November 2000
National Science and Technology Council
Committee on Environment and Natural Resources

FROM THE EDGE

Science to Support Restoration of Pacific Salmon

Committee on Environment and Natural Resources
National Science and Technology Council

November 2000

Dear Colleague,

We are pleased to provide you with a copy of the new report *From the Edge: Science to Support Restoration of Pacific Salmon* developed through the National Science and Technology Council's Committee on Environment and Natural Resources (CENR). The report supports the President's Pacific Coastal Salmon Recovery Initiative, which was proposed in 1999 to help reverse the decline of Pacific salmon and preserve them as an integral element of the culture and economy of the Pacific Northwest. A key element of the initiative is to accelerate the use of Federal science and technology to assist in the conservation of Pacific salmon. In response to this initiative, George Frampton, Chair for the Council on Environmental Quality, and Neal Lane, Assistant to the President for Science and Technology, requested in April of 1999 that the CENR lead Federal efforts to strengthen coordination and science for restoring Pacific coastal salmon.

The report identifies knowledge gaps and research priorities based on an assessment of the considerable body of scientific information that we have on salmon. Areas in which additional research might improve salmon recovery efforts include increasing our understanding of basic salmon biology, behavior, and ecology; characterizing the critical aspects of habitat (freshwater, estuarine and ocean) for restoration and understanding the effects of hydropower on these critical habitat features; the roles that hatcheries play by both augmenting natural populations and by introducing potential genetic effects and other adverse impacts; and the development of more effective monitoring techniques and data management capabilities.

The President's Salmon Initiative has also resulted in the establishment of an Interagency Salmon Science Team (ISST) that will continue the collaboration among the key agency stewards of Pacific salmon and the habitats upon which they depend. The report contains a specific set of recommendations developed by the ISST for future agency research and information sharing.

It is our expectation that this combination of science and information sharing will put Pacific salmon, the icons of the Northwest, back on the road to recovery.

Sincerely,

D. James Baker
Co-Chair

Rosina Bierbaum
Co-Chair

About the National Science and Technology Council

President Clinton established the National Science and Technology Council (NSTC) by Executive Order on November 23, 1993. This cabinet-level council is the principal means for the President to coordinate science, space, and technology policies across the Federal Government. The NSTC acts as a "virtual" agency for science and technology to coordinate the diverse parts of the Federal research and development enterprise. The President chairs the NSTC. Membership consists of the Vice President, the Assistant to the President for Science and Technology, Cabinet Secretaries and Agency Heads with significant science and technology responsibilities, and other senior White House officials.

An important objective of the NSTC is the establishment of clear national goals for Federal science and technology investments in areas ranging from information technology and health research, to improving transportation systems and strengthening fundamental research. The Council prepares research and development strategies that are coordinated across Federal agencies to form an investment package that is aimed at accomplishing multiple national goals.

To obtain additional information regarding the NSTC, contact the NSTC Executive Secretary at (202) 456-6100.

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The Committee on Environment and Natural Resources (CENR) is one of five committees under the NSTC, and is charged with improving coordination among Federal agencies involved in environmental and natural resources research and development, establishing a strong link between science and policy, and developing a Federal environment and natural resources research and development strategy that responds to national and international issues.

To obtain additional information about the CENR, contact the CENR Executive Secretary at (202) 482-5916.

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The Office of Science and Technology Policy (OSTP) was established by the National Science and Technology Policy, Organization, and Priorities Act of 1976. OSTP's responsibilities include advising the President on policy formulation and budget development on all questions in which science and technology are important elements; articulating the President's science and technology policies and programs; and fostering strong partnerships among Federal, State, and local governments, and the scientific communities in industry and academia.

To obtain additional information regarding the OSTP, contact the OSTP Administrative Office at (202) 395-7347.

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Committee on Environment and Natural Resources

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Acknowledgements

The initial drafts of this report were prepared by Dr. Charles C. Coutant of the Environmental Sciences Division of the Department of Energy's (DOE's) Oak Ridge National Laboratory. Dr. Coutant is a nationally recognized expert on Pacific salmon, and we are extremely grateful that he was able to lend his expertise to the preparation of this report. We wish to thank the Department of Energy for providing the funding to support Dr. Coutant's participation. Mark Schaefer, formerly of the Department of the Interior (DOI), led the CENR Interagency Salmon Science Team until his departure from the government on March 31, 2000. Jack Waide (U.S. Forest Service), Mike Mac (U.S. Geological Survey), and Usha Varanasi (National Marine Fisheries Service) now lead the Team and have offered considerable help with completing this report. Mike Domaratz of DOI provided valuable assistance in coordinating tasks. We also wish to thank the many agency personnel who have participated in the Science Team's activities and have served as reviewers of this report. Mark Anderson of the U. S. Geological Survey, Maggie Smith of Stanford University, and Fran Sharples of the Office of Science and Technology Policy assisted with its editing. The Corps of Engineers provided selected photographs and graphics. Most of the graphics were prepared by John Callahan, Doug Cummings, Rebecca Bruno, and Brenda Oakes of the U.S. Geological Survey.

Preface

The President of the United States proposed in January of 1999 a new partnership to restore Pacific coast salmon. This partnership was established to reverse the dramatic declines in salmon that have occurred over the past century and a half and preserve salmon as an integral element of the culture and economy of the region. The Pacific Coastal Salmon Recovery Initiative was intended to build an effective and lasting recovery for salmon in part by accelerating the use of Federal science and technology to assist in the conservation of "at-risk" Pacific salmon, primarily in the western states of California, Oregon, Washington, and Alaska. Such an initiative necessarily involves the life cycles of Pacific salmonids wherever they occur, which also includes Idaho in the U.S., British Columbia in Canada, and the international waters of the Pacific Ocean. Similarly, the initiative was designed to cross the jurisdictional boundaries of Federal, state and tribal agencies in the U.S. in a way that provides needed assistance without compromising the sovereign rights of others.

An important element of the initiative is a commitment to strengthening coordination among Federal agencies and improving access to Federal scientific expertise and research to assist communities in their salmon restoration efforts. The National Science and Technology Council's Committee on Environment and Natural Resources (CENR) was asked to lead the effort to strengthen Federal coordination and science for restoring Pacific coastal salmon. Specifically, CENR was requested to develop a scientific assessment of salmon life-cycle risks and mitigation measures. The assessment is to identify knowledge gaps and research priorities based on the considerable body of scientific information that we have on salmon recovery.

This report represents the CENR's response to this request. The report is not intended to advocate a particular option or set of options for salmon recovery. Rather, it is designed to provide an overall picture of what is known and where there are knowledge gaps that could be addressed to support recovery. Although the report draws on the expertise of many salmon science specialists, it is written for a non-specialist audience of decision-makers and the public.

The report presents a brief summary of the current scientific understanding of salmon and salmon declines and identifies gaps in our current knowledge, the filling of which has the potential to improve the choice of recovery options and the effectiveness of the options chosen. Part I of the report provides an overview of the problem of deteriorating salmon populations, describing the ecology and status of the fish and the multiplicity of factors contributing to their decline. Part II discusses the science needs for remediation, reviews the findings of several management-oriented science summaries for the Columbia River basin and other locations, discusses the role of science in a restoration program, and points out the importance of indicators for monitoring the status of salmon stocks and the magnitudes of risk factors. Part III describes the activities of a new interagency working group on salmon established as part of the initiative. A brief science priorities paper upon which the members of the working group have agreed can be found in Appendix B. This report should prove useful in the preparation of Federal budgets over the next several years.

Contents

EXECUTIVE SUMMARY

In January 1999, President Clinton proposed a new partnership to reverse the dramatic declines in salmon that have occurred on our Pacific coast and preserve them as an integral part of the culture and economy of the region. An important element of the Pacific Salmon Recovery Initiative is a commitment to strengthening and coordinating Federal science to build an effective and lasting recovery for salmon. The science element has two important components:

(1) Development of a scientific assessment of the risks to salmon throughout their life cycles and of the role of mitigation and recovery options in reducing these risks. Gaps in scientific knowledge and priorities for addressing these gaps were also to be identified.

(2) Development of a strategy for information sharing for enhanced salmon management.

The National Science and Technology Council's Committee on Environment and Natural Resources (CENR) was asked to prepare a report synthesizing the state of knowledge on salmon decline and restoration. This report represents the CENR's response to this request. The report is not intended to advocate a particular option or set of options for salmon recovery. Rather, it is designed to provide an overall picture of what is known and where there are knowledge gaps that could be addressed to support recovery. Although the report draws on the expertise of many salmon science specialists, it is written for a non-specialist audience of decision-makers and the public.

Many of the anadromous salmonids of western North America—the salmon and trout that are the icons of the Pacific Northwest--are in serious decline. The disappearance of many stocks over broad areas of the West is already complete, especially where major dams have blocked access to upstream spawning grounds. Many other stocks are dwindling under the combined stresses of landscape change, hydropower development, water pollution, fishing, introduced predators, disadvantageous ocean conditions, and other factors. Even stocks that seem to have abundant fish now are generally producing young at rates insufficient to prevent gradual decline in numbers and eventual disappearance. Knowledgeable scientists who have devoted careers to studying salmon and their ecosystems are nearly unanimous in stating that salmon can be restored if we assiduously protect and restore the habitats and water quality they require and assure escapement is adequate so that there are enough spawners remaining to reproduce. How this is achieved is specific to the regulation of sources of anthropogenic mortality that face individual stocks.

The main species of concern are five Pacific salmon - chinook, sockeye, coho, pink, and chum – plus the steelhead and coastal or sea-run cutthroat and bull trout. Most are anadromous members of the salmon family, sharing a geographically wide-ranging life cycle that includes spawning and early rearing of young in fresh water; migration of juvenile fish to the estuaries and ocean; growth and sexual maturation in salt water; and adult migrations to spawn in the same fresh water area in which they were hatched. (Only some populations of the bull trout are anadromous.) This life-cycle division between fresh and salt water is what is meant by "anadromous." These species were once naturally distributed from northern Alaska to southern California. Currently, populations of four of the salmon species as well as the steelhead, cutthroat. and bull trout are listed or proposed for listing as endangered or threatened under the Endangered Species Act in many drainages of the West. Other fish in the Pacific Northwest have also been adversely affected by many of the same factors responsible for the declines of the salmon, steelhead, cutthroat and bull trout. For example, the Kootenai River population of the white sturgeon has been listed as endangered since 1994. Remediation efforts directed at salmonids are also expected to benefit some of these other species.

While the life-cycle strategies of salmon evolved to allow the fish to exploit a diverse array of both marine and fresh water habitats in different life stages, these strategies now expose salmon populations to numerous threats. Economic development of watersheds for forestry, agriculture, mining, and urban settlements has altered salmon habitats. Free flowing rivers have been dammed for hydropower or diverted for agriculture, with resulting modifications to flow patterns, habitats, migration corridors, food chains, and water quality and temperatures. Harvest in rivers and the ocean has added to natural mortality and, by killing the larger fish, may have contributed to mature fish becoming progressively smaller over time and producing fewer eggs. Hatchery production and management practices, designed to augment population numbers, are responsible for retaining some salmon populations, but have also introduced genetic changes and reduced the fitness of other populations. Wild fish can also be over-harvested when they mix with more abundant hatchery fish that are sought by fishers. Introduced non-native species, such as bass and walleye, prey on salmon and add to the mortality rates inflicted by native predators on young fish. We know the cumulative toll of these diverse risks is greater now than in the past, for not enough adults return to sustain populations.

Actual risks vary from basin to basin and stock to stock. For example, some drainages have dams, others do not; some have seasonally high temperatures or low water flows, whereas these problems are not important elsewhere. Water diversions, primarily for agriculture, are uniquely important because of their effects on juvenile salmon's seaward migration in California from the Sacramento-San Joaquin delta and northern California rivers, such as the Trinity. The immense Federal hydropower system is characteristic of the Columbia-Snake basin. Allocations of harvest are a principal concern for stocks of salmon in Alaska and British Columbia where rivers and headwaters are less developed. The especially difficult cases to diagnose are those influenced by multiple factors, such as stocks in the Lower Columbia River and in urbanized areas like Puget Sound.

While it is true that long-term improvement of science to support salmon recovery and management is needed, the rate at which salmon are disappearing tells us we cannot always wait years for additional research results. Although additional scientific data would be useful, for the many endangered and threatened stocks we do not have the luxury of viewing their status as an interesting scientific question. Recovery of these stocks may require immediate intervention, despite continuing scientific uncertainties. Conducting adaptive management studies in which research scientists and resource managers jointly develop structured approaches for evaluating the results of different management strategies, ensures that scientific progress can be made while testing restoration techniques.

Scientific understanding is adequate to support many actions, such as: 1) restoring the natural function of streams, 2) protecting or replanting streamside forest buffer strips, 3) leaving or replacing large woody debris in stream channels, 4) protecting or recreating deep pools in streams, 5) minimizing erosion and siltation of streams from disturbed landscapes, 6) removing or bypassing dams that are migration barriers, 7) leaving enough water in streams to allow migration and others.

Key areas where the filling of gaps in our knowledge could speed progress in salmon recovery include:

- **Salmon Biology, Behavior, and Ecology** – A diversity of life-cycle timing is characteristic of the salmon species. Knowledgeable scientists generally credit this diversity for the salmon's evolutionary success in a geologically unstable environment. While the life-cycle strategies of salmonids evolved to allow the fish to exploit a diverse array of both marine and fresh water habitats in different life stages, these strategies now expose salmon populations to numerous threats, many of which were not encountered by the species before the middle of the 19th century or later. Economic development of watersheds for forestry, agriculture, mining, and urban settlements has altered salmon habitats. Free flowing rivers have been dammed for hydropower or diverted for agriculture, with resulting modifications to flow patterns, habitats, migration corridors, food chains, and water quality and temperatures. From egg to spawning adult, a host of natural and anthropogenic factors may take a cumulative toll on both the fitness of individual fish and on numbers of fish.

  Although salmon biology and ecology are generally well known, additional specific information could contribute greatly to salmon restoration. Restoration efforts would benefit from an improved understanding of the behavior of salmon smolts during downstream migration and how survival rates during migration relate to characteristics of water quality and river flow. Additional information on rates of genetic exchange among populations could improve the design and scientific underpinning of supplementation experiments and ensure viability of native salmonid populations. The ecological relationships of salmonids to other native and non-native fish are also areas where more knowledge would be helpful. For example, research is needed to address predation by, and competition from, other native and introduced fish. Predation by migratory birds and marine mammals, two other categories of protected species, may also pose significant impacts to salmon. An improved understanding of the ecological relationships among these animals could reduce management conflicts.

- **Hydropower –** The unregulated natural flow regimes in which fish life histories evolved have been altered dramatically. Healthy fish, as well as insect and plant, populations depend not only on maintenance of minimum flows, but also on flows that are heterogeneous in space and time. Although much work has already been done to reduce hydropower's impacts and raise salmonid survival levels, hydropower continues to be associated with salmonid decline. Additional research could, however, substantially improve our understanding of the relationships between salmonid survival and the creation of more "natural" seasonal river flows and more normal temperature regimes and migration and passage routes. Improved technologies might still be able to make large dams passable by both adult and juvenile salmon, but this is not a certainty. The cumulative indirect effects of passing multiple dams during migration are also uncertain, and the effectiveness of transporting juvenile salmon to the estuary by barge or truck to bypass multiple dams and reservoirs is still controversial. Because dams convert rivers to reservoirs, they are also a source of indirect effects on habitats and ecological communities, contributing, for example, to loss of spawning sites and subjecting salmon to increased predation by introduced predators in reservoirs. Hundreds of small non-hydropower dams, many related to irrigated agriculture, also block access to spawning and rearing habitats, and these could be fitted with passage or breached and alternatives to damming developed. Basin-wide water management might thus be able to accomplish some, but not all, of the same objectives as dam breaching.

- **Freshwater Habitat** – The freshwater phase of anadromous salmonid life histories can last from a few months to several years, but it is always a phase in which great mortality occurs. It is thus particularly important to understand how freshwater habitats have changed, how those changes have affected the fish, and to improve our understanding of how best to restore those aspects of habitat most critical to salmonid survival. Altered and reduced instream flows and dramatic changes in both instream and riparian structure have changed the dynamics of habitat maintenance in rivers, and natural restorative processes no longer occur. For example, gravel bars are now silted in and less available for successful egg laying and incubation. Streams that were once tree-lined and filled with woody-debris for safe rearing of young are now open and barren, resulting in poorer growth and lower survival. Spring freshets that overflowed stream banks into food-rich riparian zones are now eliminated by storage of water for hydropower, reducing much-needed food supplies in the process. Additional research on both site-specific and watershed scales is needed to improve and focus our efforts to restore the natural processes that influence salmonid survival.

- **Ocean and Estuary Effects** – The marine and estuarine environments represent areas of major knowledge gaps. Estuaries, where freshwater rivers enter saline coastal waters, pose particular challenges for salmon moving in both directions since their physiological systems for regulating the amount of water in their bodies must be reworked during this transition. Today, water pollution, dredging, shoreline development, and altered seasonal freshwater flows often intensify the already substantial stresses that salmon withstand as they move through the estuarine environment. Unfortunately, little scientific attention has been paid to this phase of the salmon life cycle. The marine environment is least understood and is a source of essentially uncontrollable influences on salmon. It is clear that ocean conditions can have a significant impact on the overall production of all species of Pacific salmon, with climate and ocean variability acting at a number of temporal and spatial scales as salmon grow and mature in salt water. In particular, decadal climate cycles that are now becoming better understood can produce major shifts in biological productivity throughout the oceanic foodchain as well as in the basic structure of the coastal marine ecosystems occupied by salmon. Basic research is needed on where and when fish occur in the estuary/ocean and the environmental factors (often cyclical) controlling occurrence, survival, and harvest.

- **Harvest** – Salmon runs are subject to substantial levels of harvest by commercial, sport, and subsistence fisheries, although the magnitude of the allowable harvest for some populations has been reduced dramatically, with accompanying large economic impacts. There are still, however, issues that remain to be resolved: incidental harvest, release mortality, allocation, mixed-stock fisheries, critical harvest locations, insufficient monitoring and control of some forms of harvest, aquaculture, and ways to reduce social, cultural, and economic effects.

- **Hatcheries** – There is disagreement over the extent to which artificial propagation programs contribute to or detract from the survival of wild populations. While it is broadly recognized that hatcheries have slowed the decline of some populations, valid questions remain on whether artificial propagation has succeeded in achieving either conservation or harvest goals. Additional data on the extent to which hatchery fish are spawning in the wild and on the reproductive success of hatchery fish and the progeny of hatchery-wild fish crosses are needed. Also needed are data on the interaction between hatchery and wild populations—for example, on the movement and spread of disease between wild and hatchery stocks and the effects of hatchery practices on the genetics of wild populations.

- **Development of Improved Metrics of Watershed Condition** – There is a large and evolving body of watershed and ecosystem-level science, the products of which include useful measures, indicators, and indices of ecosystem integrity. However, because many important restoration actions are being taken through Watershed Councils that may not be well-versed in salmonid ecosystem science, the search for informative and policy-relevant measures of overall ecological condition of watersheds must continue. For example, more attention needs to be focused on the development and testing of integrated metrics of watershed condition and of tools for evaluating functional attributes of ecosystems.

- **Monitoring, Databases and Evaluation** – Current monitoring will need to expand and , data storage/retrieval, and evaluation processes will need to evolve in complexity and increase in capacity. Monitoring and data systems need to keep pace to facilitate improved quantitative approach to salmonid recovery and restoration.

- **Development of Social Metrics Compatible with Salmon and Ecosystem Metrics** – If social uses are to be considered part of the ecosystem for restoration purposes, there must be a compatible way to factor in both human and fish futures. For example, decision- makers need to assess proposed salmon policies against alternative human futures for the Pacific Northwest, since restoration goals that might be achievable given a regional population of 14 million might be completely unworkable with a population of 50 million.

Research directed at further incremental gains in familiar subject areas must be balanced by research to close the many knowledge gaps discussed in this report. In addition, new approaches to conducting salmon science and management actions could improve the likelihood of success of recovery efforts. First, a structured interagency effort should be undertaken to refine, enhance and help guide the initiation of new scientific efforts. This should provide an opportunity to identify what works and what doesn't work, what is achievable and what is not, and improve our understanding of management responses. Second, the effectiveness of remediation is likely to be improved by management approaches that take the entire life cycle of salmon into account. Past use of piecemeal "least common denominator" solutions instead of a comprehensive focus on reducing sources of mortality across the salmonid life cycle has contributed to the failure of many past restoration efforts. Such an approach is likely to become more feasible as the risks to sal- mon are better quantified through additional research. Third, adaptive management, anapproach in which future actions can be adjusted in response to the results of carefully designed management actions, needs to be much more widely employed. Adaptive management can provide a useful alternative for gaining understanding of what is and is not likely to work in light of ever present uncertainty..

