information is useful in the recovery process, for it can highlight the processes that need to be restored to improve the health of the local habitat as well as set recovery priorities based on the degree of degradation. See the Analyses for Phase II Recovery Planning: Identifying Ecosystem Restoration Actions section, page 40, and the Prioritizing Potential Restoration Actions within Watersheds section, page 60, for related discussions.

Spatial Structure

The spatial structure of a population refers to the distribution of individuals within a population and the processes generating that distribution. It is dependent on habitat quality, spatial configuration, and the dynamics and dispersal characteristics of individuals in the population (McElhany et al. 2000). The heterogeneous stream environment may be viewed as a

series of habitat patches at an array of spatial scales. The likelihood of individuals inhabiting each patch is dependent on the quality of habitat in the patch as well as the ability of individuals to move between patches. Therefore, an investigation into how habitat changes might have altered the spatial structure of a population requires understanding the small-scale and large-scale influences on both habitat patch dynamics and salmonid movement.

Comparing historical presence of a species to current or predicted occurrence can help describe the distribution of a species and populations across a landscape, their degrees of isolation, and their sizes. Rieman et al. (1997) compared historically potential and current distribution of bull trout (*Salvelinus confluentus*) within the interior Columbia River basin, representing 20% of the species' global range. Available information on the presence and status of bull trout was summarized and validated, and classification trees were developed to predict bull trout presence and status using landscape features and management history. Bull trout were widely distributed within their potential range, with known or predicted occurrence in 44% of the historical spawning and rearing subwatersheds. Such coarse examinations can highlight the distribution of populations across the landscape and give some indication of population strength based on size. More detailed work is needed to address patch size and dynamics within individual systems.

Dunham and Rieman (1999) examined 81 patches ($\geq 10^3$ m) within the Boise River to identify patterns in juvenile bull trout occurrence. Habitat patches were defined as stream catchments above 1,600 m elevation with an accessible perennial stream (Rieman and McIntyre 1995), and patches, road densities, and interpatch distances were estimated using Geographic Information System (GIS) methodologies. Trout occurrence, stream width, and gradient data were obtained in the field. Results indicated that the large-scale geometry of catchments can strongly influence the distribution of aquatic species, though smaller scale factors also affect distribution. They concluded that bull trout populations in larger, less isolated, less disturbed patches are more likely to persist and that it is critical for disturbance within these habitats to be minimal. On the other hand, small, isolated, disturbed populations and habitats are at risk. Thus they speculate that conservation and restoration opportunities might provide best results if centered within those patches of intermediate size or isolation. In a comparison of patch size distributions for Lahontan cutthroat trout (*O. clarki henshawi*) and this bull trout data, Dunham et al. (2002) found that the size distributions were similar between the two species and skewed toward smaller patches, so that very few large patches may be critical to each species. Both species are likely to occur when patch size exceeds 10^4 ha in area and bull trout are more likely to occur in smaller patches that may in turn explain their occurrence in a large percentage of suitable habitat.

Identifying how species are distributed across the landscape and utilize habitat patches is a necessary initial step in the recovery planning process. Linking this information to their dispersal and migratory behavior can highlight "stepping stone" patches: critical patches connecting large habitat areas. Once identification of critical habitat patches is achieved, one can examine how land use actions have reduced or eliminated connectivity of these patches as well as altered or destroyed the patches themselves. This information can then guide the scale of recovery efforts by pinpointing the processes that are in need of restoration and identifying local, specific actions.

Diversity

Diversity refers to the distribution of traits within and among populations (McElhany et al. 2000). Genotypic and phenotypic diversity occur at all scales; however, the majority of genotypic diversity is contained within stocks while most phenotypic diversity is greater across populations and landscapes (Healey and Prince 1995). Thus successful conservation must focus as much on ensuring habitat quality and connectivity as on genotypes (Healey and Prince 1995). The genetic controls are beyond the scope of this document, but it is possible to examine how habitat changes influence the phenotypic expression of traits. Differences in these traits can have adaptive value and should be maintained, even if they do not have a genetic basis, and can be expressed as changes in morphology, fecundity, run timing, spawn timing, behavior, smolt age, age at maturity, and egg size (McElhany et al. 2000). For example, in Carnation Creek, British Columbia, a decline in 0+ coho salmon densities and an accompanying increased growth rate following logging resulted in greater rates of 1+ smolt production (Hartman et al. 1996). This shift in the age and size composition of smolts resulted in an increase in the variability of adult production (Holtby and Scrivener 1989). Unfortunately, long-term databases that can illustrate the results of anthropogenic activities are rare. Thus other ways to determine widespread threats to diversity are needed.

One approach is to conduct a regional examination of changes in species diversity under the assumption that where species diversity is decreasing, phenotypic and genotypic diversity might also be decreasing. For example, Frissell (1993b) expanded on the identification of Pacific salmon stocks at risk synthesized by Nehlsen et al. (1991) to map region-wide patterns in fish diversity. He used data compiled for inland fishes (Williams et al. 1989) and anadromous stocks (Nehlsen et al. 1991), focusing on the Pacific Northwest and California, which highlighted species and stocks at risk. Mapping units were based on a drainage basin size of 50 to 2,000 km² and the basins were categorized according to the number of species (0–1, 2–3, 4–5, or 6–8) classified as extinct, endangered, or threatened. Isopleths were then fit between the categories. Results indicated a general increase in endangerment from north to south. Regions with 4+ species at risk were of particular concern and species declines were attributed to large-scale dams and irrigation projects. These types of regional examinations can identify where diversity is declining, where more detailed examinations are consequently needed to identify processes responsible for the decline, and efforts needed to remedy the problem.

A variety of bioassessment tools can also help identify where anthropogenic activities have eroded stream health and threaten diversity. One method is to assess habitat degradation using invertebrate species assemblages. For example, the reference-condition approach requires the development of a reference database containing invertebrate assemblages and matching habitat descriptors for a large number of minimally disturbed reference sites. Invertebrate assemblages at these reference sites are described, classified, and related to habitat attributes to develop predictive models. The resulting reference models can then be compared to test sites to identify impairment. Results will highlight impaired areas, but will not specify the underlying causes. See the Analyses for Phase II Recovery Planning: Identifying Ecosystem Restoration Actions section, page 40, for a more detailed discussion of these methodologies.

Another method of examining the effects of land use on stream health and diversity is to characterize changes in species assemblages across land use gradients. In affiliation with the

U.S. Geological Survey's National Water Quality Assessment Program, Waite and Carpenter (2000) utilized this approach to identify how natural and land use gradients influence biological assemblages within the Willamette River basin in Oregon. Both field data (fish sampling, water quality sampling, and habitat measurements) and GIS data (land use, drainage area, and elevation) were used, covering reaches within seven major subbasins and three ecoregions. They found physical habitat a better descriptor of fish assemblages across ecoregions (i.e., all sites), whereas water chemistry was a better descriptor within the Willamette Valley ecoregion. They also suggested that the reduced riparian quality and increased water temperatures, nutrient supply, and sediment supply found in small agricultural and urban streams cause fish assemblages to shift from those dominated by native, intolerant species to those dominated by introduced or tolerant species. Amount of riffle habitat, quality of riparian cover, and maximum water temperature were the overriding variables describing variation among land uses. These biological assessments provide an opportunity to monitor long-term changes in community composition or stream health (Rabeni 1992) at multiple scales, highlighting areas of possible impairment due to land use activities, and identify possible causes that can then be further investigated.

Summary

The foregoing illustrated how the effects of habitat change on the four components of population viability can be examined over multiple scales. At large spatial scales, one can identify where population characteristics have changed from historical conditions and how they relate to population or ESU recovery goals. For example, Rieman et al. (1997) and Dunham and Rieman (1999) looked at current distributions of bull trout across several river basins and predicted historical distributions. Each study identified increased patchiness of bull trout populations over time as well as relative population sizes. Each study also examined the spatial isolation of populations to estimate their relative strength, diversity, and degree of risk. Similarly, Thurow et al. (1997) examined other native salmonids within the interior Columbia River and portions of the Klamath and Great Basins to determine their distribution and status. Their work highlighted the proportion of the potential range currently occupied by each species and the relative strength of the populations. They found all taxa have narrower distributions, fewer areas with high diversity, and lower percentages of strongholds than in their estimated potential historical conditions. Strongholds were generally found to be rare and not well distributed across the landscape. Thus examining abundance and distribution across space and time can illustrate areas retaining historical diversity and ecological structure as well as those that have possibly been altered by human influence.

The large-scale studies described above broadly correlate landscape factors (e.g., land use, climate, other species) to population trends and highlight systems that warrant closer examination. Examination of finer scale components of a system (i.e., at watershed or smaller scales) can then identify causation (e.g., road density, hydromodification, water quality degradation), which helps one understand how specific ecological processes have been impaired and indicates potential pathways for restoring them. The scale of the analysis constrains interpretations of results (Wiens 1986) and increasingly fine scales of assessment obtain more detailed information. For example, Nehlsen et al. (1991) noted a decline in summer steelhead

(*O. mykiss*) within most river systems in California. They identified the Eel River population to be at moderate risk of extinction and mentioned how floods in 1964 severely affected populations throughout California due to extensive erosion and habitat damage in watersheds stressed by poor land management. Harvey et al. (2002) highlighted potential mechanisms contributing to these declines, speculating that habitat changes caused by the floods altered summer temperature regimes and allowed extensive invasion by the nonnative Sacramento pikeminnow (*Ptychocheilus grandis*) decades later. The investigators concluded that 1) restoration of riparian vegetation within the watershed could reduce the range and ecological impact of the pikeminnow, and 2) increased riparian vegetation and improved hillslope conditions could enhance native salmonid habitat by moderating the influence of peak flows and sediment supply on channel stability, thereby improving thermal regimes and instream habitat. Thus results of larger scale work identify a problem, while smaller scale work highlights specific anthropogenic activities and ecological impairment underlying the problem and, consequently, more specific conservation and restoration strategies.

As aquatic ecosystems are arranged in an interconnected array of hierarchical systems, any study of their processes and inhabitants can be organized in a similar hierarchical manner. Species patterns and relations to habitat and anthropogenic activities can be seen at any scale; however, the scale examined dictates the level of detail that can be inferred from the results and any subsequent interpretations. By examining the abundance and distribution of species and associating these with land use activity at multiple scales, patterns in the spatial structuring and diversity of populations, and thus their level of risk, can be identified. Such information can then be used at fine scales to identify the ecological processes impaired and prioritize conservation and restoration activities.

APPENDIX B: ESTIMATING CHINOOK SALMON SPAWNER CAPACITY OF THE STILLAGUAMISH RIVER

One important task of Technical Recovery Teams is estimating both current and historical capacity of the habitat to support juvenile and adult salmonids. These estimates are needed to evaluate whether population goals derived from population viability analyses could be supported by currently or historically available habitat. For example, if viability estimates indicate that 5,000 fish are needed for a population to be viable, estimates of spawner capacity can indicate whether that number is within the bounds of what the watershed may have historically supported.

Riverine habitats function at different spatial and temporal scales, ranging from the watershed level down to microhabitats (Frissell et al. 1986). Larger scale systems such as watershed and segment generally operate over a 100 to 1,000 m linear spatial area and persist for 1,000 to 1 million years (Frissell et al. 1986). Extrinsic forces driving these larger systems include glaciation, volcanism, tectonic uplift, climatic shifts, earthquakes, and alluvial or colluvial valley infilling. Reach-scale systems operate at intermediate scales of about 100 m and 10 to 100 years, and are driven by events such as debris torrents, landslides, and log input or washout. Smaller scale habitat-unit systems are typically controlled by events or processes occurring at spatial scales of 1 to 100 m and over shorter time periods (persistence of 1–10 years, Frissell et al. 1986). Habitats at this level include pools and riffles as well as glides, rapids, side channels, and backwater pools, and have characteristic bed topography, water surface slope, depth, and velocity patterns (Bisson et al. 1982). These habitat units are driven by delivery or routing of sediment, wood, boulders, etc., small bank failures, flood scour or deposition, thalweg shifts, and numerous human activities (Frissell et al. 1986).

For a case study, we estimated the current and historical capacity of the Stillaguamish River for adult Chinook salmon (*Oncorhynchus tshawytscha*) based on habitat data at the unit scale (e.g., pool, riffle, and glide). Detailed estimates of salmonid abundance at the habitat-unit scale were extrapolated to the watershed scale to estimate change in total salmonid abundance for the basin. This analysis of capacity allowed us to estimate the maximum number of adult Chinook that the Stillaguamish River produced historically, as well as the system's potential for production today.

Methods

Our approach for estimating capacity essentially had two steps. First we assessed the amount of habitat available for Chinook spawning. We mapped where adult Chinook spawn in the watershed. Within that area, we identified streams either as large main stems or small main stems and tributaries. We quantified habitat area by estimating total stream length for small main stems and tributaries and total stream area for large main stems. The large main stems were further characterized by estimating how much reach-scale habitat was pool, riffle, or glide and how much of each habitat unit was suitable for spawning.

Second we assigned fish numbers to habitats. For small main stems and tributaries, we estimated the total number of redds possible by multiplying stream length by an estimate for the expected number of redds per kilometer. For large main stems, we calculated how many redds would fit into our estimated stream area by assuming an estimate for redd area. Then we converted estimates of total redds for each reach-scale habitat type to total adults using an estimate for number of adults per redd.

Watershed-Scale Chinook Salmon Spawning Distribution

Streams were identified as accessible to Chinook salmon based on the location of barriers and stream gradient. The historical distribution of Chinook included areas below natural barriers (i.e., waterfalls, cascades) and with streams of low (less than 4%) gradient (Montgomery et al. 1999). Similarly, current fish distribution included areas below anthropogenic barriers (primarily culverts) and natural barriers, and with low-gradient streams. At the upstream end, Granite Falls in the South Fork Stillaguamish River was not included in either current or historical capacity estimates (Figure B-1). Historically, few Chinook were able to ascend Granite Falls. At present a fish ladder allows Chinook to pass upstream, but observed juvenile outmigrant abundance is low (K. Rawson²). We defined the downstream limit of Chinook spawning as the upper extent of tidal influence, which occurs at about the confluence of Cook Slough and the Stillaguamish River, and Pilchuck Creek with the Stillaguamish River.

Reach-Scale Chinook Salmon Spawning Habitat

The main Chinook salmon spawning areas are in larger tributary streams and main stems of rivers (Miller and Brannon 1982). Chinook use of these freshwater habitats varies depending on the size of bankfull channel widths. Chinook redd density in the Skagit River generally increases up to about 25 m bankfull width, then sharply declines (Figure B-2, Montgomery et al. 1999). Similarly, channel morphology varies at different scales as a factor of channel width and large woody debris (LWD) loading. Pool frequency increases with bankfull channel width and LWD loading up to about 20–25 meter channel width, then drops off (Montgomery et al. 1995). Pools in these smaller streams can be formed by individual pieces of wood, which cross streams and form stable obstructions (Abbe 2000). In larger streams, channel morphology is most significantly affected by large logjams, which form stable obstructions that create pools but at a lower frequency (Abbe 2000). Salmon usually spawn at the transition between pools and riffles or in areas associated with a lateral bar deposition (Bjornn and Reiser 1991).