In 1999, Neal Lane, the Assistant to the President for Science and Technology, and George Frampton, the Chair of the Council on Environmental Quality, requested the CENR to lead an effort to strengthen the science underpinning the restoration of Pacific salmon and its Federal coordination. The CENR charged its Subcommittee on Ecological Systems to undertake this task, and the Subcommittee, in turn, established several new activities directed at enhancing and better coordinating Federal science and information on Pacific salmon. First, the Sub-committee and the Office of Science and Technology Policy (OSTP) commissioned the preparation of this report to obtain an independent assessment of the science needs related to salmon and salmon recovery. Second, the Subcommittee convened a new Interagency Salmon Science Team made up of a group of scientists from the Pacific Northwest regional offices of the Departments of Agriculture (Forest Service), Commerce (National Ocean Service, National Marine Fisheries Service, Office of Oceanic and Atmospheric Research), Defense (Corps of Engineers), Energy (Bonneville Power Administration), and the Interior (Bureau of Land Management, Bureau of Reclamation, Fish and Wildlife Service, U.S. Geological Survey), the Environmental Protection Agency, OSTP, and the Northwest Indian Fisheries Commission. The Science Team met under the Subcommittee's auspices to consider the report, evaluate existing Federal research programs, meet with managers in the Pacific Northwest region to discuss their needs, and plan future directions in light of the science needs identified through this effort.

Appendix B contains a statement, "Science Needs for Pacific Salmon and Related Species," that was developed by the Science Team. This consensus document outlines a set of broad topics deemed to be the most important for modifying the future research portfolio to address scientific uncertainties and is consistent with the findings presented in this report.

The Science Team was also asked to develop a new strategy for information sharing to make information needed for effective conservation and restoration measures more available and accessible. The intent is to enable and encourage the assembling and use of information by taking advantage of new tools, such as geographic information systems and decision support systems. Its purpose is to aid resource managers and communities to access information, visualize the impacts of their actions, and help citizens and policy makers make informed collaborative decisions. A group of interested state and Federal agencies as well as non-governmental organizations participated in a series of meetings to define a set of information-related activities. A Workshop on Decision Support Systems (DSSs) for salmon and related species was convened in March 2000. A DSS is an inter active computer-based system intended to held decision makers use data and models to identify and solve problems and make choices. It may be an Internet-based network of databases, hardware, software, models, and other tools. Participating government, academic, and private sector organizations would develop and maintain the network so that its information resources can be combined in ways that address the needs of all stakeholders. The workshop resulted in a general consensus to further explore the idea of a DSS for salmon. The workshop participants agreed to begin to create an inventory of existing models, tools, and systems so that any missing pieces can be identified. In addition, they called for the development of a strategy for a DSS, including an analysis of costs and benefits to managers and others.

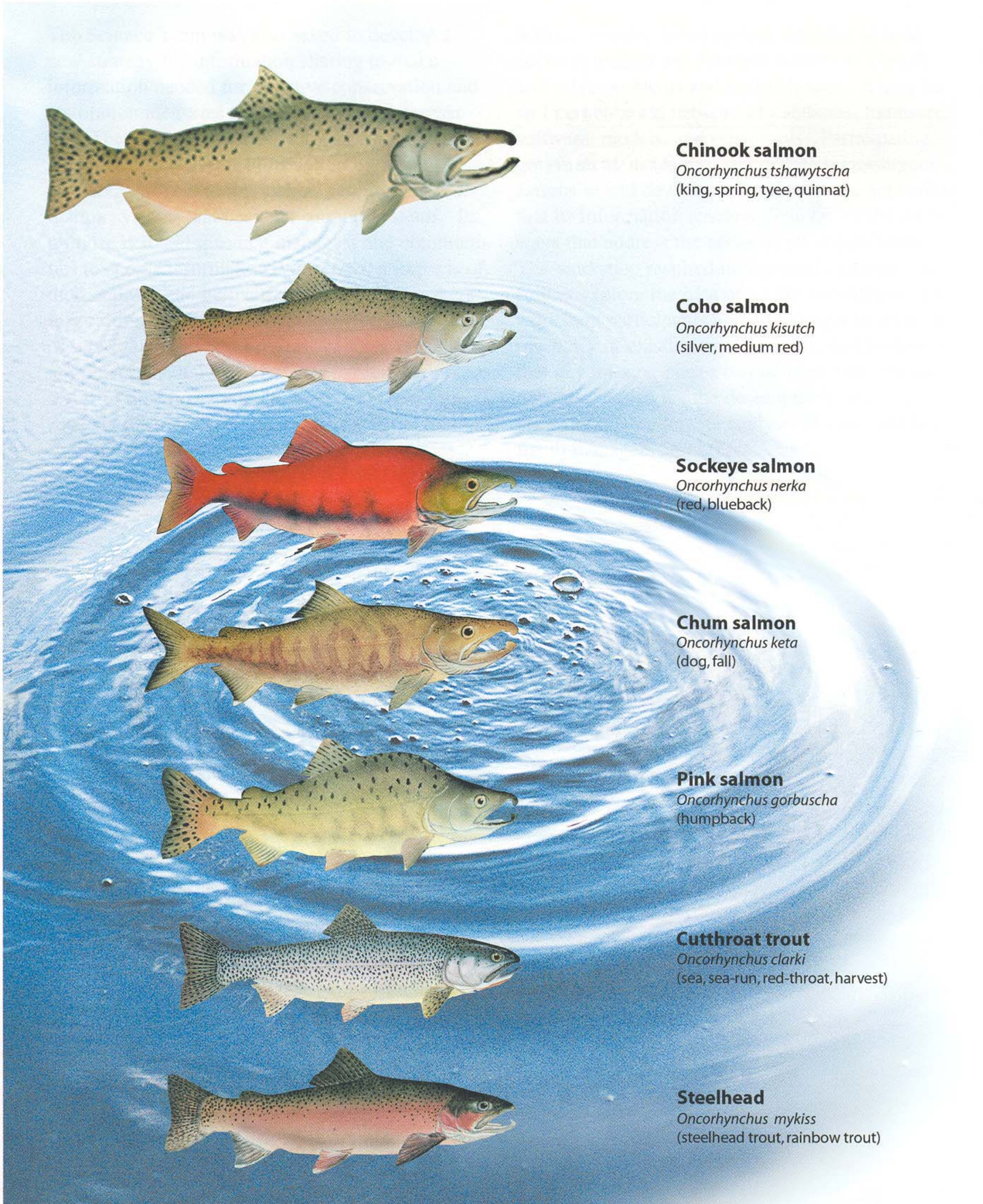


Figure 1. Endangered or threatened anadromous salmonids of western North America.

PART I
THE PROBLEM, THE FISH, AND THE RISKS

The Problem

The anadromous salmonids (**Figure 1**) of western North America—the salmon and trout that are the icons of the Pacific Northwest--are in serious decline. Not whole species, not entire races, and not uniformly from Alaska to California, but enough locally adapted stocks (that is, populations in specific geographic areas that have been identified for management) that the genetic diversity and geographic area inhabited are shrinking markedly. The downward spiral is clear and alarming. (**Figure 2**)

Extinction of many stocks over broad areas of the West is already complete, especially where major dams have blocked access to upstream spawning grounds. About 40% of historical breeding ranges in the Columbia River basin have been blocked. (**Figure 3**) Many other stocks are dwindling under the combined stresses of landscape change, hydropower development, water pollution, fishing, introduced predators, disadvantageous ocean cycles, and other factors. As of about a decade ago, a detailed inventory showed 100 stocks of anadromous salmon and trout in the lower 48 states as extinct, 102 stocks at high risk, and 54 stocks of special concern because of low numbers or restricted distribution. Currently, populations of four of the salmon species as well as the steelhead and cutthroat trout are listed or proposed for listing as endangered or threatened under the Endangered Species Act in many drainages of the West. Even stocks that seem to have abundant fish now are generally producing young at rates insufficient to prevent gradual decline in numbers and eventual disappearance. (**Figure 4**) In British Columbia in

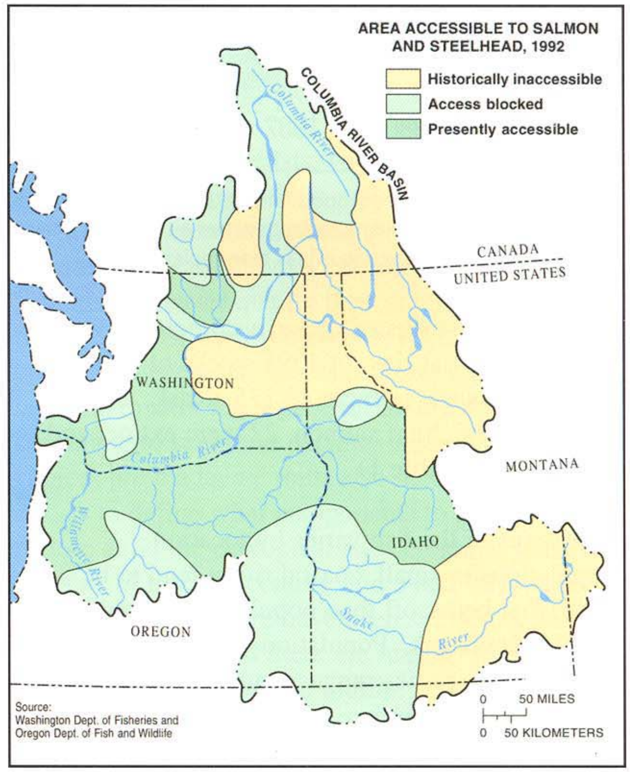


Figure 3. Large areas of the Columbia River Basiin are inaccessible to salmon, naturally and by obstructed passage.

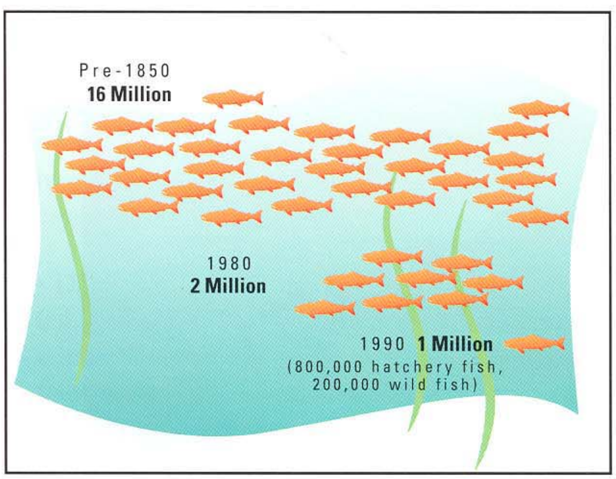


Figure 2. Adult, wild salmon entering the Columbia River have declined dramatically.

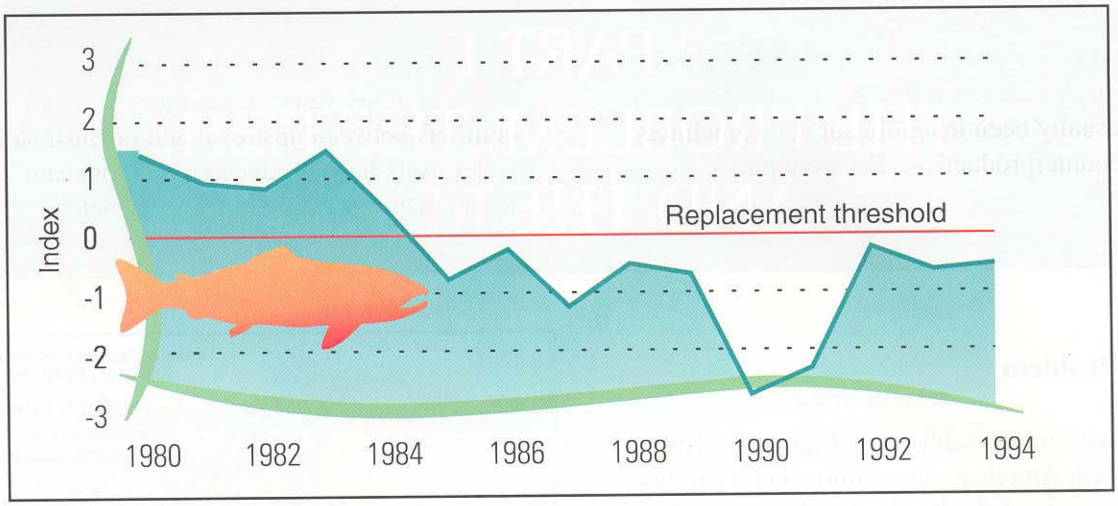


Figure 4. Monitored stocks of Snake River Spring Chinook are not reproducing at replacement rates. Index is computed by dividing new spawners by previous spawners. Zero = the replacement threshold. Negative values indicate reproduction is less than replacement.

1996, of 463 stocks of sockeye salmon, 20 were extinct and 64 at risk; of 1298 stocks of pink salmon, 17 were extinct and 175 at risk; and of 966 stocks of chum salmon, 22 were extinct and 164 at risk. (**Table 1**)

The status of the fish varies by location. Populations in small, coastal rivers tend to be somewhat better off than populations inhabiting interior drainages. Populations near the southern boundary of species ranges tend to be at greater risk than more northerly populations. Species with extended freshwater rearing are faring less well than species with abbreviated freshwater residence. There are exceptions to these broad generalizations (e.g., at-risk stocks of chum salmon and others around urbanized Puget Sound that are close to the coast), but geographic differences are evident. Alaskan stocks are generally not experiencing dramatic declines, but even there abundance normally varies widely from year to year due to fluctuating natural conditions, and several stocks and fisheries have experienced recent crashes.

Table 1

Species	Alaska	British Columbia	California	Idaho	Oregon	Washington
Pink	increasing	increasing	extinct	N/A	N/A	healthy
Sockeye	increasing except SE	increasing	N/A	endangered	endangered	mixed
Chum	declining	increasing Fraser R.; mixed elsewhere	extinct	N/A	extinct or remnant	healthy except Columbia R.
Chinook	increasing	increasing Fraser R.; declining elsewhere	declining or remnant	endangered except Clearwater R.	declining except coastal	declining except coastal
Coho	increasing except SE	declining	declining or remnant	extinct	declining	extinct or declining
Steelhead	declining	declining	declining	declining	declining	except Puget Sound

Population Status and Trends for Pacific Salmon Species (based on native naturally spawning stocks). Modified from Nehlsen, 1997; Status Reviews, 1997, 1998, National Marine Fisheries Service.

As more and more salmonid stocks have declined, there have been monumental efforts to stimulate and manage recovery, but the results for the fish have usually been insignificant and sometimes even counterproductive. For example:

- Hatcheries replaced natural spawning as dams inundated or blocked spawning grounds, but the combination of wild and hatchery fish still declined.

- Comprehensive plans for recovery were prepared by the Northwest Power Planning Council, tribes, the National Marine Fisheries Service, the Forest Service, and states, such as Oregon and Washington, but these plans have not yet led to actions that have resulted in progress for the fish.

- Dam re-licensing by the Federal Energy Regulatory Commission (FERC) imposed operating constraints on non-federal hydropower projects, including instream flow measures and managed spill to aid fish passage, with some local successes but regionally inadequate effects to stem salmon declines.

- Science reviews were commissioned by the National Academy of Sciences and the Northwest Power Planning Council, but most of the suggested science-based changes in approach have not been implemented or are fraught with uncertainty.

- The Bonneville Power Administration has expended substantial sums for recovery measures in the Columbia River basin financed through electric power rates. But salmonids have continued their slide even as costs escalated.

- Dams throughout the West have been retrofitted with massive engineering "fixes" to control temperature and dissolved gases and improve fish passage, but these modifications, which address only one part of a multifaceted problem, have produced only small reductions in total risks to salmonid survival.

- Annual flow management has been implemented in some watersheds under the assumption that more water means more fish, but conflicts between upstream and downstream water users have produced more upstream losers than downstream fishery benefits.

- Consensus-based decision-making aimed at satisfying all parties with numerous and conflicting vested interests has replaced decisive and fact-driven action with a least-common-denominator program.

Knowledgeable scientists who have devoted careers to studying salmon and their ecosystems are nearly unanimous in stating that salmon can be restored if we assiduously protect and restore the habitats and water quality they require and to reproduce. This will, of course, require society to choose to devote the necessary resources to the task and to alter the aspects of its life style that contribute to salmonid decline. Assuming such choices are made, we must also recognize that our efforts to define what components to protect and restore amid the ecological and economic transformations of the past century and a half have been inadequate. But there have been some success stories (see **Box 1**), and there are reasons to believe that such successes could multiply if efforts are well directed and focused. The resources for recovery appear to be present in well-educated people, institutional infrastructure, public and governmental support for recovery, and a wealth of data. The stage is set for a concerted, coordinated effort.

It is a basic premise of this report that an inadequate scientific understanding of some very fundamental matters has also contributed to the current lack of success. Although finding more effective institutional arrangements for salmon recovery is clearly important, we need to recognize that there are urgent scientific questions that also remain unanswered. Remedial measures to counteract the decline of salmonid populations must be prioritized according to the life-cycle needs of specific stocks and carried out using the best scientific evidence if their potential for improving recovery of fish populations is to be realized.

Box 1

Hanford Fall Chinook—A Success Story

Amid depressing histories of salmon declines, the success of fall chinook that spawn in the Hanford Reach of the mainstem Columbia River is heartening. The Hanford Reach is the one remaining un-dammed stretch in a stairway of reservoirs because of the Department of Energy's (DOE's) nuclear facilities there. As a result, the river remains a river, with rapids, back channels, subsurface flows of cool water, and other natural features needed for the spawning and rearing of young salmon. As spawning and rearing areas upstream and downstream were flooded by new impoundments, displaced salmon colonized the Hanford Reach in ever-increasing numbers. The increase was well chronicled from the mid-1940s by the DOE's monitoring programs.