Because Chinook use of channel types varies with channel width, we classified streams to reach-scale habitat types by bankfull width. Small streams (or mainstem/tributary habitat types) are from 5 to 25 m bankfull width, and large mainstem habitats are greater than 25 m width. Additionally, streams less than 5 m bankfull width were regarded as too small for consistent Chinook spawner production, based on data from the Stillaguamish, Snohomish, Skagit, Suiattle,

² K. Rawson, The Tulalip Tribes, Natural Resources Dept., 7615 Totem Beach Rd., Marysville, WA 98271. Pers. commun., May 2001.

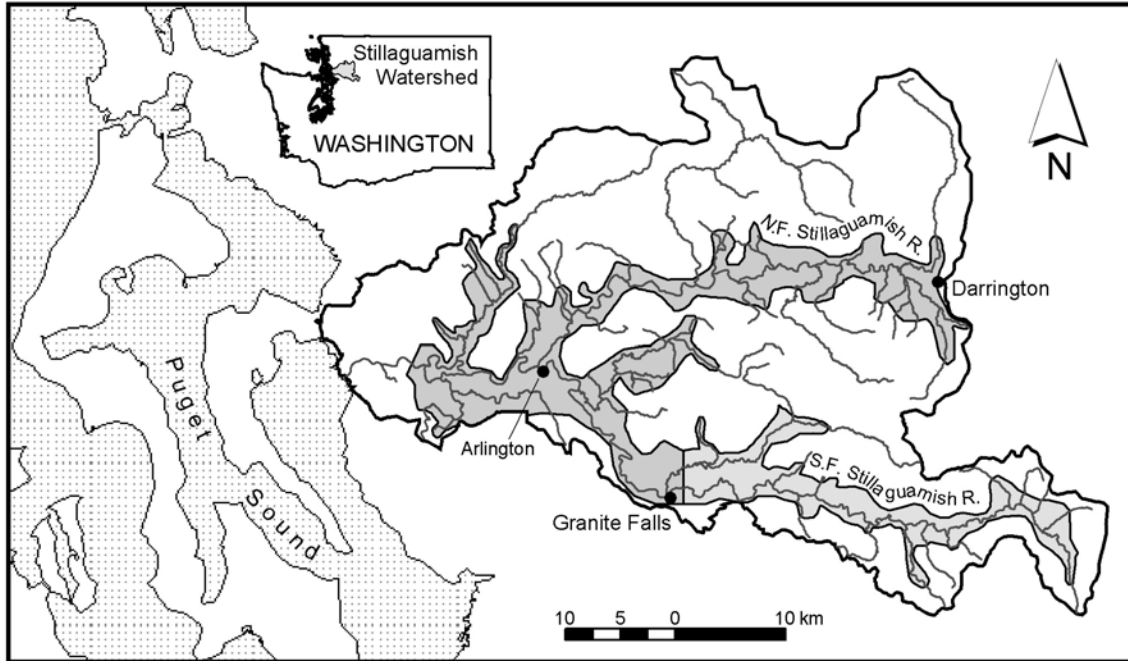


Figure B-1. Historical area of anadromous fish access (dark shading) and area opened to anadromous fish by a fish ladder around Granite Falls (lighter shading of south fork) in the Stillaguamish River basin.

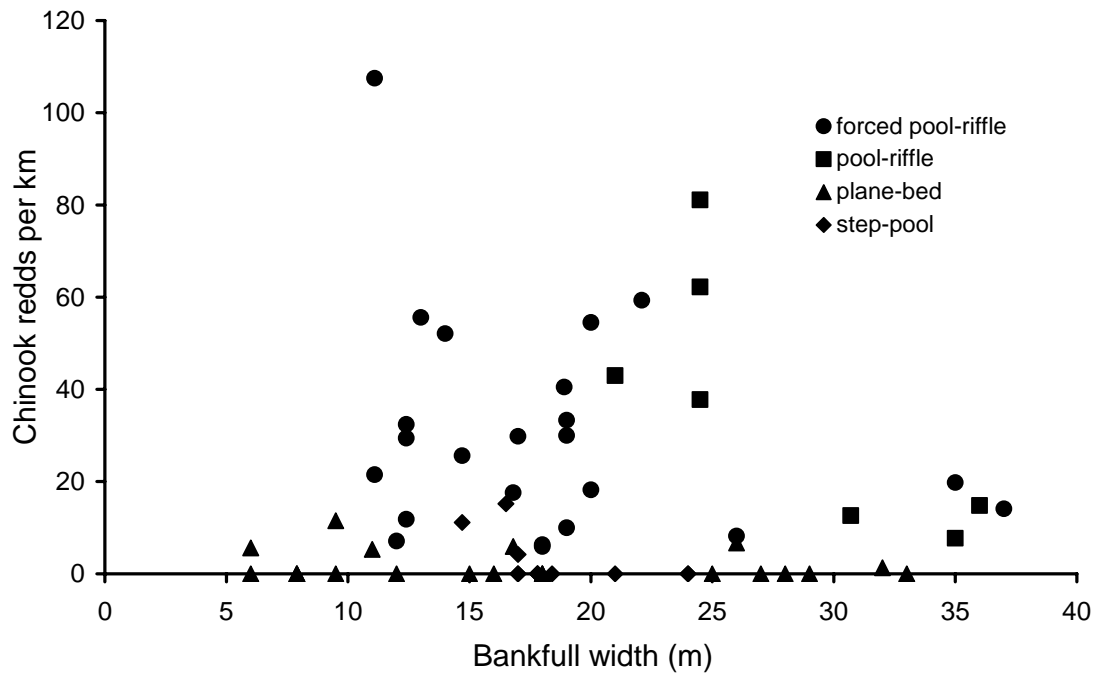


Figure B-2. Comparison of Chinook redds per kilometer to bankfull width measurements, Skagit River. (Based on data in Montgomery et al. 1999.)

and White Rivers (D. Hendrick,³ J. Doyle⁴). Chinook are occasionally observed spawning in smaller streams (Hendrick footnote 3, Vronskiy 1972). However, we wanted to include stream habitat where the majority of Chinook consistently spawn.

We estimated bankfull width for both current and historical stream conditions using regression models. For historical conditions, we developed a regression to predict channel width using channel width measurements from 1860s General Land Office Survey notes (Collins and Montgomery 2001) and basin drainage area (A) for the Stillaguamish River:

$$\text{Historical channel width} = 10^{(-2.4 + 0.54 \times \log A)}, \text{ Adjusted } R^2 = 0.70 \quad (6)$$

Basin drainage area was derived using a 30-m digital elevation model (DEM). For current conditions, a regression model was also developed using channel width data and basin drainage area:

$$\text{Current channel width} = 10^{(-1.5 + 0.43 \times \log A)}, \text{ Adjusted } R^2 = 0.68 \quad (7)$$

Channel widths were measured primarily from aerial photographs, but included field measurements as well.

Using these regression relationships, we developed a Geographic Information System (GIS) data layer of channel width for the entire Stillaguamish River watershed based on the DEM-derived drainage area data. The channel width predictions were then applied to categorize all streams in a 1:24,000 scale hydrography into the three categories: less than 5 m bankfull width, from 5 to 25 m width, and greater than 25 m width.

Chinook Salmon Capacity in Small Streams

Habitat in small streams of the Stillaguamish River basin could only be described at the reach scale due to a lack of data describing the proportions of pools, riffles, and other unit-scale habitats. Likewise the data available for estimating Chinook use of small streams (5 to 25 m width) was expressed at the reach scale (i.e., as number of redds per kilometer of stream length, Montgomery et al. 1999). Hence we estimated Chinook spawner capacity (N_{adults}) in small streams as a function of stream length, number of redds per kilometer, and number of adults per redd:

$$N_{\text{adults}} = (\text{Total stream length} \times \text{Redds/km}) \times \text{No. Adults/redd} \quad (8)$$

In generating our historical capacity estimate, we calculated the total length of small streams within historical Chinook spawning areas from the 1:24,000 hydrography data. Additionally, we included the total length of small, non-pond-like side channels estimated for historical conditions (Pess et al. 1999b). For the current capacity estimate, we excluded those streams and side channels that were blocked by culverts or dams or otherwise isolated (Table B-1).

³ D. Hendrick, WDFW, 111 Sherman St., P.O. Box 1100, La Connor, WA 98257. Pers. commun., May 2001.

⁴ J. Doyle, U.S. Forest Service, Mt. Baker-Snoqualmie National Forest, 21905 64th Ave. West, Mountlake Terrace, WA 98043. Pers. commun., May 2001.

Table B-1. Estimates of stream length (m) of small streams (5 to 25 m bankfull width) under current and historical conditions for the Stillaguamish River.

Time period	Habitat type	North Fork	South Fork	Main stem
Historical	Small streams and tributaries	209,348	87,148	39,572
	Non-pond-like side channels	10,939	2,667	28,007
Current	Small streams and tributaries	207,173	93,198	45,291
	Non-pond-like side channels	4,462	0	11,079

For estimates of redds per kilometer, we assumed that channel morphology in small streams was historically determined primarily by LWD loading. Such in-channel obstructions produce forced pool-riffle habitats—channels in which the majority of pool and bar forms are forced by flow convergence, divergence, and turbulent scour associated with obstructions (Montgomery et al. 1995). Forced pool-riffle habitats, formed by woody debris, may be considered indicative of undisturbed conditions (Lunetta et al. 1997). Therefore, data for number of redds per kilometer only include counts from forced pool-riffle habitats (vs. pool-riffle and plane-bed) for historical conditions (Montgomery et al. 1999). Redd density data were collected from 50 reach-level surveys in five tributaries to the Skagit between 1991 and 1996. The median value for redds per kilometer in forced pool-riffle channels was 29.6, and the 10th and 90th percentiles of the range are 7.0 and 57.5 redds per kilometer, respectively (Table B-2).

Spawner survey data are also available describing Chinook use specific to the North Fork Stillaguamish River for nine river reaches (Table B-3, Montgomery et al. 1999). However, these data were collected over longer time spans (up to 23 years) and it was not certain that habitat characteristics (in particular, forced pool-riffle) remained constant throughout the time period that Chinook data were collected. These data were useful for our current capacity estimate where redd counts were needed across a range of habitat types, which could vary across time and space (Table B-3). These average counts were first applied to the tributaries from which data were collected (i.e., Boulder River, Squire Creek, etc.). For the remaining small streams, we summarized the data from the nine streams (Table B-3) and applied the median (2.5 redds/km), 10th (0 redds/km), and 90th (13.8 redds/km) percentiles of the range in the current capacity estimate (Table B-2).

We estimated the number of adults per redd using data that describes the number of males per female from: 1) carcass recovery survey data from the North Fork Stillaguamish, Skagit, and Snohomish Rivers, 2) Sunset Falls counts from the Snohomish River, 3) broodstock collection data from the North Fork Stillaguamish and Skagit Rivers, 4) mark/recapture study from the North Fork Stillaguamish, and 5) gill drift net test fishery data from the Skagit River (Hahn et al. 2001, Hendrick unpubl. data). The ratio of males:females plus one is equivalent to the number of adults per redd. The median value for number of adults per redd was 1.9 and the 10th and 90th percentiles of the range were 1.4 and 3.5, respectively.

To illustrate the full range of potential current and historical capacity values, we calculated estimates using the 10th percentile, median, and 90th percentile ranges of all spawner biological variable values (redds per kilometer and adults per redd). Stream length included only one measurement each for current and historical conditions. All capacity calculations include estimates for the North Fork Stillaguamish River Chinook salmon population and the South Fork/mainstem Stillaguamish population.

Historical Chinook Salmon Capacity in Large Streams

We estimated historical Chinook spawner capacity in large streams (>25 m bankfull width) by determining the amount of area in a river that has habitat suitable for spawning and calculating the number of redds that fit in that area. We then estimated the number of adults as a function of number of fish per redd. The equation for historical capacity in large streams is as follows:

Table B-2. Values used to vary biological parameters for current and historical capacity estimates.

Percentile	Redd size ^a (m ²)	Adults/redd ^b	Redds/km ^c	
			<i>Historical</i>	<i>Current</i>
90th	4.9	3.5	57.5	13.8
Median	14.1	1.9	29.6	2.5
10th	27.9	1.4	7.0	0.0

^a Data from the North Fork Stillaguamish River.

^b Data from the Snohomish and Stillaguamish Rivers (Hendrick unpubl. data).

^c Data from the Stillaguamish and Skagit Rivers (Montgomery et al. 1999).

Table B-3. Data on number of Chinook salmon redds for repeated spawner surveys along the North Fork Stillaguamish River (Montgomery et al. 1999).

Location	Years of data	Channel type	Average redds/km
Boulder River	16	Pool-riffle	4.2
Squire Creek	23	Pool-riffle	6.4
Furland Creek	2	Forced pool-riffle	13.8
Ashton Creek	2	Forced pool-riffle	8.8
Browns Creek	10	Forced pool-riffle	2.5
Brooks Creek	4	Plane-bed	0.0
Rollins Creek	6	Plane-bed	0.0
Dicks Creek	4	Plane-bed	0.0
Segelson Creek	2	Plane-bed	0.0

$$N_{\text{adults}} = (\text{SA} \times \% \text{Spwn}) \times \text{No. adults/redd} \quad (9)$$

where SA is stream area and %Spwn is percent of area suitable for spawning.

To calculate stream area in the Stillaguamish River basin, we first generated an estimate of wetted widths across all stream reaches for the time period when Chinook spawn (mainly August/September). We measured widths from 1:24,000 digital orthophotos of the watershed. The photos were taken in mid-to-late July 1998. Mean monthly flows in July are 25% to 45% higher than in September (generally, the peak of spawning), which meant we would overestimate spawner abundance by some fraction. However, available spawning area does not increase in direct proportion to stream flow (i.e., 25% more flow does not equal 25% more spawning area), so overestimation may not be significant. We then developed a regression model to predict wetted widths based on cumulative stream lengths (total stream length above each wetted width measurement) and stream order data, derived from 30-m DEMs:

$$\text{Wetted width} = 10^{(-2.59 + 0.56 \log \text{CFL} + 0.36 \text{SOR})}, \text{ Adjusted } R^2 = 0.77 \quad (10)$$

where CFL is cumulative flow length and SOR is stream order.