Although the population of spawners rose dramatically from the 1940s to the 1980s, daily flow fluctuations by upstream dams caused mortalities of eggs and young. Adults in the autumn would spawn in shallow gravel that was later exposed and dry during times of day when low electricity demand caused generation (and river flow) to be curtailed; the same flow fluctuations in spring left high and dry many young salmon that normally concentrate in shallow, shoreline habitats. These fluctuations were stabilized through cooperation between resource agencies and the public utilities that own and operate the dams. Through preservation of good habitat and correction of sources of excess mortalities, the Hanford Reach population has become one of the few in the lower 48 states that is sufficiently vigorous to support substantial commercial and tribal harvesting. Given the tendency for populations to fluctuate over time, however, whether this population can continue to sustain current harvest levels may be an open question. On November 5, 1999, President Clinton provided additional protection to the area

The Fish

The main species of concern are five Pacific salmon - chinook, sockeye, coho, pink, and chum – plus the steelhead and coastal or sea-run cutthroat trout, all of the genus *Oncorhynchus*. All are anadromous members of the salmon family, sharing a geographically wide-ranging life cycle that includes spawning and early rearing of young in fresh water; migration of juvenile fish to the estuaries and ocean; growth and sexual maturation in salt water; and adult migrations to spawn in the same fresh water area in which they were hatched. This life-cycle division between fresh and salt water is what is meant by "anadromous." (**Figure 5**) These species were once naturally distributed from northern Alaska to southern California. (**Figure 6**). Currently, populations of four of the salmon species as well as the steelhead and cutthroat trout are listed or proposed for listing as endangered or threatened under the Endangered Species Act in many drainages of the West. Other fish in the Pacific Northwest have also been adversely affected by many of the same factors responsible for the declines of the salmon, steelhead, and cutthroat. For example, the bull trout (*Salvelinus confluentus*), another member of the salmonid family that has some anadromous populations, was listed as "threatened" under the Endangered Species Act throughout its range in

Bull trout

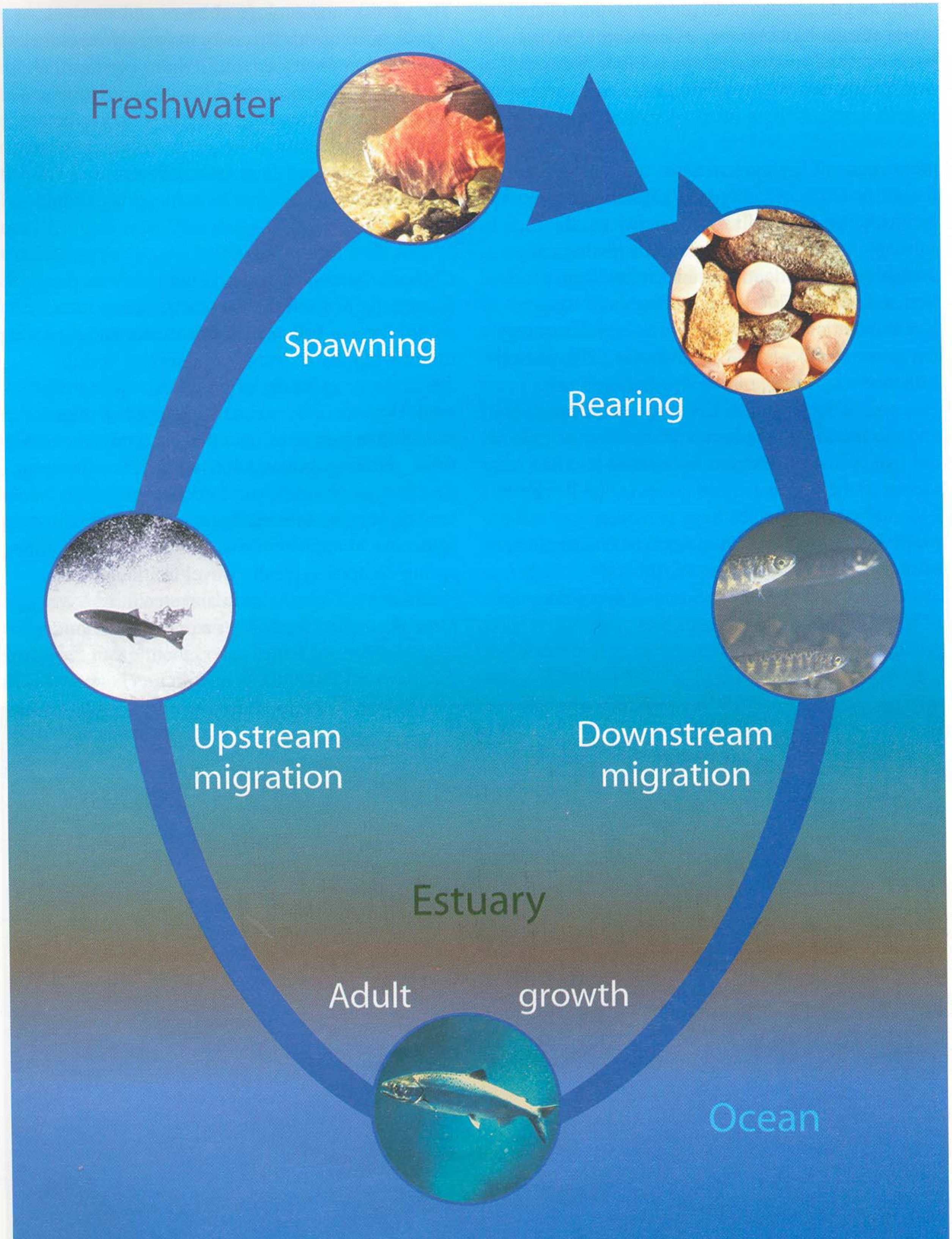


Figure 5. The life cycle of anadromous salmonids.

1999, and the Kootenai River population of the white sturgeon (*Acipenser transmontanus*) has been listed as endangered since 1994. Remediation efforts directed at salmon are also expected to benefit some of these other species.

A diversity of life-cycle timing is characteristic of the salmon species. (**Figure 7**) Knowledgeable scientists generally credit this diversity for the salmon's evolutionary success in a geologically unstable environment. Mountain-building, glaciation, volcanoes, floods, and droughts in western North America can perturb one life-cycle strategy but preserve or enhance another one. The next disturbance may favor a formerly damaged one. Because of their genetic diversity and adaptability and the remarkable geographic mobility of individual fish (some travel from the central Pacific Ocean to the headwaters of rivers in the Rocky Mountains), the species have persisted over millennia. Fidelity of spawners to natal rivers, streams, or lakes is a legendary characteristic of these fish, although it is not perfect. Some straying does occur in natural populations.

The genetic and ecological bases and survival significance of this diversity have only recently been explored with scientific rigor, even as that diversity is disappearing. Although cold season spawning, in which eggs are laid in fall in bottom gravels and incubate through the winter, is characteristic of many of these fish, different runs can spawn from late summer to early spring or into summer.

Chinook salmon have two principal strategies for rearing juveniles. The young of one race are reared for one full year in freshwater and then migrate rapidly to sea in their second spring (stream-type chinook, often called "spring chinook" for the early-year timing of adult migrations). The young of the other race migrate slowly to sea in the spring and summer of their first year (ocean-type chinook, or "fall chinook"). The races tend to occupy different habitats—the fall chinook spawning in mainstem rivers and streams whereas spring chinook typically travel to mountainous headwaters. Coho salmon and steelhead have more protracted freshwater rearing, with young

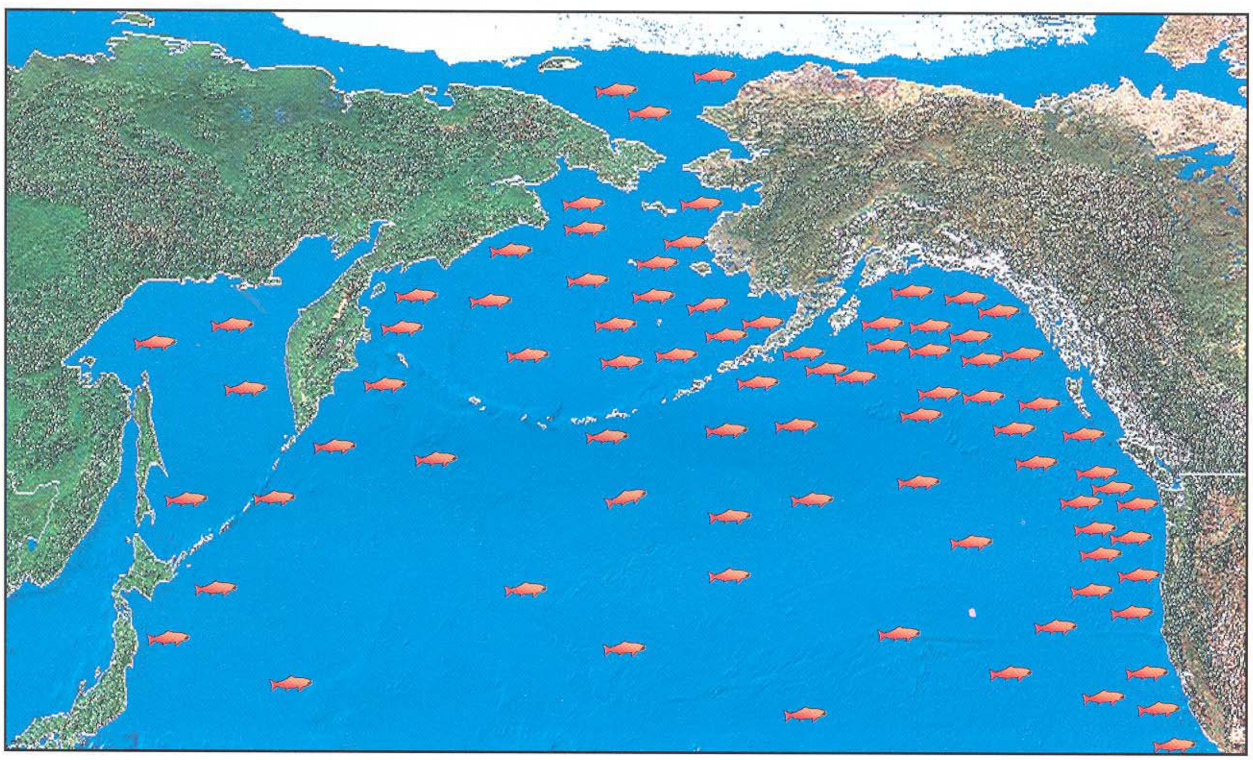


Figure 6. Distribution of salmon in the Northern Pacific Ocean.

typically growing in wetlands (coho) or stream channels (coho and steelhead) for two years or more. Sockeye salmon generally spawn near lakes, with juveniles usually using lakes, or sometimes streams, for rearing, but spawning among different races can occur everywhere near lakes--in tributary streams, lake shorelines, or outlet rivers. Most pink and chum salmon have a rapid in-and-out life cycle with little delay in fresh water. Coastal cutthroat and bull trout exhibit both resident and anadromous forms, and the cutthroat is considered to have the most complex life history patterns of all salmonids.

A student of this diversity soon recognizes that the salmonids, as a group of species, fill nearly every conceivable ecological niche in western North America accessible from the sea. And their genetic and ecological nimbleness kept the niches filled as the landscape sometimes underwent violent geologic changes.

Despite their diversity, the salmonids are not a random assortment of types. Different life-cycle strategies make them better suited for some locales than others. The fall race of chinook, for example, with its short freshwater cycle of adult migration in the autumn, spawning and early rearing in the winter, and downstream movement of small young in the spring and early summer, is well attuned to the warmer climate of California's Central Valley, where complete avoidance of warm summer temperatures is necessary for survival. The California spring and summer races of chinook use a different strategy—they migrate upstream in the cool water of spring snowmelt and literally "hole up" for the summer in deep, cold pools in the uppermost headwaters of mountain streams before they spawn in the fall. Their young enjoy the high, cold tributaries or move to mid-level streams for a year before making a headlong dash for the ocean as yearlings. Through the course of the salmon's 50-million-year evolutionary history, the anadromous strategy with its many variations served to minimize risks of mortalities and maximize fitness.

Even the legendary death of spawned-out salmon is not a tragic oddity, but a life-giving evolutionary strategy. Western rivers and streams are normally poor in nutrients that support the food web, both in the water and in riparian vegetation along shorelines. Like a dead tree in the forest that houses a bewildering abundance of life in its decaying

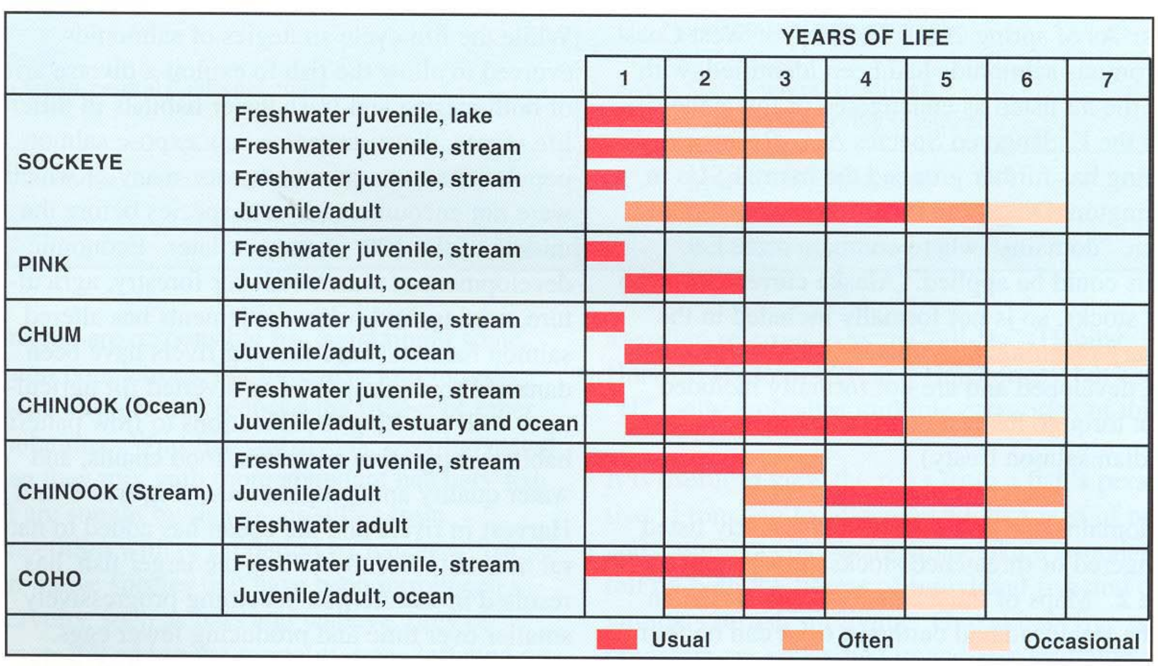


Figure 7. Variations in life cycle timing and habitat use by Pacific salmon.

frame, a salmon carcass yields the ocean-derived nutrients that grow the algae, aquatic insects and shoreline vegetation that feed the young salmon emerging from their gravel incubators. It is not clear how Pacific salmon evolved a life cycle in which adults spawn only once and fertilize their offspring's environment with their decaying carcasses, but the result has been part of a formula for success.

What do we protect as "endangered species" considering the dazzling array of ecological diversity among salmonids in western North America, much of which still remains in spite of stock extinctions and population declines? Under the Endangered Species Act, locally adapted stocks such as those found in a portion of a river basin qualify as units for protection. Such stocks are generally reproductively isolated spawning populations in spite of shared migratory routes. Recent advances in genetic analyses have allowed these stocks to be grouped into units with similar genetic and life history characteristics that now form the basis of most salmonid recovery efforts. In the language of the Endangered Species Act and U. S. Fish and Wildlife Service regulations, these units are called "Distinct Population Segments," or DPSs. In the National Marine Fisheries Service's regulations, they are called Evolutionarily Significant Units, or ESUs. As of spring 2000, 52 ESUs of West Coast anadromous salmonids had been identified, with 26 of the 52 listed as endangered or threatened under the Endangered Species Act. Recovery planning has further grouped the many ESUs in Washington, Oregon and California into 9 geographic "domains" where common remedial actions could be applied. (Alaska currently has no listed stocks, so is not formally included in the recovery planning; Canadian regulations are still being developed and are not formally included except through harvest negotiations for a U.S. – Canadian salmon treaty).

The domains and the ESUs with currently listed endangered or threatened stocks are shown in **Table 2**. Maps of the ESUs for the five salmon and the steelhead and cutthroat trout can be found at http://www.nwr.noaa.gov/1salmon/salmesa/index.htm. Formal Endangered Species Act recovery efforts are already underway for listed Snake River and Sacramento River populations. In the fall of 1999, the National Marine Fisheries Service initiated recovery planning for the Puget Sound and lower Columbia Willamette by choosing its technical review teams.

Although neatly packaged in DPSs, ESUs, and recovery domains, salmon stocks are dynamic groupings in a temporally changing ecological landscape. They always have been that way in the unstable geology of the Northwest. As we contemplate recovery, we must confront our ignorance about how stocks became distinct in the first place and about how basins laid bare by catastrophic events (e.g., volcanic eruptions) have been repopulated in the past. How much "straying" from natal spawning areas is enough to allow recolonization of such basins without loss of local adaptations in subbasin populations? How much regional isolation of stocks is natural? In some cases, we do not clearly understand the fundamental identity of what we are trying to protect, and we still have much to learn about evolutionary relationships within and between units.

The Risks

While the life-cycle strategies of salmonids evolved to allow the fish to exploit a diverse array of both marine and fresh water habitats in different life stages, these strategies now expose salmon populations to numerous threats, many of which were not encountered by the species before the middle of the 19th century or later. Economic development of watersheds for forestry, agriculture, mining, and urban settlements has altered salmon habitats. Free flowing rivers have been dammed for hydropower or diverted for agriculture, with resulting modifications to flow patterns, habitats, migration corridors, food chains, and water quality and temperatures. (**Figures 8 and 9**) Harvest in rivers and the ocean has added to natural mortality and, by killing the larger fish, has resulted in mature fish becoming progressively smaller over time and producing fewer eggs. (**Figure 10**) Hatchery production and management practices, designed to augment population

Table 2

Recovery planning areas (domains) for Endangered Species Act-listed salmon and the ESUs they contain. Listings are as of June 2000.

Recovery Planning Area	ESA Listed Salmon
Puget Sound and the Olympic Peninsula	Puget Sound chinook Hood Canal summer chum Ozette Lake sockeye
Willamette and lower Columbia River basins and Southwest Washington coast	Lower Columbia River chinook Upper Willamette River chinook Columbia River chum Lower Columbia River steelhead Upper Willamette River steelhead Coastal cutthroat (proposed)
Mid and upper Columbia River basins	Upper Columbia River spring chinook Upper Columbia River steelhead Mid Columbia River steelhead
Snake River basin Oregon coast (Columbia River to Cape Blanco)	Snake River fall chinook Snake River spring/summer chinook Snake River sockeye Snake River steelhead Oregon Coast coho
Southern Oregon/northern California coast	Southern Oregon/northern California coho Northern California steelhead
North-central California coast South-central California coast	Central California coast coho Central California coast steelhead California coastal chinook South-central steelhead Southern California steelhead
California Central Valley	Central Valley steelhead Central Valley spring chinook Winter-run chinook

numbers, are responsible for maintaining some salmon populations, but have also introduced genetic changes and reduced the fitness of other populations. Wild fish can also be over-harvested when they mix with more abundant hatchery fish that are sought by fishers, or suffer from competition with or predation by hatchery fish. Non-native species that have been introduced to reservoirs, such as bass and walleye, prey on salmon and add to the mortality rates inflicted on young salmonids by native predators. Risk factors are often referred to as the "all Hs" (Habitat, Harvest, Hydropower, and Hatcheries), but each "H" really embodies multiple categories of threats.

It is useful to view the risks from a fish's perspective. From egg to spawning adult, a host of natural and anthropogenic factors may take a cumulative toll on both the fitness of individual fish and on numbers of fish surviving. Gravel bars free of predators are now silted in and less available for successful egg laying and incubation. Streams that

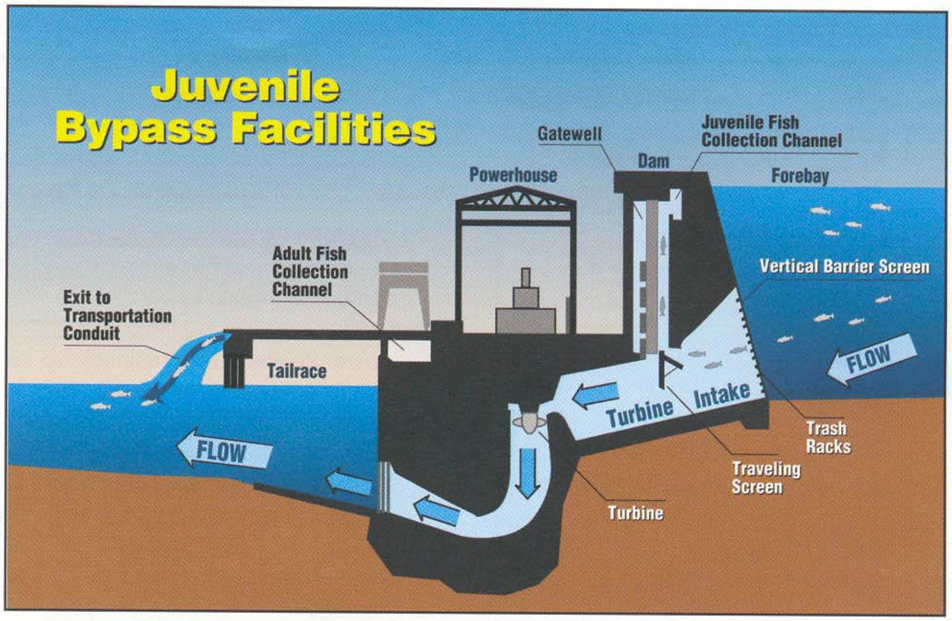


Figure 8. Engineering solutions in hydroelectric dams designed to assist juvenile salmon in their down stream migration. Courtesy of U.S. Army Corps of Engineers.

were once tree-lined and filled with woody-debris for safe rearing of young are now open and barren, resulting in poorer growth and lower survival. Spring freshets that overflowed stream banks into food-rich riparian zones are now eliminated by storage of water for hydropower, reducing much-needed food supplies in the process. Irrigation water diversions inadvertently send downstream-migrating juvenile salmon into alfalfa fields where they perish. Turbines on dams mutilate and kill some of the fish passing through them. Predation takes its toll at many points. In rivers that have been converted into reservoirs, salmon smolts are threatened by introduced predatory fish. Avian predators nesting on man-made islands in the estuaries feed heavily on young salmon as they make the physiologically challenging transition from fresh to salt water. Marine mammals (also protected under the Endangered Species Act) have proliferated and feed on juvenile and adult salmon. In addition to direct mortality from factors such as these, some stresses experienced by fish in earlier life stages may contribute to creating fish that are less able to survive in later

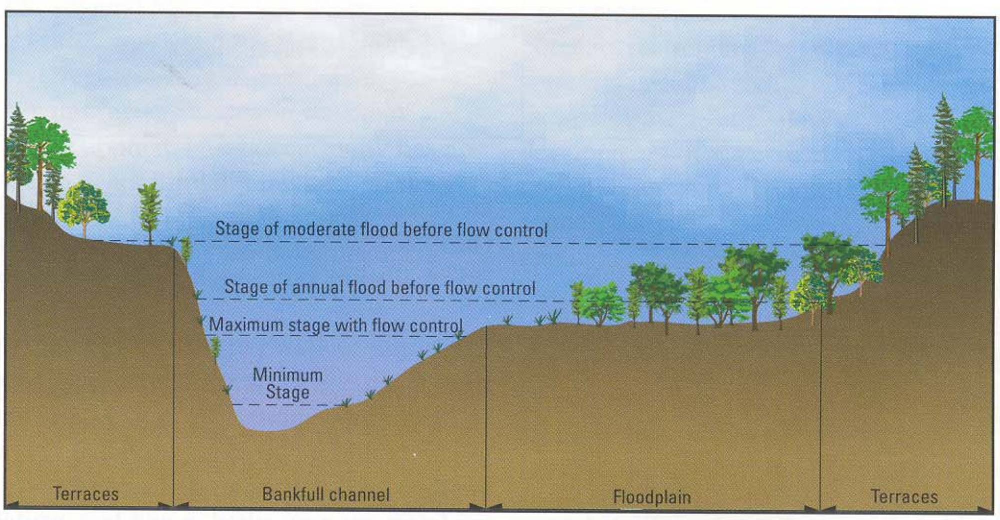


Figure 9. Streams and rivers before regulation of flow experienced a wider range of stage usually inundating the floodplain annually. Flow control limits the range of stage and involvement of the floodplain.

life stages. We know this cumulative toll is greater now than in the past, for not enough adults now return to sustain populations. Technologies for marking and recognizing individual fish are allowing many of the specific sources of damage to be pinpointed. One has to admire the adults that make it to spawning grounds as much for their good luck at overcoming adversity as for their amazing biology.