With this regression, we developed a GIS data layer of wetted width for the Stillaguamish River basin and associated the wetted width predictions to stream reaches in the hydrography layer. We then calculated stream area for each reach as a function of wetted width and stream length. These stream area estimates were used for calculations of both current and historical capacity (Table B-4). In addition, we included estimates of stream area for non-pond-like side channels for historical conditions (Pess et al. 1999b). All these side channels are presently isolated from streams accessible to anadromous fish.

To describe the stream area suitable for spawning under historical conditions, we conducted field surveys in Western Washington streams that are in relatively undisturbed condition (North Fork Sauk River, mainstem Sauk River, South Fork Stillaguamish River, Squire Creek, and the South Fork Hoh River). PSSRG (1997) developed criteria for measuring the area suitable for spawning by describing habitat characteristics in the North Fork Stillaguamish River where redds were observed. Geist et al. (2000) similarly used characteristics of spawning habitat measured within local spawning areas to evaluate Chinook salmon habitat suitability in the Columbia River. In the Stillaguamish River, substrate diameter averaged 74 mm (range of 45–120 mm, PSSRG 1997). Depths averaged 0.5 m (range of 0.3–1.5 m), and velocities averaged 0.6 meters per second (range of 0.3–1.0 m/s). Healey (1991) summarized comparable values from the literature for water depth and velocity in Chinook spawning beds.

In our habitat surveys of reference sites, the average values for substrate and depth were the primary variables used to estimate suitable spawning area, in addition to channel bed morphology. Channel bed morphology indicates the location of subsurface flow (such as at the junction of a pool's tailout and the head of a riffle), which is important in redd site choice by Chinook (Vronskiy 1972, Chapman 1943, Russell et al. 1983). Once we identified the location of subsurface flow (i.e., the primary spawning site), we measured the area suitable for spawning within a habitat (riffle, pool, glide) by surveying the extent of appropriate average substrate and depth values. We calculated historical capacity estimates where percent habitat spawnable was

Table B-4. Estimates of stream area (m²) under current and historical conditions for the Stillaguamish River.

Time period	Habitat type	North Fork	South Fork	Main stem
Historical	Large streams	2,616,542	1,842,123	1,318,877
	Non-pond-like side channels	<u>70,676</u>	<u>0</u>	<u>98,106</u>
	Totals	2,687,218	1,842,123	2,416,983
Current	Large streams	2,532,976	1,696,890	1,023,863
	Non-pond-like side channels	<u>0</u>	<u>0</u>	<u>0</u>
	Totals	2,532,976	1,696,890	1,023,863

segregated by habitat type (Table B-5). However, we had less certainty that habitat composition reflected historical conditions because of the limited size of our reference sites. Therefore, we summarized the percent of area suitable for spawning (“percent of habitat spawnable”) across all habitat units combined.

For the capacity estimate, we assumed that redds are uniformly distributed and positioned immediately adjacent to one another, without a larger territorial boundary. Geist et al. (2000) found that when redd densities were near capacity, clusters or redds were uniformly distributed and inter-redd distances ranged from 2 to 5 m. In the Stillaguamish River, median redd size was 14.1 m² (4.9 m² and 27.9 m² were the 90th and 10th percentiles, respectively, Table B-2). These redd sizes compare well with redd areas reported by others (Table B-6, Healey 1991). If we assume redds have an approximately circular shape and radius of 2.11 m, distances between redds in the Stillaguamish River would fall roughly within the range observed by Geist et al. (2000).

We calculated a range of spawner capacity estimates using the 10th percentile, median, and 90th percentile of values for all variables (redd size, number of adults/redd, percent habitat spawnable, Tables B-2 and B-5), except stream area for which we only had one measurement (Table B-4). Our best estimate for historical capacity included percent habitat spawnable with habitat units combined, but we also calculated capacity estimates with percent spawnable evaluated separately by habitat type.

Current Chinook Salmon Capacity in Large Streams

To estimate current capacity in large streams, we used field data for habitat distribution and redd location and field data characterizing habitat suitable for spawning from river kilometers 24 to 48 of the North Fork Stillaguamish River (Hahn et al. 2001). We digitized Washington Department of Fish and Wildlife (WDFW) field maps describing habitat units (pool, riffle, glide, etc.) into a GIS database and summarized the habitat composition across the 24-km reach (Table B-5). We also digitized redd locations for the same 24-km stretch from 1998, 1999, and 2000 field surveys.

We estimated current capacity similar to methods for historical capacity, except we first described the habitat composition of the river, then estimated the percent of habitat suitable for spawning based on those habitat units:

$$N_{\text{adults}} = \frac{((SA \times \%Spwn)_{\text{pools}} + (SA \times \%Spwn)_{\text{riffles}} + (SA \times \%Spwn)_{\text{glide}})}{\text{Redd size}} \times \text{No. adults/redd} \quad (11)$$

We estimated the percent of habitat that is suitable for spawning in two ways. First we estimated the actual percent of habitat with observed spawning using WDFW redd survey data. We used GIS to overlay the combined three years of redd survey data with the habitat-unit maps. A buffer was generated around all redd locations to represent area spawned. We assumed a radius of 2.11 m, which is equivalent to a 14 m² redd size. For each habitat type, the percent of habitat spawned was calculated as the area within buffers divided by the area of the habitat type. Second we estimated the percent of habitat suitable for spawning using our field survey data where spawning habitat was characterized by substrate, velocity, depth, and channel bed

Table B-5. Percent habitat composition and values used to vary percent of habitat suitable for spawning for current and historical conditions. For current conditions, percent of habitat with observed spawning was calculated using Washington Department of Fish and Wildlife (WDFW) redd data from 1998, 1999, and 2000 and National Marine Fisheries Service (NMFS) field measurements of available habitat.

Data source	Parameter	Habitat-unit type					Habitat units combined
		Riffle	Glide	Pool	Rapid	Backwater pool	
<i>Historical conditions</i>							
Reference site data	Percent habitat composition	26.0	25.8	47.0	—*	—*	100.0
	Percentile of habitat spawnable						
	90th	20.0	18.0	3.0	—	—	9.5
	Median	17.0	1.0	2.0	—	—	3.0
	10th	3.0	0.0	0.0			0.0
<i>Current conditions</i>							
WDFW habitat survey data	Percent habitat composition	46.0	39.0	11.0	3.0	1	100.0
WDFW redd survey data	Percentile of habitat spawned						
	90th	3.4	3.4	3.3	3.8	0	5.5
	Median	1.8	0.2	0.0	0.4	0	0.4
	10th	0.0	0.0	0.0	0.0	0	0.0
NMFS habitat survey data	Percentile of habitat spawnable						
	90th	77.1	50.2	0.0	0.0	0	50.0
	Median	18.8	12.0	0.0	0.0	0	2.7
	10th	1.0	0.0	0.0	0.0	0	0.0

*Rapid and backwater pool habitats were not surveyed.

Table B-6. Summary of published information on redd size (Healey 1991).

Source	Type ^a	Redd area (m ²)	
		Range	Mean
Chapman 1943		2.4–4.0	NR ^b
Burner 1951	O	4.8–6.5	NR
Burner 1951	S	2.4–4.1	NR
Vronskiy 1972	S	4.0–15.0	NR
Neilson and Banford 1983	S	0.5–27.5	9.5
Chapman et al. 1986	O	2.1–44.8	17.0

^a Reported if available, S = Stream-type (spring-run) Chinook salmon, O = Ocean-type (fall and summer) Chinook.

^b NR = Not reported.

morphology, as described for historical large stream capacity (habitat survey data in Table B-5). Both estimates of percent habitat spawned and percent habitat spawnable were calculated by habitat type and for all habitat units combined.

Similar to historical estimates for large streams, current spawner capacities in large streams were calculated using the range of values for all variables (redd size, number of adults per redd, percent habitat spawnable by habitat type) (Tables B-2 and B-6), except stream area where only one measurement was possible (Table B-4). Given the substantial length of stream area surveyed, our habitat composition estimates are robust. We therefore considered current capacities with percent spawnable measured by habitat type to be the best estimates. For comparison, we also included capacities where percent spawnable was measured across all habitat units combined.

Sensitivity Analyses

We evaluated the sensitivity of our estimates to parameter values used in the capacity equation as demonstrated by Gray and Megahan (1981). We conducted the sensitivity analysis on the historical capacity estimate in the North Fork Stillaguamish River. We selected the range of values as the 10th and 90th percentile of each variable (Tables B-2 and B-5). The base level of capacity was computed using median values for all variables. We then changed each input variable across its lower and upper range of values while holding other variables constant. Finally, the results were plotted for capacity as a relative percentage of change due to variation in each variable (Figures B-3 and B-4).

Results

Spawner Capacity Estimates

Capacity estimates based on 90th percentile of all input variables are as much as three orders of magnitude larger than estimates using the 10th percentiles for both the North Fork Stillaguamish River Chinook salmon population and the South Fork/mainstem population, under historical conditions as well as current (Table B-7). The most realistic current capacity estimates are probably those determined using the median values for the biological parameters. It is less clear which statistic is appropriate for estimating percent habitat spawnable under both current and historical conditions. If we were to assume that reference site data underestimate available habitat under historical conditions, we would use the 90th percentile for percent spawnable for historical capacity. This may be a reasonable assumption, given that some of the reference sites (e.g., Upper Sauk and South Fork Stillaguamish Rivers) are not likely as pristine as we expect streams were under historical conditions. For current conditions, we would use the 90th percentile for percent habitat spawnable with the WDFW redd survey data if we were to assume that the North Fork Stillaguamish River is presently underutilized. This assumption may also be fair, given that overall, higher proportions of the habitat types (in particular, riffles and glides) were characterized as suitable for spawning than were actually observed spawned in by Chinook (Table B-5).

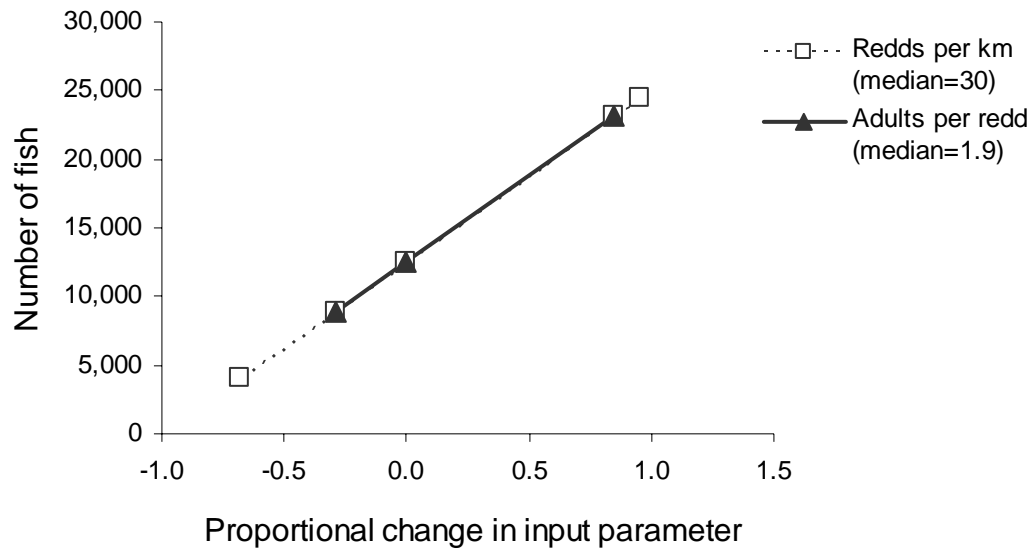


Figure B-3. Range of historical capacity estimates observed by varying parameters in the capacity equation for small streams (≤ 25 m bankfull width) in the North Fork Stillaguamish River.

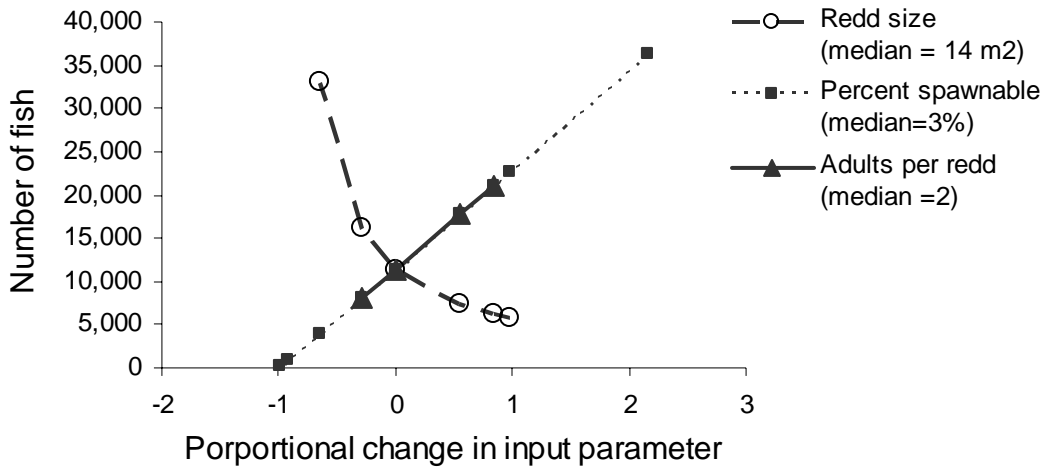


Figure B-4. Range of historical capacity estimates observed by varying parameters in the capacity equation for large streams (>25 m bankfull width) in the North Fork Stillaguamish River.

Table B-7. Range of adult capacity estimates (number of spawners) for the North Fork Stillaguamish Chinook salmon population and the South Fork/mainstem Stillaguamish Chinook population where the percent habitat suitable for spawning and combined biological parameter values are varied. Estimates in bold represent those believed to be the most likely values.

Location	Percent habitat spawnable	Range of biological parameters			Comment
		90th percentile	Median	10th percentile	
North Fork Stillaguamish River	<i>Historical conditions</i>				
	Reference site data				Percent habitat spawnable calculated independent of habitat type.
	90th percentile	228,389	46,834	14,465	
	Median	102,484	23,275	5,996	
	10th percentile	45,342	12,582	2,152	
	<i>Current conditions</i>				
	WDFW data				Percent habitat spawnable calculated by habitat type
	90th percentile	129,513	24,141	8,874	
	Median	25,166	4,615	1,855	
	10th percentile	8,533	1,503	736	
	NMFS data				Percent habitat spawnable calculated by habitat type
	90th percentile	1,013,582	189,569	68,340	
Median	252,106	47,080	17,120		
10th percentile	16,964	3,080	1,303		
South Fork and mainstem Stillaguamish River	<i>Historical conditions</i>				
	Reference site data				Percent habitat spawnable calculated independent of habitat type.
	90th percentile	254,882	50,622	16,503	
	Median	102,182	22,048	6,232	
	10th percentile	32,879	9,080	1,570	
	<i>Current conditions</i>				
	WDFW data				Percent habitat spawnable calculated by habitat type
	90th percentile	137,179	25,027	8,741	
	Median	25,096	4,054	1,202	
	10th percentile	7,231	711	0	
	NMFS data				Percent habitat spawnable calculated by habitat type
	90th percentile	1,086,786	202,720	72,616	
Median	268,860	49,668	17,598		
10th percentile	16,286	2,406	609		

The median value for percent spawnable may be more appropriate for capacity estimates than the National Marine Fisheries Service's habitat data set for the North Fork Stillaguamish. The results from the NOAA Fisheries data set, which was from a river reach that has some of the highest Chinook spawning densities in the entire basin, seem high and perhaps overestimate capacity for several reasons. First, data collected on substrate, depth, and flow may not include all the necessary variables that are important for spawning site selection. Other variables that may be important include adjacent or nearby high quality holding habitat (e.g., deep pools with instream cover) and subsurface flow conditions. Second, and perhaps more important, the data was collected for a different purpose, so the study design originally used for data collection may not suffice to properly estimate capacity for the entire basin.

Using the above assumptions, the best estimate of historical spawner capacity for the North Fork Stillaguamish River Chinook salmon population is about 46,800 adults. Current capacity would be in the range of 24,100 to 47,000 adults. For the South Fork/mainstem population, historical capacity would occur at about 50,600 adults, and current capacity would range between 25,000 and 49,700 adults.

Sensitivity Analyses

In small streams of the North Fork Stillaguamish River, historical capacity was most sensitive to changes in redds per kilometer, followed by changes in adults per redd (Figure B-3). In large streams, historical capacity showed the greatest sensitivity to percent habitat spawnable, followed by redd size (Figure B-4). This estimate was also moderately sensitive to changes in adults per redd.

Conclusions

Estimates of spawner capacity for both small and larger streams vary by several orders of magnitude. Much of the variation is due to: 1) the assumptions and sensitivity around specific variables such as the number of redds per kilometer, adults per redd, percent spawnable area, and redd size, and 2) the data used to develop capacity estimates. Assumptions combined with a sensitivity analysis help identify the suite of variables that need additional data collection in the watershed of interest. Each of the variables identified can be measured with existing methods in one to several field seasons. Developing a database on numbers of redds per kilometer, adults per redd, percent spawnable area, and redd size that are watershed specific would help identify how the variability fluctuates by ecoregion and population size.

Perhaps a more important conclusion is that utilizing data developed for a different purpose and scope may lead to large-scale variations in spawning capacity. Extrapolating such data to other parts of the basin could lead to an overestimate in spawning capacity, as noted in the preceding example. Developing an adequate sampling design for data extrapolation is an important step to incorporate prior to data collection and development in order to reduce the amount of variation in spawner capacity estimates.

APPENDIX C: RESTORATION OF HABITAT-FORMING PROCESSES—AN APPLIED RESTORATION STRATEGY FOR THE SKAGIT RIVER

[Editors' note: A more detailed description of the strategy and updates of specific results are available on the Skagit Watershed Council's Web site: www.skagitwatershed.org.]

Escapement levels of Pacific Northwest and British Columbia salmon stocks have declined dramatically in the past century due to habitat loss, high levels of harvest, and changes in ocean conditions. Freshwater habitat losses induced by land use were associated with the decline of nearly all the at-risk stocks in a review by Nehlsen et al. (1991). However, the recognition of causes of decline and the desire to restore salmon runs has not led to specific plans for recouping habitat losses in large watersheds. Rather, most habitat restoration actions have been conducted in a relatively unplanned and uncoordinated fashion.

In 1997 the Skagit Watershed Council (SWC) was formed to support the voluntary protection and restoration of salmon habitats in the Skagit River basin of northwest Washington State. Today the SWC is comprised of 36 member organizations including private industrial and agricultural interests, state and federal agencies, local governments, tribes, and environmental groups. In 1998 the SWC adopted a salmon habitat protection and restoration strategy that recognizes the influences of land use and resource management activities on natural landscape processes, which result in changed habitat conditions (SWC 1998). Since 1998 members of the SWC have completed an interim application of the strategy, which identifies causes of degraded habitats in the watershed and actions needed to restore habitats over the long term (Beamer et al. 2000). In this appendix we briefly describe the strategy and methods and present the preliminary findings of the analyses. We also discuss costs of the analyses relative to projected costs of restoration actions.

Overview of the Restoration Strategy

Figure C-1 is a conceptual diagram illustrating how watershed controls (ultimate and proximate) and natural landscape processes combine to form various habitat conditions. Ultimate controls are independent of land management over the long term (centuries to millennia), act over large areas ($>1 \text{ km}^2$), and shape the range of possible habitat conditions in a watershed (Naiman et al. 1992, Beechie and Bolton 1999). Proximate controls are affected by land management over the short term (\leq decades), act over smaller areas than independent controls, and are partly a function of independent factors (Naiman et al. 1992). Landscape processes are typically measured as rates and characterize what ecosystems or components of ecosystems do. For example, sediment or hydrologic processes in a watershed may be characterized by the rates (volume/area/time period) at which sediment or water is supplied to and transported through specific locations of a watershed. Some riparian-related functions can be viewed similarly. For example, large woody debris (LWD) "recruitment" is synonymous with the idea of supply while LWD "depletion" is the result of both LWD transport and decay

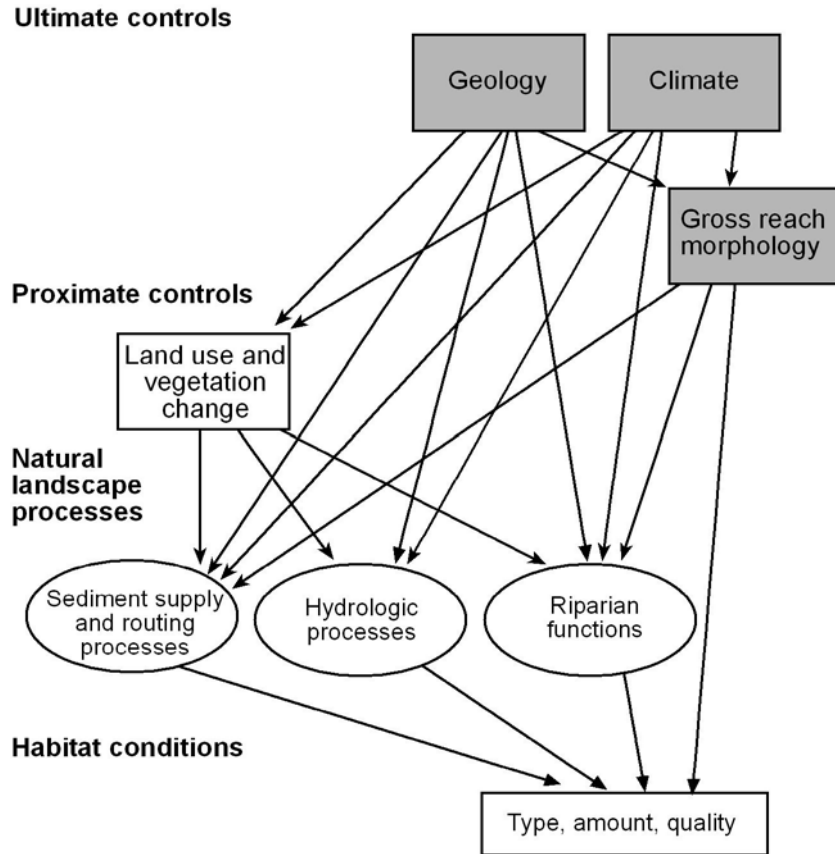


Figure C-1. Simplified flow chart depicting interactions between watershed controls and processes resulting in physical habitat conditions. Shaded boxes represent components that are not influenced by land and resource management.

rates. Natural rates of landscape processes are here defined as those that existed prior to widespread timber harvest, agriculture, or urban development.

The SWC's habitat protection and restoration strategy describes a scientific framework and set of procedures for identifying and prioritizing activities that restore or protect aquatic habitat (SWC 1998). The scientific framework strives to identify: 1) the natural landscape processes active in a watershed, 2) the effects of land use on natural processes, and 3) the causal relationships between land use and habitat conditions. It focuses not on the symptoms of watershed degradation but on the fundamental causes, and encourages protection and restoration of natural landscape processes that formed and sustained the habitats to which salmon stocks are adapted. Justification for this approach is based on our understanding from current literature that natural landscape processes create and maintain the natural habitat conditions in which native aquatic and riparian species have adapted (e.g., Peterson et al. 1992, Doppelt et al. 1993, Reeves et al. 1995, Ward and Stanford 1995, Beechie et al. 1996, Kauffman et al. 1997).

We apply the strategy by systematically identifying land use disruptions to landscape processes that form salmon habitat. These processes include peak flow hydrology, sediment supply, riparian functions, channel-floodplain interactions, habitat isolated from salmon access, and water quality. Using a series of diagnostic screens, we locate disturbances to habitat-forming processes and identify actions (i.e., projects) required to correct the disturbances. This appendix reports the SWC's progress in applying its strategy within the range of anadromous salmonids of the Skagit River basin.

Study Area

The Skagit River basin drains approximately 8,544 km² of the North Cascade Mountains of Washington and British Columbia (Figure C-2, map A). Elevations in the basin range from sea level to about 3,285 m (10,775 ft) on Mt. Baker. Numerous peaks in the basin exceed 2,500 m elevation. Average annual rainfall ranges from about 90 cm (35 in) at Mt. Vernon on the lower floodplain to over 460 cm (180 in) at higher elevations in the vicinity of Glacier Peak. Several vegetation zones occur in the study area. As defined in Franklin and Dyrness (1973), most of the lower elevations are in the western hemlock zone. This forest zone typically includes western hemlock (*Tsuga heterophylla*), Douglas fir (*Pseudotsuga menziesii*), western red cedar (*Thuja plicata*), and sitka spruce (*Picea sitchensis*). Deciduous species in this zone include red alder (*Alnus rubra*), black cottonwood (*Populus trichocarpa*), and big leaf maple (*Acer macrophyllum*). Middle elevations are in the Pacific silver fir (*Abies amabilis*) zone and higher elevations are in the alpine fir (*A. lasiocarpa*) zone (Franklin and Dyrness 1973).

The Skagit River basin is comprised primarily of mountain drainages with few lowland subbasins (low topographic relief and low elevation). The hydrographs of most low-elevation forested subbasins are dominated by autumn and winter rainfall floods (Beechie 1992). Conversely, spring snowmelt floods typically dominate the hydrographs of high elevation subbasins in the eastern Skagit. Most areas of the Skagit River basin are of intermediate elevation and exhibit both rainfall and snowmelt floods. Lowland subbasins are generally

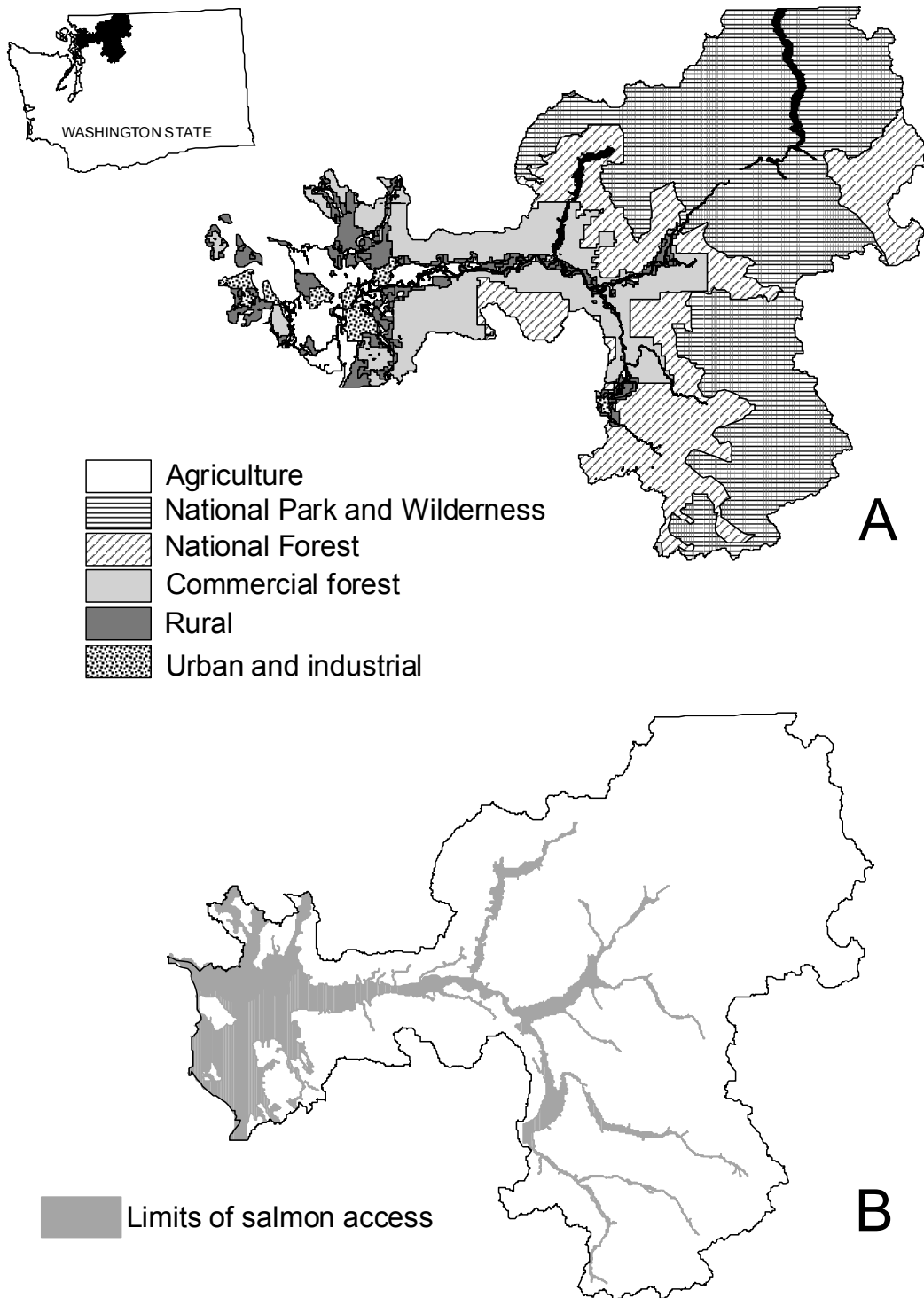


Figure C-2. Map A shows land use pattern and map B shows area of historical salmon access in the Skagit River basin.

located in the western valley (rain dominated) and usually more highly developed with urban and agricultural land use than the forested mountain basins (Lunetta et al. 1997).