The relative importance of risks varies from basin to basin, and not all stocks are exposed to all categories of threats. For example, some drainages have dams, others do not; some have seasonally high temperatures or low water flows, whereas these problems are not important elsewhere. Water diversions, primarily for agriculture, are uniquely important because of their effects on juvenile salmon's seaward migration in California from the Sacramento-San Joaquin delta and northern California rivers, such as the Trinity. The immense Federal hydropower system is characteristic of the Columbia-Snake basin. Allocations of harvest are a principal concern for stocks of salmon in Alaska and British Columbia where rivers and headwaters are less developed. The especially difficult cases to diagnose are those influenced by multiple factors, such as stocks in the Lower Columbia River and in urbanized areas like Puget Sound.

Relative importance of risks also varies as environmental conditions fluctuate. Dry years, that is, those with low rainfall and runoff, are notorious for producing few salmon in California streams compared to years with normal or especially wet conditions. Precisely where in the freshwater phase of the life cycle the water deficit has its effect is often not clear. At some locations the cause is evident, such as streamflows falling so low that adults are prevented from swimming upstream in shallow water. Climate cycles that particularly influence precipitation patterns, such as the El Niño/Southern Oscillation, have the potential to influence both the freshwater and marine portions of the salmon life cycle.

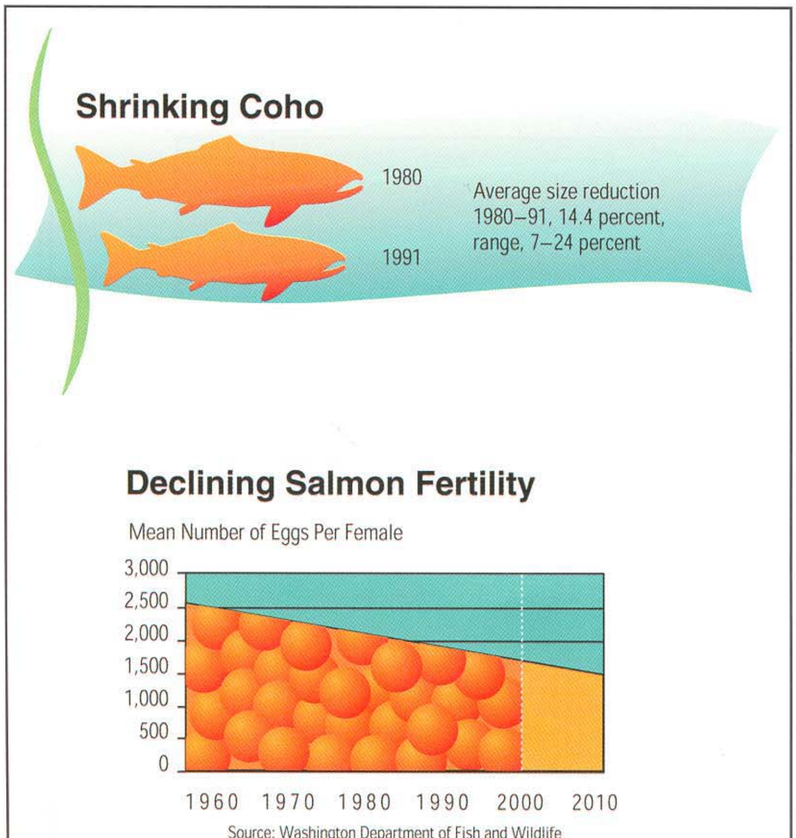


Figure 10. Mature salmon are shrinking in size and producing fewer eggs. Salmon fertility is also declining as measured by the number of eggs per female.

We confound an already sensitive time for salmon when we alter estuaries—the zones where freshwater rivers enter the saline coastal waters. The transition between salt and fresh water, in either direction, is physiologically challenging for any organism. An animal's whole metabolic system for regulating the amount of water in its body needs to be reworked during this transition. At this normal time of internal stress, we add water pollutants, dredging, harbor facilities, diking, and altered seasonal freshwater flows. Marine mammals and shorebirds ply the estuary for laggards as the salmon migrants pass up and downstream. Although what happens in estuaries is vitally important in the salmon life cycle, little scientific attention has been paid to this phase in contrast to the amount of study that has been done for the hydropower system.

The marine environment is also something of a mystery and, because of our inability to control it, a source of frustration. It is clear that ocean conditions can have a significant impact on the overall production of Pacific salmon. (**Figure 11**) Climate and ocean variability act at a number of temporal (e.g., seasonal, annual, and decadal cycles) and spatial (local, regional, and global) scales to affect the production dynamics of salmon as they grow and mature in salt water. (**Box 2 and Figure 12**) In particular, decadal climate cycles that are now becoming better understood have produced major shifts in biological production processes throughout the oceanic foodweb as well as in the basic structure of coastal marine ecosystems occupied by salmon. (**Figure 13**)

Unfortunately, the scales we understand the least may be the most important to salmon management. As a result, it is very difficult to design salmon management to minimize the risks of anticipated changes in ocean conditions. It is clear, however, that there is considerable natural variability in the environments, both marine and freshwater, of salmon, and this variability normally produces fluctuations in their populations. This fact poses several problems. First, it creates a possibility that temporary improvements in population status caused by favorable environmental conditions will be mistaken for recovery due to management decisions. Second, human impacts are now adding to natural factors that depress populations. The result may be that populations are driven to lower lows in unfavorable periods than natural variability alone produces, and may be unable to rebound to historic levels during favorable ones. Given our imperfect understanding of both long-term natural fluctuations and human effects on salmon, there is ample opportunity for productive additional research.

It is not sufficient to merely list and catalogue the risks that a particular stock faces. These risks need to be quantified so that the most important

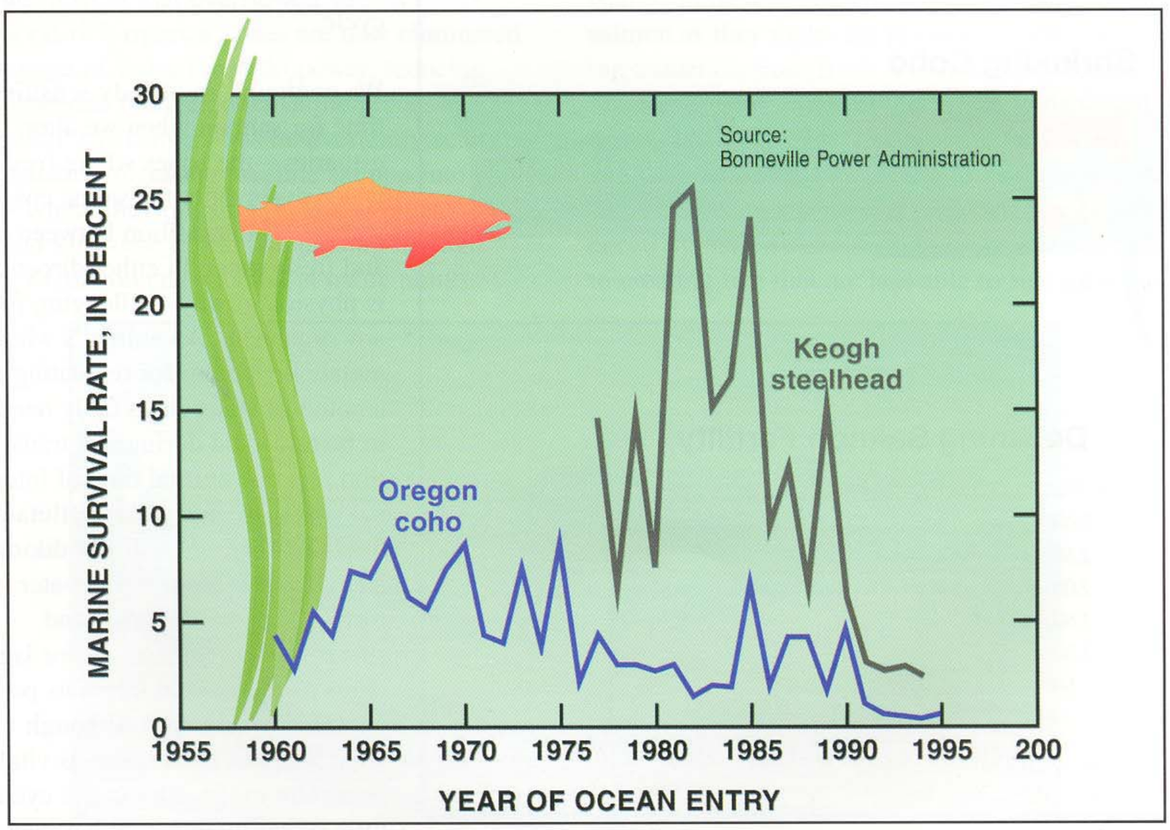


Figure 11. Comparison of marine survival of Oregon coho and British Columbia steelhead. A large drop in ocean survival occurred in both regions in the 1990's.

Box 2

Ocean Conditions

A growing body of evidence suggests that many populations of Pacific salmon are strongly influenced by marine climate variability. Recent studies indicate that interannual fluctuations in climate are the ultimate source of widespread regional fluctuations in rates of marine survival for many salmon species, particularly juveniles making the transition from freshwater to marine environments. For example, sockeye salmon in Bristol Bay and the Fraser River were both negatively affected by El Niño events that occur on average every 4 years (Mysak 1986). On longer time scales, salmon production appears to be linked to decadal-scale climate shifts in the North Pacific (Francis and Hare 1994, Hare et al. 1999). Mantua, et al. (1997) have labeled this decadal-scale climate phenomenon the "Pacific Decadal Oscillation," or PDO.

The PDO oscillates between warm and cool phases. The warm phase is characterized by above average sea surface temperatures in the tropics and along the coast of the Americas and cooler than average sea surface temperatures in the central north Pacific. These temperature anomalies are accompanied by unusually low atmospheric sea level pressure over the north and eastern tropical Pacific and high-pressure anomalies in the western tropical Pacific centered over northern Australia. The cold phase of the PDO is simply a mirror image of these patterns. These temperature and pressure changes in the ocean may result in shifts in nutrient upwelling patterns that produce corresponding increases or decreases in the populations of phytoplankton and zooplankton that are the base of the marine food chain. The changing abundance of food may translate into increases or decreases in salmon production.

The PDO has been primarily in its warm phase since the winter of 1976-77. The shift from cold to warm phases that winter has been well documented and has been termed a "regime shift" (Graham 1994; Miller et al. 1994; Trenberth and Hurrell 1994). This regime shift was followed by both a rapid expansion of Alaskan salmon production and deteriorating production of salmon in the Pacific Northwest (Hare et al. 1999). Hare and Mantua (2000) have examined climatic and biological records to determine if there is evidence of a regime shift since 1977. Although they found signs of a 1989 shift, the related changes in environmental parameters were neither as pervasive as the 1977 changes nor do they signal a simple return to pre-1977 conditions. The last prolonged cold phase of the PDO lasted from 1947 to 1976 and the previous warm phase from 1925 to 1946. These periods also match alternating production cycles for Alaska and West Coast Pacific salmon since 1925 (Hare et al. 1999). Climate regime shifts have important implications for management of fishery resources, and an improved understanding of these factors is critical for the development of prudent salmon management policies.

ones for a particular stock's life cycle can be identified and given high priority for remedial actions. The magnitude and significance of particular risks also differ among river basins, as shown qualitatively in **Table 3** for river basins from Alaska to California. Results can be surprising. For example, survival of steelhead smolts in the lower Snake River while passing dams is much higher than earlier believed, whereas previously unappreciated risk to salmon smolts from predation by birds turned out to be significant in the Columbia River Basin. (**Box 3**) Although we have only begun to quantify all the relevant risks, these examples show that it can be done.

The first step in recovery planning is to quantify

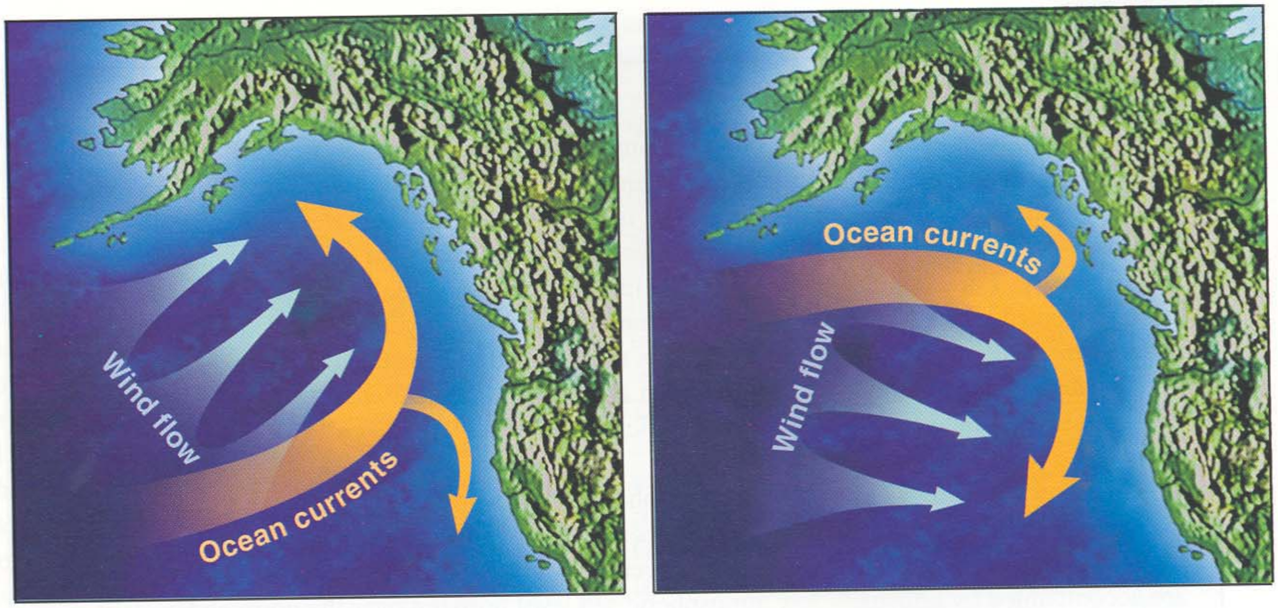


Figure 12. Climate cycles over the Pacific Ocean shift wind and water currents to alternately favor northern (left) or southern (right) salmon stocks with cool nutrient-rich water. Known as the Pacific Decadal Oscillation (PDO), on climatic pattern persists for decades then shifts to the other.

the life-cycle risk factors that affect particular species and listed stocks. From this, stock-specific recovery goals and a suite of actions necessary to achieve the goals (including estimates of management feasibility, cost, and time required) can be developed.

What is meant by recovery? There are at least two concepts, one based on the statutory requirements of the Endangered Species Act, the other dealing with a wider range of societal interests, so-called "broad sense" recovery.

Endangered Species Act recovery is "improvement in the status of a listed species to the point at which listing is no longer appropriate," i.e., when the species is no longer endangered or threatened. Delisting of an endangered species requires that both biological and administrative criteria be met. The biological criteria describe population characteristics to assure that the species will persist in the future at viable levels, which, in turn, requires that all factors for decline have been addressed. Administrative delisting criteria are used to establish that this is true.

"Broad sense recovery" is a more open-ended goal without a single definition. "Broad sense recovery goals" may reflect a variety of societal values, such as a desire to have populations robust enough to support tribal, commercial and sport harvest, to promote fully functioning ecosystems, or to provide opportunities for the public to appreciate salmon in the wild.

Identifying the causes of decline of an endangered species and assessing whether corrective measures are adequate to produce recovery are technical matters requiring the best that science can offer. Choosing which corrective measures to take to reverse decline and establishing "broad sense recovery goals" are matters of policy and social choice. Clearly, however, both definitions of recovery rest on having a sound scientific-technical footing.

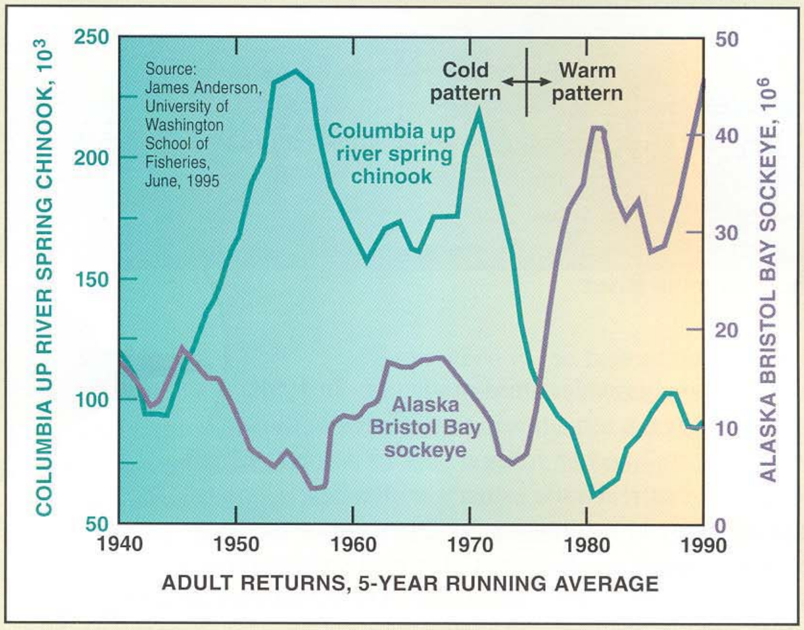


Figure 13. Oscillating conditions of ocean currents and winds alternately favor Alaskan and southern (Columbia River) salmon.

Table 3

Relative Ecosystem Risks for Salmon in River Basins Throughout Their Range.
"Hydropower" includes effects of impoundments as well as dams. Other Water Use includes irrigation and municipal water supply effects. High (H), medium (M), and low (L).

River Basins	Ecosystem Risk					
	Land Use (Habitat)	Hydro (dams)	Other Water Use	Harvest (fishing)	Ocean (climate)	Hatcheries
Alaska	M	L	L	H	H	M
British Columbia	M	M	L	H	H	M
Puget Sound	H	M	L	H	H	H
Columbia River	H	H	H	H	H	H
WA/OR/CA Coasts	H	L	M	M	H	L
CA Central Valley	H	M	H	M	H	H

Box 3

Predatory Birds and Fish Consume Many Salmon Smolts

Both birds and fish prey on young salmon. How important is this predation? Can it be quantified? The entire smolt production (both hatchery and wild) of the Columbia and Snake River Basins is estimated at some 200 million. Of these, about 50 percent -- or 100 million -- reach the Columbia River estuary.

Caspian terns are the most prevalent bird predators. In 1998, it was estimated that Caspian terns nesting on islands in the estuary consume between 7 and 15 million (7 – 15 percent) of the 100 million smolts that reach the estuary, with a best estimate within this range of about 11 million, or 5 1/2 percent of the total Columbia River Basin smolt production. Other bird species (double-crested cormorants, gulls, etc.) also consume smolts in smaller quantities. The population of Caspian terns has increased with the availability of mostly manmade islands created by the dumping of dredged material. These predators are mainly aggregated in colonies in the estuary, largely on Rice and East Sand Islands. Census estimates indicated a population size of about 20,000 terns in 1998.