Land development (primarily logging and draining or clearing lands for agriculture) began around 1860. About 1,590 km² (615 mi², 19%) of the basin is currently in private and Washington State ownership. Land uses are dominantly agricultural and urban in the lower floodplain and delta areas and upland areas are generally commercial forests. About 3,680 km² (1,420 mi², 44%) of the basin lies within the federally owned North Cascades National Park, Mt. Baker and Ross Lake National Recreation Areas, and Glacier Peak Wilderness Area. The U.S. Forest Service controls an additional 1,960 km² (755 mi², 24%) of the basin in the Mt. Baker-Snoqualmie National Forest. Approximately 1,040 km² (400 mi², 13%) of the basin is in British Columbia.

Anadromous salmonids indigenous to the basin include Chinook salmon (*Oncorhynchus tshawytscha*), coho salmon (*O. kisutch*), pink salmon (*O. gorbuscha*), chum salmon (*O. keta*), sockeye salmon (*O. nerka*), steelhead (*O. mykiss*), cutthroat trout (*O. clarkii*), and native char (*Salvelinus* sp.). Access to anadromous fishes is generally confined to elevations below 700 m by natural barriers. Upstream migration to the Baker River system has been eliminated by the installation of two hydroelectric dams, but anadromous fish production—primarily coho and sockeye salmon—is maintained through trapping and hauling operations in addition to the maintenance of sockeye spawning beaches and smolt bypass trapping. The extent of salmon upstream migration in the Skagit River basin is shown in Figure C-2, map B.

Methods

We analyze disturbances to watershed processes in the Skagit River basin in two phases. In the first (interim) phase, we locate disturbed habitat-forming processes using a combination of existing Geographic Information System (GIS) data and field-based inventories to identify disturbances to peak flows, sediment supplies, riparian functions, channel-floodplain interactions, blockages to salmon migration, and water quality. The second phase relies mainly on field-based inventories. Both phases rely on GIS to analyze and maintain landscape process data over the 8,544 km² area of the Skagit River basin. This appendix describes only the methods and results from Phase 1.

We have used more than 30 different GIS themes and partial field inventories to apply the landscape process screens identified in the strategy. The existing GIS themes provide low-resolution data covering the entire river basin. These data give us a good overview of habitat-forming processes in the entire basin, but can give erroneous answers to our questions about specific reach-level sites (10²–10⁴ m linear scale). Field inventories provide high-resolution data, but with only limited coverage at present. Because field inventories are more reliable at specific sites, the SWC members have made a long-term commitment to collecting field-based information basin wide.

We analyzed selected landscape processes that form salmonid habitats in the Skagit River basin. We selected these analyses based on current scientific knowledge of their effects on salmonid habitat and survival of salmon in freshwater, as well as knowledge of how various land

use practices affect the processes (Table C-1). We recognize that the list may not include all impacts to salmon in the watershed; however, it includes those that are clearly supported by scientific literature and responsible for a significant proportion of the total loss in salmon production from the basin. For each process we developed a series of diagnostics based on rates derived from scientific literature and local studies. The diagnostics and methods for estimating values are summarized in Table C-1.

We synthesized the ratings for individual landscape processes and functions into a single reach classification that we call the generalized habitat types. The importance of identifying generalized habitat types for watershed restoration is illustrated by Frissell (1993a) and Doppelt et al. (1993), where examples of habitat types are listed along with their biotic objective and restoration tactics. To apply this concept in the Skagit, we derived generalized habitat types based on simple correlations between our understanding of anadromous fish life history strategies and reach-level habitat types ($\approx 10^2$ to 10^4 m linear scale, Table C-2). We assume that relationships between fish life stages and habitat for each indicator species analyzed adequately identifies the habitats to which salmon stocks are adapted.

Our analysis used five species and four life stages to determine generalized habitat types. The stages examined were 1) spawning/egg to fry, 2) summer rearing, 3) winter rearing, and 4) estuary rearing. Several salmonid species in the Skagit River basin were excluded from the evaluation due to lack of data or a spatial bias in their distribution not related to geomorphic habitat types. Native char were excluded due to a lack of data describing their habitat preferences over complete life history. We know the spawning range of native char is biased toward higher elevation headwater tributary basins within the range of historical anadromous fish access. Cutthroat trout were excluded because of their spatial bias toward the lower elevation, rain-dominated subbasins of the Skagit. Coho salmon habitat preference is similar to cutthroat, and the coho range includes all of the anadromous cutthroat range in the Skagit; therefore, we assume that coho relationships in our analysis adequately represent cutthroat. Sockeye were excluded because the population is limited to the Baker River subbasin of the Skagit. While resident rainbow trout (*O. mykiss*) are found throughout the entire river basin, they are assumed to have the same juvenile habitat preferences as steelhead (the anadromous form of *O. mykiss*), which are included in our analysis.

Under pristine habitat conditions (i.e., natural disturbances only) we define reach-level habitat types for anadromous salmonids in the Skagit River as either “key” or “secondary” (Table C-2). Key habitat is “critical” for at least one life stage or is a “preferred” habitat type by the majority of life stages considered. Secondary habitat does not provide critical habitat for any life stage and is not a preferred type by the majority of life stages considered. Classification systems described in Hayman et al. (1996), Montgomery and Buffington (1997), Peterson and Reid (1984), and Simenstad (1983) were used to define the different reach-level habitat types. Local studies used to designate whether the specific reach-level habitat types were “critical,” “key,” or “secondary” for a life stage included: Beamer and Henderson (1998), Beechie et al. (1994), Congleton (1978), Congleton et al. (1981), Hayman et al. (1996), Montgomery et al. (1999), and Phillips et al. (1980, 1981). Data from outside the Skagit (Queets River, Washington, in Sedell et al. 1984) were also used to help understand juvenile fish use differences between large main channels and off-channel habitats.

Table C-1. Summary of background and methods for rating individual landscape processes.

Background	Method description	References
<p><i>Hydrology—peak flow in lowland basins</i></p> <p>The degree of urbanization is correlated with increased flooding, degraded habitat, and lower salmonid populations in lowland basins of Puget Sound. When the 2-year flood magnitude under current land use equaled or exceeded the 10-year flood under forested watershed conditions, channels were consistently degraded. Watersheds with effective impervious area (EIA) greater than 10% always had degraded channels whereas watersheds with EIA \leq 3% had high species and habitat diversity and abundance.</p>	<p>Hydrologic impairment in lowland basins rated based on planned EIA, which is the weighted average EIA upstream of the stream reach under fully developed conditions per land use zoning designation. Weighted average EIA was calculated using GIS by assigning EIA values to polygons based on land use zoning designations. EIA \leq 3% is considered “functioning,” EIA between 3% and 10% is “moderately impaired,” and EIA $>$ 10% is “impaired.”</p>	<p>Booth and Jackson 1997, Dinicola 1989, Moscrip and Montgomery 1997.</p>
<p><i>Hydrology—peak flow in mountain basins</i></p> <p>Increased peak flows result in an increased frequency of channel forming and bed mobilizing flow events, leading to channel destabilization, less complex habitat, and increased bed scour depths significantly affecting salmonids. Two common land use causes of increased peak flow in forested mountain basins relate to hydrologically immature vegetation and forest road drainage. Hydrologically immature vegetation has relatively low canopy density in winter, allowing increased snow accumulation and melt, resulting in higher runoff rates than areas with hydrologically mature vegetation. Forest road ditches extend the channel network, resulting in more rapid routing of water to main stream channels than basins without road networks.</p>	<p>Peak flow ratings for mountain subbasins in the Skagit were developed based on an empirical correlation between land use and elevated peak flow in an adjacent basin because subbasin flow data are limited in the Skagit. Subbasins with more than 50% watershed area in hydrologically immature vegetation due to land use and more than 2 km of road length per km² of watershed area are rated “very likely impaired.” Subbasins exceeding one or the other of the criteria are considered “likely impaired.” Subbasins that do not exceed either criterion are considered “functioning.”</p>	<p>Beamer and Pess 1999, Jones and Grant 1996, Lunetta et al. 1997, Montgomery 1993, WFPB 1995.</p>

Table C-1 continued. Summary of background and methods for rating individual landscape processes.

Background	Method description	References
<p><i>Sediment</i></p> <p>Clear-cutting and forest roads increase landsliding and the supply of coarse sediment (>2 mm diameter) to stream channels, although fine sediments (< 2 mm diameter) are also delivered by mass wasting. Large increases in coarse sediment supply tend to fill pools and aggrade the channel, resulting in reduced habitat complexity and reduced rearing capacity for some salmonids. Large increases in total sediment supply to a channel also tend to increase the proportion of fine sediment in the bed, which may reduce the survival of incubating eggs in the gravel and change benthic invertebrate production. Landform and land use both influence mass wasting rates. Most sediment from mass wasting originates from inner gorge landforms (steep, stream-adjacent slopes). On average these areas cover less than 20% of the mountain basins in the Skagit but produce about 75% of the sediment delivered to streams. Hillslopes >30° are also generally unstable, tending to produce shallow, rapid landslides from bedrock hollows or channel headwalls. Hillslopes <30° are generally stable. Deep-seated failures, usually located in glacial deposits or phyllite, have high mass wasting and delivery rates to streams. Compared to mature forest, the increase in mass wasting rates for clear-cut forests and forest road areas averages about 6 and 44 times higher, respectively.</p>	<p><u>Estimating impairment of sediment supply</u>: Average sediment supply for each subbasin estimated based on average sediment supply rates for 13 combinations of geology and vegetation cover (Landsat '93), which were derived from nine sediment budgets conducted within the basin. Using GIS we calculated average current sediment supply for each subbasin and the average increase over the natural sediment supply for each subbasin (current/natural). Sediment supply process is considered “functioning” where average sediment supply is <100 m³/km²/yr, or where the average is >100 m³/km²/yr but <1.5 times the natural rate. Sediment supply is “impaired” where average sediment supply is >100 m³/km²/yr and >1.5 times the natural rate.</p> <p><u>Forest road inventory—identify sediment reduction projects</u>: The inventory rates factors that influence road-related landslides and the consequences of landslides. All ratings concerning the likelihood of landsliding are summed, then multiplied by a rating of the likelihood that significant stream resources will be impacted. The final value, called the risk rating, ranks roads with respect to the threat that they pose to salmon habitat. Higher risk ratings indicate greater chance that a road will fail and impact salmon habitat. Final ratings were grouped into three categories of risk. A rating >30 is high, 16 to 30 is moderate, and ≤15 is low.</p>	<p>Collins et al. 1994, Dietrich et al. 1989, Lisle 1982, 1989, Lunetta et al. 1997, Madej and Ozaki 1996, Paulson 1997, Peterson et al. 1992, Renison 1998, Sidle et al. 1985.</p>

Table C-1 continued. Summary of background and methods for rating individual landscape processes.

Background	Method description	References
<p><i>Riparian Function</i></p> <p>Clearing of riparian forests can alter LWD recruitment to streams, which in turn alters the habitat characteristics of streams. Reduced LWD recruitment persists for several decades, leading to declining LWD abundance in the first few decades and sustained low LWD abundance between 50 and 100 years after the disturbance. A change in LWD abundance alters fish habitat characteristics such as pool spacing, pool area, and pool depth, and this alteration of habitat characteristics causes changes in the salmonid carrying capacity of a stream.</p>	<p><u>Remote sensing assessment</u>: Riparian forests that can produce $\geq 80\%$ of potential late-seral LWD recruitment over time (≥ 40 m wide) are considered “functioning.” Riparian forests producing 50% to 80% of the potential late-seral recruitment (20 to 40 m wide), are considered “moderately impaired.” Buffer widths < 20 m are considered “impaired.” We estimated the proportion of impaired, moderately impaired, and functioning riparian forests by using Landsat classifications of vegetation.</p> <p><u>Field inventory</u>: Ratings are the same as above. In addition to documenting forested buffer width, field inventories also classify stand types by species mix and seral stage, which provides sufficient information to prescribe generalized management regimes for each segment of riparian forest. Inventories also identify areas of livestock access and potential fencing projects.</p>	<p>Abbe and Montgomery 1996, Beechie and Sibley 1997, Bilby and Ward 1991, Hicks et al. 1991, Lunetta et al. 1997, Montgomery et al. 1995, Murphy and Koski 1989, Murphy et al. 1985.</p>
<p><i>Channel-floodplain</i></p> <p>Disconnecting rivers from floodplains changes the ability of rivers to supply, transport, or store one or more inputs of water, sediment, and wood. This constrains the formation and maintenance of habitat within floodplains. Streambank hardening (hydromodification) prevents channel migration, reduces LWD recruitment, and typically narrows and steepens channels, increasing both sediment and water transport rates. Mainstem channels in the Skagit dominated by hydromodification exhibited less diversity in edge habitat types and less edge habitat area than nonhydromodified mainstem reaches. Juvenile Chinook and coho salmon abundance was strongly correlated to wood and other natural cover types when compared to riprap or rubble cover, commonly used for streambank hardening.</p>	<p>Floodplain areas were delineated where the 100-year floodplain was greater than two channel widths using Federal Emergency Management Agency maps or U. S. Geological Survey 7.5-minute quadrangles and aerial photographs. Reach breaks were based on differences in floodplain width and changes in channel pattern. Hydromodified areas were delineated on copies of aerial photos by rafting or jet boating each main channel within floodplain reaches, then digitized into a GIS arc theme.</p>	<p>Beamer and Henderson 1998, Hayman et al. 1996, Ward and Stanford 1995.</p>

Table C-1 continued. Summary of background and methods for rating individual landscape processes.

Background	Method description	References
<p><i>Isolated habitat</i></p> <p>Isolation of habitat by levees and culverts has dramatically reduced carrying capacity of the Skagit River basin over the past 150 years. This includes blockages that impede upstream migration of adult salmon seeking suitable spawning areas as well as blockages to other life stages such as juvenile rearing habitat in both the freshwater and estuarine environment. Some isolated habitat can be recovered by simply removing the barrier (e.g., rebuilding road crossings that block passage), whereas others will require feasibility studies to determine a range of possible alternatives to accommodate both fish use and existing land use.</p>	<p>Manmade barriers to anadromous fish habitat are identified through a systematic field inventory of channel crossing structures (culverts, tide gates, bridges, dams, and other manmade structures). The inventory identifies the type and physical dimensions of structures as well as physical attributes necessary for modeling water flow conditions and comparing results to passage criteria for salmonids.</p>	<p>Beechie et al. 1994, Collins 1998, WDFW 1998.</p>

Table C-2. Designation of generalized habitat types. Key habitat is critical (i.e., required for the persistence of a dominant life history type) for at least one life stage or preferred by the majority of life stages considered. Secondary habitat (sec) does not provide critical habitat for any life stage and is not a preferred type by the majority of life stages considered.

Reach-level habitat type	Chum	Coho	Chinook	Steel-head	Pink	Number of life stages examined	Percent of all life stages designated key or critical	Overall designation for pristine habitat
<i>Tributary reaches:</i>								
Ponds (including beaver ponds and other wetlands with significant open water area)	sec	critical	key	key	sec	10	60	key
Pool riffle	key	key	key	key	key	10	90	key
Forced pool riffle	sec	key	key	key	key	10	85	key
Plane bed	sec	sec	sec	sec	sec	10	0	sec
Step-pool	sec	sec	sec	key	sec	10	15	sec
Cascade	sec	sec	sec	key	sec	10	15	sec
<i>Main river reaches:</i>								
Main channel floodplain < 2 channel widths	sec	sec	sec	key	sec	10	15	sec
Main channel floodplain > 2 channel widths	key	sec	key	key	key	10	80	key
Off-channel habitat (e.g., ponds, sloughs, side channels, oxbow lakes)	key	critical	key	sec	sec	10	60	key
<i>Estuary:</i>								
Estuarine or tidally influenced wetland	key	sec	critical	sec	sec	5	40	key
Blind channel	key	key	critical	sec	sec	5	60	key
Subsidiary channel	key	key	key	sec	key	5	80	key
Main channel	key	key	key	sec	key	5	80	key

Under disturbed habitat conditions (i.e., both human and natural disturbances), we designate reach-level habitat types as: “key” when all landscape screening results are rated as functioning, “important” when at least one landscape screen is moderately impaired, “degraded” when at least one landscape screen is impaired, “secondary” when channel type is step-pool or steeper, “isolated” when upstream of a manmade barrier to fish migration, or “unknown.” Some reaches are designated as unknown because of high probability of error in rating the riparian condition correctly by land cover types.

Mainstem areas with any of the following conditions are considered degraded: riparian buffer is less than 20 m wide, streambank edge is hardened (e.g., riprap), or levee is present within 60 m of the bankfull channel edge. All other lower Skagit mainstem areas are considered important. In the estuary, hydromodified areas are considered degraded, areas adjacent to levees are considered important, and areas at least one distributary channel away from a levee are considered key.

Results and Discussion

Hydrology—Changes in Peak Flow

We estimate 23% of the mountain subbasins in the Skagit are very likely impaired or likely impaired with respect to peak flow hydrology (Figure C-3, map A). In lowland basins, we estimate 7% of the streams historically accessible to anadromous salmon will be impaired when urban and residential areas are fully built out and 18% will be moderately impaired (Figure C-3, view B). We use the results shown in Figure C-3 to help evaluate the likelihood of success of proposed restoration projects. In general we do not support restoration efforts directly in or adjacent to channels that are classified as impaired without evidence that the proposed work will succeed in spite of the likely increase to peak flows. We also use the results to identify areas currently in good condition that are planned for future development to an extent that hydrology will likely be impaired. For these areas we consider protection actions such as rezoning to a less intensive land use or acquisition. We also identify areas to investigate for potential restoration of hydrologic processes.

Reduced peak flows as a result of flood control change a channel’s ability to create and maintain the suite of diverse floodplain habitats to which aquatic species are adapted (Ward and Stanford 1995). Annual peak flows in the Skagit River basin have changed since flow regulation through the construction of reservoirs capable of flood storage in the Skagit and Baker Rivers. Before flood storage capability, floods in the lower Skagit River commonly approached or exceeded 5,500 cubic meters per second (m^3/s), and floods in water years 1815 and 1856 were estimated at 11,327 and 8,495 m^3/s , respectively. Since the advent of flood storage capability, a flood approaching 5,500 m^3/s has not yet occurred. The number of floods between the 2-year and 100-year return period has been reduced by roughly 50% since the dams were built (Table C-3). Flood storage on the Skagit has likely impacted channel-floodplain processes in reaches downstream of the dams, but we have not yet quantified the effects. Until we have a better understanding of these impacts, we view the dams as ultimate controls as shown in Figure C-1. That is, they operate independently of our management control because they are licensed for up

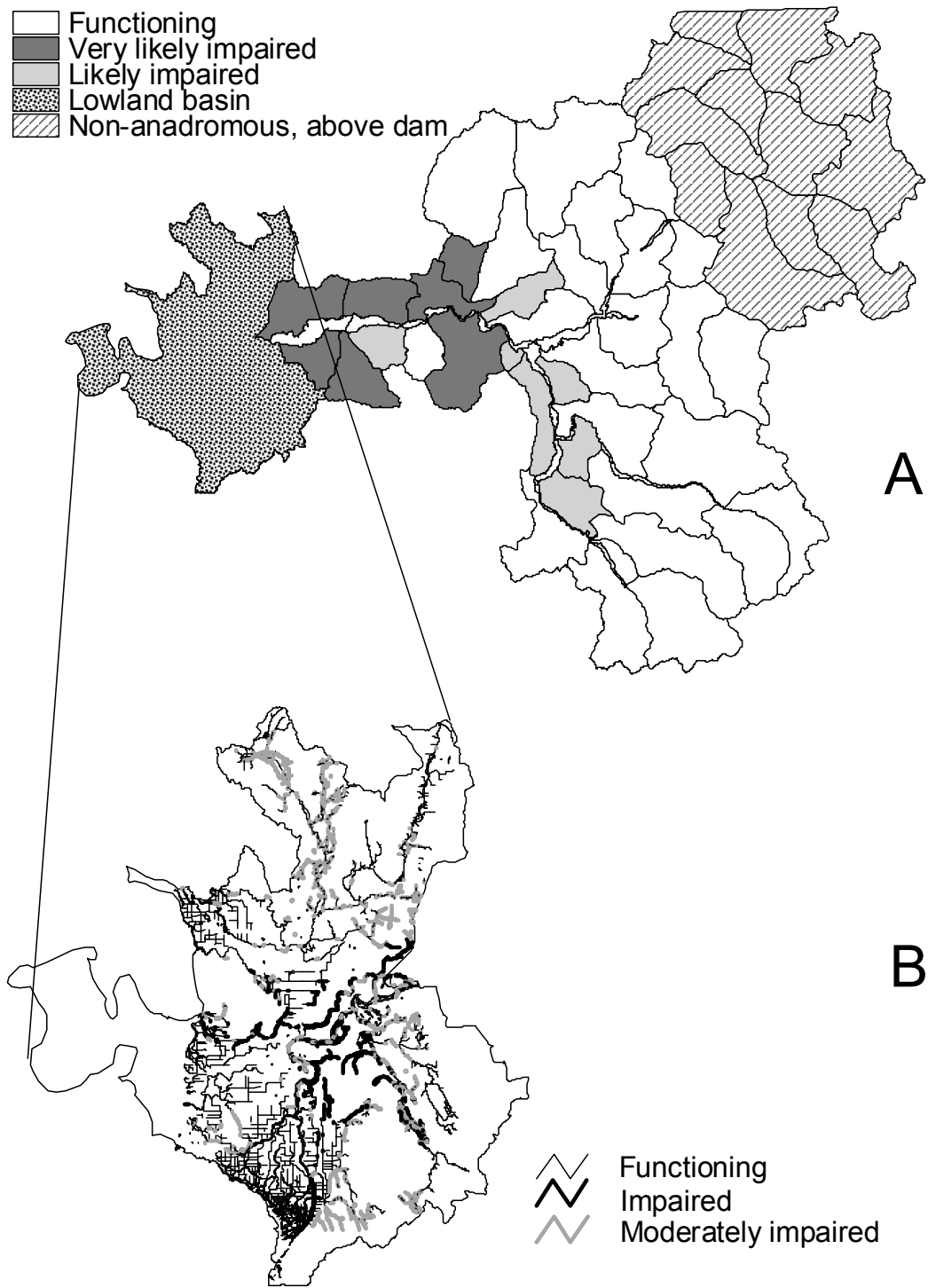


Figure C-3. Map A shows subbasins in forested mountain areas of the Skagit River basin where peak flow is likely impaired. Exploded view B shows streams in lowland subbasins where peak flow will be impaired if current zoning is built out.

Table C-3. Magnitude of peak flows for the lower Skagit River before and after flood storage capability.
 Flood storage is the combined capacity of the Skagit and Baker dams.

Flood return period (years)	Before flood storage^a (cms)	After flood storage^b (cms)
2	3,147	1,830
5	4,735	2,479
10	5,862	2,934
25	7,361	3,540
50	8,528	4,015
100	9,734	4,508

^a Skagit River near Sedro-Woolley (river km 36), reported in Williams et al. 1985.

^b Skagit River near Mt. Vernon (river km 25), Sumioka et al. 1998.

to 50 years and are unlikely to be removed. Accepting that this disturbance will not likely be altered during the license period of each dam, the artificial creation of off-channel habitat then may be justified in stream reaches where off-channel habitat has been lost due to this disturbance. Alternatively, it may be possible to reestablish certain channel-forming flows that have been eliminated in the past.

Sediment Supply

We estimate that 46% of the area in mountain subbasins of the Skagit has impaired sediment supply (Figure C-4, map A). Our evaluation of the accuracy of the method shows that it correctly estimated the sediment supply rating for seven of the 10 subbasins where sediment budget data were available. It overestimated average sediment supply for two of the 10 test basins (i.e., rated them impaired when they are functioning), and underestimated sediment supply for one subbasin. Therefore, we recognize that this product should not be used to identify potential restoration projects. Rather, it is used for project screening where field-based sediment budgets are not available and for general planning of watershed-level sediment reduction projects. Project proponents use this map for project screening to determine whether the proposed area is likely to have an impaired (i.e., high) sediment supply. For reaches where sediment supply is impaired, 1) sediment supply in the watershed should be restored to functioning levels before downstream reaches are worked on or 2) evidence demonstrating that the proposed work will not fail due to increased sediment supply should be presented.

Specific sediment reduction projects are identified based on the results of forest road inventories. We focus on forest roads for sediment reduction projects because mass wasting rates from forest roads averaged about 44 times more than mass wasting rates in mature forest (Paulson 1997). Currently about 1,300 km of road are inventoried with another 3,000 km remaining (Figure C-4, map A). Risk ratings from the current inventory show that a significant number of forest roads in the Skagit River basin pose a landslide hazard and potentially threaten fish habitat. Based on this inventory, we will focus initial sediment reduction projects on the high-risk and moderate-risk road segments.

For example, the Bacon Creek watershed (Figure C-4, view B) has 3.7 km of high-risk and 18.6 km of moderate-risk roads. The high-risk road segments cross more landforms sensitive to disturbance for mass wasting (e.g., inner gorges and steeper hillslopes) than moderate or lower risk roads. Sediment reduction projects on these roads would reduce the risk of increased sediment supply and therefore increase the level of watershed protection. Specific road projects primarily involve stabilizing or recontouring road fills, removing stream crossings or improving drainage conveyance, and improving road surface drainage. For basin-level planning, we consider subbasins with the lowest total cost of road restoration per kilometer of salmon stream as the highest priority.

Riparian Function

Before interpreting the Landsat classification of riparian forests, we used field inventory results from 234 riparian sites to describe the distribution of field-based riparian classifications within each satellite-based forest class (Table C-4). All of the sampled late-seral forest sites and

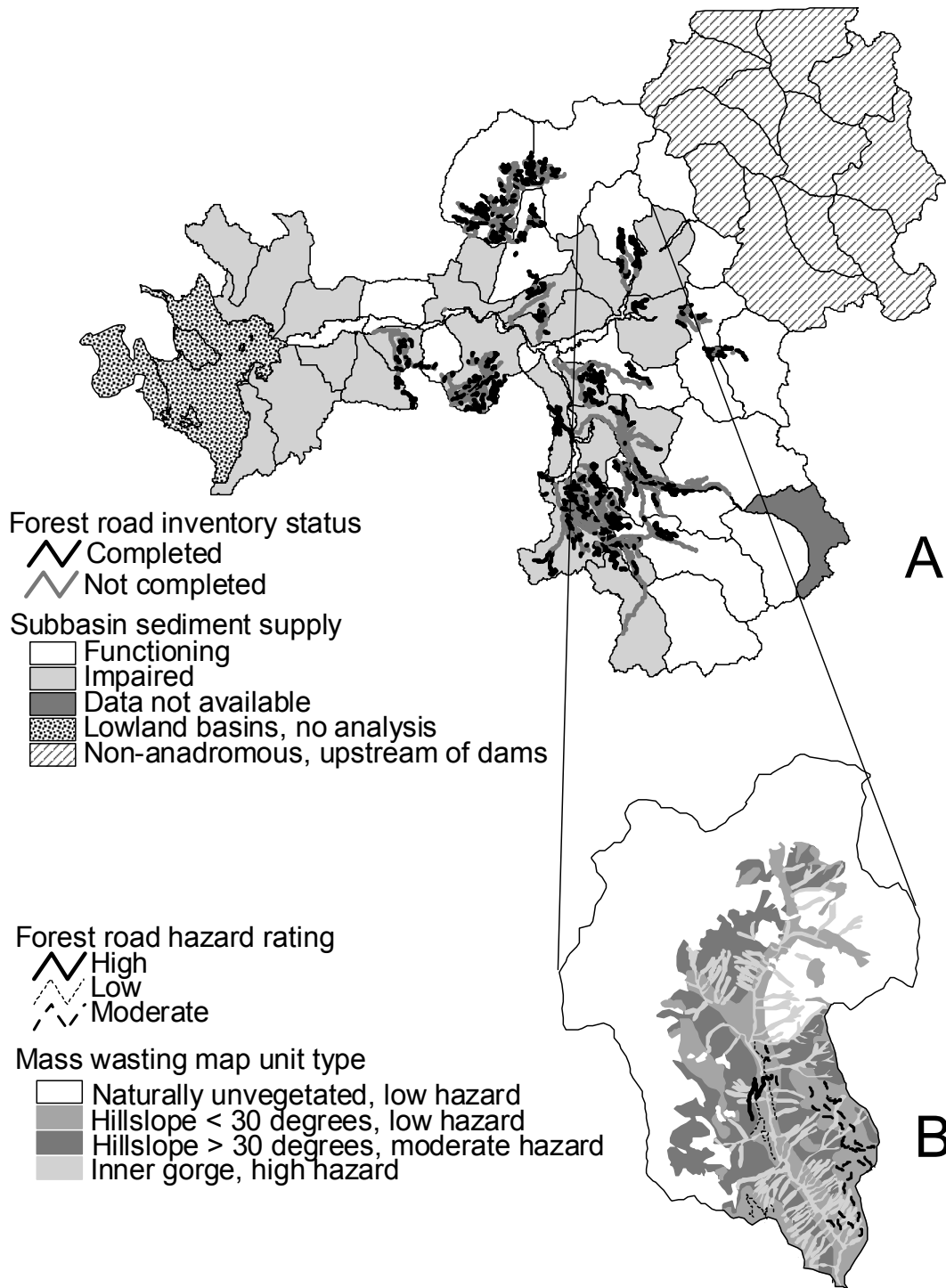


Figure C-4. Map A shows sediment supply ratings for mountain subbasins and status of forest road inventory on National Forest lands in the Skagit River basin. Exploded view B is example of detail for road segments and landslide hazard units in the Bacon Creek watershed. (See also Figure 12 for additional illustration.)