Northern pikeminnows are the most prevalent fish predator in fresh water in the Columbia River basin. Total smolt losses to northern pikeminnow predation in all reservoirs, river reaches, and the estuary, are estimated at 16 million, or 8 percent, of total Basin smolt production. Northern pikeminnows in the estuary to Bonneville Dam consume about 10 million (10 percent) of the 100 million smolts that reach the estuary. The population of northern pikeminnows has increased with the development of the hydropower system in the Columbia River basin. These predators can be found from the estuary upstream in the Columbia River to Priest Rapids Dam and upstream in the Snake River to Hells Canyon Dam. According to Beamesderfer et al. (1996), the total population size of northern pikeminnow in the system during a 1983-1986 census totaled 1,765,000 individuals. About 734,000 of these pikeminnows were in the estuary. Other predatory fish (walleye, bass, catfish) also consume smolts in significant, and apparently growing, quantities.

There are concerted efforts to reduce this predation. Terns are being lured to other nesting sites where salmon would make up less of their diet. The Columbia basin initiated a northern pikeminnow removal program through managed fisheries in 1991 (sport-reward, dam angling, gill-net). To date, these combined fisheries have removed over 1 million northern pikeminnow greater than 11 inches (the size that consumes most smolts). In a 1999 analysis, Friesen and Ward estimated that the annual system-wide potential predation by northern pikeminnow has been reduced to about 11 million juvenile salmonids, a decrease of about 25 percent in potential predation by this species since fishery implementation. The managed removal of northern pikeminnow between 1991and 1996 has resulted in an estimated net gain of nearly 4 million juvenile salmonids every year. This gain, in turn, represents about 2 percent of the estimated 200 million downstream migrants. [Northwest Power Planning Council]

PART II
SCIENCE FOR SALMON RECOVERY

The State of Our Knowledge

While it is true that long-term improvement of science to support salmon recovery and management is needed, the rate at which salmon are disappearing tells us we cannot always wait years for additional research results. Although additional scientific data would be useful, for the many endangered and threatened stocks we do not have the luxury of viewing their status as an interesting scientific question. Recovery of these stocks may require immediate intervention, despite continuing scientific uncertainties. But salmon research directed at recovery measures has already been conducted for years, and in many cases we have enough information to proceed with some types of remediation immediately. (**Box 4**) The appropriateness of various measures will vary among stocks and from site to site just as the threats to salmon survival vary. Although it may be necessary to proceed in the face of uncertainty, careful analysis at watershed scales can identify options that have relatively high probabilities of being effective so that action can commence.

Basic scientific information is lacking, however, for many of the remedial actions that we would like to take over a longer term. The lack of a basic understanding of the behavior of downstream-migrating salmonids in relation to the hydraulic dynamics of water flow in rivers is but one example. (**Box 5**) Understanding whether migrating fish respond differently to turbulent rivers and slowly moving reservoirs has implications for the usefulness of modifications that might be made to dams and bypass structures. It will be difficult to increase survival rates of juvenile salmon by manipulating river flow without understanding more about the relationships between river discharge and juvenile salmon needs.

Box 4

What can be done now?

Scientific understanding is adequate to support many actions. A few examples:

- Restoring the natural function of streams
- Protecting or replanting streamside forest buffer strips
- Leaving or replacing large woody debris in stream channels
- Protecting or recreating deep pools in streams
- Minimizing erosion and siltation of streams from disturbed landscapes
- Removing or bypassing dams that are migration barriers
- Leaving enough water in streams to allow migration
- Recreating periodic flood flows in heavily regulated rivers
- Fencing spawning streams from intrusion by cattle
- Maintaining cool temperatures by restricting the addition of heated water
- Reducing toxic and organic pollutants in streams and estuaries

Box 5

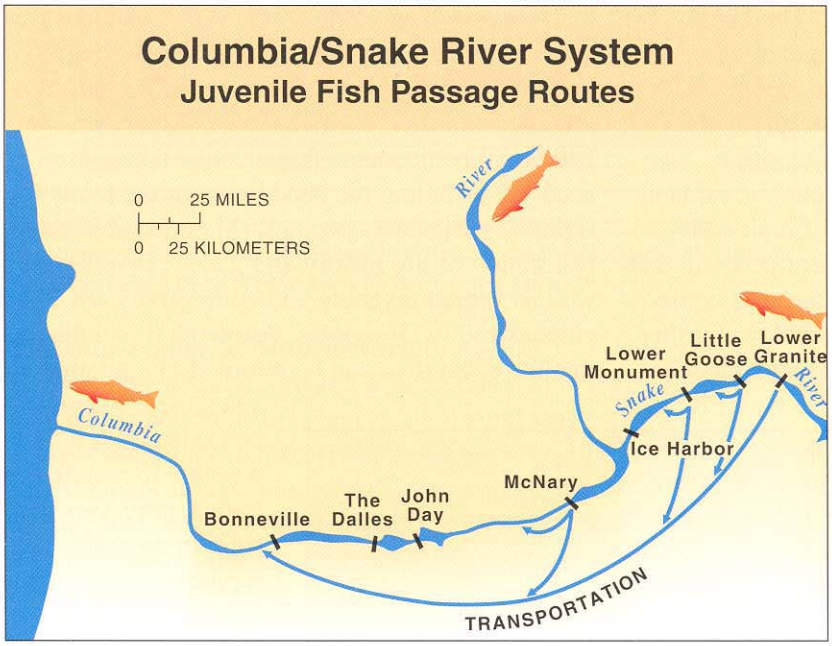
Knowing more about how fish migrate.
An improved understanding of the poorly researched behavior of migrating fish would be of value for evaluating the significance of delays in reservoirs, increased energy expenditure during migration, and poor guidance to bypasses as risk factors and for designing better remedial measures. Migrating juvenile salmonids are assumed to drift passively with water flow, even though there is evidence to the contrary. They most likely manage their migration by doing things behaviorally that we do not currently understand. They stop and go, they have daily cycles of activity, and their migration pattern changes over time as they descend tributaries and the mainstem migration corridor and enter the estuary. There are indications of differences among species and races. They apparently migrate downstream by swimming weakly head-upstream most of the time. The published literature implies that this orientation is to feed while they drift, but elementary hydraulics suggests that its purpose is to maintain hydrodynamic stability. The fish change from weak head-upstream swimming to more active, head-downstream swimming under circumstances that we also do not understand. The percentage of time spent swimming head-upstream versus swimming actively downstream must affect the overall rate of migration and the amount of energy expended, perhaps as much or more than augmenting flows from a Montana or Idaho storage reservoir hundreds of kilometers upstream. Based on telemetry techniques that provide information on location, we know that migration behavior changes when fish leave riverine reaches and enter more slowly moving reservoirs, but we do not know how. Could normal migratory behavior, which we do not understand, be sustained by changes to the hydraulics of dam forebays? Could surface bypasses at dams, which have worked in some places but not in others, be better designed to make use of normal migratory behavior if we understood it? Research on migration behaviors of the salmonid species and races would almost certainly provide a better foundation for developing improved hydraulics in reservoir flows and dam bypasses.

Although many stocks are in peril, we have already made some important progress. Cumulative risk assessments for Columbia River salmon using data collected since the early 1970's have shown some improved survival. Before implementation of dam bypass systems, fish barging, and managed spill, survival during down-river migration was so poor that populations were declining at rates of about 50% per year. Thanks to these measures, the calculated annual rate of population "growth" has doubled, although this has not been enough to reverse population declines. Although recent progress does represent improvement, it is not yet sufficient.

There are two basic approaches to remedial technology: (1) technological fixes that replace natural processes with human engineering and investment, both initial and continuing; and (2) designs that work with nature, making use of natural processes to minimize continual human investment. The latter have the potential to recreate a sustainable system; the former are likely to require constant, and even increasing, human intervention. Although any remediation program will likely include a mix of the two approaches, it is preferable to maximize the second. (**Figures 14, 15, 16**)

Obviously, some aspects of risks to salmon are not amenable to engineering solutions. Salmon production cannot, for example, be manipulated by oceanic scale engineering projects. But we can modify our management of freshwater ecosystems, hatcheries, and harvest to accommodate uncontrollable ocean conditions. Even our fragmentary knowledge suggests that there is a dynamic interaction between ever-changing ocean conditions and the historical diversity of salmon species and stocks. This diversity is directly related to the availability of healthy and complex freshwater habitats for spawning, rearing, and migration. Thus, "remediation" for poor ocean conditions will also entail taking an ecosystem approach to salmon management in which variability and diversity on the freshwater side are key normal attributes to be safeguarded. We should protect the diversity that allows fish populations and ecological communities to sustain themselves in a changing world with management strategies that adjust ocean harvest and protect stocks that may be weakened by currently operating cyclic influences.

Remediation for each of the many large risk factors faced by salmon is not, however, simply a matter of applying what we know. In many cases, adequate scientific and technical underpinnings to guide selection of remedial actions are missing, and the absence of a sound scientific basis is likely to promote continued failure.



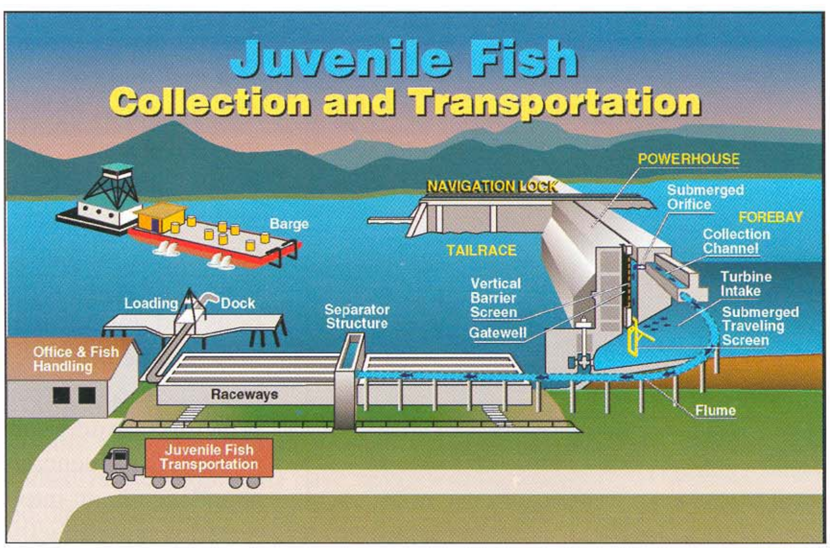


Figure 14. Juvenile salmon are now transported downstream by barge and released below Bonneville Dam. Courtesy of U.S. Army Corps of Engineers.

The next two sections summarize what is known about the status of salmon in the major subregions of the Pacific Northwest and provide an overview of scientific, management, and restoration issues.

Columbia River Basin

The Columbia River basin is a major focus of concern and, within the last several years, a number of important reports have been produced related to salmon recovery issues in this region. Each report represents an interpretation of the state of the scientific knowledge for the region and each contains conclusions and recommendations for changes in management practices. They are Return to the River by the Independent Scientific Group (ISG 1996); Upstream by the National Research Council (NRC 1996); a draft report by an interagency task force on management of Federal lands in the interior Columbia River basin, issued as a report of the U.S. Forest Service and the Bureau of Land Management (USFS/BLM 1997); a 1995 Proposed Recovery Plan for Snake River Salmon by the National Marine Fisheries Service (NMFS 1995);

and Wy-Kan-Ush-Mi Wa-Kish-Wit, Spirit of the Salmon, a recovery plan by the Columbia River Inter-Tribal Fish Commission (CRITFC 1995). These management-oriented reports focused on restoration objectives that each group felt were supported by a scientific foundation.

A useful comparison of these reports was prepared by the Independent Scientific Advisory Board (ISAB), an advisory body of 11 independent scientists for the salmon restoration efforts of the National Marine Fisheries Service and the Northwest Power Planning Council. The ISAB comparison identified the major points of agreement and disagreement among these reports on eight common management topics or alternatives. Focused on the Colombia River Basin, these reports represent a tremendous regional investment in scientific thinking about a very difficult and complex natural resource management problem that transcends the Columbia. The key areas of consensus among the reports are presented below. Further details on areas of consensus and disagreement are presented in Appendix A. (The areas of disagreement described in Appendix A provide considerable insight into the scientific unknowns, from which much of the disagreement arises.)

Salmon Recovery Will Require An Ecosystem Approach: Restoration of salmon will require restoration of ecological functions and processes to reestablish healthy watersheds. But restoring natural processes and ecosystem health requires a much better understanding of those processes and how to evaluate and monitor ecosystem health than we now have. The "ecosystem" includes fresh water (**Figure 17**), estuarine, and ocean environments. There is also recognition that human communities and their socioeconomic dimensions are additional components that must be taken into account, including the need to honor the treaty rights of indigenous peoples. Maintenance and restoration of life history and genetic diversity as well as habitat diversity and connectivity are emphasized in all reports. Although it is unlikely that the ecosystem can be returned to a pristine state, there was a consensus that it is possible to restore ecological processes that support naturally reproducing populations at sustainable levels. Salmon have declined as a result of the cumulative impacts of a multitude of human actions operating over decades, and it will take decades to reverse these impacts. Changes in salmon management institutions and governance may also be needed to implement ecosystem principles. Addressing all factors influencing abundance in an integrated way will facilitate recovery.

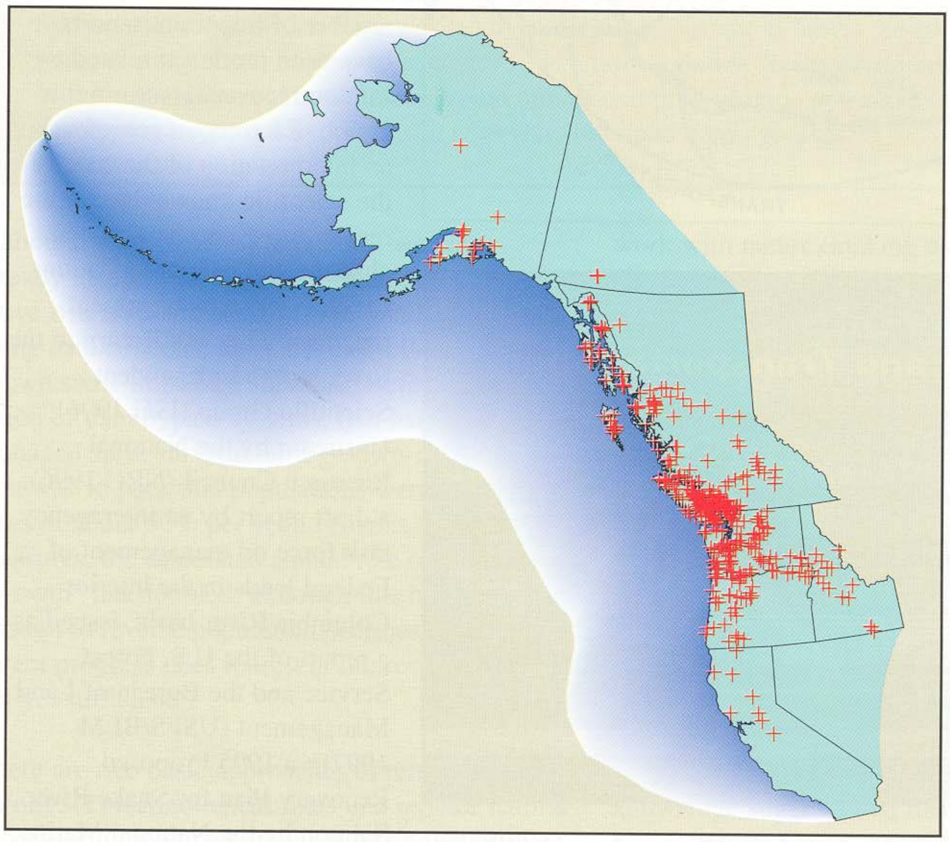


Figure 15. Location of salmon and steelhead hatcheries.

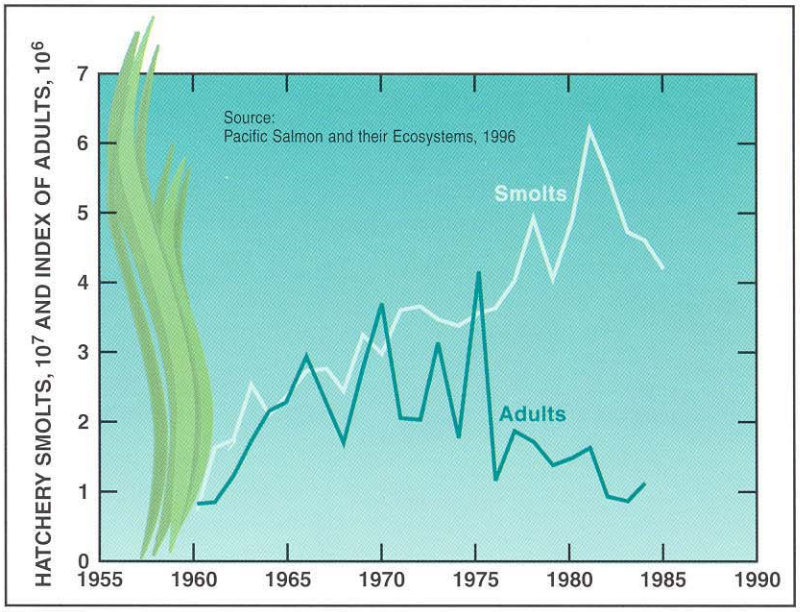


Figure 16. Numbers of hatchery coho salmon smolts released and estimated abundance of adult salmon produced the following year in the Oregon Production Area. Increasing smolt production is no longer increasing adult returns.

The Importance of Natural Variation: Environmental variability and genetic diversity may be the keys to salmon survival. Natural variability contributes to the diversity of habitat types necessary for maintaining genetic variability, and the role and value of variability must be recognized. One-size-fits-all solutions are generally inappropriate; planning and implementation should be tailored to local conditions. Decadal cycles of ocean productivity have the potential to mask changes in the survival of salmon during freshwater phases of their life cycle, leading to erroneous interpretation of the performance of restoration efforts and increased losses of some stocks. Changes in marine survival need to be tracked closely and findings incorporated into management planning. Protection of freshwater habitats is particularly important during periods of low productivity in the ocean. Salmon harvest rates should take changes in marine survival into account.

Habitat Factors: Human activities (forestry, agriculture and grazing, hydropower, and urban and industrial development) have degraded, fragmented, and disconnected riverine and adjacent riparian habitats. Major long-term intervention will be required to restore the spatial and temporal diversity of these habitats and to reconnect habitat types important for continuity in the life cycles of salmon, including spawning and rearing sites and migratory corridors. Riparian features and processes, large woody debris recruitment, water quality, natural sedimentation rates, floods and other natural disturbance regimes, adequate stream flows, and upland (watershed) processes are all key elements in restoring habitat. Some ecosystem processes need research more than others to establish how much remediation will be sufficient. Core or reserve areas that currently maintain strong populations of salmon are of particular ecological importance and should be protected and reconnected with one another. Habitat rehabilitation will require action on both public and private lands, and among all types of land uses.

Impacts of Artificial Propagation Programs: Artificially propagated salmon have largely replaced naturally spawning populations over much of the Columbia River basin, but the degree to which hatchery programs have been detrimental to or contributed to the survival of naturally reproducing populations is not clearly understood. There is an urgent need for fundamental information on the interactions of hatchery-produced fish with wild populations. Effects of hatchery-produced fish on wild stocks potentially include genetic alteration, competition, predation, and disease.

Hydroelectric Development and Operations: There is general agreement that hydropower development in the Columbia and Snake River basins has adversely affected salmonid populations, but there is still much disagreement about the specific mechanisms that cause these adverse effects. There are many unresolved issues dealing with river discharge and its relationship to salmon survival, including the efficacy of flow augmentation, transportation, reservoir drawdown, and structural and operational improvements at mainstem dams.