Table C-4. Distribution of 234 field-sampled riparian sites by GIS-based land cover type.

Buffer width class	Late-seral forest (n = 24)	Mid-seral forest (n = 13)	Early-seral forest (n = 24)	Other forest (n = 96)	Nonforest (n = 77)
<20 m forested buffer “impaired”	0%	8%	8%	42%	90%
20–40 m forested buffer “moderately impaired”	0%	0%	4%	15%	6%
>40 m forested buffer “functioning”	100%	92%	88%	43%	4%

between 88% and 92% of the mid-seral forest and early-seral forest sites met the greater than 40-m wide riparian buffer criteria, fitting our functioning designation. Conversely, 90% of the areas mapped as nonforest had less than 20-m wide riparian buffers, fitting our impaired designation. Areas mapped as other forest (ranging from clear-cuts to mature hardwoods) were found 43% functioning, 15% moderately impaired, and 42% impaired.

Based on this analysis, we estimate that 29% of the nonmainstem channels in the anadromous zone (by length) are in the nonforest land cover category, and therefore have a very high likelihood of being impaired and in need of riparian restoration (Figure C-5). Conversely, 19% of the nonmainstem channels in the anadromous zone are in the mid- to late-seral forest land cover category, and therefore have a high likelihood of being functioning and needing protection. While we cannot accurately map stream reach-scale riparian conditions associated with channels adjacent to all GIS land cover types, we can estimate with reasonable accuracy the total of each riparian category at a larger scale. Based on the results in Table C-4, we estimated the percentage of nonmainstem channel length in the Skagit anadromous zone by each land use designation (Figure C-6).

We rely on field inventories to identify actual restoration projects because of the above-mentioned limitations in the satellite classification of riparian forests. We conducted field inventories of riparian forests by walking all streams accessible to anadromous fish and assessing the riparian vegetation conditions for each stream reach. We classified riparian conditions by buffer width, stand type, and age of vegetation within 60 m of stream channels. From these data, we selected all stream segments with forested riparian vegetation less than 40 m wide as requiring planting and all segments with evidence of livestock access to the stream channel as requiring fencing. Riparian planting and restoration projects have been identified through a series of field inventories. The inventories were completed systematically as four separate projects between 1995 and 1998 in 24% of the Skagit's subbasins (Figure C-5). Together the inventories identified 130 km of stream corridor for riparian planting and fencing projects.

Isolated Habitats and Disrupted Channel-Floodplain Interactions

The inventory efforts through September 1999 identified 229 manmade barriers out of 572 channel crossing structures with 32% of the anadromous zone inventoried. In tributary habitat, 143 km of channel is blocked. In the delta, we estimate 185 km (56%) of the channels have been isolated or lost to salmon access under present conditions (Figure C-7). Isolated channels are those where a channel and water exist, but juvenile or adult salmon access is blocked due to manmade disturbances. Lost channels are those areas that were channels historically but currently do not have a distinct channel or water present.

Because manmade barriers are not evenly distributed throughout the Skagit River basin and our inventory efforts have focused in areas where barriers are more common, we anticipate that the majority of the isolated habitat in the basin has been found. Based on a subsample of 111 inventoried structures within subbasins of the Skagit with similar land use intensity as the subbasins yet to be inventoried, we found that 14% of the inventoried structures do not meet fish passage criteria. Therefore, we expect to find about 150 more blockages in noninventoried areas of the basin, blocking about 60 km (4%) of the estimated length of tributary habitat in the anadromous zone.

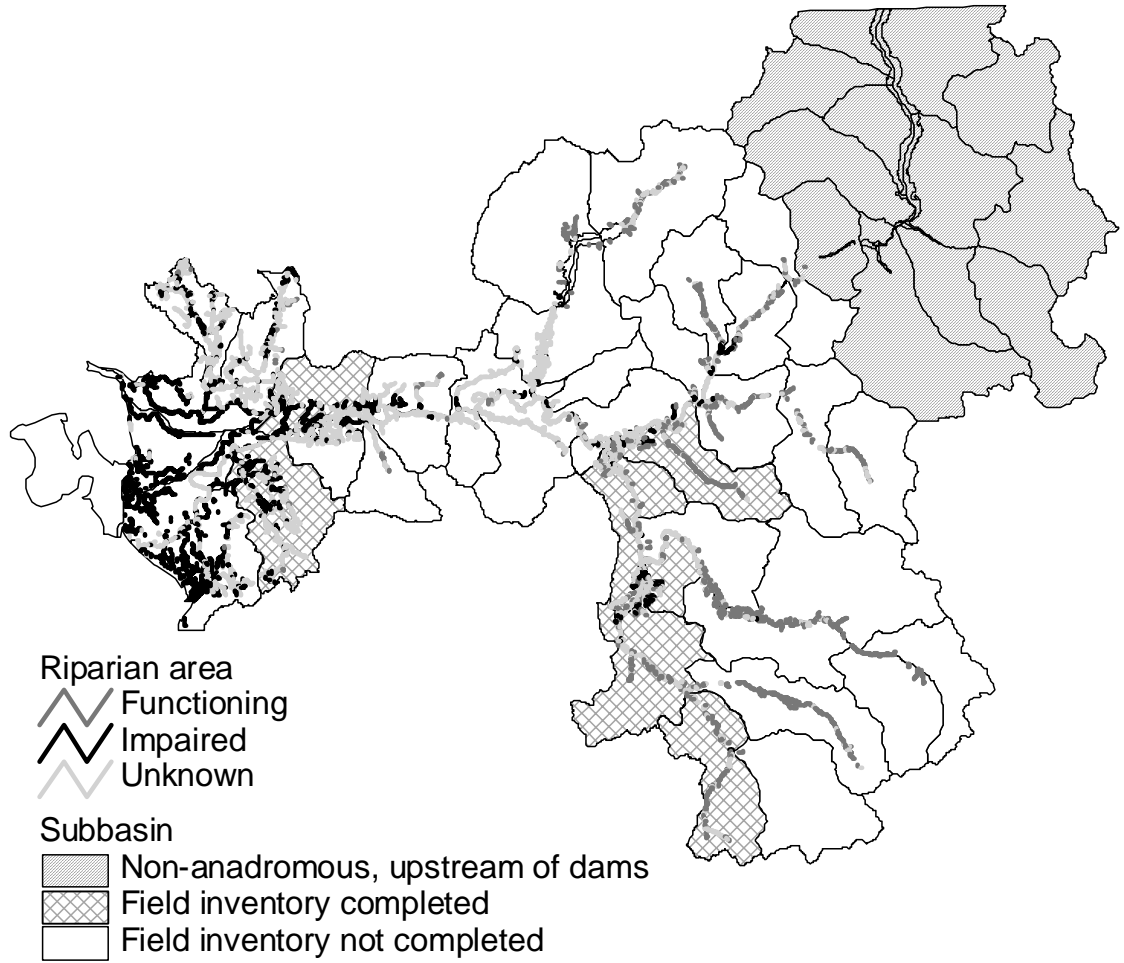


Figure C-5. Map of riparian inventory status and riparian areas likely functioning or impaired in the Skagit River basin.

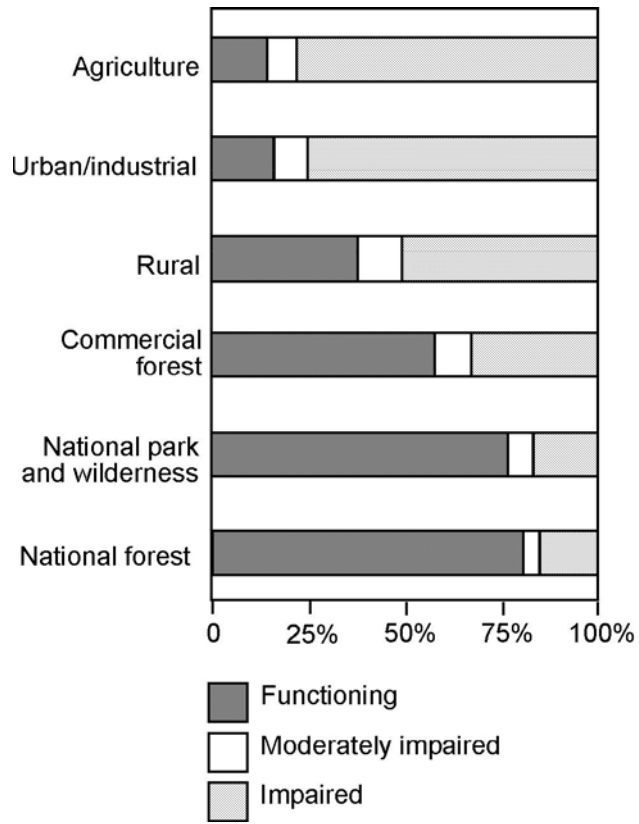


Figure C-6. Estimated percentages of riparian categories (functioning, moderately impaired, and impaired) for land use categories along nonmainstem channels in the anadromous zone of the Skagit River basin.

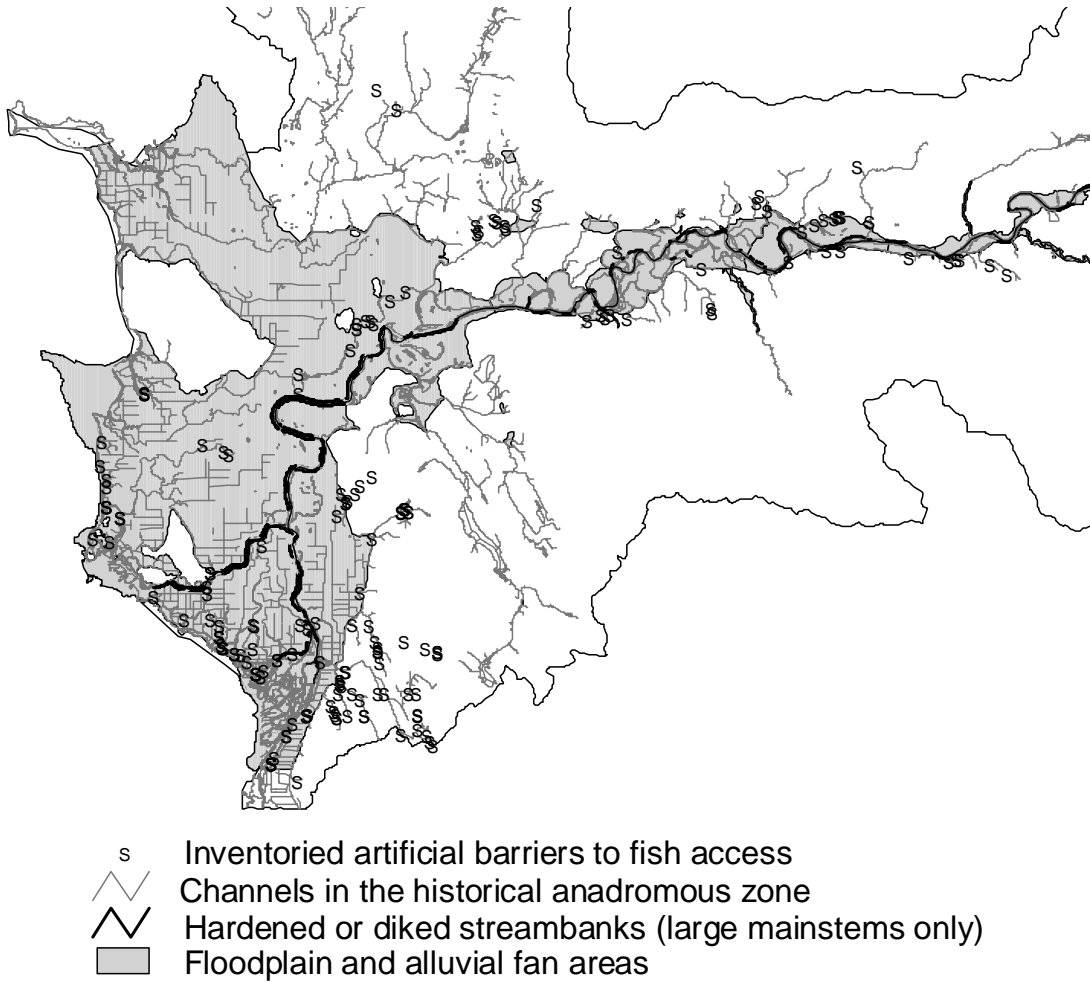


Figure C-7. Location of hydromodification and manmade barriers (lower Skagit River basin only).

Upstream of the Skagit River delta, 46 km of streambanks have been riprapped (Figure C-7). In the geomorphic delta, 51 km (62%) of the mainstem channel edge is either hardened, diked within 60 m of the channel's edge, or both. These inventory results provide the basis for identifying potential riprap removal (or modification) projects, primarily where hardened banks no longer protect capital improvements (e.g., house, road).

Generalized Habitat Types

The final result of our analysis is the identification of generalized aquatic habitat types throughout the entire river basin, which are based on salmonid habitat preferences combined with the results of the landscape process screens. The resulting analysis in the Skagit River basin yields a mosaic of reach-level habitat patches (Figure C-8). Key habitat areas have all habitat-forming processes functioning at or near historical levels and are targeted for habitat protection. Because protection of habitat is generally considered less expensive than restoration, we view key habitats as some of the highest priority areas for habitat expenditures. Isolated habitats are typically the most cost-effective restoration projects and therefore receive strong consideration for funding. Important and degraded habitats are both areas targeted for restoration.

Secondary habitat is not targeted for restoration under this strategy. That is, we do not intend to restore secondary habitat to key habitat. However, it is important to understand how secondary habitat may function in a watershed in order to protect or restore the other habitat types. For example, the source of degradation may originate in secondary habitat (i.e., the idea of contributing critical areas, discussed in Frissell 1993a). In such cases, restoration of processes originating in secondary habitat areas may be required in order to restore downstream degraded or important habitats.

Identification of Restoration Projects

The main objective of the strategy is to identify habitat protection and restoration projects based on application of the landscape process screens. Together our analyses have led to the identification of more than 400 individual restoration projects. For example, our analysis of the U. S. Forest Service road inventory identified approximately 650 km of high-hazard and moderate-hazard roads that are candidates for restoration. The total estimated cost for all of these roads (which does not include forest roads on state and private lands) is approximately \$11.6 million. We also identified 122 riparian planting and fencing projects during inventories of only 24% of the river basin, with a total cost estimated at \$1,687,000. Of these riparian projects, 39 are already funded.

We completed migration barrier inventories in 13 out of 38 subbasins and identified 229 blocking structures. Some blockage removal projects have uncomplicated designs and relatively clear benefits. These projects can each be considered independently of other culverts because salmon currently access the culvert sites and repair of the structures will provide benefits commensurate with the amount of habitat upstream. By contrast, groups of completely blocking structures on the same watercourse should be considered either in combination or sequentially, and projects that involve flood protection levees or coordination of numerous landowners require feasibility studies to determine suitable restoration actions. Currently we have a list of 36

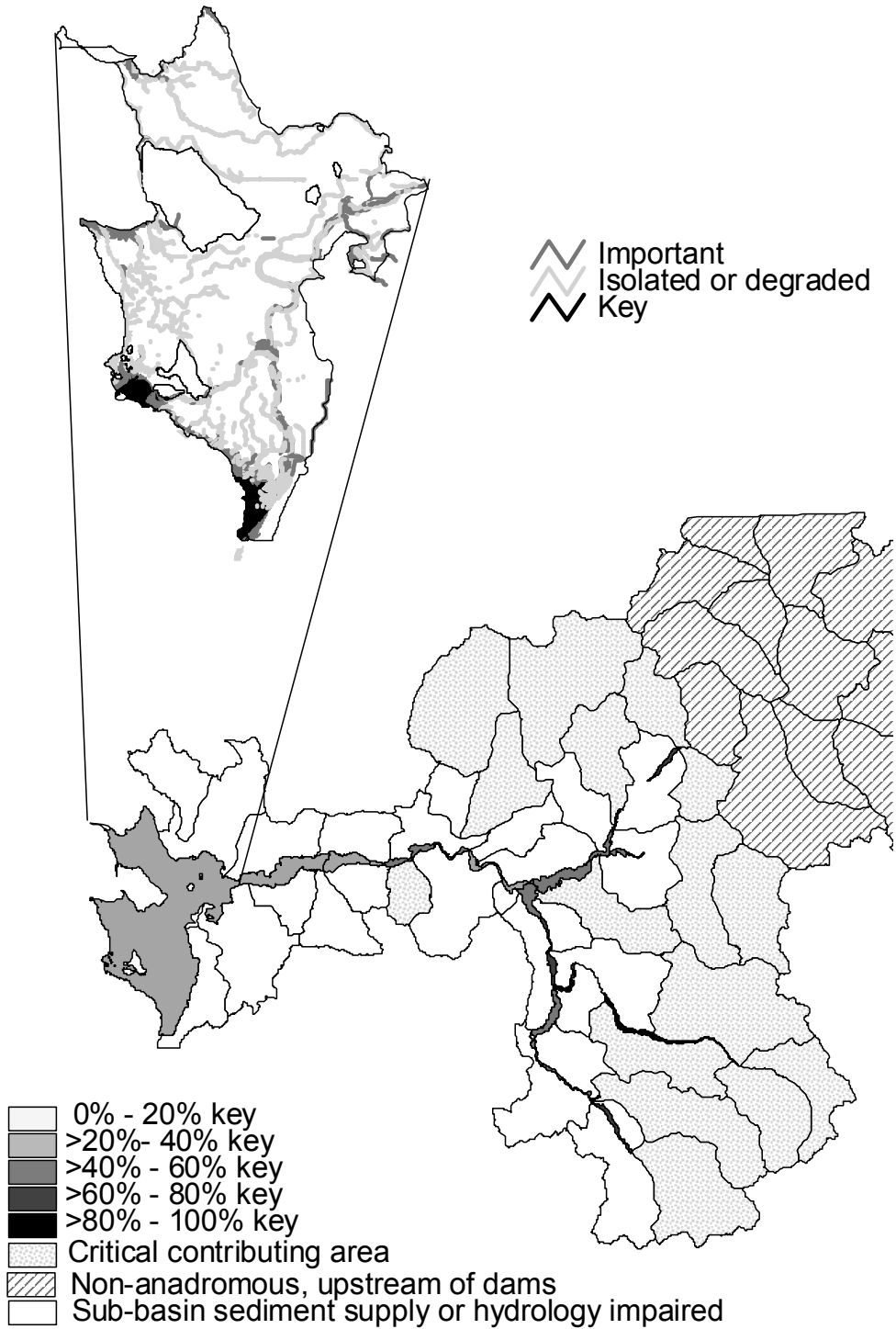


Figure C-8. Distribution of generalized habitat types (key, isolated or degraded, important) in floodplain areas of the Skagit River basin, with exploded view of the delta region.

isolated sloughs and blind tidal channels that require further assessment for design of appropriate solutions.

Each restoration project is mapped on a GIS theme and relevant data are stored in the associated databases. These themes can be updated as new inventories are completed, or as project status changes (e.g., design phase, construction, completion). Additionally, we can develop related databases for monitoring the effectiveness and costs of different project types. Over time the GIS maps and databases will help display progress made in restoring habitats in the Skagit River basin and help us modify our actions to more efficiently restore habitat.

Current Limitations and Future Work

Both lowland and mountain basin GIS-based results give us operating hypotheses for peak flow impairment throughout the river basin. Because subbasin flow data are limited in the Skagit, peak flow ratings for mountain subbasins in the Skagit were developed based on an empirical correlation between land use and elevated peak flows in the adjacent North Fork Stillaguamish River basin. The North Fork Stillaguamish has exhibited a 38% increase in mean annual maximum flow between 1928 and 1995 with climatic variables explaining less than 40% of the increase, suggesting that changes in the watershed condition have caused the balance of the increase (Beamer and Pess 1999). However, future efforts for the mountain basin methodology must confirm that correlations between land use and peak flows in the North Fork Stillaguamish are a cause-effect relationship, then identify the appropriate thresholds for land use before reapplication to the Skagit. The lowland basin methodology should be repeated with land cover data that estimates current effective impervious area to complement the results reflecting impervious area at fully developed watershed conditions per zoning designations.

Field-based sediment budgets more accurately estimate the sediment supply in a subbasin and describe the relative effects of different land uses on sediment supply. Therefore, they provide more accurate information for project screening and planning than do our current GIS-based estimates. Field-based sediment budgets from Paulson (1997) were completed for approximately 12% of the total area and used to develop the GIS-based estimates. Since Paulson (1997), we have completed field-based sediment budgets for 51% of the basin. In lowland basins, mass wasting is not a dominant sediment supply process, but increased fine sediment supply to channels is directly related to urban, livestock grazing, and agricultural land use. We anticipate future development of a surface erosion and sedimentation screen for these low-slope areas, focusing on quantifying surface erosion from agricultural or developed areas.

The U.S. Forest Service is continuing its road inventory. Similar road inventories have not yet been conducted on state or private timberlands. The inventory method appears to be appropriate for identifying segments of road that pose the greatest threat to stream resources. However, it does not identify the types and locations of work needed to reduce the landslide hazard. We anticipate that some inventories will be more detailed than those used by the U.S. Forest Service and better identify the specific work actions required for each segment of forest road.

Satellite data do not provide sufficient information for identifying all riparian protection and restoration actions at the reach level. The GIS-based riparian screen is reliable for only late-

seral and mid-seral conifer dominated forest and nonforest areas. Because of the higher probability of error in rating stream reaches by the remaining land cover types, they are excluded from the interim riparian screen. The screen is thus applied to only about 50% of the anadromous zone (based on length). Field inventories are far more reliable than remote sensing data and can provide sufficient information for reach-level project planning. Therefore our primary task is to complete the field inventory of riparian forest conditions throughout the river basin.

The field-based inventory of manmade blockages to salmon migration has been completed for only a portion of the basin. Areas currently identified as isolated are accurately characterized as upstream of manmade blockages to salmon because they are based entirely on field inventory. We assume that some areas yet to be inventoried are isolated, although extrapolation from current inventories suggests that no more than 4% of the remaining channel length is likely to be upstream of a manmade blockage to salmon migration. In addition to the remaining blockage inventories, we have yet to complete our inventory of wetland habitat losses in the delta.

Water quality parameters such as dissolved oxygen, temperature, turbidity, nutrient loading, and levels of toxic substances are critical to salmon health and survival. Identifying areas where water quality is impaired and the various factors contributing to impairment and addressing the causes of water quality degradation is important to restoring salmon habitat in the basin. Currently we consider stream reaches, lakes, and estuary areas that are included on the Washington Department of Ecology's Candidate 1998 Section 303(d) Impaired and Threatened Water Bodies listings as impaired. These water bodies are known to fail Washington State's surface water quality standards and not expected to improve in the near future. We anticipate our future water quality screen to include locations of known point and non-point sources that may contribute to water quality degradation in the basin. These land use indicators will identify areas where water quality problems may exist and direct further investigation (e.g., water quality sampling, benthic invertebrate community analyses) to determine if water quality is actually impaired. The continuing objective is to improve the quality and quantity of water quality data and land use information available to guide protection and restoration of aquatic habitats.

The primary limitations in accurately identifying generalized habitat types are incomplete natural landscape process screens and the accuracy of individual screens used. The consequence of incomplete landscape process screens is an underestimate in the amount of "degraded" and "important" habitat and an overestimate of the amount of "key" habitat. However, we have high confidence that areas identified as degraded are in fact degraded. That is, there is a very low likelihood that areas identified as degraded with this analysis will later be identified as important or key habitat. Conversely, some areas identified as key habitat with this analysis will be changed to degraded or important as more detailed information becomes available.

Conclusions

The SWC first identified its conceptual framework and diagnostic criteria, thus enabling systematic application of a strategy supported by all members. Without this step, a systematic

and objective inventory of habitat problems in the Skagit River basin would not have been possible. Following development of the strategy, the SWC quickly applied the simplest diagnostic criteria over the entire basin with limited funds. This effort identified the most obvious project ideas (some socially or politically difficult) and provided a good overview of the spatial pattern of disturbance in the basin. By contrast, a haphazard inventory or professional judgment system would have produced lists of projects, but would not necessarily have given resource managers the tools to be strategic or comprehensive in restoring salmon habitats. In other words, managers would have been unable to focus on important biological hotspots or impaired landscape processes because they would have lacked a comprehensive understanding of the causes of habitat degradation in the basin.

The strategy recognizes that land use and resource management activities influence natural landscape processes, which result in changed habitat conditions (Figure C-1). Therefore, protection and restoration actions identified by implementing this strategy should be directed at the habitat-forming processes instead of attempting to build specific habitat conditions. Focusing actions on “building” habitat for specific species may be to the detriment of other species and may not be sustainable due to potential conflicts with natural processes (Frissell and Nawa 1992, Kauffman et al. 1997, Beechie and Bolton 1999). Instead, actions implemented by this strategy will aim to create the conditions necessary for natural landscape processes to reestablish at levels similar to those that existed historically. This should 1) result in a high likelihood of long-term project success, 2) protect and restore habitat for all salmonid species as well as other native aquatic and riparian-dependent species, and 3) ensure the effective use of public and private restoration funds.

The SWC overcame diverse interests to develop and apply the interim phase of its protection and restoration strategy in about a two-year period. The field inventory phase of the strategy is still in progress. The cost of all inventories and analyses required to develop a restoration plan (including a list of required protection and restoration actions) for the 8,500 km² basin is only about \$1.1 million. This total is less than the cost of opening one large, isolated estuary channel and wetland complex (\$1.9 million, USACE 1998) or a few culvert blockages on local or state highways (\$250,000 to \$600,000 each, D. Brookings⁵). The estimated cost of potential projects identified during this first phase of applying the strategy is well over \$100 million, suggesting that the total cost of the inventories will be less than 1% of the cost of protection and restoration actions. Moreover, development of the restoration plan should save millions of dollars by avoiding projects that are not effective at restoring salmon habitats. On a per unit area basis, the cost of all interim assessments and final field inventories will total only \$210 per km², assuming that costs remain relatively constant in the near future.

Application of the strategy gives the SWC the ability to become truly strategic (not merely opportunistic) in its protection and restoration efforts by providing a consistent set of principles that guide actions and systematically identifying hundreds of projects that can be prioritized. Having a complete river basin overview of landscape processes and resulting habitat conditions allows the SWC to set goals on how much protection or restoration is needed to meet a specific priority. The strategy allows priorities to be based on locally defined objectives such

⁵ D. Brookings, Skagit County Public Works, 1111 Cleveland Ave., Mount Vernon, WA 98273. Pers. commun., Dec. 1997.

as recovery of a certain species or completion of certain types of restoration (Lichatowich et al. 1995, Beechie et al. 1996). However, prioritization does not alter the types of projects enacted, but only the sequence in which projects are completed (Beechie and Bolton 1999). Currently the SWC prioritizes projects based on the relative cost-effectiveness of different projects, which means that projects protecting or restoring the greatest proportion of anadromous fish habitat function per dollar cost are considered higher priority. Additionally, individual restoration groups may choose projects from any list of projects in order to fulfill their respective missions.

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- 56 MacCall, A.D., and T.C. Wainwright (editors). 2003.** Assessing extinction risk for West Coast salmon. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-56, 198 p. NTIS PB2003-104642.
- 55 Builder Ramsey, T., et al. 2002.** The 1999 Northwest Fisheries Science Center Pacific West Coast upper continental slope trawl survey of groundfish resources off Washington, Oregon, and California. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-55, 143 p. NTIS PB2003-104641.
- 54 Krahn, M.M., et al. 2002.** Status review of southern resident killer whales (*Orcinus orca*) under the Endangered Species Act. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-54, 133 p. NTIS PB2003-104520.
- 53 Waknitz, F.W., T.J. Tynan, C.E. Nash, R.N. Iwamoto, and L.G. Rutter. 2002.** Review of potential impacts of Atlantic salmon culture on Puget Sound chinook salmon and Hood Canal summer-run chum salmon evolutionarily significant units. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-53, 83 p. NTIS PB2002-108143.
- 52 Meador, J.P., T.K. Collier, and J.E. Stein. 2001.** Determination of a tissue and sediment threshold for tributyltin (TBT) to protect prey species of juvenile salmonids listed under the Endangered Species Act. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-52, 21 p. NTIS PB2002-103161.
- 51 Emmett, R.L., P.J. Bentley, and G.K. Krutzikowsky. 2001.** Ecology of marine predatory and prey fishes off the Columbia River, 1998 and 1999. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-51, 108 p. NTIS PB2002-101699.
- 50 Turk, T.A., et al. 2001.** The 1998 Northwest Fisheries Science Center Pacific West Coast upper continental slope trawl survey of groundfish resources off Washington, Oregon, and California. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-50, 122 p. NTIS PB2002-101700.
- 49 Nash, C.E. (editor). 2001.** The net-pen salmon farming industry in the Pacific Northwest. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-49, 125 p. NTIS PB2002-100948.
- 48 Meador, J.P., T.K. Collier, and J.E. Stein. 2001.** Use of tissue and sediment based threshold concentrations of polychlorinated biphenyls (PCBs) to protect juvenile salmonids listed under the Endangered Species Act. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-48, 40 p. NTIS number pending.

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