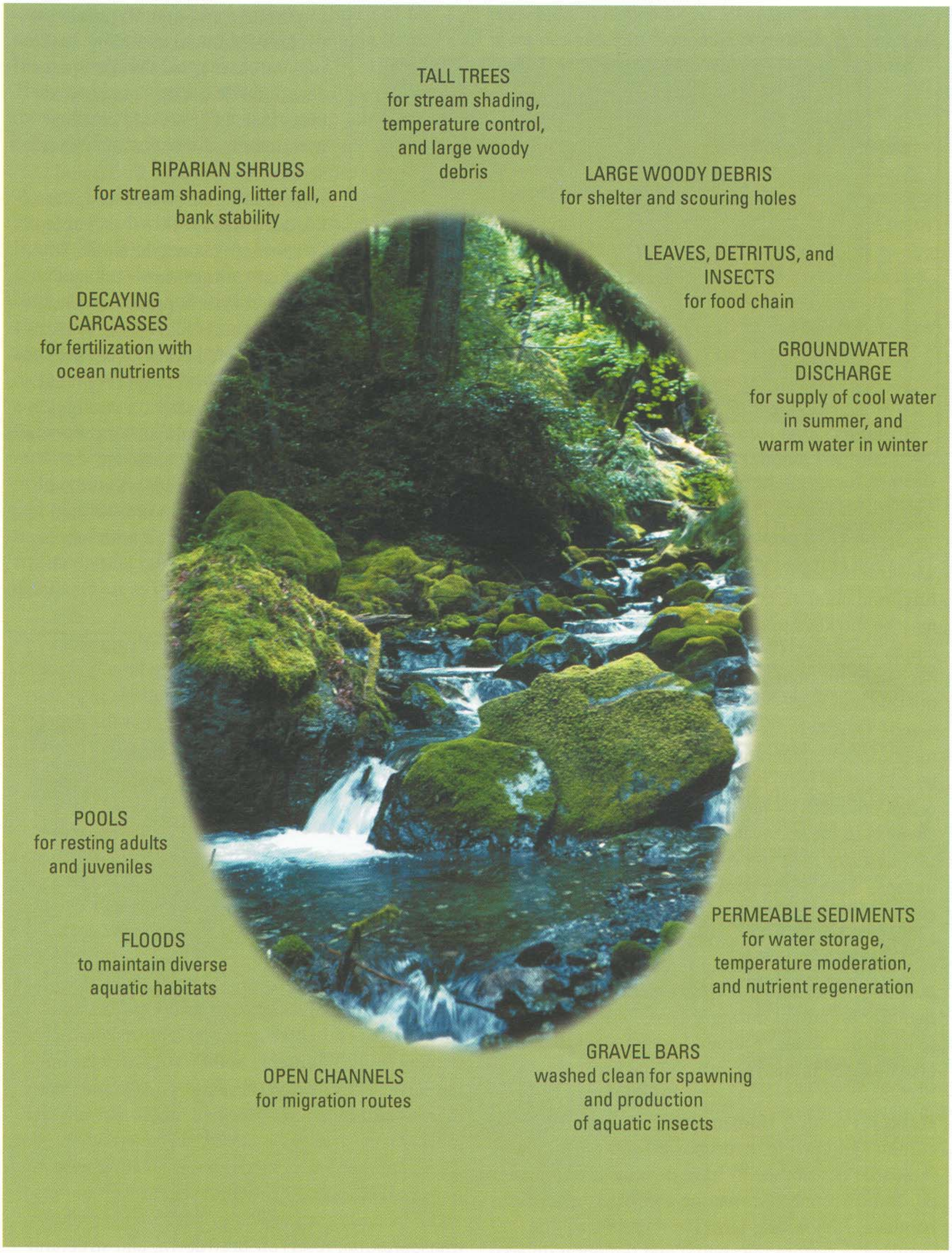


Figure 17. The freshwater ecosystem for most salmon. Photograph by Robert Ettner, USDA Forest Service.

In general, there is a need for science to define what functions of a riverine ecosystem must be restored for salmon and how to accomplish this restoration while maintaining the societal benefits of electricity production, navigation, flood control, irrigation, and recreation provided by dams.

Harvest Effects: Harvest should be managed with the goal of sustaining populations, allowing adequate adult escapement to maintain populations over time without compromising the diversity of salmon stocks. Harvest is only one of numerous sources of mortality and cannot be viewed as independent of other sources, i.e., when one source goes up another must go down to maintain populations. Mixed-stock fisheries can lead to over-harvest of less productive stocks and loss of stock diversity. A definition of the number (including annual variability) of salmon in individual stocks that must escape the fishery to sustain reproduction is needed, especially when there appears to be abundant spawning habitat for many stocks. Science could contribute to the goal of developing stock-specific fisheries.

Institutional Factors: Current institutional arrangements are not succeeding at halting salmon declines and new or altered arrangements are needed. An understanding of how to include "good science" as part of the institutional arrangement is important.

Monitoring and Evaluation: A regional science-based monitoring and evaluation program is necessary to assess the status of populations and habitat, as well as the adequacy of management and restoration actions in achieving restoration goals. The monitoring and evaluation program should have an ecosystem/watershed focus, deal with all life stages in the life cycle of salmonids, and be conducted in an adaptive management framework, that is, an approach in which future actions can be adjusted in response to the results of current actions. The program should be designed and conducted cooperatively by agencies and tribes, and should provide critical data, analyses, and integration to assess the status and trends of ecosystem components, address monitoring objectives, test alternative hypotheses, and provide input for adaptive management. Research needs include monitoring technologies, indicators of stock success and environmental health, databases for information storage and retrieval, straightforward evaluation procedures, and mechanisms to ensure communication to those who implement adaptive management.

California to Alaska—Coastal and Selected Interior Basins

Similar analyses of the scientific foundation for salmon recovery have been carried out for certain other areas, such as the Trinity River basin in northern California, where there is also a strong consensus that an ecosystem approach to salmon management and restoration is needed. In the Trinity River, where water diversions for California's Central Valley Project have reduced instream flows and stopped most of the natural re-working of the streambed that maintains habitat diversity, the emphasis of restoration has been on hydrology, temperature, sediment distribution, and riparian vegetation as important ecosystem characteristics. In California there is a stronger emphasis on managing relatively scarce water supplies than is the case in the Columbia River basin. Annual cycles of water abundance are critical for salmon and other water uses, causing management actions and the underlying science to be oriented to categories of water-year classes (years that are extremely wet, wet, normal, dry, and critically dry). Management for suitable stream temperatures is a high priority in the south.

Alaska is somewhat unique because there are currently no ESA-listed salmon species or stocks. Alaska faced salmon disaster in the past, but came back from the precipice. Prior to statehood, Alaska's fisheries were on the brink of collapse due to over fishing. The Federal government had failed to provide sound practices or adequate financial resources to manage the fisheries. Alaska's fishing industry was in such bad shape that President Eisenhower declared Alaska a Federal disaster area in 1953. One of the driving forces behind Alaskan statehood was the desire to gain control over management of Alaska's fisheries. When the Constitutional Convention met in

November of 1955, the delegates mandated that *Fish...and other replenishable resources belonging to the State shall be utilized, developed, and maintained on the sustained yield principle, subject to preferences among beneficial uses.* Alaska has for many years invested substantial resources in gathering and analyzing the biological data necessary to maintain a healthy resource. Their model is based on a four-pronged approach: (1) protection of habitat, (2) a sustained yield management regime that puts conservation and escapement to the spawning beds first, (3) a citizen Board of Fisheries that insulates the scientists and managers from allocation decisions, and (4) a commitment from fishermen and communities to support a sustainable industry.

Alaska intended to conserve and protect important salmon habitat by (a) creating strict development standards for road building, coastal development, and mining to protect spawning and rearing streams, estuaries, and near shore areas; (b) adopting a Forest Practices Act that seeks to restrict timber harvest in buffer zones along salmon streams to prevent erosion and to protect spawning and rearing habitat; (c) closely monitoring water discharges, such as sewage and other pollutants, to protect water quality; and (d) working with the Federal government to meet or match these measures on Federally-managed land. Although Alaska's statutes also protect salmon runs by making it illegal to dam or in any way obstruct the free passage of salmon into and out of anadromous fish streams, in reality there are many impediments to salmon passage. Alaska has salmon hatcheries, but manages and sites them to minimize genetic interference with wild stocks, which have priority over hatchery stocks. And Alaska bans finfish farming because of concerns about potential pollution from fish waste and chemicals, genetic deterioration of wild stocks, and introduction of disease and exotic species. Despite all these measures, Alaskan salmon do exhibit cyclical changes in abundance that are largely attributed to climate-driven ocean cycles. In general, good and bad years oscillate between the lower states and Alaska; that is, when Alaskan fish do poorly, Pacific Northwest stocks do well, and vice versa. (See Fig. 13 in the previous section.) It is also possible, however, that the continued success of Alaska's salmon resources may be due as much to the fact of its low human population density and relatively low levels of development as much as to active protection measures. If this is true, it is possible that Alaska's salmon protection measures may become less effective as development pressures grow.

In British Columbia, overall abundance of adult Pacific salmon declined sharply for all species between the turn of the century and recent decades, but numbers of pink, chum, chinook, and sockeye have increased lately. The Fraser River basin (about one quarter of the area of British Columbia) has remained one of the world's greatest producers of salmon. It is agreed that railway construction in 1913 caused blockages at Hells Gate in the middle mainstem, exterminating upriver pink salmon and sharply reducing sockeye. The blockage has been removed, but constriction of the channel in high-flow years can still retard salmon migrations. Over-fishing, selective harvesting of certain stocks and sizes, and human-induced changes to upriver spawning habitat are implicated as contributory causes for declines of most species. The mainstem Fraser has no large dams, but the large watershed contains many smaller ones that have blocked access to spawning grounds. Coho salmon in British Columbia appear to be the most vulnerable to various human activities, which influence the small streams this species occupies for long periods of rearing. Coast-wide decline of Coho is a problem common to British Columbia and the Pacific Northwest states.

Causes of long-term declines and in some cases extinction of salmon in British Columbia are multiple and confounded by many concurrent factors. An understanding of trends is limited by the poor quality of records of escapement to major rivers and streams. The accuracy of available data varies among species and areas in the region, which has been of considerable concern in British Columbia.

Excellence in scientific studies does not necessarily produce excellent salmon management. There has been considerable work on the environmental requirements of salmon in British Columbia, particularly for sockeye, and much of the leading-edge physiology and behavioral science on salmon has been the product of researchers in British Columbia. This information has not, however, been applied fully to the problems of salmon stock abundance either in Canada or the U.S. But the "salmon crisis" has stimulated both increased activity and scientific rigor in nearly all aspects of salmon conservation biology.

Science Needs

Historically, science has played two different roles in salmon management. The first, a technical leadership role, has involved establishing the fundamental relationships between salmon and their environment that collectively form the basis for management decisions. The second, a "sustaining"role, has involved selectively seeking data and analyses to support regulatory actions or policy decisions by agencies, tribes, or other organizations. Ideally, science focuses on the more objective first role, but, in fact, salmon management has been dominated by the second.

Recognizing this dominance does not impugn the quality of the scientific studies supported for this role, but it does help to explain the disparities in the availability of data to support the various management alternatives. There is, for example, much less information available on the less palatable management alternatives, such as total elimination of harvest of a stock, in the existing scientific literature. In the selection of new research projects, agencies understandably tend not to fund studies that seem to have limited usefulness for supporting current management policies or that might produce results that actually contradict current practices. Thus, the scientific basis for making management decisions has been skewed by the interests of research sponsors and their choices about what to study.

Science is also subject to the common tendency to add knowledge about already well defined topics instead of seeking entirely new approaches and concepts. For example, research proceeds steadily on improving estimates of the survivorship of salmon transported downstream in barges and on incremental improvements to turbine intake screens. While incremental gains in understanding recognized problems are certainly necessary and it is appropriate to use science to support and refine existing management options, its value as a means to identify and test new options should not be overlooked. For example, truly new research might identify other productive pathways to recovery, such as new approaches to minimizing in-river mortality through habitat modifications in reservoirs.

Six broad categories of relevant and important research that have been under-emphasized in the past are:

- definition of critical ecosystem features for the full life cycle of salmonid species and stocks;
- quantitative definition and assessment of risks (natural and anthropogenic) during upstream, downstream, and estuary/ocean life stages;
- clarification of fundamentals of biological diversity in salmon species, races, and stocks;
- clarification of the regional variation in the physical, biological, social, cultural, and economic environments of salmon;
- development of remedial technologies that work with nature rather than replacing it; and
- development of quantitative indicators and analytical methods to assess the status of salmon, characterize risk factors, and evaluate the out comes of remediation efforts to improve environmental conditions or reduce risks.

The first four of these categories focus on aspects of the biology and ecology of the salmonids and on characterizing their environment, while the last two deal more with the development of methods and tools. The more detailed lists below, which represent key areas where knowledge gaps may hinder progress in salmon recovery, are likewise divided into basic biology/ecology/environmental science and method/tool development. All of the items in these lists are significant and require prioritization. It will be obvious that many overlap, so that much of the needed research is likely to address more than one area. The potential Federal role is highlighted where Federal agencies have particular expertise, facilities, or institutional arrangements.

Biology/Ecology/Environmental Characterization

Basic Biology and Ecology of Salmonids – Although the general outlines of salmonid biology and ecology are well known, there is a great deal of specific information that is still missing. For example, as noted in Box 5 above, we do not know enough about the behavior of salmon smolts during downstream migration and how survival rates during migration relate to characteristics of river flow. Development of "integrated rule curves" for regulated rivers compatible with the needs of all native species remains an important challenge, as does a thorough assessment of opportunities for retaining more water in river systems through water exchanges or altering timing or sites of withdrawal. Genetic diversity among salmonids is highly valuable, but we do not know what rates of genetic exchange among populations are appropriate to ensure viability of populations. The relationships of salmon to other native and non-native fish are also areas where more knowledge would be helpful. Native fish communities in many western rivers are severely threatened by introduced plants and animals, and salmon in large river basins are often eaten or out-competed by introduced species. Research to address competitive and predatory interactions of walleye, bass, catfish, shad, and other introduced species with salmon is overdue. Results need to be incorporated into Federal and state policies for non-native species management. Predation by migratory birds and marine mammals, two other categories of protected species, also significantly impacts salmon, and an improved understanding of the ecological relationships among these animals would be helpful to the establishment of improved practices to reduce management conflicts. Federal research to foster more balanced ecosystem and community approaches to species protection is needed.

Hydropower - Although much of the blame for salmon declines in the Pacific Northwest has been attributed to hydropower, much work has already been done to reduce hydropower's impacts and raise salmonid survival levels. Additional research could, however, substantially improve our understanding of the relationships between salmonid survival and the creation of more "natural" seasonal river flows and more normal temperature regimes and migration and passage routes. Improved technologies might still be able to make large dams passable by both adult and juvenile salmon, but this is not a certainty. A Federal role in refining and deploying these technologies if they prove effective would help both Federal and non-Federal (Federal Energy Regulatory Commission-licensed) projects. The cumulative indirect effects of passing multiple dams during migration are also uncertain, and the effectiveness of transporting juvenile salmon to the estuary by barge or truck to bypass multiple dams and reservoirs is still controversial. Because dams convert rivers to reservoirs, they are also a source of indirect effects on habitats and ecological communities, contributing, for example, to loss of spawning sites and subjecting salmon to increased predation by introduced predators in reservoirs. Hundreds of small non-hydropower dams, many related to irrigated agriculture, also block access to spawning and rearing habitats in headwaters in the U.S. and Canada. These could be fitted with passage or breached, and alternatives to damming developed. Water budgets (basin-wide, annual rule curves for water storage and release) need to be rigorously evaluated to determine what is actually being accomplished for survival of salmonid populations. If basin-wide water management can be shown to accomplish some of the objectives of dam breaching, it should be more effectively used. Water budgets and rule curves are hypotheses to be evaluated through adaptive management. Because Federal agencies manage much water storage and use, a strong Federal role is logical.

Freshwater Habitat – The freshwater phase of anadromous salmonid life histories can last from a few months to several years, but it is always a phase in which great mortality occurs. It is thus vitally important to understand how freshwater habitats have changed, how those changes have affected the fish, and how best to restore the aspects of habitat most critical to salmonid survival. Altered and reduced instream flows and dramatic changes in both instream and riparian structure have changed the physical dynamics of habitat maintenance in rivers, and natural restorative processes no longer occur. Research and adaptive management on both site-specific and watershed scales are needed to determine what natural processes are critical to salmonid survival and then reintroduce them, if possible. Experimen-tation on Federal lands would provide examples for later implementation elsewhere. Many habitat modifications are also related to agriculture, which has diverted stream water for irrigation, drained wetlands important for salmon rearing, encouraged river channelization to reduce flooding and allow riparian tilling, pumped groundwater reducing natural cooling of streams, and made other landscape modifications that have been detrimental to salmon. Spent salmon carcasses are important to nutrient-deprived freshwater streams because of the nutrients they contribute that sustain many aspects of terrestrial and aquatic ecosystem function. Such ecological values have not been considered in the setting of harvest quotas and escapement goals.

Ocean and Estuary Effects – The marine and estuarine environments represent areas of major knowledge gaps. Estuaries, where freshwater rivers enter saline coastal waters, pose particular challenges for salmon moving in both directions since their physiological systems for regulating the amount of water in their bodies must be reworked during this transition. Today, water pollution, dredging, shoreline development, and altered seasonal freshwater flows often intensify the already substantial stresses that salmon withstand as they move through the estuarine environment. Unfortunately, not enough scientific attention has been paid to this phase of the salmon life cycle. The marine environment is also a mystery and a source of essentially uncontrollable influences on salmon. It is clear that ocean conditions can have a significant impact on the overall production of all species of Pacific salmon, with climate and ocean the oceanic food chain as well as in the basic structure of the coastal marine ecosystems occupied by salmon. Basic research is needed on where and when fish occur in the estuary/ocean and the environmental factors (often cyclical) controlling occurrence, survival, and harvest. An improved understanding of estuarine degradation caused by urbanization and agriculture is also needed. The Federal role is logical for oceanographic and estuarine studies.

Harvest – Salmon runs are subject to substantial levels of harvest by commercial, sport, and subsistence fisheries, although the magnitude of allowable harvest for some populations has been reduced dramatically, with accompanying large economic impacts. There are still, however, issues that remain to be resolved: incidental harvest, release mortality, allocation, mixed-stock fisheries, critical harvest locations, insufficient monitoring and control of some forms of harvest, aquaculture, and ways to reduce social, cultural, and economic effects. If a return to substantial harvests for tribal, commercial and recreational fishers is to be the ultimate goal of recovery, coordinated action is required that can be led by Federal funding.

Hatcheries – There is substantial disagreement over the extent to which artificial propagation programs contribute to or detract from the survival of naturally reproducing populations. Proponents have asserted that hatcheries have slowed the decline of some populations, while critics question whether artificial propagation has succeeded in achieving either conservation or harvest goals. Basic data on the extent to which hatchery fish are spawning in the wild and on the reproductive success of hatchery fish and the progeny of hatchery-wild fish crosses are lacking. Also lacking are data on the role of hatchery fish in producing adverse effects, such as disease and genetic deterioration, in wild populations. Hatcheries are now undergoing a detailed effectiveness review under the auspices of the Northwest Power Planning Council. Because many hatcheries are Federal (e.g., Mitchell Act), a Federal lead in implementing recommendations (perhaps including subsidies to non-Federal facilities) can be essential.

Research for Intensive Management - As salmon decline, management for recovery of stock remnants will become more and more intensive. To recover stocks that have dwindled to only a few hundred—or worse, only a few – individuals, extreme measures may be required, such as captive rearing of fry for release in the wild or archiving of genetic material. These activities might buy time while issues of ecosystem restoration are addressed. Because of high levels of intervention, intensive management is likely to be stressful to fish. and reduced fitness (that is, reduced ability to produce healthy young) can become a substantial issue. Disease, as well as outcomes such as delayed mortality and disease transmission in captive-raised fish, need to be understood. These engender science needs that are complimentary to life cycle risk issues in wild fish and hatchery/wild genetic or behavioral issues.

To sum up for this first group of science needs, the overwhelming majority of scientists involved with salmon research and management agree that an ecosystem approach and provision of appropriate habitats for maintenance of full and diverse life cycles are necessary to return salmon from the edge of extinction. We would be remiss if these were not a focus of scientific activity for sound salmon management.

But the use of a broad ecosystem perspective does not imply that scientists should be asked to seek to understand everything about the environment of the salmonids before any actions are taken. This would clearly be inappropriate given the potential for more stocks disappear. It also does not mean that the preferred solution is to return to pristine rivers, streams, and coastal waters. Considering the pervasive human development of the geographic range of the Pacific salmonids, such a goal would be completely unrealistic. But if restoration to pristine is going too far, what is the alternative?

Every scientific team involved in salmon restoration programs has confronted this dilemma. The Northwest Power Planning Council's Independent Scientific Group, in particular, addressed this issue in its attempt to formulate a new conceptual foundation for salmon restoration in its 1996 report *Return to the River*. It coined the term "normative" to describe a condition to which research and management could reasonably aspire. Referring approximately to "natural" or "normal," "normative" is distinguished from these terms by describing a less-than-pristine norm or standard for conditions sufficient to sustain the critical ecosystem processes needed by salmon. Normative is "partway back" from today's degraded habitats in the direction of the pristine conditions that we know sustained salmon. How far back is determined by the particular needs of the fish (as identified, for example, by cumulative risk analyses) and the degree to which the habitat has been modified by human activity.

The concept of normative establishes a fundamental question to be asked of any development of the salmon's habitat: Does it move the system more toward meeting the ecosystem and life-cycle needs of salmon than away from them? The goal would be to turn our inevitable human development toward those ecosystem needs without necessarily quashing development. This question places an obligation on the scientific community to show what the *essential* needs are and how they might best be met in the context of development and its risks to salmon. "Normative" embraces our best scientific understanding of how ecosystems and diverse life cycles function and are naturally maintained. The question also establishes an obligation to communicate those needs, because development policies and decisions will be made at all societal levels, from local planning commissions to national regulatory bodies, and they need the information science can provide. Technical reports and analytical methods are not stand alone documents for most policy makers or the public. It falls to scientists who develop information that is often complex, detailed, and voluminous to (1) quantify scientific information so that its significance is most readily apparent, and (2) simplify this information to improve communication.

The norm or standard may be applied differently depending on the degree of prior development and the criticality for salmon. For example, a normative condition may mean effective juvenile bypasses and adult fish ladders at dams that work for a diverse array of life histories without requiring dam removal. It may also mean preservation of near-pristine habitats in reserves where successful stocks can reproduce maximally and help repopulate less optimal locations. Development of the knowledge to foster migration of diverse fish runs through bypasses and determination of the number, size, and location of reserves needed to maintain generic stocks are examples of where focused scientific input is needed to establish appropriate norms.

Development of Methods and Tools

Analytical Methods – Analyses of cumulative risks and how these change over time as we apply remedial measures will tell us how well we have repaired the salmon's ecosystem. Analytical methods for this purpose need development, nurturing, refinement, and acceptance to be of value. Pressed by the urgency of salmon declines and economically threatening remedial measures, the search for appropriate analytical methods is urgent. **Box 6** provides four examples of alternative analytical approaches, all of which have both advantages and drawbacks.

Monitoring and Indicators – The necessary interchange among three functional and interdependent domains for sustainability – environment, society, and decision-making institutions – argues for the use of indicators to assess current conditions, simplify and communicate the information, and monitor progress toward ecological, social and institutional goals of sustainability. At the moment, we lack good indicators of the status of salmon stocks, and selection of indicators and establishment of monitoring and evaluation programs to use in ecosystem-based salmon management is an urgent need.

Although "monitoring and evaluation" have too often been afterthoughts at the ends of past agency plans, the determination of what to monitor and evaluate is a serious step in any recovery effort. Some salmon stocks, but not enough, have been monitored for years by counting redds, the gravel spawning beds made by salmon on spawning grounds, or by counting adults passing dams. Although there have been spectacular successes, such as electronic identifier tags for juvenile salmon, we still rely on imprecise measures of stock numbers and ecosystem health. Basic research on monitoring tools (e.g., electronic sensors for fish and stream environments) is needed. Some risk factors have been monitored, such as water pollution, water temperatures and flow rates, but many monitoring stations are being decommissioned because of budget shortfalls. Few management programs have sufficiently monitored the outcomes of their actions. And despite the proliferation of a wide variety of measures, indicators, and indices of ecosystem integrity, none has proved completely satisfying from either a scientific or policy standpoint for characterizing the overall ecological condition of watersheds for salmon and other aquatic resources. More attention needs to be focused on the development and testing of integrated metrics of watershed condition.

Social metrics that are compatible with the needed salmon and ecosystem metrics are also lacking. For example, social data organized according to political or administrative jurisdictions are not spatially consistent with the watersheds, stocks, or ESUs relevant to salmon. If social uses are to be considered part of the ecosystem for restoration purposes, there must be a compatible way to factor in both human and fish futures. For example, decision-makers need to assess proposed salmon policies against alternative human futures for the Pacific Northwest because restoration goals that might be achievable given a regional population of 14 million might be completely unworkable with a population of 50 million.

Testing Technologies – Restoration techniques need to be tested and evaluated. Applications of engineering technologies such as adult fishways, surface bypasses, fish guidance systems, flow regulation, and habitat modifications require study of their effectiveness and iterative modifications to improve their performance. This type of work has dominated much of salmon restoration and has been effective at the level of the individual technologies, although overall salmon recovery has not resulted. Technology applications could probably be more effective if the basic research underpinnings were stronger and there was an emphasis on natural maintenance. We need not engineer all of the salmon's needs if it is possible to recreate the environmental processes (such as periodic flooding) that meet the needs for us at lower social cost. Science can focus on defining those processes.

Box 6

Four Approaches to Quantitative Analysis of Risks to Salmon

To date, there have been four different methods used in the Pacific Northwest to quantify risks to salmon populations and evaluate the relative merits of recovery actions. Each is a method for evaluating our attainment of a salmon-sustaining ecosystem, with or without continuing human subsidy, and each has important distinguishing features. They are (1) the modeling framework of the multi-agency Plan for Analyzing and Testing Hypotheses (PATH) process, (2) models used in the National Marine Fisheries Service's (NMFS's) initial Anadromous Fish Appendix (AFA), (3) the approaches being developed in NMFS's Cumulative Risk Initiative (CRI), and (4) the Ecosystem Diagnosis and Treatment (EDT) models being developed by the Northwest Power Planning Council's Framework process. They represent optional analytical frameworks and a rapid evolution of thinking about the application of scientific information to urgent management decisions. The NMFS proposes application of the CRI to all ESA-listed populations, even though the initial focus of all methods has been on the Columbia River basin. The Northwest Power Planning Council views EDT as a template for watershed habitat improvements in the Columbia River basin.

PATH – The PATH approach uses detailed life cycle and passage (i.e., survival through the hydropower system) models to estimate abundance of salmon in the Columbia River system. Past trends in fish abundance are explored through retrospective analyses that examine the consistency of various assumptions about the functioning of the salmon ecosystem with historical data. Conclusions from these retrospective analyses are then used to project fish abundance under various alternative hydrosystem management actions (prospective analyses). PATH is thus an iterative "process" that defines and tests a framework of hypotheses to reduce uncertainties and characterize relative probabilities for recovery under various management options. The work has involved intensive scientific analyses of fisheries data on index stocks (primarily fall and spring/summer chinook) by a multi-agency team using complex statistical techniques. It did this using an open and inclusive process that provided funding to support participation by state and tribal, as well as Federal, scientists. PATH introduced two general terms, "extra mortality" and "differential delayed mortality" (D) to quantify fish losses otherwise not accounted for. Although highly successful at providing new and informative scientific analyses, the method has been criticized for requiring that too many parameters be estimated and leaving too many untested assumptions for use in management evaluations. Several reports have been published since 1996. Additional information on PATH can be found at: http://www.efw.bpa.gov/PATH/.

AFA - AFA is distinguished by a simplification of the PATH procedures. It originated when the NMFS prepared a draft appendix on anadromous fish, primarily salmon, for the U.S. Army Corps of Engineers' Environmental Impact Statement related to breaching of four lower Snake River dams in early 1999. Although still being modified, it has generated much discussion. The approach was to make use of some of the PATH analyses in a simpler setting, evaluating only a few management alternatives, principally dam breaching and barging. The relative

Box 6

Box 6–Continued

effectiveness of management alternatives for recovery were highly dependent on values assigned to the least definable factors, extra mortality and delayed mortality (D). The AFA was widely circulated for public comment and is available at http://www.nwr.noaa.gov/1hydrop/hpp01.htm.

CRI - The CRI represents NMFS's attempts at a second simplified approach not tied to the history of PATH. It is an analytical framework designed to have broader application for endangered stocks and species than just the Columbia River basin. It is characterized by explicitly quantifying extinction probabilities and provides places in the model to include numerous restoration alternatives organized into the "all H's" realms: habitat, harvest, hydropower, and hatcheries. The CRI also includes "biological feasibility assessments," such as analyses of freshwater habitat production capacity on a landscape scale to evaluate restoration alternatives. The approach is to statistically estimate the probability of extinction and construct life-cycle tables that mathematically depict survival of a stock's population through discrete life stages (e.g., downstream migration). Analyses are performed to assess where in the life cycle (periods of time, not specific risks) there are the greatest opportunities for promoting recovery, as measured by changes in annual population growth rate. The CRI approach does not make use of the mathematical constructs of "extra mortality" and "differential delayed mortality" although the uncertainties they represent are part of the model. The approach has been presented in workshops and as a draft addendum to the initial draft AFA. Reviewers have found that the approach has much promise, but that the specific analyses are at an early stage and in need of refinement. A key commitment is the intention to make all analyses available to the public and simple enough to be repeatable. Further information on CRI is available at http://www.nwfsc.noaa.gov/cri/. Reviews of the AFA and CRI by the Independent Scientific Advisory Board can be seen at http://www.nwppc.org.

EDT - EDT is an entirely different approach that focuses on the quality of the ecosystem in a unit of the physical and biological landscape and the ability of that ecosystem to produce fish, wildlife, and plants. It is being implemented in the Framework process of the Northwest Power Planning Council. EDT combines knowledge about how ecosystems function and produce desired species through a set of rules in an "expert system." This approach takes a long-range view, asking what productivity we can expect of a landscape with particular characteristics in the long term. When the landscape characteristics are changed in the model, the long-term results of different actions (e.g., remedial measures) are expressed. Although the method has been published, it only underwent its first full test in fall 1999. It is described more fully at http://www.nwframework.org/EDT/. A paper comparing the CRI and EDT approaches.

Databases and Information – Current data storage/retrieval and evaluation processes are inadequate for quantitative approaches to salmon recovery. Major rethinking and restructuring are needed, coordinated across all watersheds and states. The Federal government can provide an overall framework for others (states, private organizations), and fund needed work. Traditional methods for sharing scientific information are also inadequate for the urgent needs of salmon recovery. Scientists have always shared information by publication in scientific periodicals. Although still important, public decision-making on salmon science issues requires more rapid availability of information, shared access to the primary data, and an ability to collectively use analytical tools, such as population models.

This report is partly an admonition to policymakers to, where possible, allow science to lead. Allocation of a portion of available research funds to innovative, academic, or even bizarre ideas has potential to yield significant benefits for salmon management in the future. Research directed at further incremental gains in familiar subject areas must be balanced by research to close the many knowledge gaps discussed in this report and summarized above.

In addition, new approaches to conducting salmon science and selecting management options could help to improve the likelihood that new research will produce useful answers and that actions will produce effective results. First, the adoption of a coordinated interagency approach to new scientific efforts could help to reduce the skewing of supported topics toward areas of past agency investment. Coordination might also increase the chances of success in remediation and improve the chances that what works and what doesn't work will be accurately understood. By working together in a coordinated program, the stakeholder agencies are more likely to be able to design a program based on a framework of systematic hypothesis testing to better understand cause and effect in interpreting results. Without such coordination, each agency might be able to pursue certain remediation actions on its own, but evaluating successes or failures would be difficult.

Second, the effectiveness of remediation is likely to be improved by management approaches that take the entire life cycle of salmon into account. In the past, the management process has tended to promote actions negotiated on a case-by-case basis with a focus on minimums - minimum possible flow, minimum reduction in harvest rate, etc. Use of piecemeal "least common denominator solutions" instead of a comprehensive focus on reducing sources of mortality across the life cycle of the salmon has contributed to the failure of past restoration efforts and the continued decline of many salmon populations. A comprehensive approach is also likely to become more feasible as the risks to salmon are better quantified through additional research.

Third, adaptive management, an approach in which future actions can be adjusted in response to the results of current actions, needs to be much more widely employed. Adaptive management is a structured process of "learning by doing." It can provide a useful alternative for gaining understanding of what works and does not work in systems that we do not fully understand because the science is incomplete so that we lack predictive capabilities. Adaptive management can integrate science and action and may allow something to be accomplished on the ground in the short term, satisfying the need for both immediate action and for more information.

A Strategy for Project Prioritization

Having a goal of systematically quantifying all risks to each stock throughout its life cycle in order to rank and remediate the most important ones would set an impossible task for science. Even if the definition of a "stock" were unambiguous, there are too many risks in a complete ecological setting to quantify practically. Furthermore, each risk factor varies in relative importance over time with fluctuations in the environment. Given our understanding of environmental and biological diversity, it might be counterproductive to seek to quantify the risks that on average are the most important. In contrast to this data-hungry and costly approach, risk-based assessment could go to the other extreme of using very little data. This strategy increases the chance that something important important might be overlooked.

As a compromise, we can seek guidance from the fish populations themselves and let the ecosystem do as much of our work as possible by recognizing nature's own winnowing of risks, which normally creates year-to-year variation in abundance of salmon stocks. Cycles of "good years" leading to peaks in population numbers and "bad years" leading to lows in abundance are characteristic of salmon in the wild. Clearly, something goes right for stocks when numbers rise from year to year, and something, perhaps many things, go wrong when stocks decline. It may be helpful to focus in part on determining and quantifying the risks that were minimized in the good years than to attempt to deconvolute the multitude of risk factors acting negatively in bad years. Recognizing that there will always be "good years" and "bad years" over time, remediation could seek to maximize the conditions that contribute to good years.

For example, consider a fall chinook stock in a river draining into California's Central Valley. As one moves upstream, there are multiple risk factors operating through San Francisco Bay, the Bay-Delta area where the Sacramento and San Joaquin rivers merge into a vast and agriculturally modified wetland, the upper Delta where water is diverted to Southern California, the lower tidal river where irrigation drainage adds toxic materials and warm, silty water, the upper river where low flows can impede adult migration, and the spawning reaches where upstream dams have lessened the amount of available spawning gravel and completely blocked historical spawning grounds further upstream. Characterizing and quantifying the risks to salmon at every step of the way up river and back (even excluding the ocean) is daunting. Yet examination of the history of fish abundance in this river shows that there have been series of years that were especially productive for these fish, when their numbers rose for several years in a row. Especially good years seemed to come when five conditions were met: (1) fall flows occurred in peaks that stimulated upstream movement by adults holding in the Delta, (2) fall flows were high enough to provide water depths of 10 inches or more at several critical rapids, (3) there were stable water flows in winter that did not expose redds to drying, (4) spring high flows occurred in a critical 3-week period when juveniles were physiologically ready to migrate downstream, and (5) water diversions from the Delta were low in the two weeks immediately following peak smolt outmigration from the river. Although many other risk factors were still operating at unknown levels, these five conditions seem to have made a difference in success. Success by itself has prioritized the risks for us. Science can now focus on further quantifying the key risks sufficiently to allow their management for benefit of salmon.

In addition, therefore, to continuing efforts to quantify the risks already recognized, we could also place priority on examining carefully the success of stocks for important additional clues to effective remediation. A set of scientific evaluations could be conducted of ecological conditions in the full life cycles of geographically representative salmon stocks that contribute to the success of those stocks. The objective would be to identify key risk factors that can be managed to mimic the fortuitously occurring successes of the past. Stocks could be selected for analysis from Northern Alaska to the Central Valley of California, with weight being given to those stocks with sufficient numbers remaining that year-to-year variations in productivity are evident.

Summary

Failure to stem the decline of salmon populations is due, in part, to an inadequate scientific base for management actions. Institutional shuffling and further funding will not have the desired beneficial effects so long as scientific deficiencies remain unaddressed. Nonetheless, there is hope for both improved scientific information and salmon recovery.

The overwhelming consensus among scientists is that an ecosystem-based salmon recovery program that concentrates on meeting the life-cycle requirements of a large range of specific stocks has the highest potential for improving overall fish populations and is best founded in scientific evidence.

Diversity of habitats and the resulting diversity of stocks are essential for long-term persistence in the face of unstable and human-altered freshwater environments and an ocean that undergoes cyclical changes in currents, temperatures, biological productivity, and ecosystem composition. Suitable habitats must remain connected so that the migratory salmon can move among the different habitats needed by different life stages, and at the correct times.

The human-altered salmon ecosystems of the lower 48 states and British Columbia can benefit from comprehensive assessments of risks to salmon populations (natural and anthropogenic) throughout their life cycle. The contributions of key sources of mortality need to be quantified so that remedial measures can be focused on the most significant threats. However, quantification of all risks in order to establish which are the most important is probably unrealistic. A complementary alternative might be to focus in part on evaluating conditions in good years that promote salmon production to identify ecosystem factors that might be recreated to produce substantial benefits.

Consideration of what is normal should accompany evaluation of what causes excessive mortality. Priority should be given to defining the normative condition, that is, the condition that is not simply pristine, but rather provides essential salmon requirements in an ecosystem that includes humans. Normative is preferably a condition that has as many self-sustaining aspects as possible and requires the least amount of continued human intervention and investment. The means to reestablishing normative conditions will vary by location depending on the degree of human alteration and the needs of salmon. They can range from providing dam bypasses that match the migration behavior of fish to preservation of refuges and reserves in remaining near-pristine habitats.

The necessary interchange among three functional and interdependent domains – environment, society, and decision-making institutions – argues for the use of indicators to assess current conditions, simplify and communicate the information, and monitor progress toward ecological, social and institutional goals of sustainability. (**Figure 18**) Selection of indicators and establishment of monitoring and evaluation programs to use in ecosystem-based salmon management is an urgent need. It falls to scientists who develop information that is often complex, detailed, and voluminous to (1) *quantify* scientific information so that its significance is most readily apparent, and (2) *simplify* this information to improve communication.

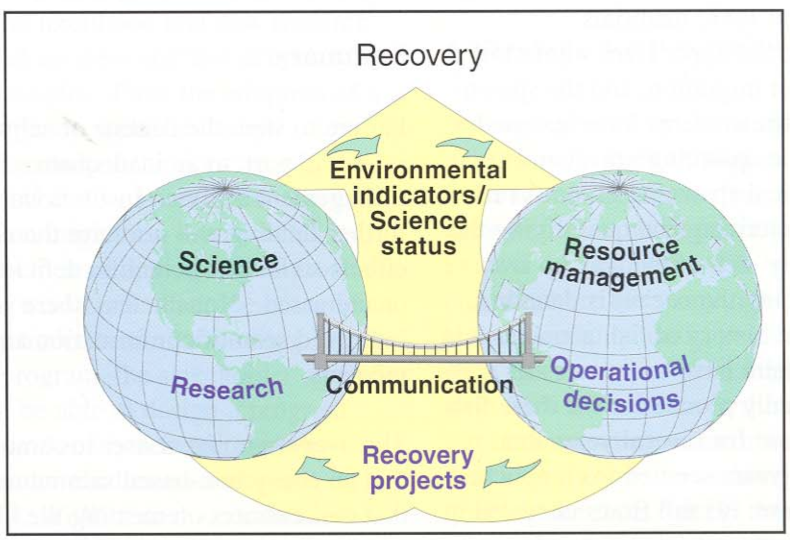


Figure 18. Recovery of Pacific Coastal Salmon will require constant communication between scientist and managers in order to complete a feedback loop of monitoring and design of recovery actions.

PART III
A NEW INTERAGENCY EFFORT IN SCIENCE COLLABORATION

In April 1999, Neal Lane, the Assistant to the President for Science and Technology, and George Frampton, the Chair of the Council on Environmental Quality, asked the Committee on Environment and Natural Resources (CENR) of the National Science and Technology Council to lead an effort to strengthen the science underpinning the restoration of Pacific salmon and its Federal coordination. The CENR charged its Subcommittee on Ecological Systems (SES) to undertake this task. In response, the Subcommit-tee established several new activities directed at enhancing and better coordinating Federal science and information on Pacific salmon and other related species to improve the knowledge resources available for current and anticipated resource management needs. First, the Subcommittee and the Office of Science and Technology Policy (OSTP) commissioned the preparation of this report to obtain an independent assessment of the science needs related to salmon and salmon recovery. Second, the Subcommittee convened a new Interagency Salmon Science Team. This Science Team is made up of a group of scientists from the Pacific Northwest regional offices of the Departments of Agriculture (Forest Service), Commerce (National Ocean Service, National Marine Fisheries Service, Office of Oceanic and Atmospheric Research), Defense (Corps of Engineers), Energy (Bonneville Power Administration), and the Interior (Bureau of Land Management, Bureau of Reclamation, Fish and Wildlife Service, U.S. Geological Survey), the Environmental Protection Agency, OSTP, and the Northwest Indian Fisheries Commission. The Science Team met under the Subcommittee's auspices to consider the report, evaluate existing Federal research programs, meet with managers in the Pacific Northwest region to discuss their needs, and plan future directions in light of the science needs identified through this effort.

Appendix B contains a statement, "Science Needs for Pacific Salmon and Related Species," that was developed by the Science Team. This consensus document outlines a set of broad topics deemed to be the most important for modifying the future research portfolio to address scientific uncertainties and is consistent with the findings presented in this report. This needs statement has been circulated to the agencies to encourage them to incorporate its science priorities in their planning for the FY 2002 budget request and beyond.

To support the science needs analysis the agencies reviewed their own research programs and exchanged information about on-going projects. They are currently discussing the creation of an on-line database for salmon science projects that would eventually be publicly accessible. Such a database could aid scientific collaboration, assist in refining of our understanding of knowledge gaps and assessing current efforts, and facilitate coordination.

Finally, SES was also asked to develop a new strategy for information sharing to make information needed for effective conservation and restoration measures more available and accessible. The intent is to enable and encourage the assembling and use of information by taking advantage of new tools, such as geographic information systems and decision support systems. Its purpose is to aid resource managers and communities to access information, visualize the impacts of their actions, and help citizens and policy makers make informed collaborative decisions. A group of interested state and Federal agencies as well as non-governmental organizations participated in a series of meetings to define a set of information-related activities.

The SES also convened a Workshop on Decision Support Systems (DSSs) for salmon and related species in March 2000. A DSS is an interactive computer-based system intended to help decision makers use data and models to identify and solve problems and make choices. It may be an Internet-based network of databases, hardware, software, models, and other tools. Participating government, academic, and private sector organizations would develop and maintain the network so that its information resources can be combined in ways that address the needs of all stakeholders. There are currently a number of efforts ongoing in the Pacific Northwest to create decision support systems by linking existing databases, models, and tools. Because there has been little cooperation among groups to date, each effort has had to invent many system elements with considerable effort and cost. Creating a linked network would, therefore, have advantages to all participants in allowing access to data and tools developed by others. The workshop resulted in a general consensus to further explore the idea of a DSS for salmon. The participants agreed to begin to create an inventory-of existing models, tools, and systems so that any missing pieces can be identified. In addition, they called for the development of a strategy for a DSS, including an analysis of costs and benefits to managers and others.

The Interagency Salmon Science Team will continue its work into a second year. Goals and objectives for future activities include (1) developing an interagency budget initiative for FY 2002 and beyond and expanding collaboration in salmon science research among the Team's member agencies; (2) enhancing collaboration and cooperation with states, tribes, non-governmental organizations,universities, and others; and (3) enhancing scientific and technical support for management and recovery of Pacific salmonids, including improving transfer of scientific information to policy makers. Specific tasks being planned include organizing a major symposiumto summarize the state of science pertinent to issues of interest to policy makers; completing the development of an on-line inventory of salmon research projects that will be accessible to all who are interested in management and restoration of Pacific salmonids; and expanding the Team's initial work promoting sharing of information for salmon restoration and recovery.

PART IV
REFERENCES AND ADDITIONAL INFORMATION SOURCES

URLs for Salmon Databases in the Pacific Northwest

University of Washington: http://www.cqs.washington.edu/
StreamNet: http://www.streamnet.org/index.html
NMFS Northwest Fisheries Science Center: http://research.nwfsc.noaa.gov/
Corps of Engineers: http://www.usace.army.mil/inet/functions/cw/cecwo/reg/techbio.htm
NMFS Northwest Region: http://www.nwr.noaa.gov/1salmon/salmesa/index.htm
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Resource Guide to Indicators by the Green Mountain Institute:http://www.gmied.org

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APPENDIX A. COMMON GROUND: DISAGREEMENTS AMONG COLUMBIA RIVER BASIN PLANS

The Independent Scientific Advisory Board (11 independent scientists screened by the National Academy of Sciences as an advisory body for the salmon restoration efforts of the National Marine Fisheries Service and the Northwest Power Planning Council) identified the major points of agreement and disagreement among several reports and plans for salmon restoration in the Columbia River basin. The reports evaluated included:

- the Independent Scientific Group's report *Return to the River* (ISG 1996);
- the National Research Council's report *Upstream* (NRC 1996);
- the draft report of the interagency task force on management of Federal lands in the interior Columbia River basin, subsequently issued as a report of the US Forest Service and Bureau of Land Management (USFS/BLM 1997);
- the National Marine Fisheries Service's 1995 *Proposed Recovery Plan for Snake River Salmon* (NMFS 1995); and
- the Columbia River Inter-Tribal Fish Commission recovery plan *Wy-Kan-Ush-Mi Wa-Kish-Wit, Spirit of the Salmon* (CRITFC 1995).

Points of agreement were discussed in the text of this document, with only brief comments about points of disagreement, which are further amplified here for the sake of completeness.

Conceptual Foundation

Lack of consensus: Two of the reports (NMFS and CRITFC) stress tactics for implementing strategies and goals whereas the others define a set of principles for governing ecosystem function. Differences arise in implementation. Three of the reports (NRC, CRITFC, and NMFS) distinguish actions needed to sustain long-term recovery from short-term actions needed to prevent further declines and extinction. The reports differ in acceptability of short-term actions. The tribal plan (CRITFC) differs from the other reports in that it directly addresses the cultural, economic, and religious significance of the salmon to the Columbia Basin's native peoples.

Natural Variation, Climate Change, and Ocean Productivity

Lack of consensus: There were no major areas of disagreement, but reports generally ignored whether hatchery production during periods of low ocean productivity constituted competition with wild stocks.

Habitat

Lack of consensus: There were no major areas of disagreement. Two plans (CRITFC and NMFS) sought in-stream habitat standards based on the defined needs of salmon; others emphasized restoring the full range of natural conditions.

Artificial Propagation

Lack of consensus: Reports were divided over the extent to which artificial propagation programs have contributed to the survival of naturally reproducing populations. CRITFC and NMFS asserted that hatcheries have supported fisheries and slowed the decline of some populations, while the NRC and ISG reports found relatively little evidence that artificial propagation has succeeded in achieving either conservation or harvest goals. The reports were sharply divided over the issue of supplementation—using artificially propagated fish (with local broodstock where possible) to augment wild populations with the goal of building sustainable natural runs. CRITFC advocated supplementation over broad areas; NMFS was supportive of existing programs albeit with precautions against genetic and other potentially harmful effects. The ISG and NRC reports were skeptical of supplementation. The reports did not agree on the use of artificial propagation as a tool for supporting harvest. The CRITFC report questioned the ESU concept with respect to introduction of salmon from one watershed to another (which they view as essential if salmon are to be reintroduced to locations where original stocks were extirpated).

Hydroelectric Development and Operations

Lack of Consensus – Lack of consensus centered on several types of effects, including flow-survival relationships and flow augmentation, transportation, reservoir drawdown, and structural and operational improvements at mainstem dams. Not surprisingly, these are the main alternatives currently under intense evaluation related to proposed dam breaching on the Snake River.

- *Flow-Survival Relationships and Flow Augmentation* – There was no clear consensus, and considerable uncertainty, regarding relationships between river discharge (flow) and fish survival, and the efficacy of managing flows to provide more water at certain times (augmentation). The ISG stated that a complex and variable relationship exists between flow and survival, but that it has been oversimplified to a relationship centering on water velocity and travel times for juveniles in reservoirs. This simplified view is inadequate for a full range of life-history types and stocks. The flow management strategy does not consider inherent variation in natural migratory behavior. A natural seasonal pattern of flows is desirable for ecosystem processes. The NRC stated that it is doubtful that declines in Snake River Salmon have resulted from or are reversible by seasonal changes in flow regime alone. NMFS asserted a direct relationship between juvenile survival and flow, although it is difficult to determine the exact mechanism by which increased flow increases survival or which flow level is ideal. The natural hydrographic conditions under which the species evolved are best. CRITFC argued for flow augmentation to achieve mean historical flows during juvenile migration periods. Major uncertainties included (a) the amount of flow needed to achieve a specific survival rate for all species and life history types; (b) the mechanisms underlying effects of increased flows, which are complex and poorly understood; (c) the complex migratory behaviors of juvenile salmonids, which the present flow management strategy does not take into account; and (d) the benefits of trying to duplicate in reservoirs the natural or historical hydrographic conditions that existed in a free-flowing river.

- *Transportation* – Juvenile salmon are hauled by barge or truck from upstream dams to the estuary as a way to bypass the risks of passing multiple dams and reservoirs. Although there was consensus among the documents that transportation alone would not be sufficient to overcome the negative effects of habitat loss and would not halt the decline of Snake River salmon, there was no clear consensus on the role of transportation as a mitigation strategy and considerable uncertainty. Views on transportation ranged widely among the documents. The ISG report was skeptical of the evidence for the efficacy of transportation. Concerns were expressed about impacts on life history and stock diversity. The NRC report identified evidence for survival of transported fish exceeding that of in-river migration and recommended continued transportation as long as this relationship existed. Research should evaluate the effectiveness of transportation. CRITFC found only evidence that transportation should be halted. NMFS asserted that available empirical data indicate that transportation benefits Snake River spring/summer chinook and is likely to benefit Snake River sockeye and fall chinook. Transportation of juvenile fish was supported under most conditions. Research should be conducted to evaluate the effectiveness of transportation. Major uncertainties include the (a) impact on homing ability of adult salmon; (b) effectiveness of transportation if evaluation is based on successful returns to a hatchery or successful reproduction on the spawning grounds, rather than adult returns to the point where tagged juveniles were released; and (c) impacts on life history and stock diversity .

- *Drawdown of Some Reservoirs to Natural River Levels or Spillway Crest* – Most documents agreed that drawdowns of this nature would have large-scale social and environmental impacts and that there are major biological, economic, and social uncertainties associated with such drawdowns. The feasibility of drawdowns, including the ecological, economic and social costs and benefits, was not agreed upon. The CRITFC plan asserts that evidence is already sufficient to implement drawdowns. NMFS contends that before drawdowns are considered, both the transportation option and methods to improve in-river migration conditions should be tested.

- *Structural and Operational Improvements at Mainstem Dams* – The reports differed in the specific structural and operational modifications that were deemed to be justified. All documents supported efforts to modify the structure and operation of hydropower projects to improve survival of downstream migrating juveniles and adults. There is a general agreement on the need to proceed with a dissolved gas abatement program to reduce levels of supersaturation. The NRC and ISG reports called for a better understanding of migratory characteristics of salmon in order that structural and operational improvements be oriented toward the natural migratory patterns of salmon.

Harvest

Lack of consensus: Lack of consensus on harvest was mostly a matter of different degrees of specificity. The ISG and NRC reports focused on general principles whereas the others were more detailed.

Institutions

Lack of consensus: The reports differed considerably on their specific recommendations for institutional reform.

Monitoring and Evaluation

Lack of Consensus: There was no fundamental disagreement.

APPENDIX B. INTERAGENCY SCIENCE NEEDS STATEMENT

Science Needs for Pacific Salmon and Related Species

I. Integrating Habitat Influences on Aquatic Productivity

Many environmental and human factors act on salmonids during their entire life-cycle, from their outmigration from headwaters of rivers to the sea, during their time in the sea, to their return to headwaters as adults. Native fish species that are not anadromous also may rely on a variety of riverine habitats to complete their life cycle. Traditionally, these factors have been considered in isolation. A comprehensive life-cycle approach that addresses both natural variability in environmental conditions and human impacts on physical, chemical, and biological processes that affect salmonids is critically needed to define the relationship between habitat and salmonid productivity. Understanding this relationship is critical to conserving and restoring habitat that will meet population-based salmonid restoration/recovery and conservation goals. Such studies will include habitat use by life stages, the barriers to safe passage, and physical, chemical, and biotic conditions at a watershed scale. Also, the role of ocean environments, estuaries, instream flow, and water quality issues, such as temperature and contaminants, need to be studied. These will be necessary to assess the cumulative effects of human influences in headwater streams (logging, mining, agriculture, introduction of non-native species), main stem rivers (dams, recreation, agriculture, development), estuaries (dredging, filling, contamination, urbanization, agriculture), and the ocean (harvest and marine productivity). Based on such an integrated analysis, protection and restoration/recovery strategies can then be developed to help account for natural fluctuation and changes in environmental systems, such as ocean circulation and climate.

II. Determining Needs, Goals, and Means

What levels of protection and restoration/recovery activities are needed to maintain and rebuild salmonid populations sufficient to meet Federal trust and species protection mandates? Which protection and restoration/recovery strategies are effective, what actions should be undertaken, and where and when should they be applied? The huge geographic scale and complex life cycle characteristics of anadromous salmonids require a careful, integrated assessment of what is effective and what is achievable. Species such as bull trout and white sturgeon will present other characteristics that must be considered in developing restoration/recovery strategies. For both short and long-term success, strategies to sustain aquatic productivity must be practical, work with nature, and account for competing resource uses. Restoration/recovery must proceed with due consideration of consequences for other native species. Evaluating "achievability" will require development of linked models that account for the natural progression of past and future watershed conditions. These models also must be capable of simulating various combinations of "preferred" habitat, hydropower, hatchery, and harvest conditions with respect to their overall ability to sustain productivity of particular salmonid stocks. Specific protection and restoration/recovery strategies need to be evaluated on sound scientific criteria that explicitly consider practicality, permanence, and effectiveness.

III. Identifying and Characterizing Populations

Independent populations must be identified before they can be restored/recovered. Populations often are adapted to specialized ecological and habitat settings, and restoration/recovery of self-sustaining populations may often depend upon conserving the capacity of a particular group of fish to adapt to a particular habitat. Additionally, populations are often the fundamental unit of viability analyses, so effectively evaluating the status of a species may depend on correctly understanding its population structure. Several types of data and analyses are required to identify the populations and metapopulation structures recognized by the Endangered Species Act. On a landscape scale, this requires an understanding of how different salmonid populations are distributed within watersheds. Finally, for restoration/recovery to work, there must also be some understanding of how these distinct populations individually respond to environmental variables that are likely controlled by very different limiting factors. Sub-watershed and site-specific restoration/recovery actions must be tailored to specific populations and to their particular environmental and biological attributes.

IV. Understanding Habitat Processes at Different Scales

Habitat for salmonids and all native aquatic species, and hence their populations, are strongly influenced by watershed conditions at a landscape scale. Modification of land cover and ecological processes by urbanization, transportation, logging, agriculture, or grazing, for example, can alter the riparian environment, stream flow regimes, fish passage conditions, water quality, and physical characteristics of streams (geomorphology), and can decrease or eliminate the connectivity of habitats important to metapopulations of salmonids. Modeling and decision support tools are required to incorporate land use change relative to habitat on this extensive spatial scale, and must incorporate temporal changes (habitats are dynamic). These models also need to be verified, and compared for their utility in assessing the sources and impacts of uncertainty, to effectively guide and evaluate restoration/recovery efforts. Development of this understanding requires better knowledge of specific watershed processes, such as determining how grazing and silviculture (forestry) can be managed optimally for both riparian and stream habitat protection, and how land use affects instream flow and sediment dynamics.

V. Understanding Ecological Processes That Limit Populations

Basic aquatic ecological processes have significant effects on the population dynamics of salmonids. Many of these processes are understood poorly. Ecosystems research, from the headwaters through the ocean, is needed to understand how these processes affect the survival of salmonids throughout their life. For example, the creation of reservoirs on the Columbia River favors voracious predators, such as northern pikeminnows and introduced game fish, which feed on outmigrating juvenile salmonids. Effects of predation and other ecological processes have largely been estimated rather than empirically measured. Research is needed regarding interactions between native and invasive species (including predators, prey, food chain organisms, and those that alter habitat structure); how competitors respond to altered systems and to restoration/recovery actions; and how food supplies have been altered and how they can be restored. Marine-derived nutrients from the carcasses of spawned out salmonids appear to be critical in sustaining stream and riparian productivity, but this process, and how restoration/recovery should proceed, are not known. The role of physiological stress on the fitness of fish, as induced by altered environments (e.g., higher water temperatures, contaminants) or by intensive management such as captive broodstock operations (for severely reduced stocks), and fish transportation also need to be better understood to improve management strategies. Disease, exacerbated by environmental stress, is a major concern both in the wild and in intensive management situations. Understanding the effects of these factors on fitness of individual fish can be addressed with modern techniques ranging from molecular biology to physiology and epizootiology. This information is critical in developing full life cycle models for many species.

VI. Understanding Genetic Requirements and the Role of Hatcheries

Hatcheries, while continuing to meet legally-mandated mitigation requirements, must successfully evolve from a strict focus on fish production to one that is consistent with recovery and restoration of wild populations. This change should occur in two ways: (1) promote recovery of wild populations (for example, through supplementation under an adaptive management approach) and (2) produce fish that have minimal adverse ecological or incidental harvest effects on wild populations. Artificial propagation of a listed salmonid species is not a substitute for eliminating the factors causing or contributing to the species decline. The intent of using artificial propagation for the recovery of listed species is to facilitate the rapid restoration of naturally sustainable populations. However, under current environmental conditions, many biologists and managers consider artificial propagation to be essential for the continued existence of some listed species. The use of captive broodstock and associated propagation techniques that can help recover wild fish must include genetic, physiological, ecological, behavioral, and fish cultural insights that can only be acquired through scientific research – for example, on the emerging promise of conservation hatcheries, genetic management planning, hatchery/wild genetic and ecological processes such as domestication selection, and hatchery/wild genetic crosses. How can hatcheries maintain genetic, behavioral, physiological, and ecological adaptations to natural environments? Under what conditions can conservation hatcheries be expected to provide a net long-term benefit to viability of wild populations? How can adverse ecological effects of hatchery fish on wild populations be minimized? What foods, rearing conditions, and hatchery management practices can favor the establishment of self-sustaining wild runs? Are hatchery fish subject to delayed mortality or other fitness losses in the marine phase of their life cycle? Production-scale evaluations of genetic, husbandry, and other artificial propagation strategies will be needed. This research will help align the Pacific Northwest's huge investment in hatcheries more squarely with recovery and restoration.

VII. Developing Alternative Futures

How will restoration/recovery activities interact with land use and human population growth to affect species requiring protection and restoration of their habitats? On a watershed scale, basic research and modeling is needed to evaluate the consequences of alternative scenarios on both ecological and socioeconomic variables. The many different elements of habitat and water protection and restoration activities need to be considered together, rather than one at a time, to determine in advance which alternatives can yield the greatest benefits, and the level of uncertainty associated with each. Alternative futures analysis may provide synthesis products that enable fish managers and the public to understand the range of outcomes prior to making the major investments.

VIII. Monitoring and Evaluating Actions

Monitoring and evaluating actions taken to protect and restore/recover listed salmonid species will be a key element of the process. Effective monitoring should provide measures of success and reduce uncertainty, leading to improved adaptive management and policy decisions. However, because of the complexity of the causes for salmonid declines, the huge geographic range of the planning areas, the numbers of species and different life histories, and the multiplicity of agencies and stakeholders involved, the monitoring of salmonid restoration/recovery efforts, and evaluation of the efficacy of actions, will be a daunting scientific task indeed. Major issues include establishing restoration/recovery activities within a context of specific experimental designs with predictions and measured outcomes; assessing baseline conditions; rapid assessing of efficacy to allow for adaptive management; and monitoring at appropriate scales, both spatially and temporally. Research efforts in these areas will greatly enhance the scientific credibility of salmonid restoration/recovery plans by providing timely feedback to management and policy.

IX. Integrating Science and Community-based Values for Decision Making

Public policy decisions must combine economic, political, social, cultural, ethical, and esthetic interests with relevant scientific information to make decisions that are best for society as a whole and that ensure the legal interests of Native Americans are protected. To ensure that relevant scientific information, including socioeconomic information, is available to decision makers in a useful format, a structured process is needed to involve community stakeholders and tribal governments, and their issues, values, and priorities. Advanced geographic information systems (GIS), decision support systems, and visualization techniques are needed to present the scientific information and management alternatives in a form readily comprehensible by a non-technical decision maker and the public. The costs, benefits, risks, and opportunities associated with management alternatives must also be identified and presented. This will assist the decision makers in optimizing restoration/recovery actions based on community values and relevant scientific information.

Abstract

From the Edge: Science to Support Restoration of Pacific Salmon was prepared by the Committee on Environment and Natural Resources in response to a request for a scientific assessment of the risks to salmon throughout their life cycles and of the role of mitigation and recovery options in reducing these risks. Gaps in scientific knowledge and priorities for addressing these gaps were also to be identified. Part I of the report provides an overview of the problem of deteriorating salmon populations, describing the ecology and status of the fish and the multiplicity of factors contributing to their decline. Part II discusses the science needs for remediation, reviews the findings of several management-oriented science summaries, discusses the role of science in a restoration program, and points out the importance of indicators for monitoring the status of salmon stocks and the magnitudes of risk factors. Part III describes the activities of a new interagency working group on salmon. A brief science priorities paper upon which the members of the working group have agreed can be found in Appendix B. This report should prove useful in the preparation of Federal budgets over the next several years. The report is not intended to advocate a particular option or set of options for salmon recovery. Rather, it is designed to provide an overall picture of what is known and where there are knowledge gaps that could be addressed to support recovery.

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